



Final Report

Quartile 2 - 2022-2023

Full Name	Student ID	Study
[REDACTED]	[REDACTED]	Mechanical Engineering
[REDACTED]	[REDACTED]	Mechanical Engineering
[REDACTED]	[REDACTED]	Mechanical Engineering
T.S Wejbora	[REDACTED]	Mechanical Engineering
[REDACTED]	[REDACTED]	Mechanical Engineering
[REDACTED]	[REDACTED]	Mechanical Engineering
[REDACTED]	[REDACTED]	Mechanical Engineering
[REDACTED]	[REDACTED]	Mechanical Engineering

Group 015

Tutor: Ricardo Hoogenes

Case coordinator: I. Cortes Garcia, H.C. de Lange, M. van Gorp, M.H.M. Willems, Gerard van Hattum
Eindhoven, April 2, 2026

Contents

1	Introduction	4
1.1	Task:	4
1.2	Requirements, Preferences and Constraints (RPC's)	4
2	Concept	5
2.1	Initial designs	5
2.1.1	Floating Arm	5
2.1.2	Whipper Trebuchet	6
2.1.3	Spring	6
2.1.4	Golf Club	6
2.2	Projectile	7
2.3	Decision on the concept	7
3	Preliminary Design	8
3.1	First decisions	8
3.2	Early firing of the projectile	8
3.3	Final Preliminary design	9
4	Detailing	10
4.1	The Frame	10
4.2	Front Axle	10
4.3	Golf Club Shaft	10
4.4	Head	10
4.5	Projectile	11
4.6	Sled	11
4.7	Rails	11
4.8	Drum	11
4.9	Trigger Mechanism	11
4.10	Ball Bearing Sleeve	11
4.11	Final Assembly	11
4.12	NX Simulation	12
5	Realization	14
5.1	Printed parts	14
5.2	Assembly	14
5.3	Finishing the launcher	14
5.4	Relocating the firing pin	14
6	Testing	15
6.1	First test	15
6.2	First test at launch conditions	15
6.3	Adding torque	15
6.4	Minimizing vibrations	15
6.5	Official testing	15
7	Evaluation	16
8	Bibliography	17
9	Appendix Chapter 2	18
9.1	Assumptions and estimates	18
9.2	Determining ideal firing angle	18
9.3	Torque	19

9.4	Function list	20
10	Appendix Chapter 4	21
11	Appendix Chapter 6	28
11.1	Step-by-step guide to constructing the assembly	28
11.2	Arming and firing the mechanism	28

List of symbols:

Symbol	Meaning	SI-unit	Symbol SI-unit
θ	Angle	Radian	[-]
ρ	Density	Kilogram per Meter ³	[Kg/m ³]
τ	Torque	Newton Meter	[Nm]
a	Acceleration	Meters per Second ²	[m/s ²]
E	Energy	Joule	[J]
F	Force	Newtons	[N]
g	Gravitational Acceleration	Meters per Second ²	[m/s ²]
h	Height	Meter	[m]
L	Length	Meter	[m]
m	Mass	Kilogram	[Kg]
r	Radius	Meter	[m]
T	Period	Seconds	[s]
v	Velocity	Meters per Second	[m/s]
V	Volume	Meter ³	[m ³]

1 Introduction

1.1 Task:

The students at TU/e have been tasked with creating a launching mechanism that launches a self-made projectile as far as possible. The launcher has to be made out of versatile and durable Nylon12 plastic. The actual manufacturing has been outsourced to Shapeways Eindhoven, who specialise in 3D printing via SLS (Selective Laser Sintering).

The report is structured linearly and supported by the 7 design phases. In general, the report will explain the starting phase of the project, for example, eliminating and narrowing down design choices while also providing reasoning behind doing so. Then, the formulation and construction of a dynamical CAD model is discussed and the expected results are evaluated. Lastly, the realization, testing and tuning process of the physical 3D printed model is outlined.

1.2 Requirements, Preferences and Constraints (RPC's)

All projects come with their own set of requirements and constraints that are necessary to adhere to. The requirements for this project are the following;

- The construction should be durable.
- The construction should be original.
- The projectile should be launched at least 5 meters away.

Furthermore, the constraints of this project are listed below;

- The construction must be mounted to the steel base plate with up to 4 pieces of M5 bolts
- The front of the base plate is located on the edge of a table with a height of 75 cm
- The trigger mechanism can only be operated with one hand.
- Both the launching mechanism and projectile have to be 3D printed, using a maximum of 10% of the printing box of 300 x 100 x 50mm.
- The only power source is four falling M20 nuts, transferring energy via a drum.

Preferences are also chosen. For example, during the brainstorming phase, it became aware that the strength and durability of the design plays an immense role when dealing with strong forces/weights. It takes only one structurally unstable part to weaken the entire structure. Furthermore, the design should be easy to assemble to an extent that it can be constructed as intended and not cause complications. Not to mention that the design is preferred to be original and not based on a previous design. The setup of this project can be seen below in Figure 1.1.

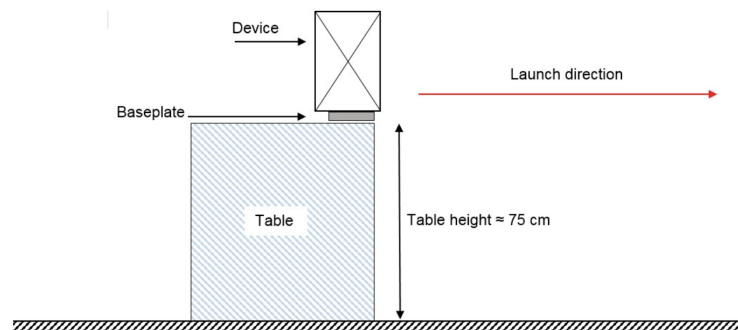


Figure 1.1: Design Setup

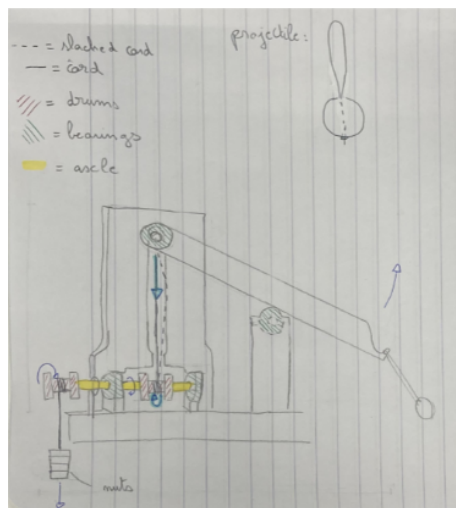
/

2 Concept

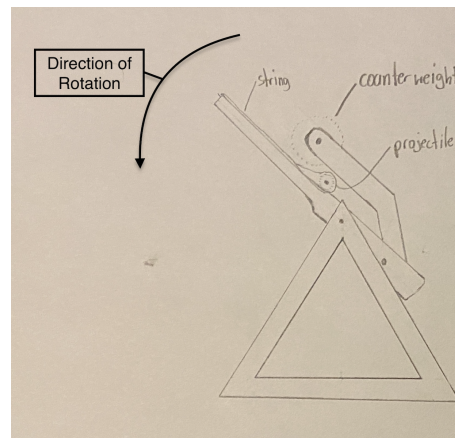
After correctly defining the requirements, preferences and constraints, the conceptualization of various types of designs was most important. Initially, the RPC's were not too influential when bringing designs into consideration as the main goal was to think outside the box and be inspired by creative design options. Afterward, the extensive amount of designs were critiqued and narrowed down by all group members. All in all, four different possible designs were chosen.

