MARMARA UNIVERSITY

FACULTY OF ENGINEERING

DESIGN OF WOOD CHIPPER FOR TRACTOR

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GRADUATION PROJECT REPORT

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Design of Wood Chipper for Tractor

by

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June, 2022 Fatih GÖRGÜN

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ABSTRACT

Design of Wood Chipper for Tractors

Wood has been one of the basic materials used almost everywhere since the beginning of human history. It is still used in almost everything from kitchen appliances to furniture, from construction to ornaments. Due to the fact that we can process wood in different ways thanks to today's technologies, the use of wood has increased rapidly, as it paves the way for the diversity of wood use. The subject of this project is the design of wood chipper, which is one of the types of wood processing. Today's global world obtains wood chips from different tree species in different sizes. While the purpose of use is determined according to the size of these chips, the distribution of the specific size within itself determines the quality of the chips. Thanks to this research, calculations were made about how the wood chipper machines decide on the size of the chips, what factors affect this size, and what power engine should be used.

SYMBOLS

d: Diameter of the wood, cm

ε: Spout angle, degree

L: Length of the chip, mm

α: Clearance angle, degree

β: Edge angle of the blade, degree

H: Knife height, mm

R_c: Cutting radius, mm

i: Number of blades

E: Specific cutting energy, J/m^3

J: Joule

m: meter

F_c: Force acting in the direction of cutting, N

F_t: Thrust force, N

P_r: Resultant force of F_n and F_s, N

F: Friction force between tool and chip, N

N: Normal force between tool and chip, N

F_s: Shear force, N

F_n: Force normal to shear plane, N

Δx: Distance difference, mm

V: speed, m/s

s: second

Δt: Time difference, second

m_{chip}: Weight of chip, kg

ω: angular speed, rad/s

K_{tb}: Stress concentration factor for bending stress

K_{ts}: Stress concentration factor for shear stress

σ: Normal stress, MPa

τ: Shear stress, MPa

S_t: Ultimate tensile stress, MPa

S_e: Endurance limit, MPa

K_{fb}: Fatigue stress concentration for bending

K_{fs}: Fatigue stress concentration for shear

ABBREVIATIONS

SCE: Specific Cutting Energy

PTO: Power Take-Off

MPa: Mega Pascal

kN: Kilo Newton

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1. INTRODUCTION

Trees have always been one of the most important resources of humans throughout human history. The trees, which meet the need for oxygen from the very foundation, contribute to our nutrition with the fruits they produce, while their roots prevent landslides and avalanches on sloping lands.

However, with the effect of industrialization in the following years, many usage areas of trees and especially the woods that make up their trunks have emerged. It takes place as a raw material in paper production, which occupies an important place in the world economy, except for carving wood trunks and using them as ornaments, using them in furniture or as a building material in villages. Almost all papers produced, from toilet papers to cardboard, from papers used in book printing to first-degree photocopying papers, are made using wood.

For the production of paper, first of all, a substance called wood pulp must be produced from wood. Wood pulp is formed by mixing the shredded (kind of shredded) wood pieces with the help of various chemicals and turning them into a pulp. Although this process is, of course, a complex process with multiple stages, the part that interests us includes the adventure of splitting the wood.

The splitting of wood is a process that usually takes place in farmers and large paper mills. In the production of these chips, machines called wood chippers of different sizes are generally used. These machines come in different sizes. There are models that can be attached to the back of small tractors and used to break up the branches formed after the pruning of the orchards, while there are models that are large enough to contain almost an entire tree at once. However, the common purpose of all machines, regardless of size, is to turn wood into sawdust. Because larger machines are much more complex and complex, I chose relatively simple and small disk chippers for this research.

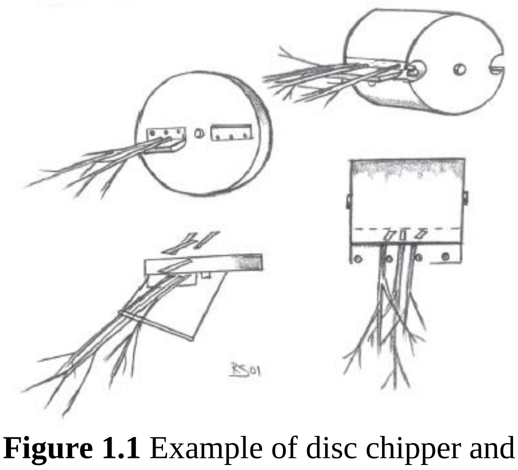

Figure 1.1 Example of disc chipper and drum chipper *(Raffaele Spinelli, 2020, p. 27)*

These tools are generally divided into two. These are disc chippers and drum chippers. Although the processing logics are similar to each other, there are structural differences. The species called disc chipper consists of a steel round disc named after it. Depending on the size of the disc, a different number of blades are mounted parallel to the disc (there may be a slight inclination according to the blade angles), and with the rotation of this disc, it starts to shred the wood. On the other hand, drum chippers use large cylinders instead of discs as rotating elements. The blades placed parallel to the rotation axis begin to split the wood with the rotation of this huge cylinder. Drum chippers are generally used on very large machines because they are more prone to shredding whole trees due to their geometry. Also, drum chips usually have a piece called screen. This piece acts as a sieve and allows chips of the desired size to pass through. Those that are too large to pass through the sieve are usually sent back to the grinder so that they can be shredded again. Since these screens are usually replaceable, it is a little easier to control the chip size in drum chippers.

Figure 1.2 Screen of a drum chipper
(Raffaele Spinelli, 2020, p. 28)

Although this wood splitting job looks simple from the outside, there are fine mathematical calculations in it. The reason for this is the importance of the size of the chips. As I mentioned in the previous paragraphs, these chips are used in the production of a material called wood pulp. While producing wood pulp, chemicals interact with wood chips. Here the size of the chips comes into play. If chips over the desired size are produced, the chemicals cannot penetrate the chip sufficiently. As a result, chips become "undercook". On the contrary, if the size of the chips gets smaller than desired, this time the chemicals are too much penetrated into the wood, so there is a situation called "overcook" (Hellström, 2010, p. 8). Therefore, the size of the chip part is very important for this process. In order to achieve the desired size, factors such as the position of the blades on the disc and the angle of approach of the wood to the blade must be regulated. In this research, wood chipper, which is used to break the branches of fruit trees whose diameter does not exceed

10 cm, was studied.

2. MATERIAL AND METHOD

When I started my research, I had to first understand what exactly was required of me. First of all, I had to understand what I was going to do. My goal here is to create a way for myself to begin design and research. One of the biggest benefits of searching the literature was that it helped me understand what the main parts of a wood chipper were. When I have already examined the researches on the Internet, I have noticed that certain issues always come up. Generally, the reviews were always gathered under a few main headings.

The first of the main researched items was the blade element. After reading many articles about it, I realized that the blade is perhaps one of the most important parts in the system. So much so that everything from the position of the knife, the position it makes with the piece of wood to the number of knives on the disc has an important place in the production of the chip. The change made in even one of these data has a great impact on the properties of the wood chip produced. So I realized that the knife would be one of the main topics in my research.

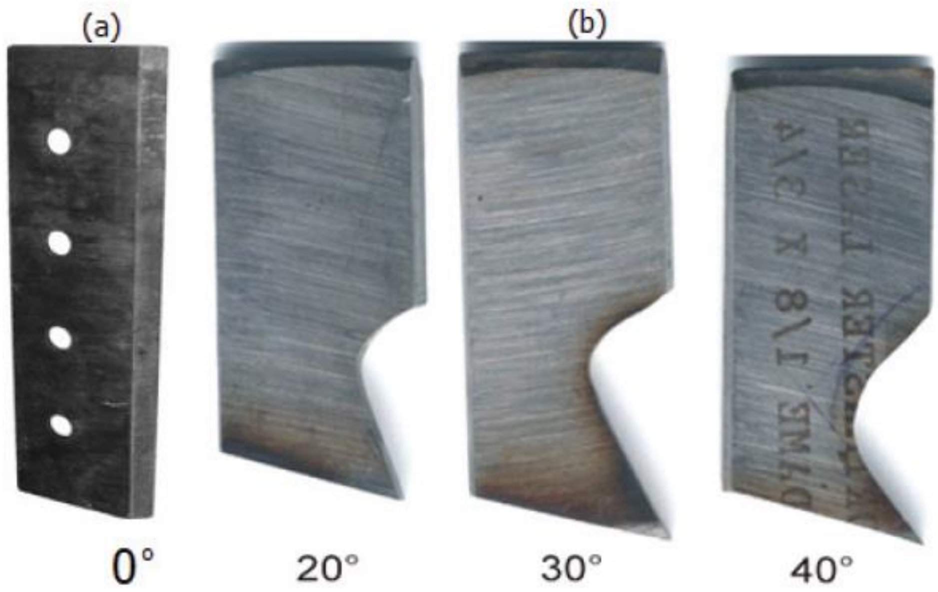

Figure 2.1 Blades with different angles *(Segun R. BELLO, 2011, p. 19)*

The importance of the knife was actually the subject of another title. In this way, we see here that the knife directly affects many things. The second main topic is to find the forces created by the blade. As a result, the knife applies a certain force to the wood while cutting the wood. Factors such as the position of the blade and the angle of approach to the wood are a major factor in the formation and change of these forces. Another important reason for finding the forces is that they will be used to calculate the power that must be applied to the machine. After all, these forces must be known in order to calculate this power. Another importance of the forces is that they directly affect the stress under which the shaft and bearings will carry the disc. This will play a role in shaping important information such as the life of the piece.

After these processes were completed, it was finally time to calculate the stress to be caused by all these processes. Bearings carry the shafts. While these bearings ensure that the shaft and disc rotate smoothly, they also prevent the shaft from slipping on the rotational axis. The part must be able to withstand the bending and torsional stresses created by the forces applied on the shaft. Therefore, the shaft should be designed accordingly. Likewise, the selection of bearings is also very important. Since the dimensions of the bearings depend on the shaft itself, it is necessary to pay attention to the appropriate diameter and durability. In addition, the size and frequency of the stress they will be exposed to is one of the important factors affecting the life of the bearings.

The above-mentioned issues were the ones that caught my attention the most in the literature research I have done. As the number of researched documents increased, I realized that their contribution to me decreased because the subjects started to become more subjective. Because the topics were starting to fall out of my topic. Finally, when I spared the information I need for myself, I decided to go through the 3 main topics that I mentioned before, operationally. Therefore, I will now examine these topics under sub-headings.

2.1 Design of Blades

As I started this process, I realized that I had to make some limitations first. I had to set criteria for myself to start from a point. Because design and calculations could be started within these limits. Starting with some videos that my teacher Bülent showed as an example, I started to examine the features of the machine I will build and what it looks like. In this way, I had a rough idea of the dimensions of the machine. The diameter of the discs of the chippers I examined generally did not exceed 1 meter. Based on this, I decided that the diameter of the disc should not be larger than 90 cm.

One of the limits I set for myself from the very beginning was what size branches this tool would cut. Since there is no limitation here, and the research is more like real life, I decided to take examples from real life. I asked them to measure the diameters of the branches to be pruned from the cherry trees in the cherry garden owned by my family in the İnegöl district of Bursa. When I examined the measurements I took from the branches to be cut, I saw that the diameter of the branches did not exceed ten centimeters. With this information, as a second limitation, I decided that the diameter of the wood to be cut by the machine should be a maximum of ten centimeters. Apart from these, there are other minor limitations that I have made. I'll add them when I get there.

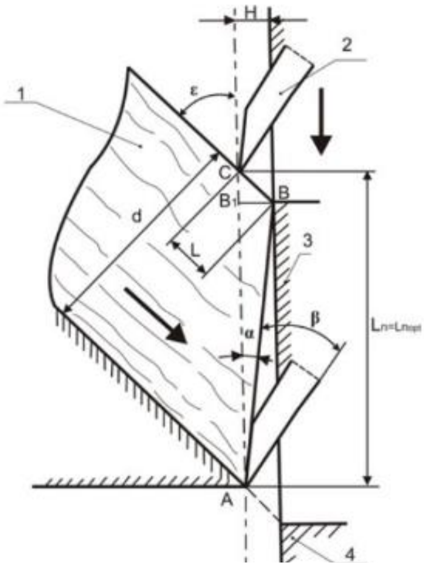

Figure 2.2 The scheme of wood cutting *(Reczulski, 2016, p. 436)*

Figure 2.3 Diameter measurement of sample wood that can be cut

Apart from these, there are other minor limitations that I have made. I'll add them when I get there.

During the literature research, I came across the first of the most useful examples in the source (Reczulski, 2016) that I use most frequently. When Figure 2.2 is examined carefully, the position of the blades on the wood, the dimensions and the angles are clearly seen. To explain the values here;

- d is the diameter of the wood.
- ε is spout angle which represents the angle between the disc and wood.
- L is the length of the chip.
- α is the clearance angle.
- β is the edge angle of the blade.
- H is the knife height.
- Number 1 represent the wood.
- Number 2 represent the knife.
- Number 3 represent the disc.
- Number 4 represent the anvil.

At this point, I realized that I should put another limitation, because in the following sections, there were too many unknowns in the equations and they could not be solved. In this, I decided to define the clearance angle and the knife angle, which are partially connected to each other, from the beginning. I took the clearance angle 3 degrees as per the suggestion in the article (Reczulski, 2016, p. 436). Another article said that the angle of the blades used in such chippers varies between 20 and 30 degrees. That's why I took this angle as 30 degrees (Segun R. BELLO, 2011, p. 20).

When we examine the figure in Figure 2.2, geometrical connections can be made between some values, which has already been done in the article (Reczulski, 2016). If we examine these equations;

$$L = \frac{H}{\sin \varepsilon} \tag{2.1}$$

$$\tan \alpha = \frac{B_1 B}{AB_1} = \frac{L * \sin \varepsilon}{L_n - L * \cos \varepsilon} \tag{2.2}$$

The L_n value here indicates the length of the long part of the elliptical shape on the wood as the blade cuts wood. To find this;

$$L_n = 2 * R_c * \sin \frac{\pi}{i} \tag{2.3}$$

As you can see here, there are two different values that we do not know. R_c and i values. The i value indicates the number of blades that will be found on the disc. The meaning of R_c value defines the distance of the middle point of the wood from the center of rotation of the disc while it is being cut. The most important event of this value is that the chip sizes of the woods are distributed equally. We want the wood to be in the middle of the blade when cutting the blade. Ideally, the second blade should begin cutting the wood immediately after the first of the blades has finished cutting. If the wood is too close to the center of the disc, the second blade starts cutting the wood before the first blade has finished cutting. If, on the contrary, it is too far from the center of rotation than it should be, this time, after the first blade finishes cutting, a gap occurs until the second blade starts cutting (Figure 2.4). This is undesirable in the first cases because it negatively affects the size distribution of the chips.

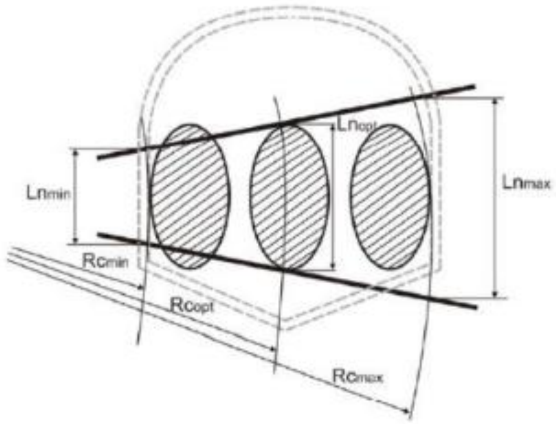

Figure 2.4 Visualization of cutting radius *(Reczulski, 2016, p. 438)*

I chose the 155mm-395mm range as the R_c range. I set the number of blades as i = 6 as a starting point. The diameters of the branches that my family measured did not exceed 10 cm. With these limitations, I started to calculate for chip sizes of 30 mm.

$$L_n = 2 * 155 * \sin\frac{\pi}{6} = 155mm \tag{2.3a}$$

$$\tan\alpha = \frac{L * \sin\varepsilon}{L_n - L * \cos\varepsilon} \rightarrow \tan 3 = \frac{30 * \sin\varepsilon}{155 - 30 * \cos\varepsilon} \tag{2.2a}$$

$$\varepsilon = 12° \rightarrow \sin\varepsilon = 0{,}219$$

$$H = L * \sin\varepsilon \rightarrow H = 30 * 0{,}208 = 6{,}237mm \tag{2.1a}$$

When I examined the results, I saw that the spout angle was very low. The angle being 12 degrees meant the wood was almost parallel to the disc. This was also illogical, because no machine I've studied did not get wood that way. It also seemed unreasonable that the distance between the disc and the tip of the blade was about 6mm. In the article (Reczulski, 2016) where I got the equations, the blade height was between 11,5 and 14 mm and wood was used close to the dimensions of my woods. I decided to increase the R_c value and chip size to increase the spout angle. When you increase the values to 395mm and 50mm, respectively, and perform the operations;

$$L_n = 2 * 395 * \sin\frac{\pi}{6} = 395mm \tag{2.3b}$$

$$\tan\alpha = \frac{L * \sin\varepsilon}{L_n - L * \cos\varepsilon} \rightarrow \tan 3 = \frac{50 * \sin\varepsilon}{395 - 50 * \cos\varepsilon} \tag{2.2b}$$

$$\varepsilon = 21{,}4° \rightarrow \sin\varepsilon = 0{,}365$$

$$H = L * \sin\varepsilon \rightarrow H = 50 * 0{,}365 = 18{,}250mm \tag{2.1b}$$

When I looked at the results, I thought that although I saw some improvement in the angle, I still could not achieve the result I wanted. The angle was still too small. I also thought that the R_c value was a little too high. Since my main goal is still to reduce the angle, I decided to reduce the number of blades. When I calculate for both 30 mm and 50 mm chip length;

$$L_n = 2 * 395 * \sin\frac{\pi}{4} = 558{,}6mm \tag{2.3c}$$

$$\tan 3 = \frac{50 * \sin\varepsilon}{395 - 50 * \cos\varepsilon} \tag{2.2c}$$

$$\varepsilon = 32{,}75° \rightarrow \sin\varepsilon = 0{,}541$$

$$H = L * \sin\varepsilon \rightarrow H = 50 * 0{,}541 = 27{,}05mm \tag{2.1c}$$

$$L_n = 2 * 155 * \sin\frac{\pi}{4} = 219{,}2mm \tag{2.3d}$$

$$\tan 3 = \frac{30 * \sin\varepsilon}{219{,}2 - 30 * \cos\varepsilon} \tag{2.2d}$$

$$\varepsilon = 19{,}51° \rightarrow \sin\varepsilon = 0{,}334$$

$$H = L * \sin\varepsilon \rightarrow H = 30 * 0{,}334 = 10{,}0mm \qquad (2.1d)$$

Two things caught my attention in the face of these results. As a result, there are sides that I want and don't want. First of all, if we look at the 395 mm R_c value, I brought the angles to the desired level, but this time I ran into a problem. My H value is 27.05mm and this causes such a problem. The thickness of the knives I will use is usually between 1-2 cm. When the clearance angle is also engaged, the blade stays in the air above the disc and its contact with the disc is lost (Figure 2.5).

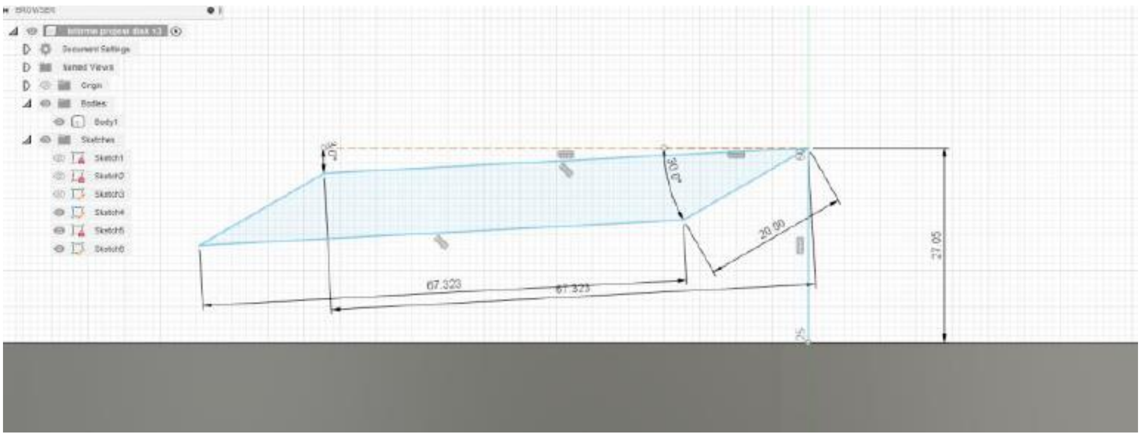

Figure 2.5 Visualization of the blade hovering above the disc

As can be seen in the drawing, an absurd image is formed. On the other hand, if I take the R_c value as 155 mm, the value of the spout angle drops again as before. I tried 30 and 50 mm chip sizes in both R_c values, but the results were always problematic, so only two were written above to avoid crowding.

At this point I decided there was another parameter I needed to change. When I examine the operations and find the angle as I want, the high value of H creates a problem. I realized that I need to make changes to L_n and chip size to lower the H value. Until now, I had taken the diameter of my disc as 90 cm. Therefore, the range of my R_c value was high. To prevent this, I decided to reduce the diameter of the disc to 60 cm. I also placed my blade in the radius range of 150mm-275mm. From this point of view, I reduced the R_c value to 212,5 mm, which will come right in the middle of the blade. I also reduced the desired chip size to 20 mm because I could reduce the H value because of this, because the L value got smaller, and in many articles I read, the size of the chips varied between 8-12-25 mm. As a result, I decided that the chip size I wanted in the first place was not realistic compared to the maximum wood diameter. When I do the calculations over all these variables again;

$$L_n = 2 * 212{,}5 * \sin\frac{\pi}{4} = 300{,}52mm \qquad (2.3e)$$

$$\tan 3 = \frac{20 * \sin\varepsilon}{300{,}52 - 20 * \cos\varepsilon} \qquad (2.2e)$$

$$\varepsilon = 31{,}93° \;\rightarrow\; \sin\varepsilon = 0{,}529$$

$$H = L * \sin\varepsilon \rightarrow H = 20 * 0{,}529 = 10{,}58mm \qquad (2.1e)$$

This time I was able to get the data I wanted. Both the height of the blade was slightly higher than 1 cm, so there was no problem in its placement on the disc, and the angles came to reasonable levels. This way I can move on to the force calculations.

2.2 Force Calculations

At this point, since I have completed the calculations of the knife, I move on to the second main topic. In order for wood to be cut, the blade must exert force on the wood. Thanks to this force, the knife splits the wood and begins to break off the pieces of wood. Here we realize that energy is involved. After all, the blade travels some distance while applying force. We know from physics that this operation is the definition of the work done. The work done is equal to the change in energy.

At this point, before I go deeper into the business, I will first need to determine some of the data that I will need in future transactions. First of all, if I'm going to use energy equations, I will definitely have to deal with mass. Since I will determine the volume in the future, I must know the density of the tree from the beginning so that I can multiply it by the volume and find the mass where necessary. For this, unfortunately, I could not find anything clear about the density of cherry trees in the sources I looked at on the internet. However, I learned that the density of pine trees varies between 350 kg/m^3 and 700kg/m3 depending on the species, and the density of an average wood is 600kg/m^3. That's why I decided to take the density of the tree to be cut down to 600kg/m^3.

Another variable that I had to choose at the beginning was the rotational speed of the disk.

As it is known, PTOs of tractors work at different speeds for different jobs. It was written on the internet that such machines work in the range of 360-560-720rpm. That's why I set the speed of the disk as 560 rpm from the beginning.

To find out how much power would be required to cut, I first had to find the energy required to cut a unit chip. If I write the equation of this energy based on the article (Segun R. BELLO, 2011) I examined during the literature research;

$$E = \frac{F_c L}{hwl} \frac{J}{m^3} \tag{2.4}$$

The E value here represents SCE (Specific Cutting Energy). In the beginning, I did not understand how to use it and even though I tried many times on it, I could not get a result. Later, I realized that I had to try a different method to find this value. I need to find the SCE myself and then write it in the above equation and get the F_c value from there. First of all, I need to explain what the F_c value is.

The F_c value actually represents only one of many forces on the blade. If we look at Figure 2.6 here;

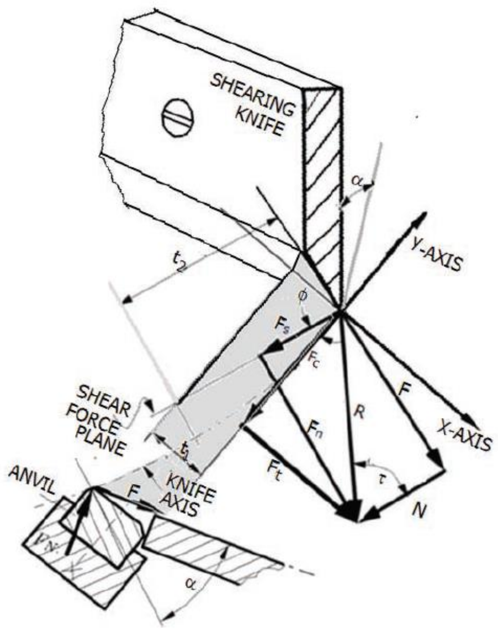

Figure 2.6 Vector illustration of the forces created by the blade cutting wood *(Segun R. BELLO, 2011, p. 23)*

If we list forces at Figure 2.6 here;

- F_c = Force acting in the direction of cutting.
- F_t = Thrust force needed to keep the tool in the work piece (direction perpendicular to the work piece surface).
- P_r = Resultant force of F_n and F_s
- F = Friction force between tool and chip
- N = Normal force between tool and chip
- F_s = Shear force with which the knife has to act in order to cause the cutting of the fibers in the wood (it is assumed that this force is perpendicular to the grain).
- F_n = Force normal to shear plane

These vectors are connected to each other on the 2D plane. The links between them are given in the article (Segun R. BELLO, 2011, s. 23). If we write these;

$$F = F_t \cos\alpha + F_c \sin\alpha \tag{2.5}$$

$$N = F_c \cos\alpha - F_t \sin\alpha \tag{2.6}$$

$$F_s = F_c \cos\varphi + F_c \sin\varphi \tag{2.7}$$

$$F_n = F_t \sin\varphi - F_c \cos\varphi \tag{2.8}$$

Here are some problems encountered. Even though we had the equations, we didn't know where the angles between the vectors were on the figure or what they were. I had to draw many times to understand how the vectors lie on the two-dimensional plane. I needed to find the angles between the vectors because I would find their parallel and vertical projections on the shaft axis and then I would need to use this information to make the shaft and find out how much power the machine would need.