2.1 Initial designs

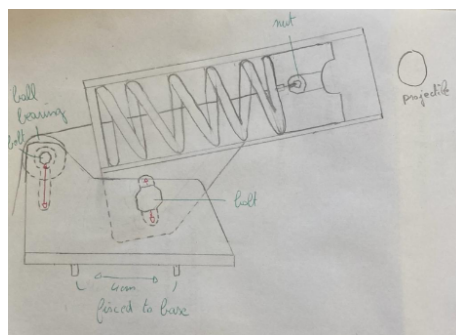
The four chosen designs are illustrated in the form of technical sketch as seen in Figure 2.1.



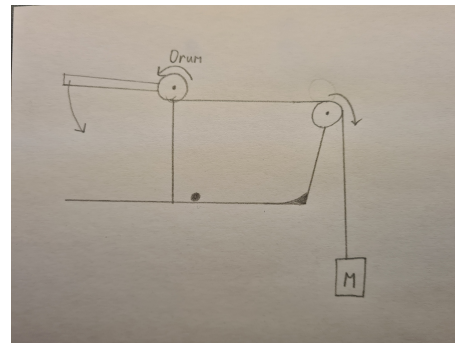
Floating Arm



Whipper Trebuchet



Spring



Golf Club

Figure 2.1: The four different launching mechanism ideas

2.1.1 Floating Arm

The first design that was discussed is the so called 'Floating Arm'. As the counterweight falls off the edge of the table, it rotates the drum above it. This drum rotates an axle that leads to the center of the design. This axle is then connected to a second drum. This drum starts rotating as well. Note that above this drum is a slot (denoted by the blue arrow) where the arm will be pulled down by the rope attached to the drum in the center. On the other end of this arm is where the projectile is mounted, the arm will accelerate and release this projectile via a hook system. Due to the positioning of the hook, the projectile will be released

at the exact time the arm hits the ground. The conventional 'floating arm' design has the counterweight attached directly to the arm (above the blue arrow in Figure 2.1). However, since this does not harness the full gravitation potential energy of the counterweights and the fact that a drum is required, leads to the reason why the system described in the previous paragraph is used. Moreover, another benefit of this design is that there are two drums, this makes it easy to implement gearing ratios. The drum diameters can be changed independently from each other, so an optimal ratio between the two can be found. On the other hand, because two drums need to be used in this design, there could be a lot of friction and adjusting the firing angle is hard to accomplish.

2.1.2 Whipper Trebuchet

The whipper trebuchet design gets its inspiration from the trebuchets used in the middle ages as a weapon. The counterweight is connected to a small arm which is on a hinge with the main arm that holds the projectile. As shown in Figure 2.1, as the arm falls due to gravity, so does the counterweight. Once the counterweight is at its lowest point, the main arm creates a whipping motion causing the projectile to fly off due to sudden increase in jerk. Rope is used to connect the projectile to the end of the arm. Once the arm makes a full rotation, a hook system is used to release the projectile at the right time. This can be seen in Figure 2.2.

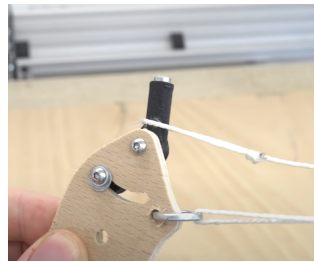


Figure 2.2: Hook System

A strong point on this design is that it has proven itself to work. As mentioned earlier, it has been used for many years already and is seen to be a reliable shooter. However, a way to implement a drum has not yet been found and at the scale of this design, it is possible that the projectile being released at the right moment is inconsistent.

2.1.3 Spring

Another method of transferring the gravitational potential energy from the falling mass to the projectile was also discussed intensively. One of the ideas was to translate this energy into potential energy of a spring. The falling mass would be guided, via a ball bearing, towards the end of the spring. This weight would then press the spring. The spring should then be released, launching the projectile.

If the spring is released, it causes all energy to be released at once, giving the projectile a huge acceleration. An advantage of this design is that it is very easy to shoot the projectile at the optimal angle, since the angle of the spring can be easily adjusted. However, it was very difficult to think of a method to release the spring when its maximum suppression was reached. Also, no idea was thought of that would not cut down on the working of the design when a drum was implemented somewhere. Furthermore, it was the question if the 3D printing material would be suitable to make a spring. The material should not be too stiff, because then the spring would not be pressed enough or even break. On the other side, if the material is too weak, the spring could be suppressed very far, but not have enough energy stored in it to release the projectile.

2.1.4 Golf Club

The final design is the so-called golf club. The falling mass will be guided, via a ball bearing towards the drum, causing it to rotate. A beam, or golf club, is on one side connected to the axle of this drum. This

beam will spin and hit the projectile.

The main positive aspect of this designs is its implementation of the drum. With the other designs described earlier, the use of a drum would negatively impact the efficiency of the design, whilst in this design it is necessary for the functioning of the design. There are multiple methods of obtaining an optimal firing angle as well. For example, a ramp can be added at the end of the runway, which is visible in Figure 2.1, and the drum diameter can be modified using gearing ratios.

2.2 Projectile

Similar to the launching mechanism itself, multiple designs were considered for the projectile, since different designs required different projectiles. Firstly, a plane design was investigated. This would only be possible to use with the spring design, since the rotating motion of the launching mechanisms of the other proposed designs would lead to a high chance of an inconsistent flight path. Thus this projectile could only be used for the spring design. Similar explanations can be given for both a disc and a bullet.

The best option is to use a small sphere as the projectile. Although it is a very simple design, it can work with various designs. It can be implemented into the golf club design best, but also the whipper trebuchet, floating arm and the spring design. In the golf design, it is possible that the projectile isn't hit perfectly, meaning that the projectile could start rotating. Thus, having a perfectly symmetrical and round object reduces drag.

2.3 Decision on the concept

When deciding on the concept to pursue in this project, an important aspect that arose was the use of the total potential energy provided. In an ideal situation, the mass falls the whole 75 centimeters (the height of the table) before the projectile is being hit or released. In the current designs, this is not the case as for example, a mechanism only rotates once before hitting the projectile. Thus, the main design improvement to be made at this point was to try and include multiple rotations so that more energy can be transferred into the projectile.

Firstly, the spring design was discarded due to the fact that not enough potential energy could be created from the falling weight and the use of other external sources of energy are not allowed. Also, there were doubts if a printed spring would work well.

The trebuchet and the floating arm were considered, but they were dismissed since the performance of these designs could not be predicted easily by means of calculations. Although they were promising designs it would have been risky to choose a design just based on intuition.