As can be seen in Figure 2.7, I have found the angles between all vectors by typing the angles we know into the drawing. The important point here is that we know that the Fc force is in the direction of the progress of the wood. That's why I leaned that force on the y-axis and shaped the other vectors accordingly. Now that I've handled the position and orientation of F_c on the blade, I can move on to finding its size.

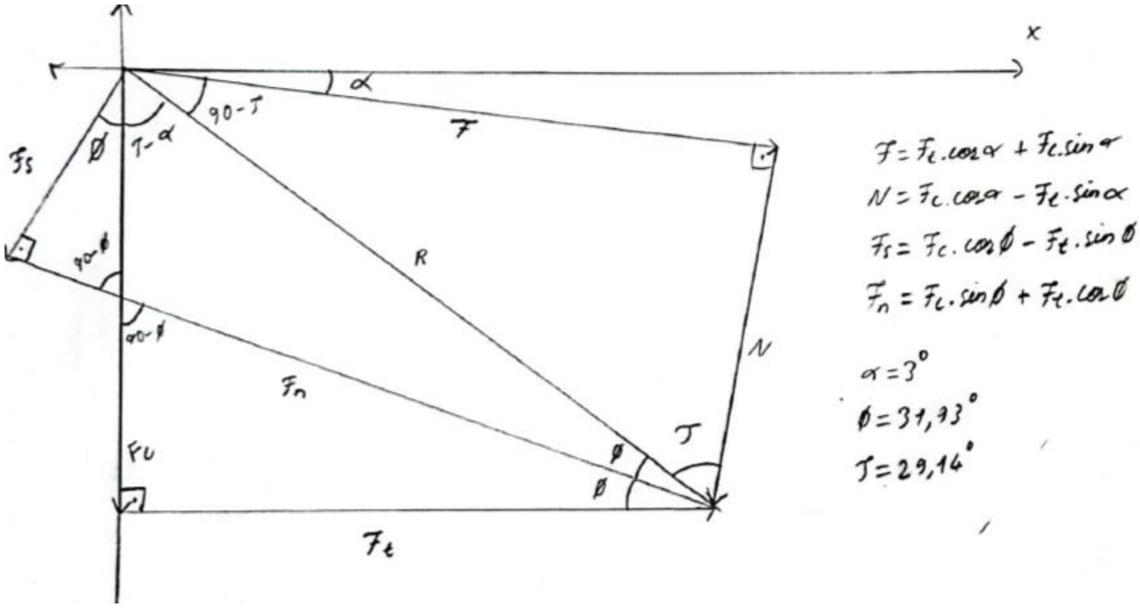

Figure 2.7 Drawing to find angles between vectors

Coming back to finding the SCE value, the biggest mistake I made when dealing with the equation was trying to simplify the L values in the numerator and denominator and continue. At some point, when I realized that the part above the equation was actually the energy required to move the wood in a way, my whole perspective on the equation changed and I started to try the method that came to my mind. We know that the work done is equal to the change in the energy of the system.

$$F * \Delta x = \Delta E \tag{2.9}$$

While cutting wood shavings, it travels some distance by accelerating from the steady state due to the thickness of the blade. In short, the blade transfers the cutting energy it applies to the wood, and as the chips gain speed during this time, they convert the energy they receive from the blade into kinetic energy. If I can find the kinetic energy gained by the wood chips, I indirectly find the energy spent by the knife for cutting. For this, I need to find the distance traveled by the piece of wood and the speed it reaches after cutting. I know that;

$$\Delta x = V * \Delta t \tag{2.10}$$

First I know that the piece of wood is moving in the direction of the Fc vector. Apart from that, I also know that the blade height H value is 10,58 mm. Then if I find the movement of the wood in that direction with a simple operation;

$$\Delta x = \frac{10{,}58}{\cos 31{,}93} = 12{,}47mm \tag{2.11}$$

After finding the path he took, it's time to find out how long it took him to take that path. For this I need to know how long it takes the blade to cut the wood. If we look at how much of an angle the disc scans while cutting the wood;

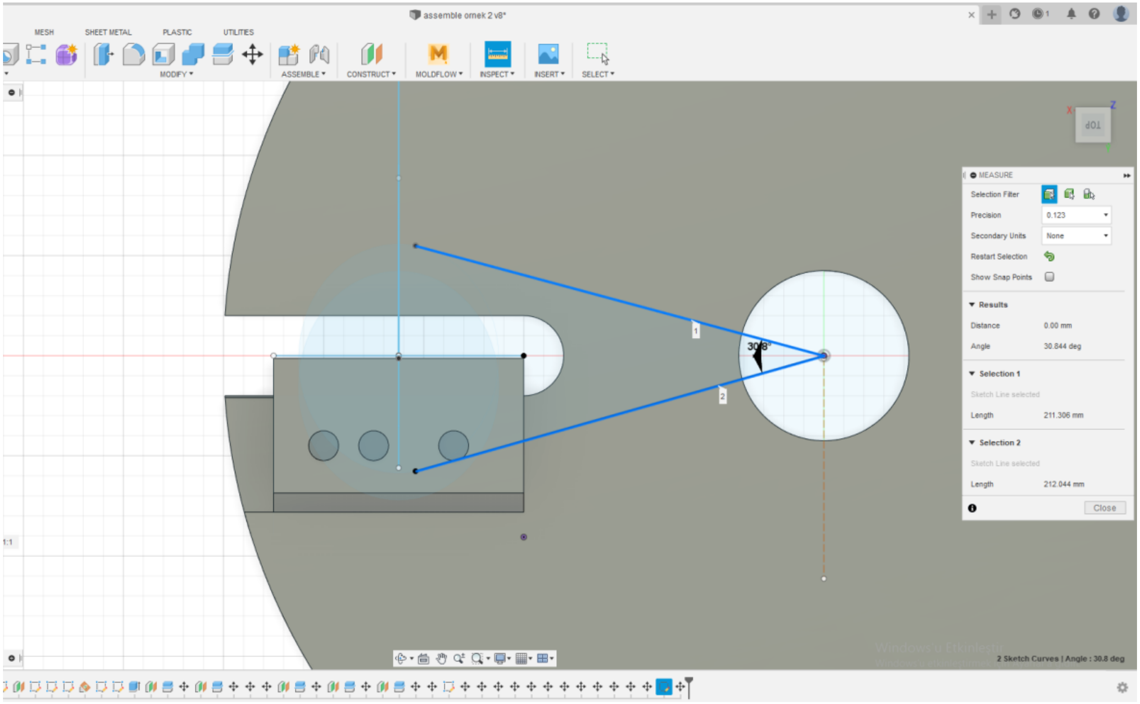

Figure 2.8 Finding the angle the blade scans while cutting wood

With the help of Fusion 360, when I looked at the angle of the blade, I found that the angle was 30,84 degrees. If I convert 30,84 degrees to radians, I would have found 0,54 radians. I know that 560 rpm equals 58,64 rad/s. Then if I divide 0,54 rad by 58,64 rad/second;

$$\Delta t = \frac{0{,}54}{58{,}64}\,\frac{rad}{rad/second} = 0{,}0092\ second \tag{2.12}$$

If I replace the values, I found in equation (2.10);

$$12{,}47mm = V * 0{,}0092second \rightarrow V = \frac{1355{,}43mm}{s} = \frac{1{,}355m}{s} \qquad (2.10a)$$

Acceleration is not taken into account because the action taking place here is so fast. I assumed it was reaching the speed it should have been directly without any acceleration.

Now I will need to find the wood chip produced by the machine in unit time. For this, I must first determine how much wood the blade removes each time. In this, I made a virtual cut in the drawing program and found how much wood the blade cuts each time.

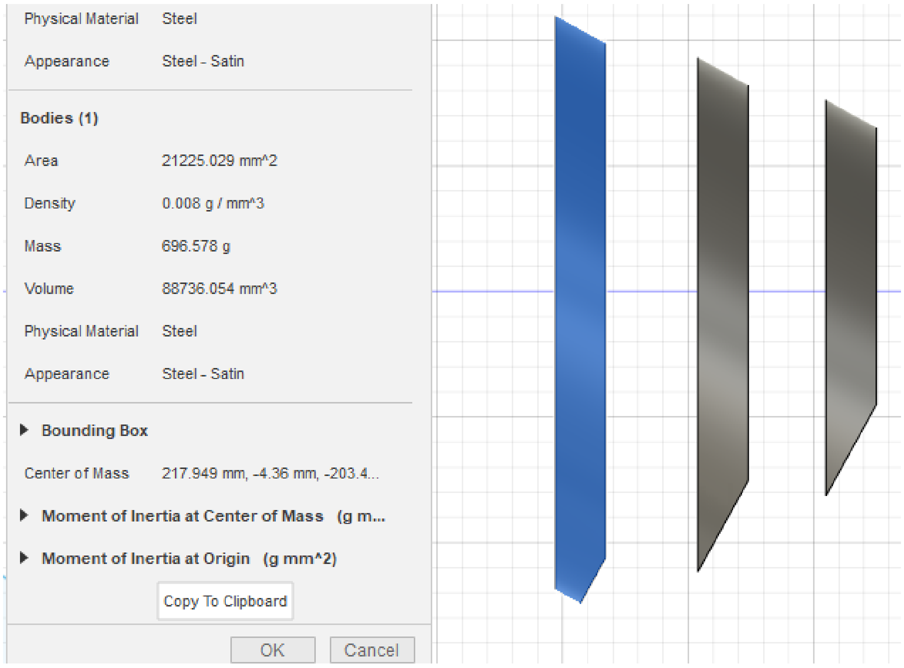

Figure 2. 9 Finding the volume of wood shavings removed by each turn of the blade

In the program, we see that the volume of the cut piece is 88736mm^3. I will take this value as 8,9*10^-5 m^3 for ease of calculations. When I started to write this part, I initially determined the density of the tree as 600 kg/m^3. If I want to find the mass of the piece from here;

$$m_{chip} = 8{,}9 * 10^{-5} * 600 = 5340 * 10^{-5}kg \qquad (2.13)$$

Now I have both mass and velocity. From here, kinetic energy can be found;

$$\Delta E = \frac{1}{2}mV^2 = \frac{1}{2} * (5340 * 10^{-5}) * 1{,}355^2 = 0{,}049\,Joule \qquad (2.14)$$

According to the result found here, the energy consumed by the blade for one cut is 0,049 Joules. I already know the volume of the piece he cuts. In this way, I will be able to find out how much energy it will take to cut one cubic meter of wood, which will be my SCE value that I have been looking for from the very beginning.

$$E = \frac{0{,}049\,J}{88736 * 10^{-9} m^3} = 552{,}2\,\frac{J}{m^3} \qquad (2.4a)$$

I have solved perhaps one of the biggest problems of this project by finding the SCE value. Now I can find the F_c value using this value. If I substitute this in the equation (2.4);

$$552{,}2 = \frac{F_c * 10{,}58}{8{,}9 * 10^{-5}}\frac{J}{m^3} \rightarrow F_c = 4{,}63\,\frac{N}{mm} \qquad (2.4b)$$

From that point on, all I did was find the other forces again with the equations in the article. I found the Ft value using geometry. If we look at Figure 2.7, the vector F_c and T and the vector F_t form a triangle. Since I know the F_c value and all the angles in that triangle, I draw my F_t value from there and;

$$\tan(2 * 31{,}93) = \frac{F_c}{F_t} \rightarrow F_t = \frac{4{,}63}{2{,}04} = 2{,}27\,\frac{N}{mm} \qquad (2.15)$$

Now if I solve the equations to find the other forces;

$$F = F_t * cos\alpha + F_c * sin\alpha = 2{,}27 * cos3 + 4{,}63 * sin3 = 2{,}51\,\frac{N}{mm} \qquad (2.5a)$$

$$N = F_c * cos\alpha - F_t * sin\alpha = 4{,}63 * cos3 - 2{,}27 * sin3 = 4{,}74\,\frac{N}{mm} \qquad (2.6a)$$

$$F_s = F_c * cos\varphi - F_t * sin\varphi = 4{,}63 * cos31.93 - 2{,}27 * sin31{,}93 = 2{,}73\,\frac{N}{mm} \qquad (2.7a)$$

$$F_n = F_c * sin\varphi - F_t * cos\varphi = 4{,}63 * sin31{,}93 + 2{,}27 * cos31{,}93 = 4{,}38\,\frac{N}{mm} \qquad (2.8a)$$

Now that I've found all the forces, it's time to find the power from here. Although I have found the forces, I must take the components of these forces perpendicular to the axis of rotation of the disk. Here we will see why I found the angles between the vectors. As can be seen in Figure 2.10, the forces are at different angles. Since my woods will have a maximum diameter of 100mm, I will multiply these values by 100. When I get the vertical components;