For the golf club there were many points in favour of the design idea:

Firstly, by using conservation of energy, circular motion and projectile motion equations a rough estimation of the balls reach could be calculated. Calculations were made in which a range of shooting distances were determined depending on the firing angle of the projectile. These can be found in Section 9.1 of the appendix. As mentioned earlier, the design is most simple to build out of all the designs, so it could be easily constructed into a physical prototype. Moreover, since the working of the design is quite simple, the design can be easily improved. Those improvements will be discussed later in the report. It is important to mention that a function list was created. The function list, which can be found in Appendix-Section 9.4, was beneficial since it encompasses the analysis of each concept. In conclusion, the golf club was deemed the most suitable design to pursue.

3 Preliminary Design

After deciding the conceptual design, the concept had to be turned into a preliminary design. This design did not have to fully adhere to the given RPC's since its main function was to test the concept and to discover any aspects that need to be improved upon during the detailing phase. To make a physical prototype, materials are needed. For this model, using lego bricks is ideal because of the ease with which one can implement changes into the design. With the many different bricks available, the freedom of 3D printing could be closely simulated.

3.1 First decisions

Amongst the first drawings was a design which had the weights at the club head, which would have been better for simplicity and material cost. This idea did however have some major drawbacks, mainly being that the motion is only accelerated for half a rotation, and that the weight does not move vertically, which limits the acceleration of the club, thus limiting the energy being transferred to the projectile. Instead of this, the first physical design seen in Figure 3.1, featured a drum being spun by a falling mass, which rotated the golf club. The advantages of this are the vertical path of the weight, the constant acceleration and the larger initial potential energy, caused by the weight hanging over the edge of the table. This overhang was achieved by using a pulley that hangs over the table and guides the rope towards the drum that is on the same axle as the club arm. It was decided that a simple sphere would work best as the projectile, since it is the most predictable when it has rotations, and it is heavy for its size.

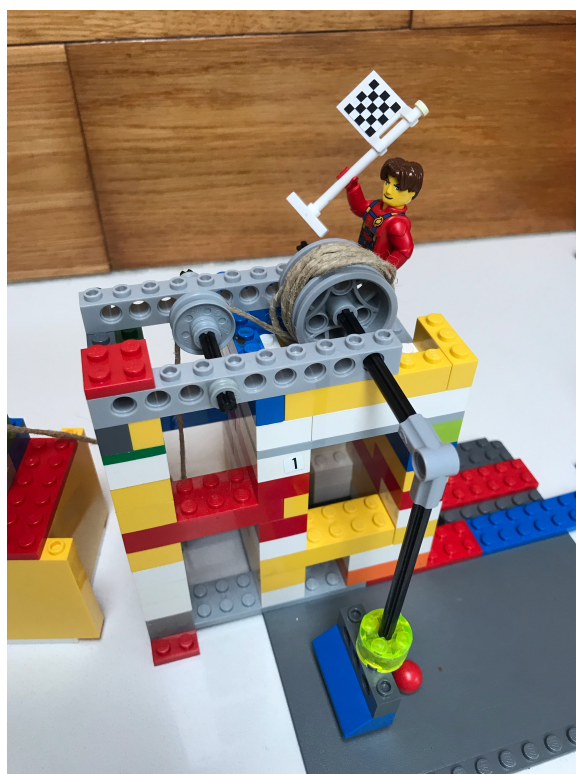


Figure 3.1: Lego Prototype 1

3.2 Early firing of the projectile

As the weight falls, the axle with the club rotates and hits the ball after a full rotation. The biggest problem with this design was that the ball gets hit on the first rotation, which gave the weight little time to fall before the projectile was launched, which resulted in a lot of wasted potential energy and low exit speed.

Rope slack

The first solution to this problem that was tested was the introduction of slack in the rope connecting the weights to the axle. This gave the weight some time to accelerate before moving the club arm. The advantages of this were that the large jerk caused by the momentum of the weight accelerated the club arm faster, which resulted in a larger exit speed. Also, a smaller drum ratio could be used, because less torque is needed to overcome the initial static friction and inertia of the system. The drawbacks of this option are however quite substantial. The big jerk means that a lot of stress gets put on the system, and it is clear that this setup is not an efficient way of transferring energy into the projectile, since the weight hit the ground with a very large velocity during testing, which meant a lot of the potential energy was still in the counterweight after the launch.

Sled

The second solution for this problem was to introduce the projectile into the club's path after multiple rotations. This was made possible by using a sled driven by a second rope that was attached to the weight as well. The moment at which the sled gets pulled can be adjusted by increasing or decreasing the slack in the rope. By adjusting it so that the projectile gets launched on the last rotation before the weight hits the ground, a larger exit speed can be achieved. This design can be slightly unpredictable since the projectile could fall out of place as the sled is being pulled, which means it would roll out of the club's path. However, during testing it was found that the arm rotates so quickly that the projectile already gets hit before it has a chance to fall out of the club's path, which helps in the reliability of this design. The sled does take up some extra material, but it was decided that it's advantages in the range and originality category outweigh its cons in reliability and material cost.

3.3 Final Preliminary design

With this final problem solved, the preliminary design is finished and illustrated in Figure 3.2. The design works as intended, and the adjusting of the timing also works as expected. Thus a successful prototype has been created proving the concept behind the design.

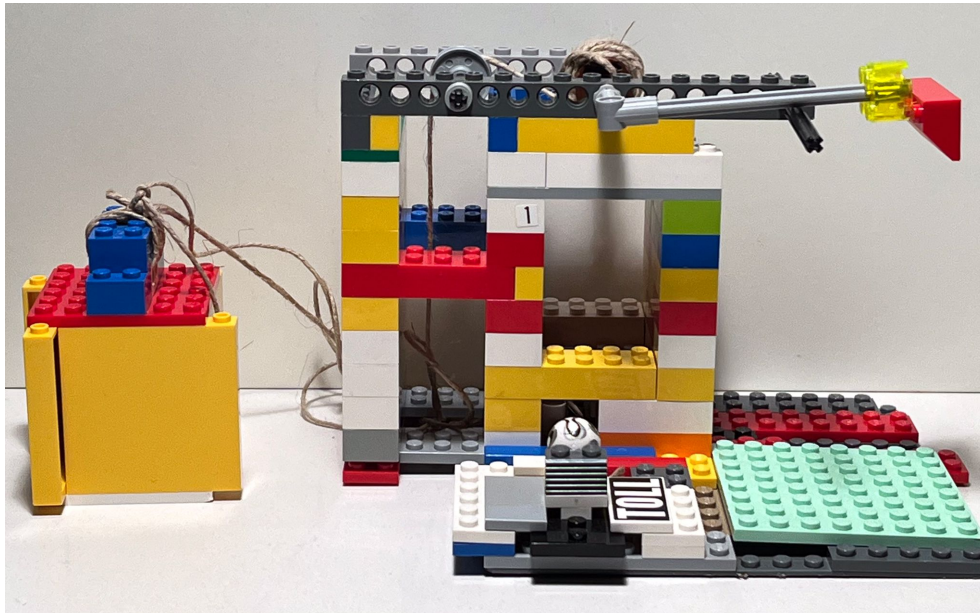


Figure 3.2: Lego Prototype 2

4 Detailing

In order to transform the design from a mere sketch to a physical product, Siemens NX, a CAD package, is used. Although the preliminary Lego design provides proof of concept, the CAD design produces a integrated custom product tailored to the RPC list. The design is comprised of various parts which will aim to act as one fluid mechanism, achieving the goal of launching a projectile. This section of the report justifies the effectiveness of the underlying CAD design process by decomposing the design into its parts and exploring their individual significance to the design. The dimensions of each part can be found in Table 10.1.

4.1 The Frame

The frame of the launch structure is one of the most crucial and structurally significant parts of the design. It must be a strong, rigid design that keeps material use in mind. Through multiple prototypes, such a design has been achieved.

The first version of the frame can be found in ?? in the appendix. It consists of a base with 4 M5 screw holes, which is used to attach the frame to the provided base plate. Furthermore, integrated into the base is a tunnel system used to feed the counterweight rope from the counterweight to the sled. The main segment of the frame consists of 6 thick pillars and 13 truss members that support the top of the design. The rear of the top of the frame holds the big bearing mounts that house the bearings for the golf club axle. Additionally, at the front of the top, there are smaller holes for the front axle to slide through.

The second and final version of the frame employs 8mm pillars that have a hollow center, 4mm in diameter. This design choice was implemented instead of the old 10mm pillars due to the material constraint of $150,000mm^3$. Because of this change, the volume of all the pillars decreased from $58,800mm^3$ to $45,700mm^3$ representing a $13,100mm^3$ or a 27% decrease in volume. A picture of the final version of the frame design can be found in Figure 4.1.

4.2 Front Axle

The front axle, seen in Figure 10.2, is designed to hold a bearing fitted with a bearing cover. The bearing and bearing cover will efficiently guide the rope that powers the golf club axle with the lowest friction possible. The front axle has a diameter of 8mm which matches the inner diameter of the type 608 bearings provided. Since the front axle doesn't have to support a lot of force, it was also made hollow to reduce volume. Making the center, 3mm hollow reduced the volume by $1,400mm^3$.

4.3 Golf Club Shaft

The golf club shaft, as seen in Figure 10.3, connects the head of the golf club to the drum that is powered by the counterweight. Thus, the shaft provides the rotational motion of the system.

4.4 Head

The head of the golf club, seen in Figure 10.4, is based on a long range driver used by golf players, most notably, both a long range driver and this design have a flat front face and aerodynamic curves on the rear. However the flat face in this design is tilted to fire the projectile at an angle. As explained in Section 9.1 this angle is 55° . This was the easiest and most efficient way to fire the projectile since unlike this design, a golf club player can change their stance and follow through their swing to change the angle of the projectile. It is important to mention that the golf club head will cause a lot of vibration due to its high mass, rotational velocity and long arm to the centre of rotation. This means a counterweight would need to be added on the other end of the golf club shaft with an equal moment, to balance the arm. However, it has been determined that establishing a good way to allow the golf club to spin multiple rotations before contacting the projectile is an advantage that out weights the disadvantage of having an imbalance in the golf club. It has been deemed impossible to achieve both of these due to material constraints. Because high forces are expected, the frame has been made as stiff and strong as possible.

4.5 Projectile

The chosen projectile still remains a perfect sphere. The projectile size of 15mm was chosen because it is not too big to not fit on the sled and not too small for the golf club to not hit it properly. The spherical shape allows for an even flight path while still remaining aerodynamic. A sphere is also the best option for carrying the projectile in the sled as it can simply rest like a golf ball on a tee. This concept is discussed in Section 4.6.

4.6 Sled

The sled, seen in Figure 10.6, is used to carry the projectile into the path of the golf club head, as discussed in Section 3.2. The design used in this launching mechanism is based on the Lego sled and rail system used in the Lego prototype. The main body of the sled is the foundation for the 4 pegs that combine to act like a golf club tee. These serve the purpose of not only holding the projectile in place, but propping it up so that if there are any inconsistencies in the golf club height, then the golf club won't crash into the sled. Attached to the main body of the sled are two wing-like pieces that slide into the rails and restrict the sled from translating upwards and sideways. Lastly, at the front of the sled is a bar where the rope that pulls the sled can be attached to.

4.7 Rails

The rails, Figure 10.7, work hand in hand with the sled due to the fact that they are a system. They implement a sideways U shape which perfectly lets the wings of the sled slide through with 2mm of tolerance to allow for minimum friction while sliding.

4.8 Drum

The drum seen in Figure 10.8, is a mandatory part that needs to be included in the launching mechanism. Besides the fact that it is a mandatory part, it also is a part that works very well in this launching mechanism because it is used to turn the gravitational potential energy of the counterweight into rotational motion of an axle. A clever design feature incorporated into the drum is the asymmetrical cylindrical hole for the axle to slide through. This makes the cross section of the axle resemble a circle with a straight side. This greatly eases the physical assembly since this eliminates the possibility of the drum and the axle slipping and not moving together. The drum is 26mm in length because the inside distance between one side of the frame and the other is 30mm, leaving 2mm of space on either side as tolerance.

4.9 Trigger Mechanism

A trigger mechanism is also mandatory on the launching mechanism. The simplest and most effective way to control the motion of the mechanism is to use a pin that slides in front of the golf club when it is wound up, hence stopping its motion. When the projectile is ready to be fired, the pin can be pulled out of the way of the golf club's path, allowing it to spin. The trigger mechanism can be seen in Figure 10.9.

4.10 Ball Bearing Sleeve

The aim of the ball bearing sleeve is to guide the rope across the bearing in a controlled manner. It is important that the sleeve fits snug onto the bearing so that it does not fall off. The ball bearing sleeve can be found in Figure 10.10.

4.11 Final Assembly

After the completion of individual parts an assembly can be created. This allows for proof of concept, realization and further testing. While constructing the assembly it became clear that almost all the parts were finished, however, some minor detailing had to be done to be within the material constraint. This was solved by using less material in the frame and in the golf club.

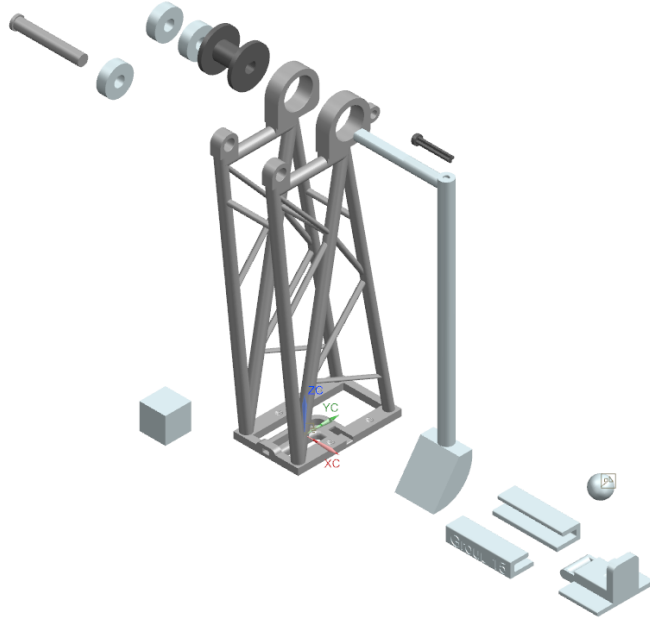


Figure 4.1: Exploded View: ISO

4.12 NX Simulation

One of the goals that was set within this project was to compare the differences between the theoretical and experimental values obtained from the final design. To calculate the theoretical distance travelled from the final design, the motion application within the Siemens NX software was used, this application made it possible to create different simulations for different parameters within the design which helped in verifying whether the final design was functional and helped in figuring out areas that may need improvement.