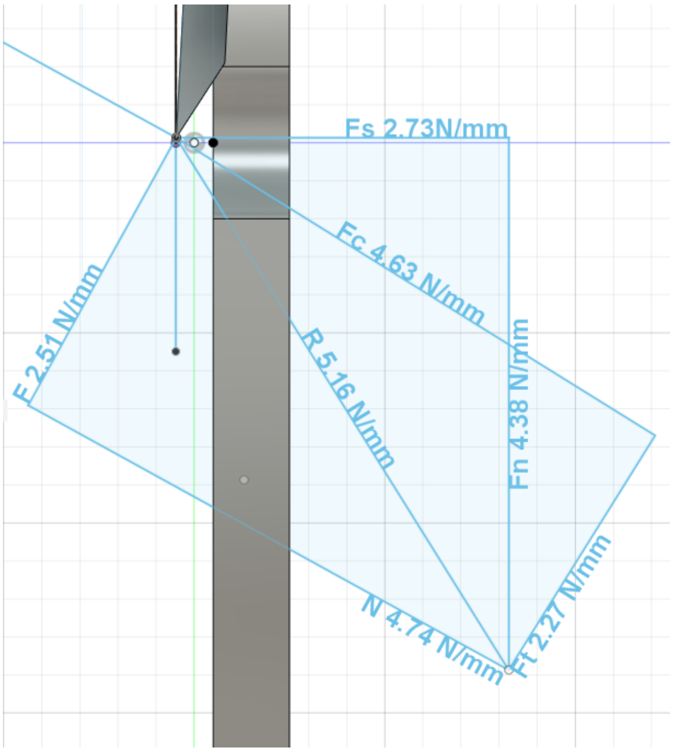

Figure 2.10 Representation of forces in the drawing application on the knife

$$F_{\ n,vertical} = 438\ N \tag{2.16}$$

$$R_{vertical} \ = 516 * cos(31{,}93) = \ 437.92\ N \tag{2.17}$$

$$F_{c,vertical} = 463 * cos(26{,}14 + 31{,}93) = 244{,}87\ N \tag{2.18}$$

$$F_{t,vertical} \ = 227 * cos(31{,}93) = 192{,}65\ N \tag{2.19}$$

$$F_{vertical} \ = 251 * cos(28{,}93) = 219{,}67\ N \tag{2.20}$$

$$N_{vertical} \ = 474 * cos(61{,}07) = 229{,}29\ N \tag{2.21}$$

If we add these;

$$\sum F_{total} = F_{\,n,vertical} + R_{vertical} + F_{c,vertical} + F_{t,vertical} + F_{vertical} + N_{vertical}$$

$$= 1762{,}4\ N \quad (2.21)$$

Now that we've found the perpendicular components of the forces, we can now multiply by their distance from the axis of rotation to find the torque. Once we find the torque, we can calculate the power. All forces are equidistant from the center of the disk. For this reason;

$$Torque = \left(\sum F_{total}\right) * (distance\ from\ the\ axis\ of\ rotation) = \ 1762.4 * 0.2125$$

$$= 374{,}51\ Nm \quad (2.22)$$

After this point, the only thing left is to find the power. I have both torque and angular velocity.

$$Power = Torque * \omega = 374{,}51 * 58{,}64 = 21961{,}26\ watt = 29{,}43\ Hp \quad (2.23)$$

2.3 Shaft and Bearings

As for the shaft and bearings, I first started with the shaft for calculations. Since the length of the disc in the Figure 2.11 on the x-axis is just over 90 mm, I decided to keep the main part of the shaft length at 120 mm. As it can be seen here, the total length of parts 1 and 2 is 80 mm. Since the tips of the blades are 10,58 mm high from the disc surface, the overall length is just over 90 mm.

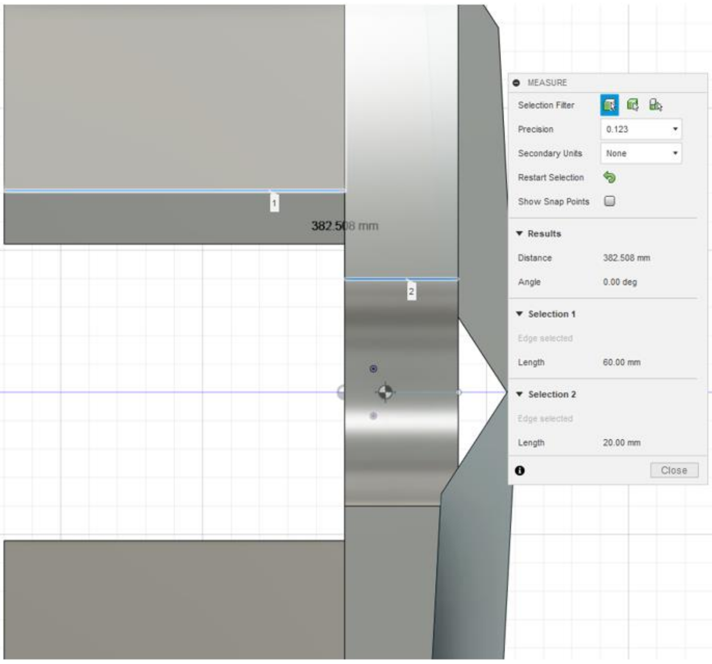

Figure 2.11 Finding the total thickness of disc to determine the length of shaft

Then I positioned all 4 of the knives on the disc over the fusion, and after adding the panels that will help to throw the wood chips up on the disc, I found the center of gravity of the formed piece with the help of the program. Since it is difficult to tell exactly where that spot is, I will show it with a picture.

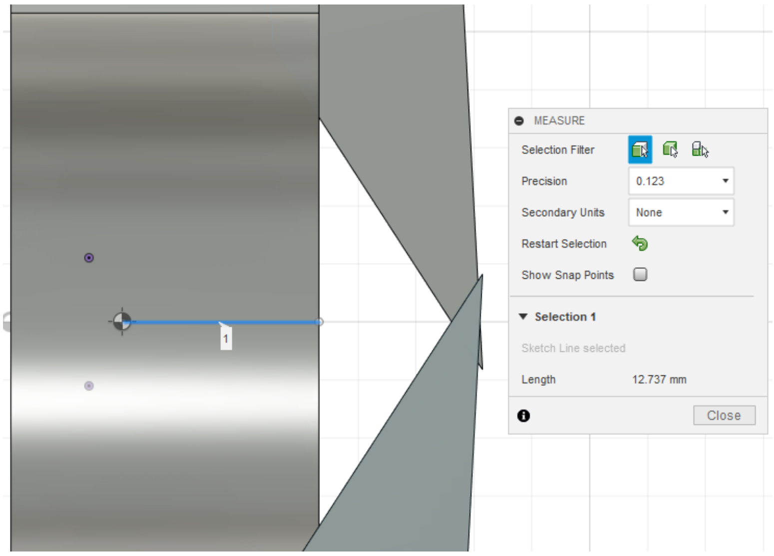

Figure 2.12 Finding the center of gravity of the disc

In this picture, we see the center of gravity. The length of the selected number 1 is 12,74 mm and falls within the 20 mm thickness of the disc. I needed these lengths because I was going to draw the bending moment diagram according to these data.

From this point I focused on the rest of the shaft. The length of the main piece was 120 mm and the diameter was 85 mm. In addition, I placed 50mm diameter and 35mm long cylinders on both ends of the shaft. This was because these parts would carry the bearings. At the same time, I applied fillet with a radius of 5 mm at the point where the diameter transition is, so that the stress intensity at that point decreases. When we looked at the weight of the completed disc from the program, we saw that it was 44817,02 grams. However, to find its mass;

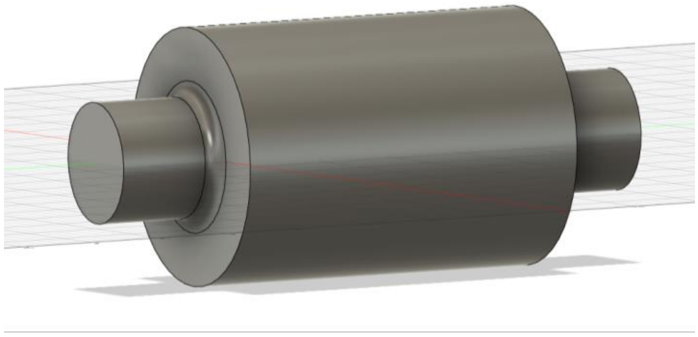

Figure 2.13 Example of shaft

$$total\ mass\ of\ disc = 44{,}81702 * 9{,}81 = 439{,}65\ N \qquad (2.24)$$

After finding its mass, it was time to show all the forces on the shaft and find the unknown forces and moments. At this point I positioned the disc 20mm back from the beginning of the thick part of the shaft and started to place the forces on the shaft accordingly.

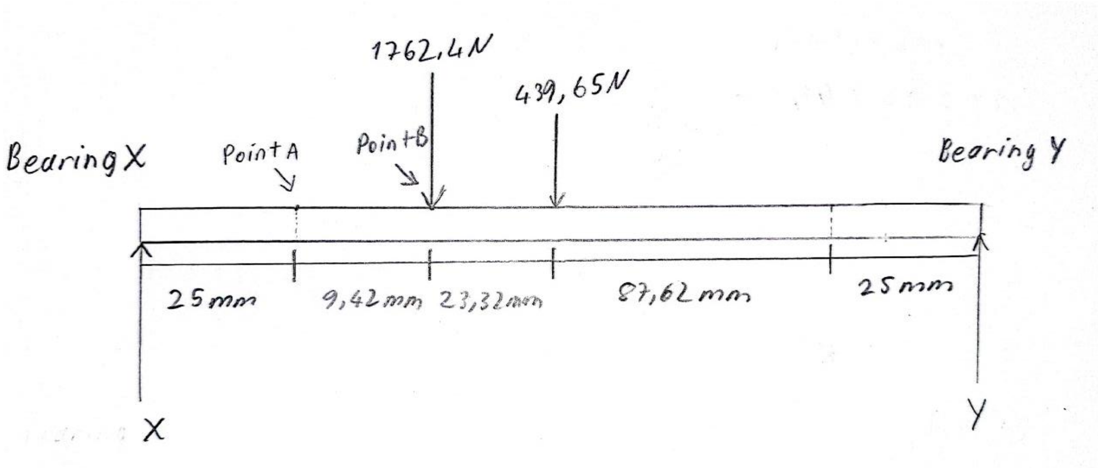

Figure 2.14 FBD of the shaft

In the picture above I have shown where the forces come from on the shaft. If I accept the point where the X vector is applied as the zero point;

$$\sum M = 0$$

$$\sum F = 0$$

$$(-(25 + 9{,}42) * 1762{,}4) - \big((25 + 9{,}42 + 23{,}32) * 439{,}65\big) + Y * 170 = 0 \qquad (2.25)$$

From here Y is equal to 506,16 N. If I apply total force rule;

$$-1762{,}4 - 439{,}65 + 506{,}16 + X = 0 \ \rightarrow X = 1695{,}49\ N \tag{2.26}$$

After finding all the unknown forces, I can now start drawing the bending and force diagram. If we look at the moments at the points where the forces are;

$$M_b = 1695{,}49 * (25 + 9.42) = 58358{,}766\ Nmm \tag{2.27}$$

$$M_c = 506{,}16 * (25 + 23.32 + 87.26) = 56798{,}425\ Nmm \tag{2.28}$$

After finding the moments as well, I wanted to draw diagrams of both forces and moments. For this, I entered the data in excel and extracted the graphs and;