To optimize the final design further, the NX simulations were used to create displacement-time graphs of the projectile which helped in finding the most suitable parameters for the final design. One of the parameters that were tested was the position of the golf club before firing which greatly affected the initial velocity of the golf club hence producing better results when the position of the club was placed above the trigger. Another variable that was changed was the time at which the sled moves to the firing position which was found to be 0.5 seconds after the weight is released, this gives the golf club enough time to accelerate as much as possible before hitting the ball. As the simulation used couplers instead of rope, the experimental time for the sled to be moved to the firing position will be much higher due to the weight and golf club being counted as one part, which meant that both the weight and golf club would stop once the weight hit the ground.

After several simulations the maximum horizontal distance found was around 4.9m without taking into account air resistance and friction between parts which will effect the actual horizontal distance. The horizontal and vertical graphs can be seen in Figure 4.2 and Figure 4.3 respectively. The values highlighted in yellow show the time and displacement when the projectile touches the floor.

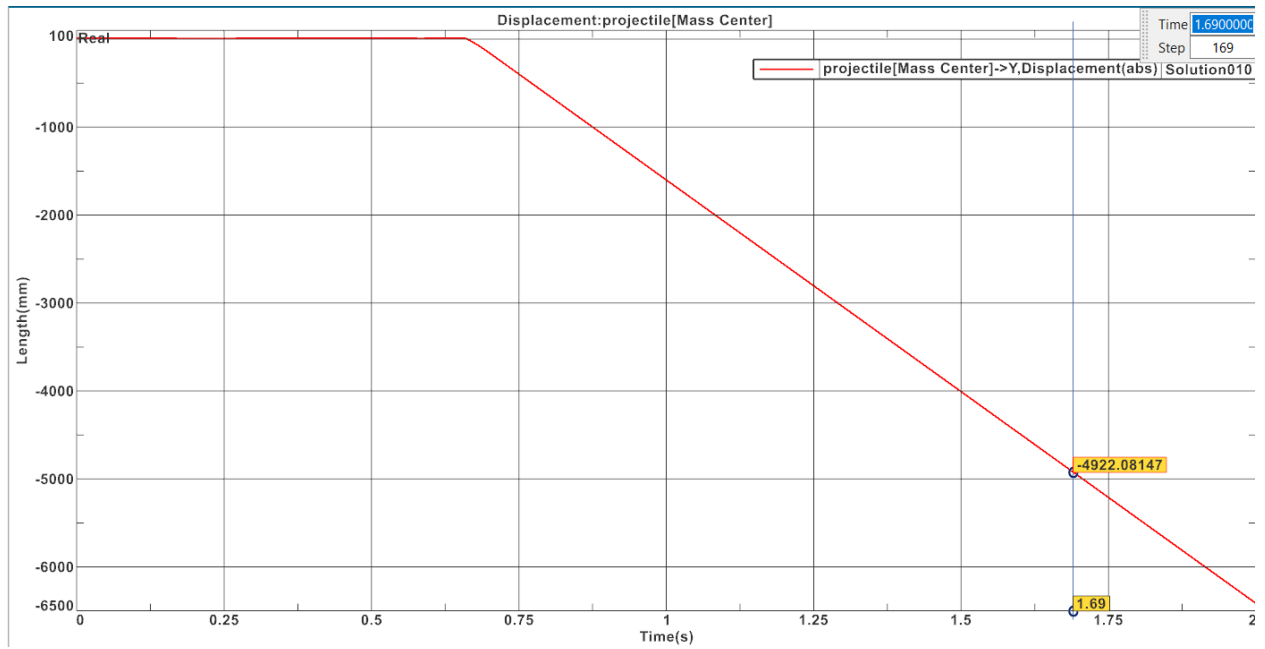


Figure 4.2: Horizontal displacement

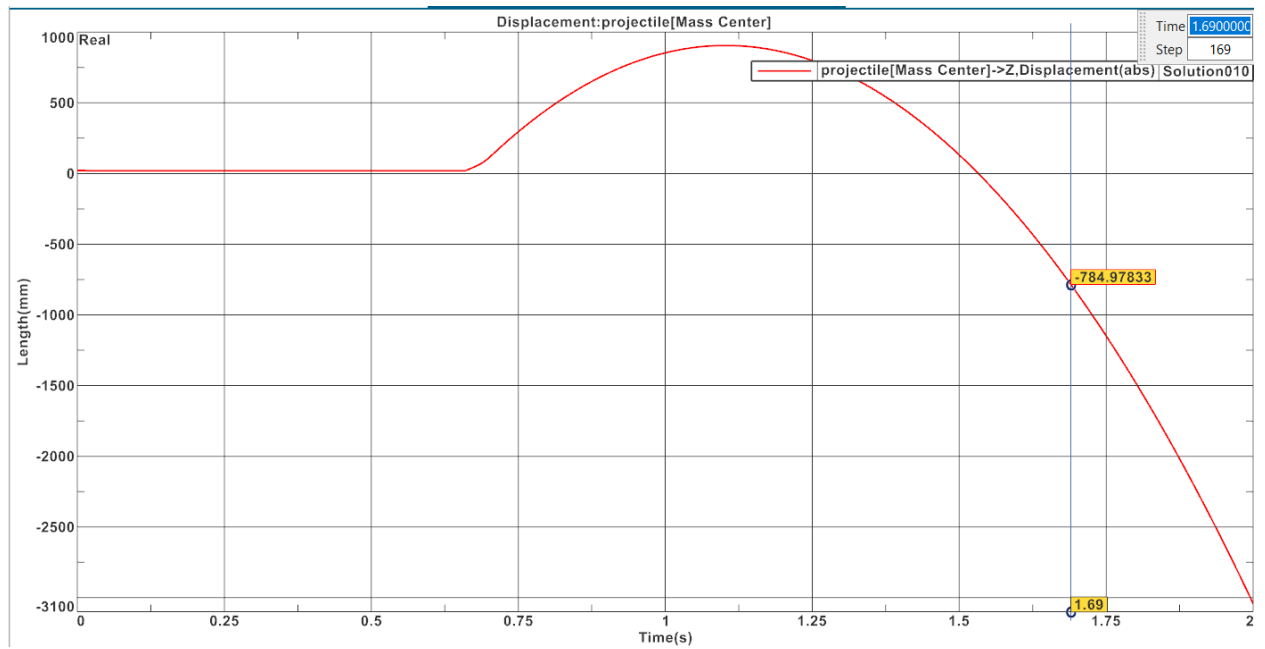


Figure 4.3: Vertical displacement

5 Realization

5.1 Printed parts

With the Siemens NX parts printed, the building phase could begin. The SLS process that was used to print the parts required every separate piece to be connected by a small rod. The first step was to remove these pins with a small knife and to sand down the ends to get the intended pieces.