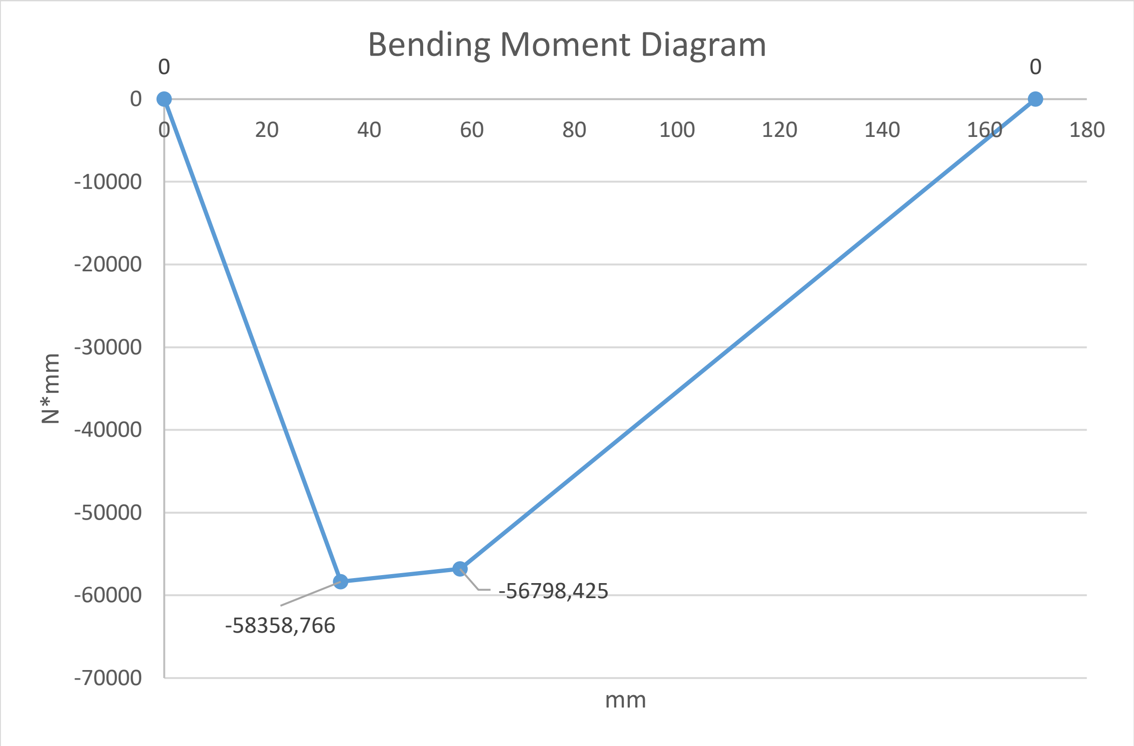

Table 2. 1 Bending Moment Diagram

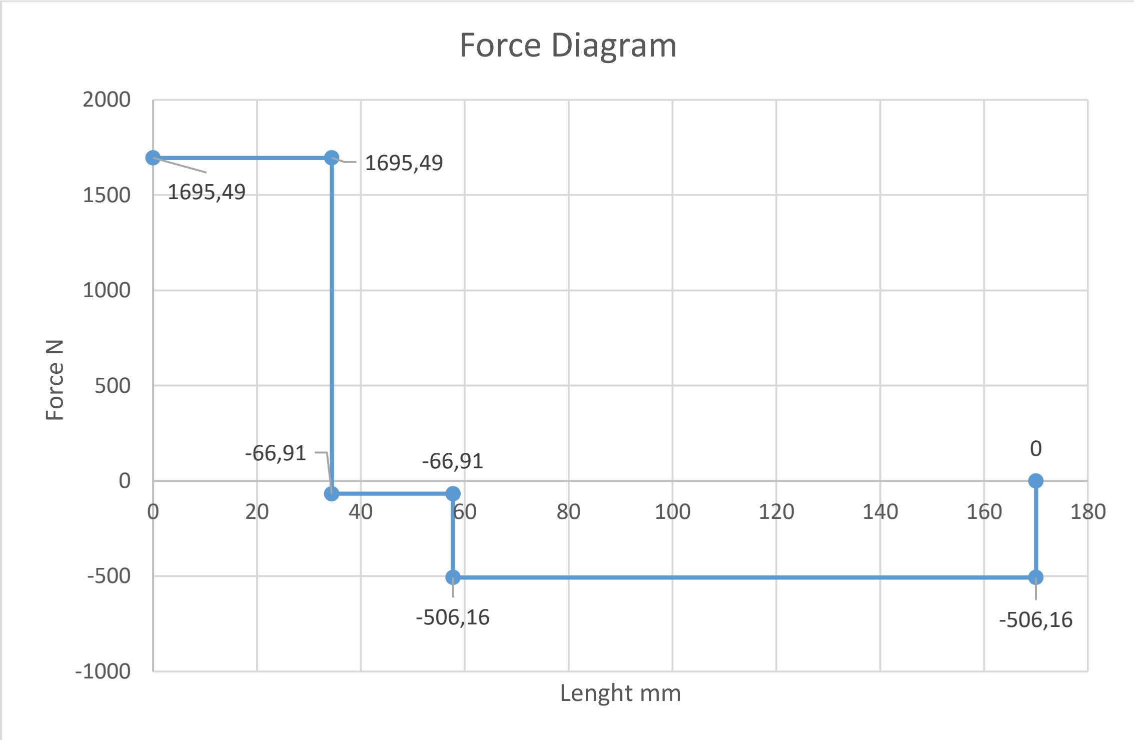

Table 2. 2 Force Diagram

As it can be seen here, the part with the highest bending moment passes through the force applied by the blades. But I can't say "the weak point of the shaft" here because the shaft has two different diameters and I will have to look at the point at that transition point. As can be seen from the graph, the point close to the forces will be exposed to more stress, so I need to examine that point.

As it can be seen from the diagram, I started from the part where the stress is the most and the diameter change. I will refer to this point as point A from now. I predict this point will be the weakest point of the shaft. When the moment applied to the mentioned point was found with the help of slope on the graph, the result was 42387,25 Nmm. If I start writing the bending and buckling equations for that point;

$$\sigma_{bending,cylinder} = \frac{32 * M}{\pi * d^3} \tag{2.29}$$

$$\tau_{torsion,cylinder} = \frac{16 * T}{\pi * d^3} \tag{2.30}$$

$$\sigma_A = \frac{32 * 42387,25}{\pi * 40^3} = 6,764\ MPa \tag{2.29a}$$

$$\tau_A = \frac{16 * 374,51 * 10^3}{\pi * 40^3} = 29,802\ MPa \tag{2.30a}$$

At this point I have to use stress concentration factors as there are diameter transitions. The necessary information to be used in the calculations to be made here is taken from the Shigley`s Mechanical Engineering Design 9th Edition book. First of all, if we look at each other of the diameters and the ratio of the fillet to the small diameter;

$$\frac{D}{d} = \frac{85}{40} = 2{,}125 \ \ and \ \frac{r}{d} = \frac{5}{40} = 0{,}125$$

Thanks to these values, I find the K_{tb} and K_{ts} values from Table A15-8,9 (Budynas & Nisbett, 2011, p. 1028) 1,65 and 1,4 from the graphics in the book. If we then write the equations to find the K_{fb} and K_{fs} values;

$$K_{fb} = 1 + q_b * (K_{tb} - 1) \qquad (2.31)$$

$$K_{fs} = 1 + q_s * (K_{ts} - 1) \qquad (2.32)$$

$$K_{fb} = 1 + 0{,}83 * (1{,}65 - 1) = 1{,}54 \qquad (2.31a)$$

$$K_{fs} = 1 + 0{,}9 * (1{,}4 - 1) = 1{,}36 \qquad (2.32a)$$

Now if I want to find stress again;

$$\grave{\sigma_a} = K_{fb} * \sigma_A = 1{,}54 * 6{,}764 = 10{,}388\ MPa \qquad (2.33)$$

$$\grave{\sigma_m} = \sqrt{3} * K_{fs} * \tau_A = \sqrt{3} * 1{,}36 * 15{,}262 = 70{,}201\ MPa \qquad (2.34)$$

Now I have to fınd the S_e value;

$$S_e = \grave{S_e} * K_a * K_b * K_c * K_d * K_e \qquad (2.35)$$

At this point, it will be necessary to decide which material I should use because I am going to have to find $\grave{S_e}$. I know that AISI 1050 steel is a cheap and durable material that is frequently used in industry, so I decided to use it in the shaft. When we look at table A-20 (Budynas & Nisbett, 2011, p. 1040) in the book, we see that the S_t value is 620 MPa.

$$620MPa < 1400MPa \ \rightarrow \ \grave{S_e} = S_t * 0{,}5 = 620 * 0{,}5 = 310\ MPa \qquad (2.36)$$

Now it's time to calculate the K values. If we start from K_a;

$$K_a = a * S_t^b \tag{2.37}$$

From Table 6-2 (Budynas & Nisbett, 2011, p. 345) I choose a and b values. Since my steel is hot rolled a = 57,7 and b = -0,718

$$K_a = 57{,}7 * 620^{-0{,}718} = 0{,}57 \tag{2.37a}$$

When it comes to K_b value there is a bunch of equations and limitations (Budynas & Nisbett, 2011, p. 288) about how to choose it. Because my d = 40mm;

$$K_b = 1{,}24 * 40^{-0{,}107} = 0{,}835 \tag{2.38}$$

$$K_c = 1$$

$$K_d = 1$$

Since I want %90 reliability from table 6-5 (Budynas & Nisbett, 2011, p. 345);

$$K_e = 0{,}897 \tag{2.39}$$

So;

$$S_e = 310 * 0{,}57 * 0{,}835 * 1 * 1 * 0{,}897 = 132{,}347\ MPa \tag{2.35a}$$

Using Solderberg criterion;

$$\frac{\grave{\sigma_a}}{S_e} + \frac{\grave{\sigma_m}}{S_y} = \frac{1}{n} \rightarrow \frac{10{,}388}{132{,}347} + \frac{70{,}201}{340} = \frac{1}{n} \rightarrow n = 3{,}50 \tag{2.40}$$

As a result of the calculations, we see that my safety factor is 3,5. I think it will be enough for such a machine and I continue. Now it's time to calculate the stress at point B. Although this point is subject to the greatest force, I predict that the factor of safety will be much higher than point A. Because even though the moment at point B is slightly higher than at point A, the diameter at point B is more than twice that at point A, which means the surface area is about 4 times larger. We know that the stress is inversely proportional to the surface area, and we already see in the equations that find the stress that the stress is inversely proportional to the cubic size of the diameter. The result when the B point is calculated;

$$\sigma_B = \frac{32 * 58358{,}766}{\pi * 85^3} = 0{,}968\ MPa \tag{2.29b}$$

$$\tau_B = \frac{16 * 374{,}51 * 10^3}{\pi * 85^3} = 3{,}101\ MPa \tag{2.30b}$$

$$\grave{\sigma_a} = \sigma_B = 0{,}968\ MPa \tag{2.41}$$

$$\grave{\sigma_m} = \sqrt{3} * \tau_B = \sqrt{3} * 3{,}101 = 5{,}372\ MPa \tag{2.42}$$

In this part, all K values are the same except for the K_b value. So if I calculate the K_b value again;

$$K_b = 1{,}24 * 85^{-0{,}107} = 0{,}752 \tag{2.38a}$$

$$S_e = 310 * 0{,}57 * 0{,}752 * 1 * 1 * 0{,}897 = 117{,}940\ MPa \tag{2.35b}$$

$$\frac{\grave{\sigma_a}}{S_e} + \frac{\grave{\sigma_m}}{S_y} = \frac{1}{n} \rightarrow \frac{0{,}968}{117{,}940} + \frac{5{,}372}{340} = \frac{1}{n} \rightarrow n = 41{,}666 \tag{2.40a}$$

As predicted, the factor of safety value of point B was much higher than that of point A. The reasons for the prediction of this result were mentioned at the beginning. Since the processes here are completed, it can now be started to calculate the bearings.

The first thing that caught my attention when starting the calculations of the bearings was that the bearings would not be subjected to constant forces. The force on the shaft was different when the blade was cutting wood, and different when not cutting it. At this point, I first needed to find the radial forces acting on the bearings while the blade was not cutting the wood. For this, I need to find these forces by solving the system in Figure 2.14 when the blades are not applying force. If I accept the point where the X vector is applied as the zero point again;

$$\sum M = 0$$

$$\sum F = 0$$

$$-\big((25 + 9{,}42 + 23{,}32) * 439{,}65\big) + Y * 170 = 0 \rightarrow Y = 149{,}326\ N \tag{2.43}$$

$$-439,65 + 149,326 + X = 0 \ \rightarrow X = 290,324\ N \tag{2.44}$$

Now that I have found these forces, I will now need to find the forces applied in the axis. The vertical components of these forces have already been found before. Now if horizontal components are found;

$$F_x = 251 * \sin(28,93) = 121,419\ N\ (-) \tag{2.45}$$

$$R_x = 516 * \cos(26,14 + 31,93) = 272,904\ N\ (+) \tag{2.46}$$

$$F_{c,x} = 463 * \cos(31,93) = 392,946\ N\ (+) \tag{2.47}$$

$$F_{t,x} = 227 * \sin(31,93) = 120,056\ N\ (-) \tag{2.48}$$

$$N_x = 474 * \sin(61,07) = 414,850\ N\ (+) \tag{2.49}$$

The + sign indicates the force is to the right, while the - sign indicates that the force is to the left. I know that the sum of the forces in the axis direction must be zero. Then;

$$\sum F = 0$$

$$F_x + R_x + F_{c,x} + F_{t,x} + N_x + F_X + F_Y = 0 \tag{2.50}$$

Here, F_X and F_Y are the indicators of the forces acting on the bearings in the axis direction, and since the two bearings are equal, F_X and F_Y are equal to each other. Then;

$$-121,419 + 272,904 + 392,946 - 120,056 + 414,850 + F_X + F_Y = 0 \quad (2.50a)$$

$$F_X + F_Y = -839,225 \ \rightarrow\ F_X = F_Y = \ -419,612\ N \quad (2.50b)$$

After this point, I can find the resultant force when different forces are applied at different times. If I write the formula needed to calculate this;

$$F_e = \sqrt[3]{P_1^3 * s_1 + P_2^3 * s_2} \tag{2.51}$$

Here, the P_1 value is the resultant force when the blade is applying force, while the P_2 value is the force when the blade is not applying force. Although this equation can be used for an unlimited number of force components, since I have 2 forces, P_1 and P_2 will suffice. First of all, if I start from bearing X, I already know my P_2 value. P_2 is equal to 290,324 N which I found earlier. Because when the blade is not applying force, only radial force is generated. To find the value of P_1, I need to find the composite force formed by the forces in the two axes. In order to find it, I will first choose my bearing and accordingly select the required values from Table 11-2 (Budynas & Nisbett, 2011, p. 581). For the 40mm diameter deep grove 02 series, my C10 value is 30,7 kN, while my C0 value is 16,6 kN. Formula of resultant force;

$$P_1 = X_i V_i F_r + Y_i F_a \tag{2.52}$$

My Vi here is equal to 1 because my inner ring will spin. F_r means radial force at bearing X while F_a means axial force. I used Table 11-1 (Budynas & Nisbett, 2011, p. 580) to select the Xi and Yi values and;

$$\frac{F_a}{C_0} = \frac{419{,}612}{16600} = 0{,}025 \ \rightarrow e \ \cong 0{,}215 \tag{2.53}$$

$$e = \frac{F_a}{F_r * V_i} = \frac{419{,}612}{1695{,}49} = 0{,}247 \tag{2.54}$$

When we compare the two e values we found here;

$$0{,}247 > 0{,}215$$
$$\rightarrow I\ am\ going\ to\ chose\ my\ X\ and\ Y\ values\ from\ second\ part\ of\ table\ 11-1$$

$$X_2 = 0{,}56 \quad Y_2 = 2{,}08$$

Now If I put them to the equation;

$$P_1 = 0{,}56 * 1 * 1695{,}49 + 2{,}08 * 419{,}612 = 1822{,}267\ N \tag{2.52a}$$

The s_1 and s_2 values in the F_e function show which force acts for how long. I already knew that the blade took 0,0092 seconds to cut, scanning a 30,84-degree angle as it did so. Following this, I found that the blade rotates 59,16 degrees at idle until it comes back to the wood. When I compared this information;

$$\frac{0{,}0092}{30{,}84} = \frac{t}{59{,}16} \rightarrow t = 0{,}0176\ second \qquad (2.55)$$

Then my s_1 and s_2 values are respectively;

$$s_1 = \frac{0{,}0092}{0{,}0268} \quad s_2 = \frac{0{,}0176}{0{,}0268}$$

Now, if we substitute all the values we found in the F_e equation;

$$F_e = \sqrt[3]{1822{,}267^3 * (\frac{0{,}0092}{0{,}0268}) + 290{,}324^3 * (\frac{0{,}0176}{0{,}0268})} = 1279{,}22\ N \qquad (2.51a)$$

Calculating life;

$$L_{10} = \frac{10^6}{n * 60} * \left(\frac{C_{10}}{F_e}\right)^3 \qquad (2.56)$$

n means the rpm so n = 560 rpm and C_{10} = 30,7 kN so;

$$L_{10} = \frac{10^6}{560 * 60} * \left(\frac{30700}{1279{,}22}\right)^3 = 411377\ Hour \qquad (2.56a)$$

Here, when we look at the life of the bearing, we see that it is quite high. Also, this will probably be the bearing with a shorter lifespan. If we perform all these operations for the Y bearing;

$$\frac{F_a}{C_0} = \frac{419{,}612}{16600} = 0{,}025 \rightarrow e \cong 0{,}215 \qquad (2.53a)$$

$$e = \frac{F_a}{F_r * V_i} = \frac{419{,}612}{506{,}16} = 0{,}83 \qquad (2.54a)$$

$$0{,}83 > 0{,}215 \rightarrow I\ am\ going\ to\ chose\ my\ X\ and\ Y\ values\ from\ second\ part\ of\ table\ 11 - 1$$

$$P_1 = 0{,}56 * 1 * 516{,}16 + 2{,}08 * 419{,}612 = 1156{,}242\ N \qquad (2.52b)$$

$$P_2 = 149{,}326\ N$$

$$F_e = \sqrt[3]{1156{,}242^3 * (\frac{0{,}0092}{0{,}0268}) + 149{,}326^3 * (\frac{0{,}0176}{0{,}0268})} = 810{,}702\ N \qquad (2.51b)$$

$$L_{10} = \frac{10^6}{560 * 60} * \left(\frac{30700}{810{,}702}\right)^3 = 1616188\ Hour \qquad (2.56b)$$

As expected, the life of the bearing in this section was approximately 4 times higher than the other. Because the forces applied to the Y bearing were less than the forces applied to the X bearing.

3. RESULT AND DISCUSSION

When we examined the results of our studies, we saw that the materials used in production were quite durable. Maybe a little too durable. Although the forces we found were normal in general terms, the high lifespan of the parts was the factor that caught my attention. Here I attribute the reason for this to the durability of the material used. The reason why I chose 1050 steel during the calculations was what other engineers told me during my production internship.

According to what the engineer responsible for me told me, 4140 and similar Nitrating steels and AISI 10XX steels are the most commonly used steels in heavy industry. Although the cost of these steels is low, their high durability is the reason why they are used in almost every part of the machine. He even said that in the factory where I did my internship, they used 1050 steel instead of the most commonly used 1040 because 1050 steel, although only slightly more expensive, outperformed 1040 steel, so they used 1050 steel to improve the quality of their goods. I decided to use this steel, taking into account what was told. Looking at the results, we see that it can easily handle the stress under the shaft. It is natural that the resulting stress is not high since it is not exposed to very large forces in the machine it is used in.

Another issue that draws my attention is the high lifetime of the bearings. I attribute this to the fact that the forces they are exposed to are not very high, as I have just mentioned. At the same time, I think that the diameter of the bearings has an effect on this issue. If we look at Table A-20, the larger the diameter of the bearings, the larger the forces they can withstand. When calculating the diameters of the part of the shaft that will carry the bearings, I took the diameter as 50 mm for the first time. However, as I made the calculations and progressed, I saw that the life of even the bearing with the shortest life is over 700000 hours. After seeing this result, I decided that the diameters could be reduced a little more. I had to stop when I got to 35mm while gradually reducing the diameters. Because if I chose 35 mm, this time the safety factor value of point A on the shaft was approaching 1. Since I don't want the value to get that small, I finally decided on 40 mm. Even though their lifetime is high, I have brought the result to a reasonable point compared to the value in 50 mm diameter.

4. CONCLUSION

Thanks to this project, I learned what kind of machines are needed to produce wood chips. It has been examined how the size of the chips are determined and by which factors they can be changed. Although the results are more or less at the level I want, I think the project can still be improved. In particular, improvements can be made on the lifetime of the bearings. I think that the bearing life can be reduced to a slightly more reasonable level with the changes in material and design. In the general design, maybe add-ons that make life easier can be added. The material change can also be used to reduce the overall weight of the tool.