5.2 Assembly

The assembly of the launcher did not take long, since the launcher only consists of a small axle, and two big parts, the frame and the club. First, the frame was bolted to the base plate. The bearings were inserted in their designated holes, after which the club axle was inserted halfway through, so the drum could be fitted over the axle, before the axle was pushed into the second bearing. The same was done for the guiding pulley axle, where the bearing with the guiding cover was slid on instead. Next, the rails should be installed. At first the rails were a bit too tall, which made the sled sit too high, to the point where the club hit the sled during its rotation. After some sanding, the rails were lowered enough to the point where the sled would not get hit, even when taking the flexion of the club arm into account. The sanding paper used was 80 grit, because this relatively coarse paper got rid of the excess material quickly. The inside of the rails have been coated with a layer of graphite powder, to lower the friction between the sled and the rails. The rails were first attached with some duct tape to find out the most ideal spacing, before finally being glued down with a special glue, intended for metals and plastics with tight gaps between them. Because of the sanding of the bottom of the rails, the glue had a nice rough surface to hold onto. With the rails attached, the assembly of the printed parts was done.

5.3 Finishing the launcher

To complete the launcher, the rope had to be cut into two pieces, one for the drum and one for the sled. To determine the ideal lengths, the rope needed for the sled was measured first, since this length was only dependent on the height of the table, and does not benefit from being any longer than the minimal length required. To measure the length, the sled with a rope attached was placed in the rails, and the other end was put on the ground. The rope was cut at the point where it touched the ground, plus an extra of three centimeters to tie the knots with. This came down to a total of around 85 centimeters, which left 115 centimeters for drum rope. This rope was clamped around the drum and knotted tightly so it would not slip. The other end of the rope was tied to the counterweight which comprised of the M20 nuts, together with the leftover bearings, nuts and bolts. A step by step guide to assembling the mechanism can be found in Appendix-Section 11.1.

5.4 Relocating the firing pin

Before firing the launcher for the first time, it became clear that there was a small error when designing the trigger mechanism. The holder for the trigger pin was positioned in such a way that the club arm rested on it at a 90 degree angle, which meant that a lot of weight rested on the pin, which made it hard to pull the pin out and fire the mechanism. To fix this, a leftover nut, seen in was glued a bit higher up on the frame, so that the club arm rests almost vertically on the pin. This made it so that less force was needed to pull the pin out, which decreased the amount of vibrations caused by firing the launcher. Another advantage of this starting position is that less torque is needed to accelerate the arm at the beginning of the movement, because the heavy club head starts with more potential energy. With this problem solved, the testing stage can begin.

6 Testing

6.1 First test

With the building of the launching mechanism done, the testing could begin. The first test was conducted from a workbench with a height of around a metre. The design worked as intended and hit the opposing wall with a great speed. A step by step method of arming and firing the mechanism is located in Appendix-Section 11.2.

6.2 First test at launch conditions

After the initial test the mechanism was moved to a table with the official launching height of 75 centimeters. The slack on the sled rope was changed accordingly to the lower launching height, and the launcher was tested again. This time the exit speed was much lower than the first test. It was hypothesized that the low torque caused by the small drum limited the acceleration a lot, while allowing for a higher top speed. This means that this design benefits enormously from a higher drop height, because without it the higher potential top speed will not be reached due to the low acceleration. Since this is not possible given the constraints, another solution was necessary.

6.3 Adding torque

Using hot glue, the drum was given a much bigger diameter. With this bigger drum, the enormous increase in torque became apparent during the first firing test. The arm accelerated much faster, which made the rotational speed of the arm a lot larger. This together with the unbalanced mass of the arm caused a lot of vibrations, which ultimately caused the arm to bend so much to the point where the club head hit the frame itself. After multiple tests that gave the same result, it was decided that the frame was not rigid enough to handle this great of a velocity.

6.4 Minimizing vibrations

The only thing that could be done to combat this was too make the drum diameter smaller again. The drum was repeatedly taken off and had some glue shaved off each time to make it smaller, until the point was reached where the arm could reliably hit the projectile again. With this final setup, a distance of eight metres was reached in the official testing conditions. This is the highest value that has been measured with this design. It was decided that this setup is the most ideal for the launcher, and with that the testing phase is over.

6.5 Official testing

Three tries were given to show the launching mechanism, with the main goal to see how far it came in comparison with all other mechanisms built by other groups. The first two tries did not go to plan; the trigger mechanism, the release pin, was not pulled out completely.

7 Evaluation

After going through the first six phases of design, producing a physical product and testing the mechanism, the official and moderated testing commenced. During this testing, the maximum distance reached by the projectile was 7.5 meters.

A lot of positive aspects regarding the design can be mentioned. Firstly, the maximum distance reached by this design outperformed the majority of other concepts during testing. Based on the results that were posted when this design was tested, more than half of the other launching mechanisms failed to reach half of the distance that this design reached. The sled and rail system allowed the arm to make multiple rotations before launching the projectile, which gave it time to accelerate up until the maximal rotational velocity that the frame rigidity can handle, this limit was caused by the golf club hitting the frame or the sled due to flexion in the arm. The velocity had to be limited by decreasing the torque, which negatively affected the launching distance. This means that the weakest link is the low resistance to vibrations and for example a heavier counterweight would not benefit the system. Despite of the high vibrations, the sleeve for the guiding bearing did its job to prevent the rope from slipping off the pulley, keeping the rope under control during motion.

To solve this limiting factor and the main sources of unpredictability in the design, namely the vibrations caused by imbalance of the arm, and the randomness of the position of the club head when the sled gets deployed, a new idea arose. If some material could be saved in the height of the launcher or strengthening of the club, this height could be used to make a duplicate of the club on the other side. Thus we would have two golf club heads. This would fix the mass imbalance, and also have the maximal distance between the projectile and the head after deployment of the sled in the worst case scenario reduced from a full rotation to only half of a rotation. This change would improve the design a lot, and would definitely be implemented if the launcher was to be redesigned.

Furthermore, the RPC's of the project have been met, which makes the launcher a success. Apart from the small changes mentioned earlier in the evaluation, the design is close to ideal for this concept. It was a shame that the velocity had to be limited due to vibrations, but there will always be a limiting factor in every design. This clearly indicates that this project has provided adequate feedback for further improvement.

8 Bibliography

Shapeways. (2022, November 1). Printing Versatile Plastic.

<https://www.shapeways.com/materials/versatile-plastic>

Fendt, Walter. (September 13, 2000). Projectile Motion Simulator

https://www.walter-fendt.de/html5/phen/projectile_en.htm

Instructables. (2021, July 18). The Floating Arm Trebuchet.