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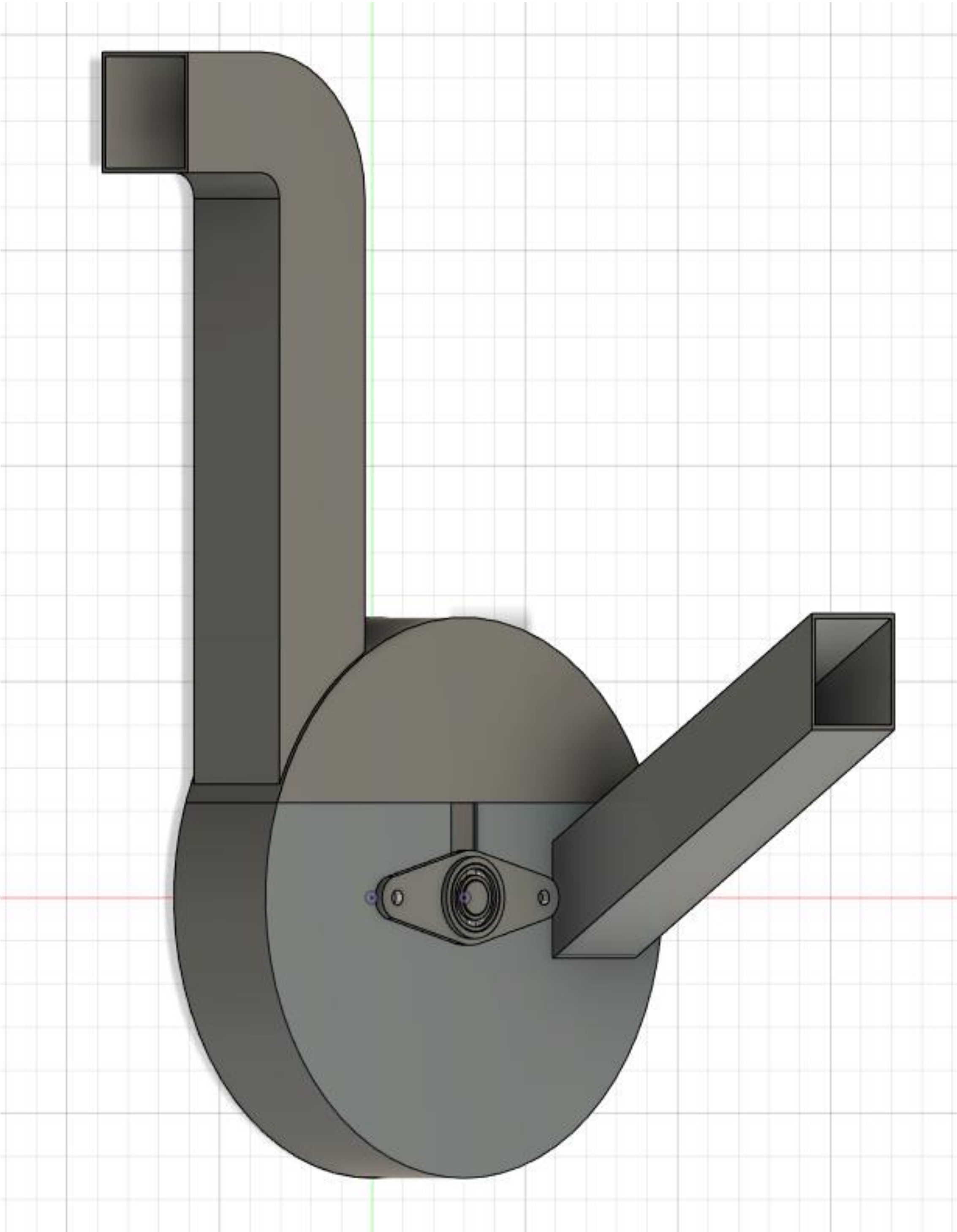
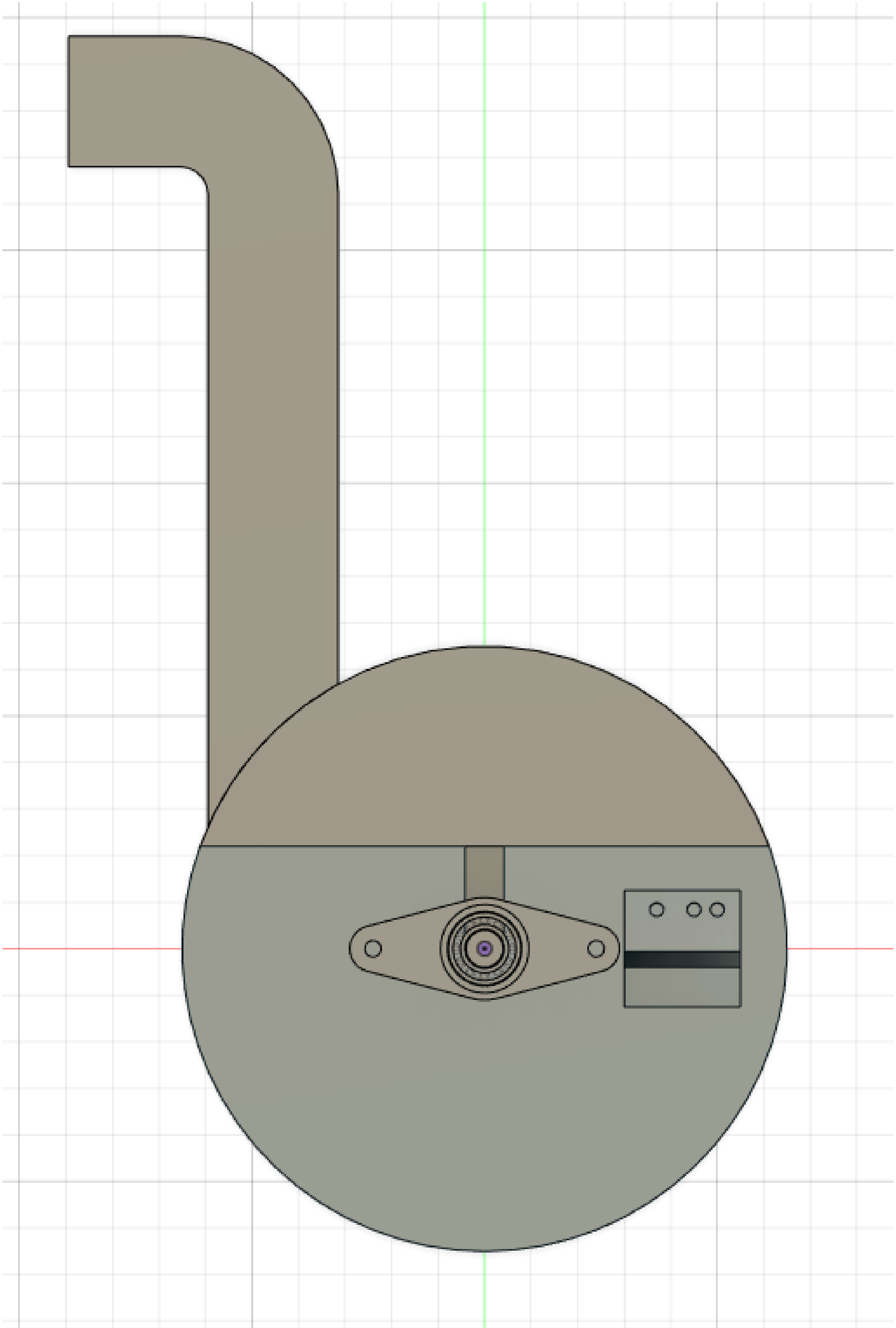
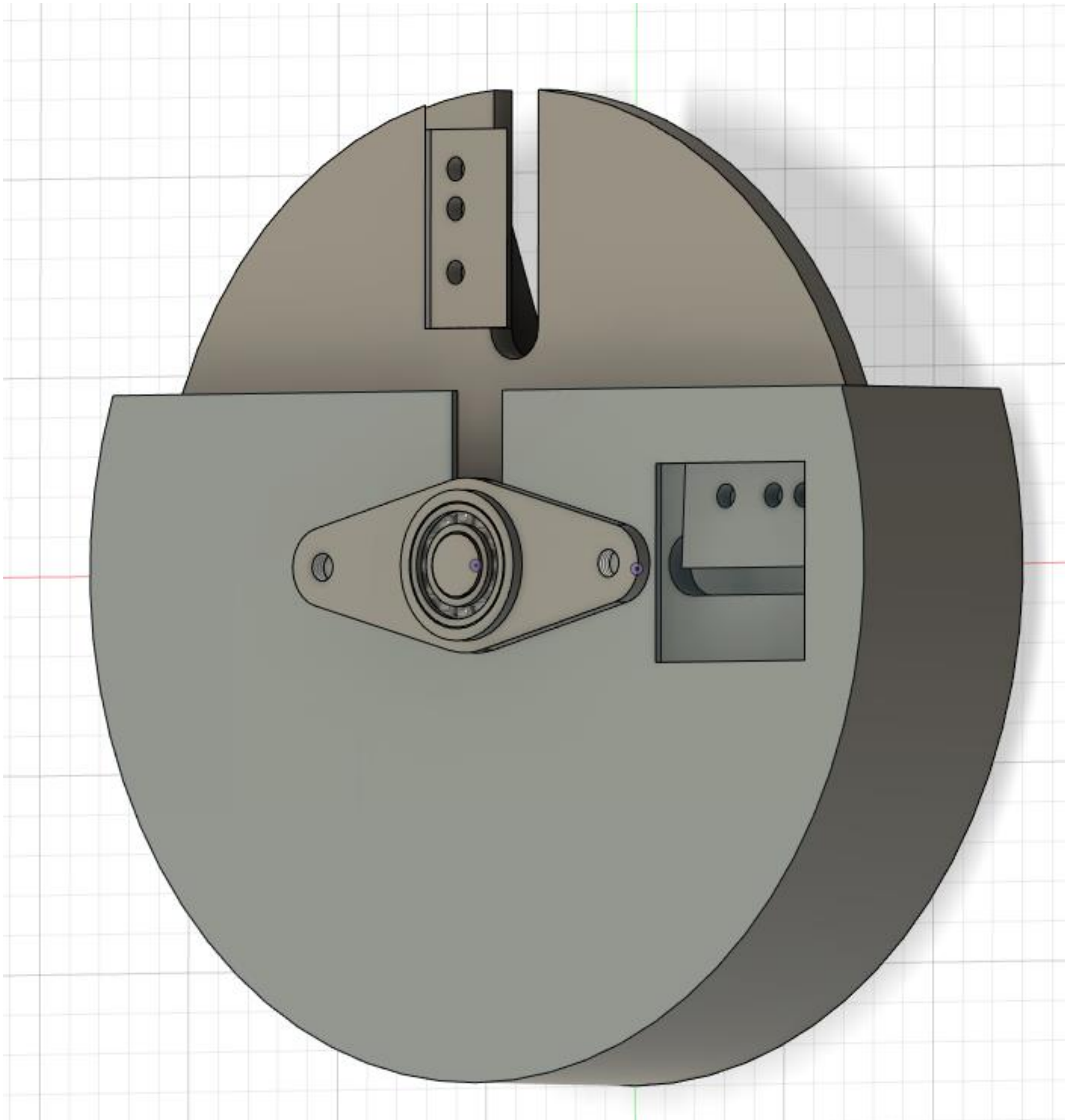
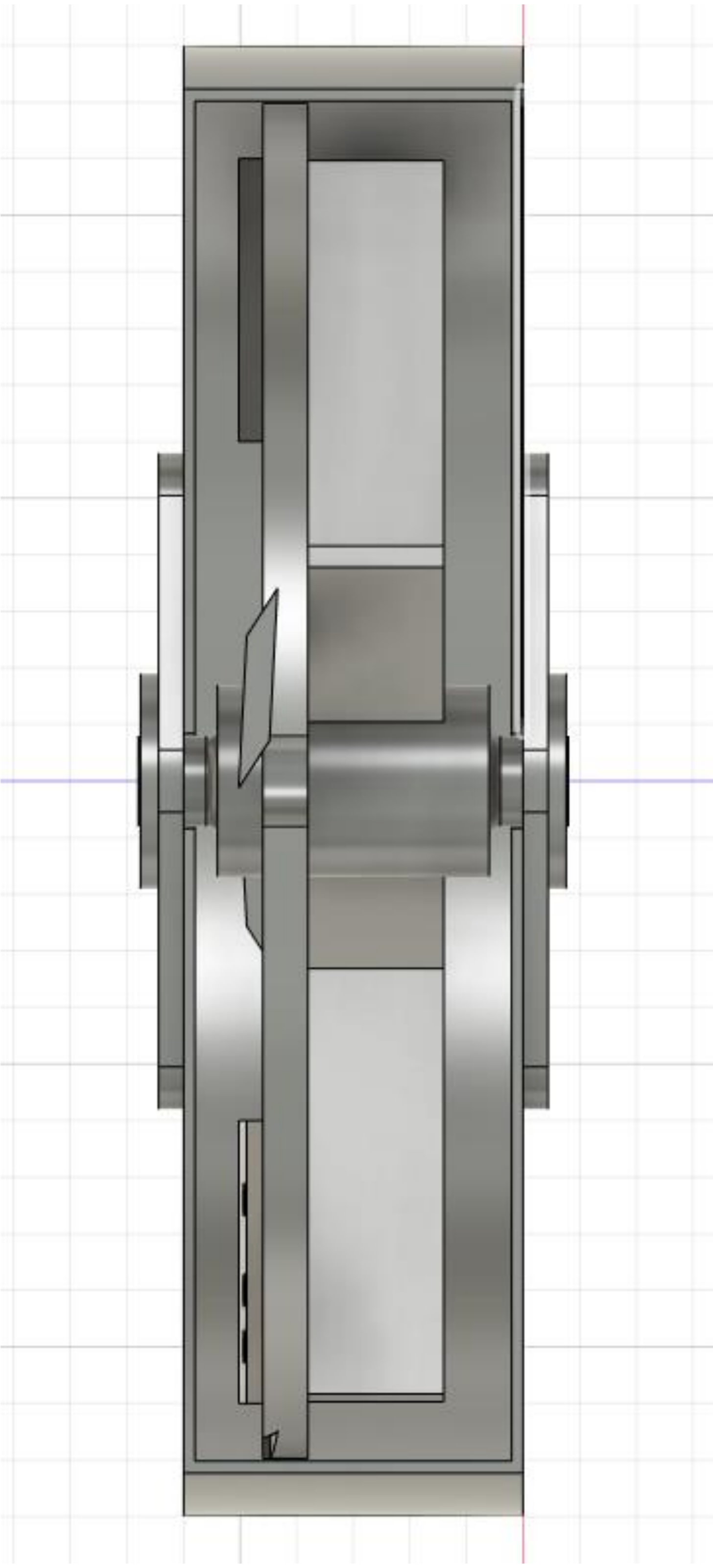
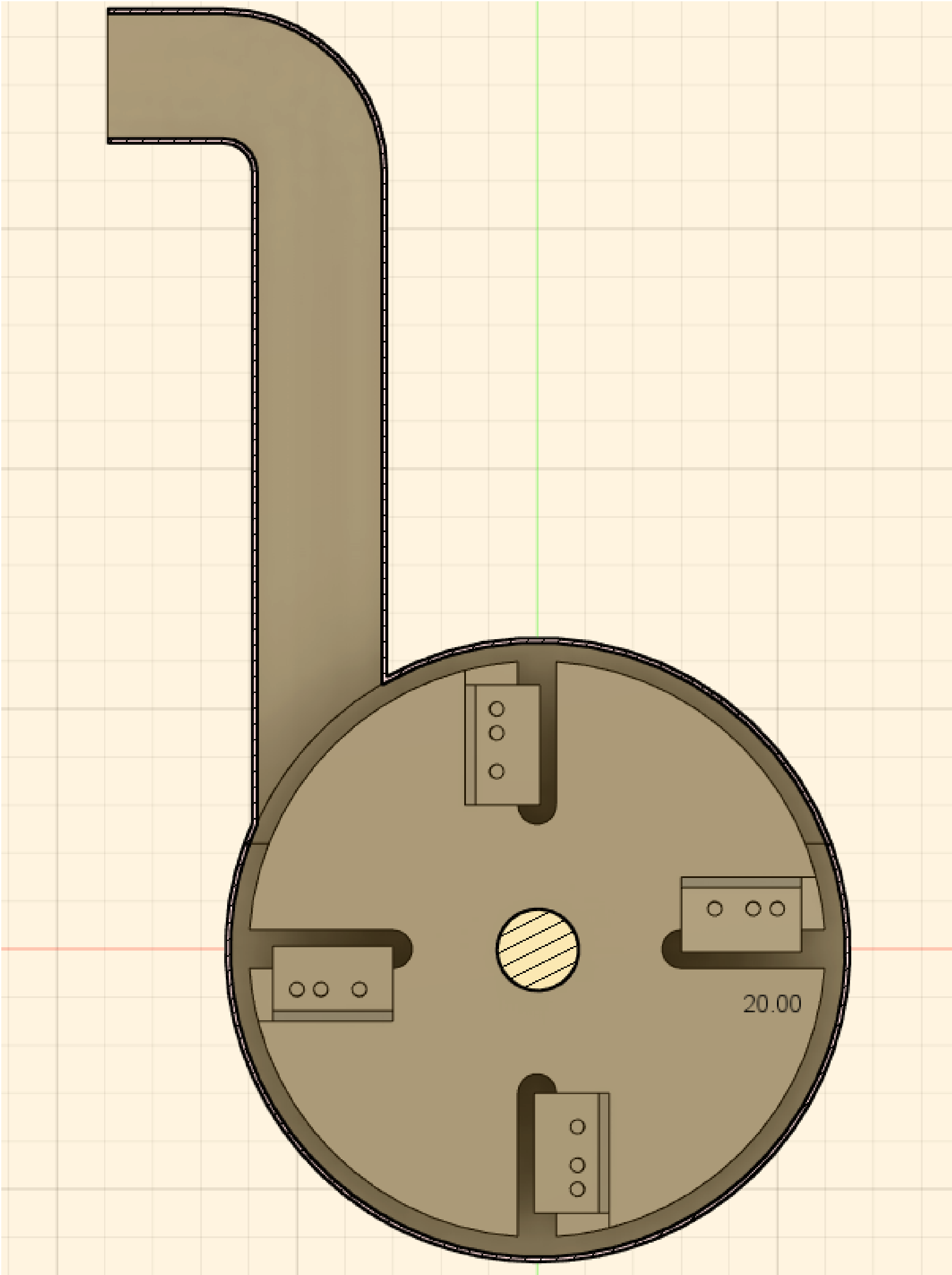
APPENDICES







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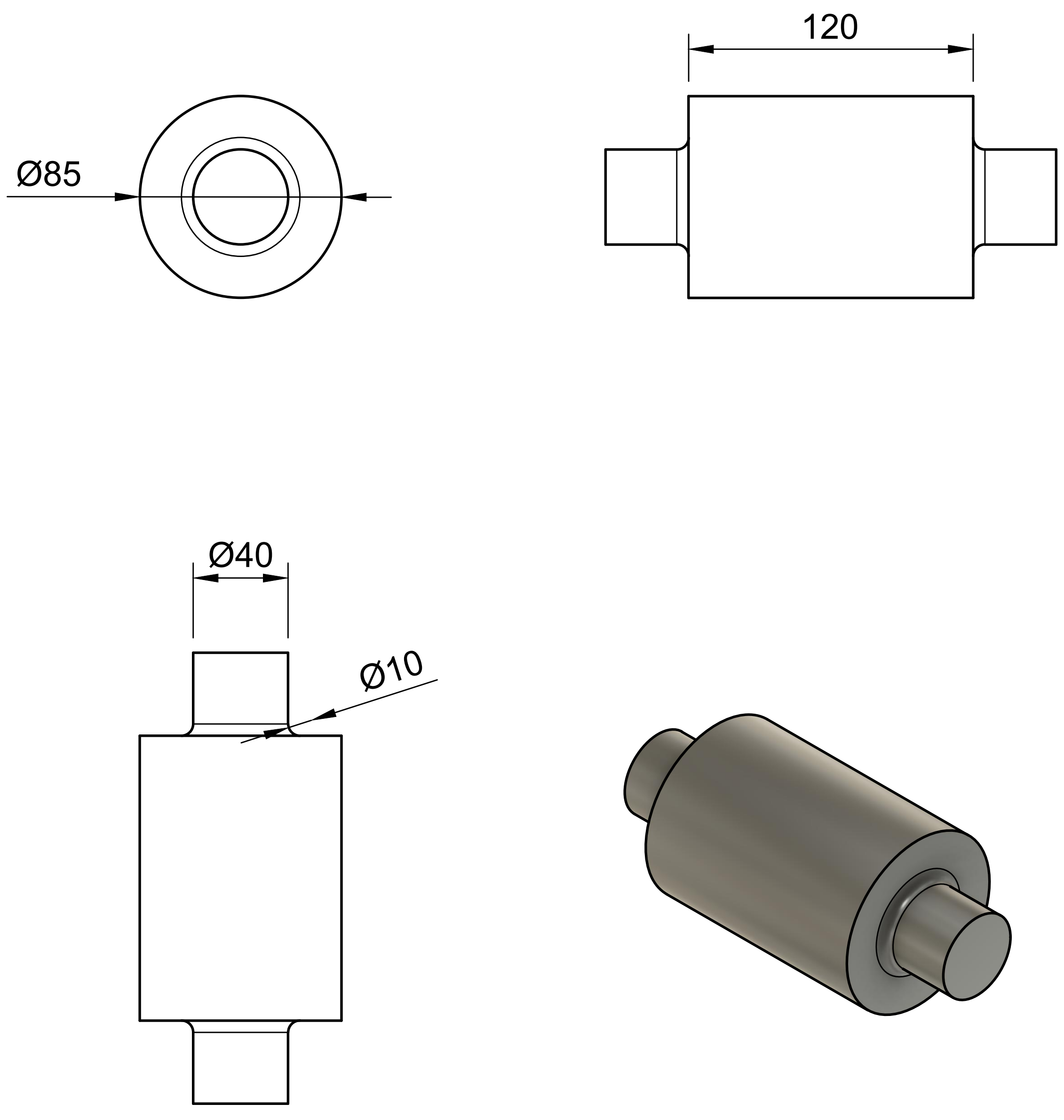

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		Fatih GÖRGÜN 15.06.2022	
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			Rev. / Date of issue / Sheet
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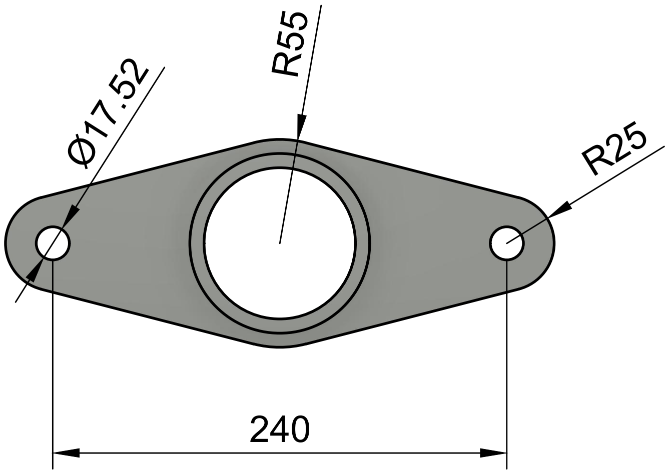

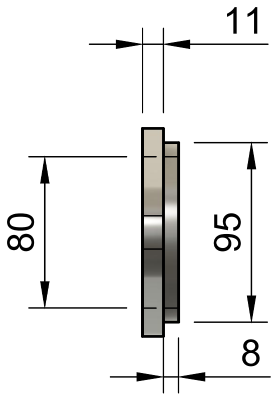

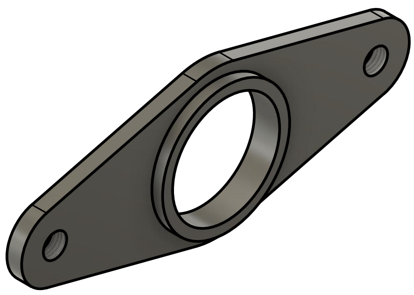

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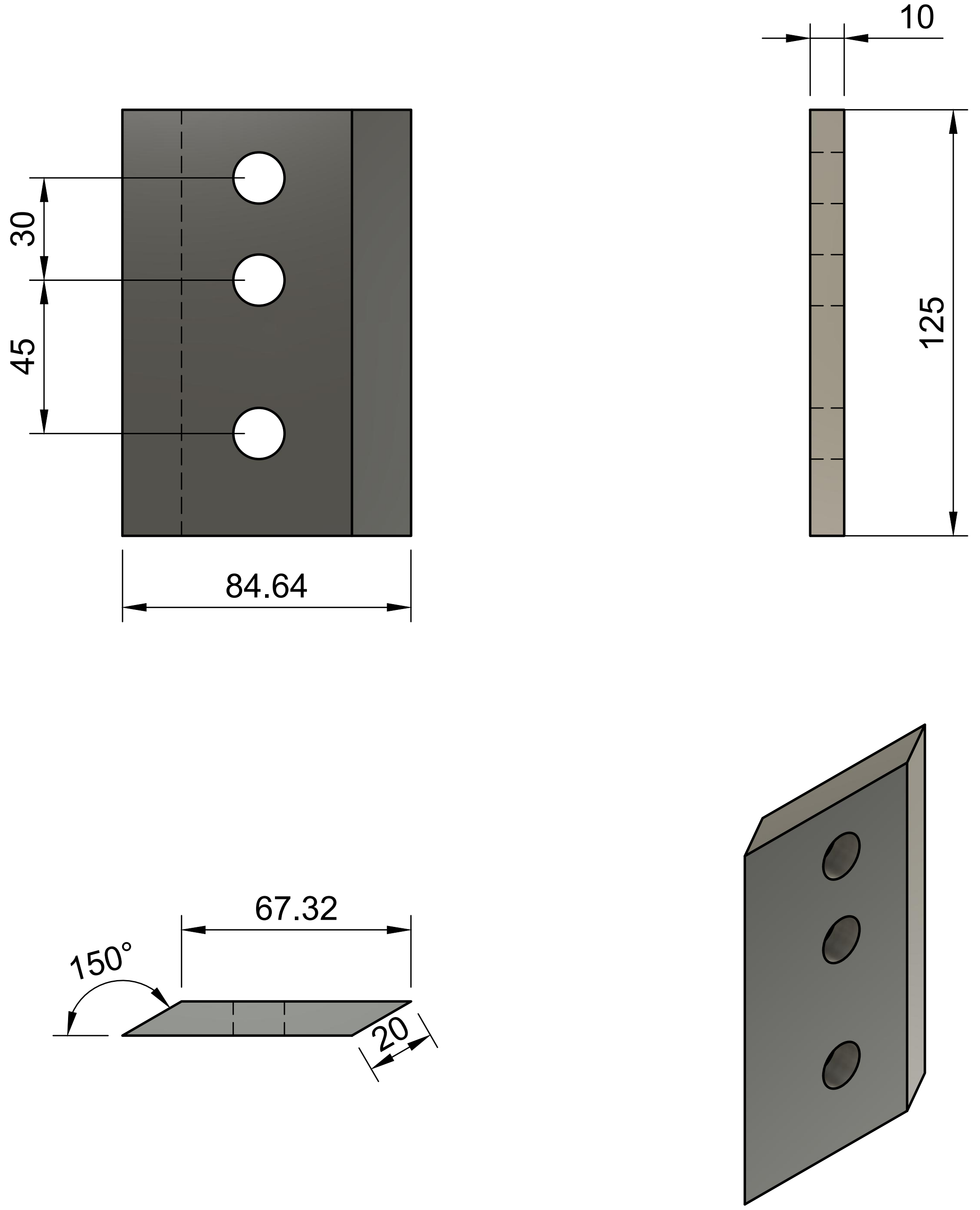

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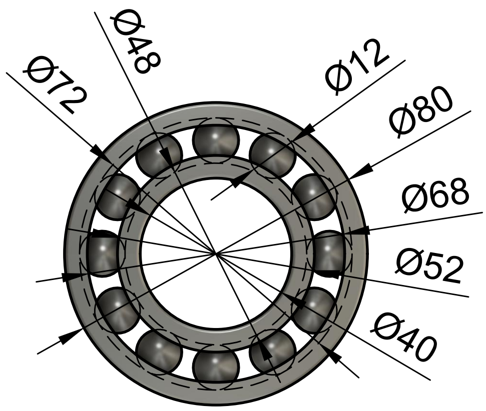

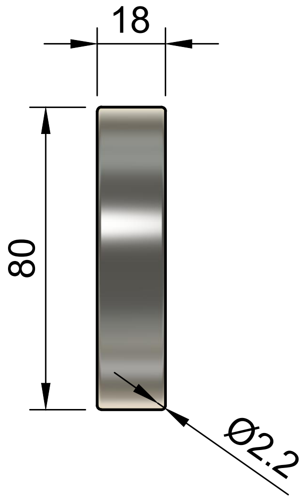

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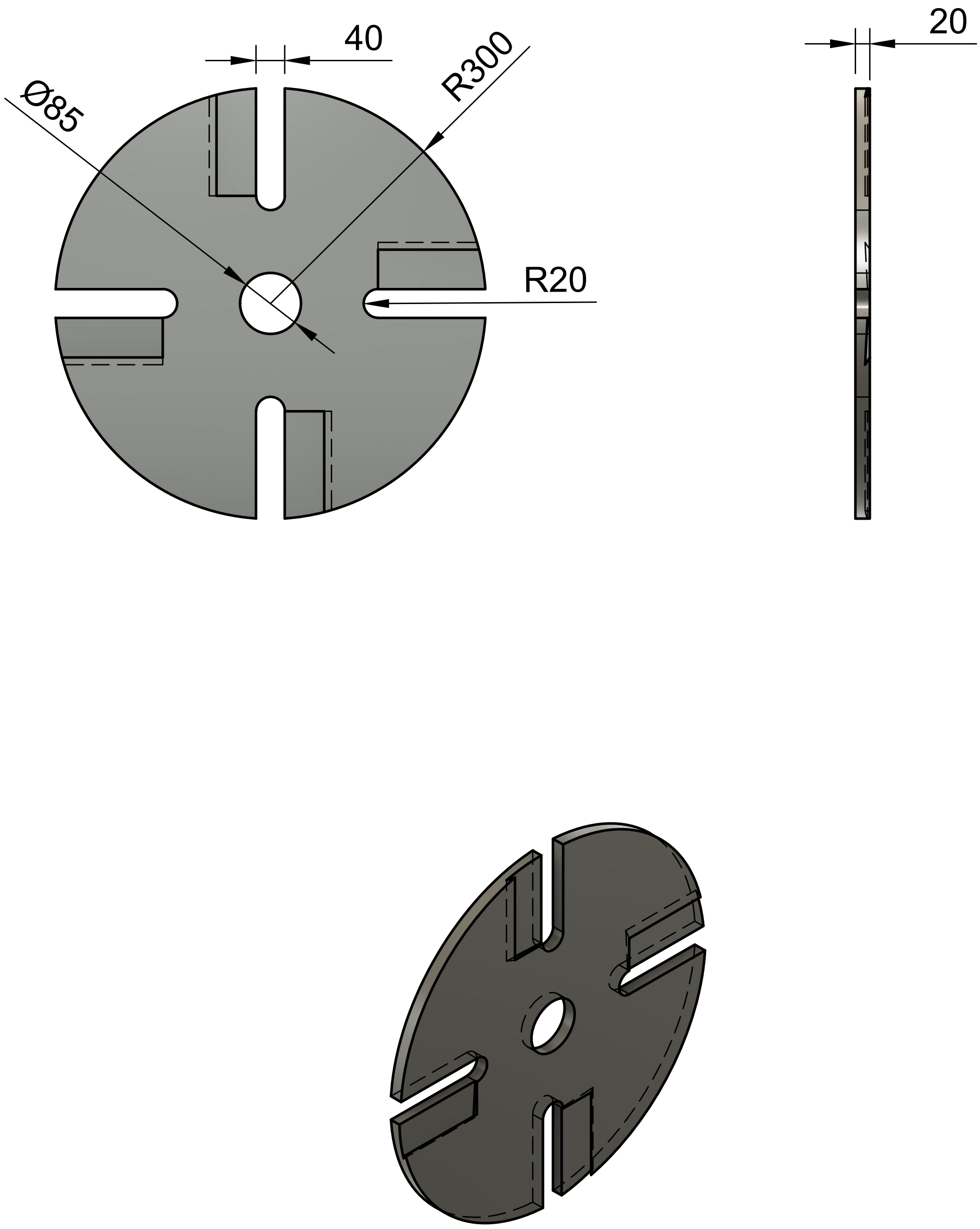

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