<https://www.instructables.com/The-Floating-Arm-Trebuchet/>

9 Appendix Chapter 2

9.1 Assumptions and estimates

To be able to make calculations in this stage of design, some estimations and assumptions have been made:

- Since the printing assembly needs to fit in a box of 300mm x 100 mm x 50mm, this will also be around the dimensions of the mechanism.
- The only masses taken into account are the projectile, a small ball, and the four M20 nuts as falling weight: The material of the ball (PA12) has a density of $930\text{kg}/\text{m}^3$ [Shapeways] and a radius of the sphere of 10 mm will be assumed.
 $V = (4/3) * \pi * r^3 = 10^{-6}\text{m}^3$
 $m = \rho * V = 9.3 * 10^{-4}\text{kg}$ (mass of the ball)
 The 4 nuts have a mass 0.2576 Kg
- The weight will fall the height of the table, which is 0.75 meters
- The golf club will have a maximum radius of 0.3m

Calculations

The mass will have a potential energy in the starting position:

$$E = m * g * h \text{ so } E = 0.2576 * 9.8 * 0.75 = 1.8953\text{J}$$

Because of conservation of energy, the potential energy is being turned into kinetic energy: $E = 0.5 * m * v^2$.
 so $v = 3.836 \text{ m/s}$.

This will be the velocity of the nuts, which are connected to the drum via a rope.

The circular motion formula is

$V = 2 * \pi * r / T$. With that, T can be calculated for both diameters (30 and 50 mm), giving a T of 0.025 s and 0.041 s respectively.

Assuming that the transfer of energy from the drum to the club by means of the axle would be perfect the angular velocity can be calculated with the same period time but with a radius of 0.3

$$V = 2 * \pi * r / T$$

This gives angular velocities of 76.7 m/s and 46 m/s respectively.

9.2 Determining ideal firing angle

After that with a projectile motion simulator the estimated balls reach within a range of initial velocities and firing angles were determined [Fendt, Walter].

For an initial velocity of 1, 2, 3, 4, 5, 10, 15 m/s respectively

Angle [°]	Range [m]
10	0.403
15	0.401
20	0.402

Table 9.1: Velocity of 1m/s

Angle [°]	Range [m]
20	0.878
25	0.882
30	0.876

Table 9.2: Velocity of 2m/s

Angle [°]	Range [m]
25	1.47
30	1.49
35	1.48

Table 9.3: Velocity of 3m/s

Angle [°]	Range [m]
30	2.23
35	2.26
40	2.25

Table 9.4: Velocity of 4m/s

Angle [°]	Range [m]
15	2.63
30	3.12
45	3.15

Table 9.5: Velocity of 5m/s

Angle [°]	Range [m]
15	7.1
30	9.98
45	10.9

Table 9.6: Velocity of 10m/s

Angle [°]	Range [m]
15	13.8
30	21.1
45	23.7

Table 9.7: Velocity of 15m/s

Optimal angle

As can be seen in Table 9.1 until Table 9.7, the higher the velocity, the greater the angle that is needed to achieve the optimal range. Already from a velocity of about 3 m/s, the optimal angle does not change significantly anymore. With the predicted initial velocity to be greater than 3 m/s, and the help of the tables above it can be concluded that the optimal initial angle needs to be around 35 degrees. Therefore the head forms an angle with the horizontal of 90 minus the ideal launching angle (35 degrees), which is 55 degrees.

9.3 Torque

There needs to be enough torque for the golf club to be able to swing. In other words, there needs to be enough torque. The formula for torque is given by

$$\tau = Fr\sin(\theta)$$

Due to the use of a drum, the force is always applied perpendicular to the direction of rotation, leading to $\sin(90)$, which is equal to 1. The force from the falling nuts can be calculated:

$$F = ma$$

So the force due to gravity is equal to 0.2576 (mass of the nuts) $\times 9.81 = 2.527$ N. Filling in the r , which is the radius of the drum, gives a torque of 0.038 and 0.063 Nm for the diameters of 3 and 5 cm respectively.

These calculated values tell that it is easier to rotate a drum with a larger diameter. However, the top speed of the drum will be sacrificed when a larger drum diameter is being used.

9.4 Function list

	Floating arm design	Trebuchet design	Spring design	Golf club design
Projectile	Ball connected to a string	Ball connected to a string	Standard ball	Standard ball
Launch mechanism	Uses drums to pull arm down at fast speeds causing the projectile to be released	Ball attached to a rope which is connected to the edge of a trebuchet arm, this arm is then rotated and the projectile is released	Uses a spring connected to a weight to convert gravitational energy to elastic energy which is then used to release the projectile	Uses a fast rotating golf club to hit the projectile
Variability	Diameter of drum can be varied	Most variables are fixed	Firing angle can be varied	Drum diameter and time when sled moves to firing position can be varied
Consistency	Due to the use of a string to release the projectile it is not consistent	Due to the use of string to release the projectile it is not consistent	Very consistent	Due to timing of sled not very consistent
Reliability	Not very reliable as not much information is available for this design	Very reliable as this design has been proven to work by multiple sources	Not very reliable as this design heavily relies on the stiffness of the 3D printed material	Very reliable as a lot of variables can be changed to make it work

10 Appendix Chapter 4

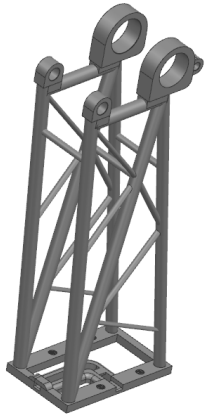


Figure 10.1: Frame



Figure 10.3: Shaft



Figure 10.5: Projectile

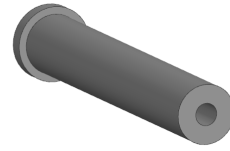


Figure 10.2: Front Axle

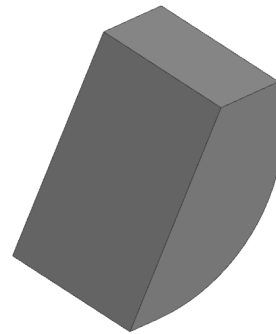


Figure 10.4: Golf Club Head

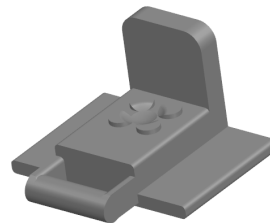


Figure 10.6: Sled

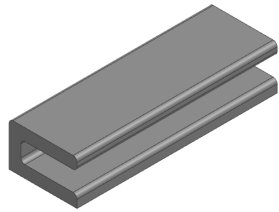


Figure 10.7: Rail

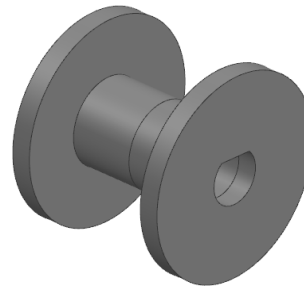


Figure 10.8: Drum

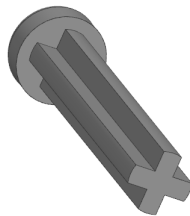


Figure 10.9: Trigger Axle

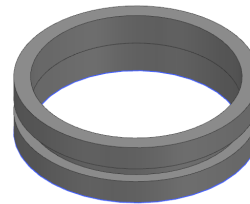


Figure 10.10: Ball Bearing Sleeve

The dimensions for each individual part can be found in the figure below. Note that for cylindrical and spherical parts the length, width and height may refer to the diameter of the part depending on the part. The length width and height of each part are defined in Figure 10.11.

Part Name	Length	Width	Height
Frame	10mm	5mm	215mm
Front Axle	10mm	52mm	10mm
Golf Club Shaft	10mm	98.5mm	177mm
Sled	38.5mm	48mm	20mm
Rail	50mm	18mm	13mm
Drum	30mm	26mm	30mm
Trigger Axle	7mm	30mm	7mm
Projectile	15mm	15mm	15mm
Ball Bearing Sleeve	22mm	22mm	7mm

Table 10.1: Dimensions of each individual part

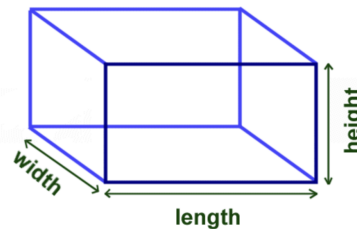


Figure 10.11: Length, Width, Height

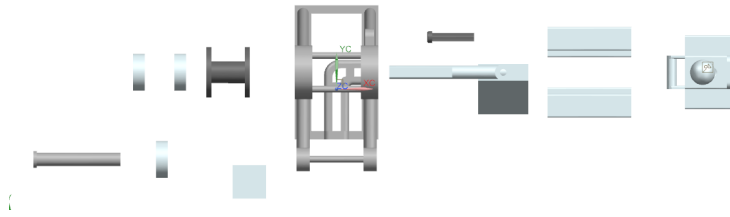


Figure 10.12: Exploded View: Top

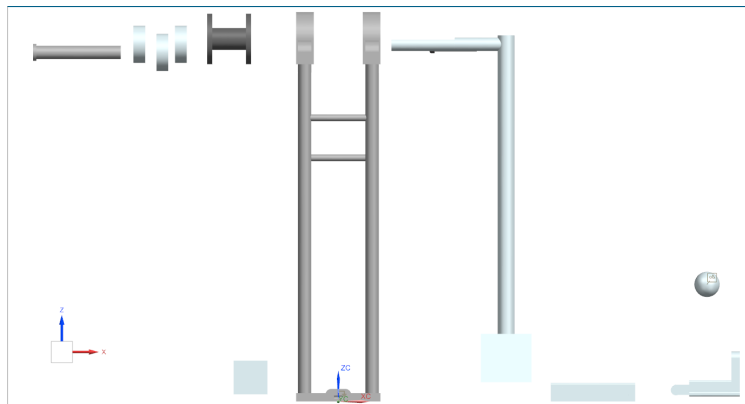


Figure 10.13: Exploded View: Front

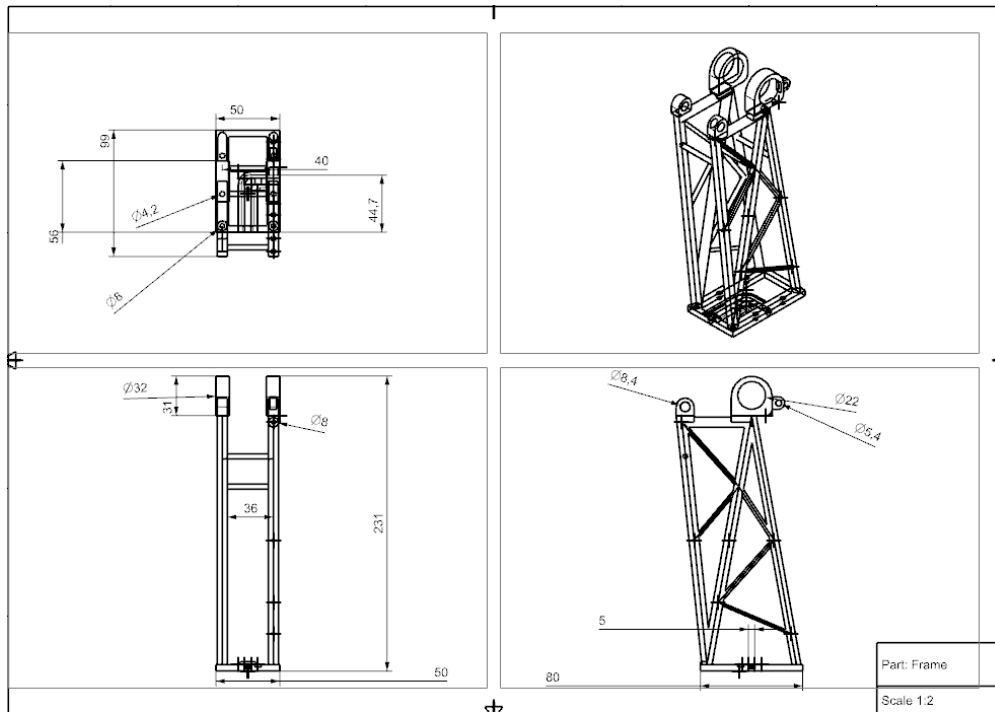


Figure 10.14: Technical Drawing: Frame

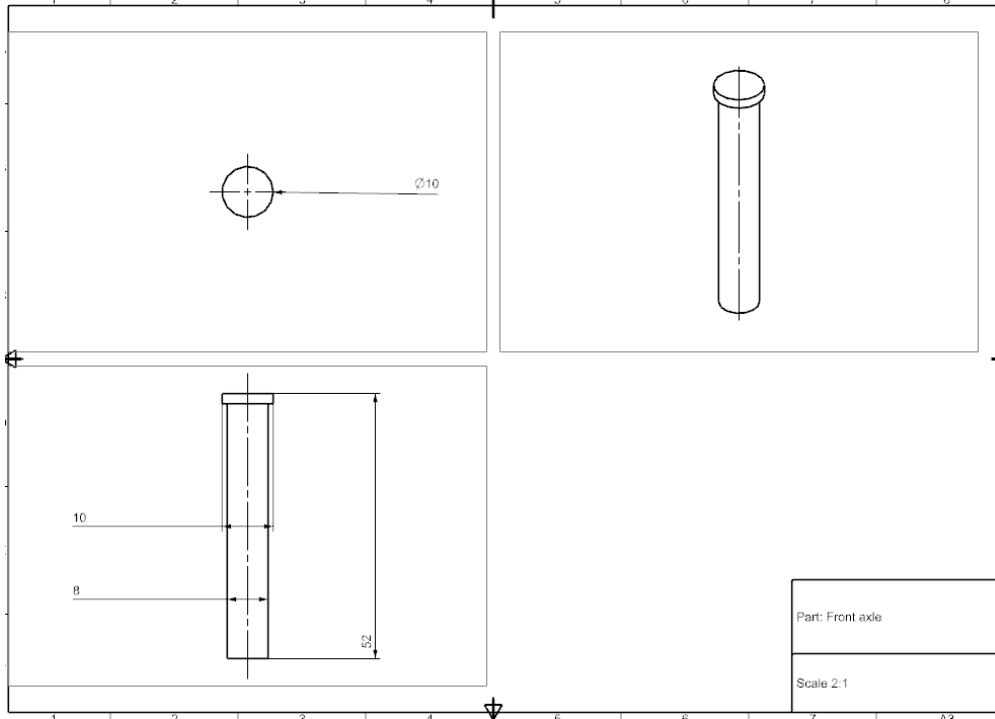


Figure 10.15: Technical Drawing: Front Axle

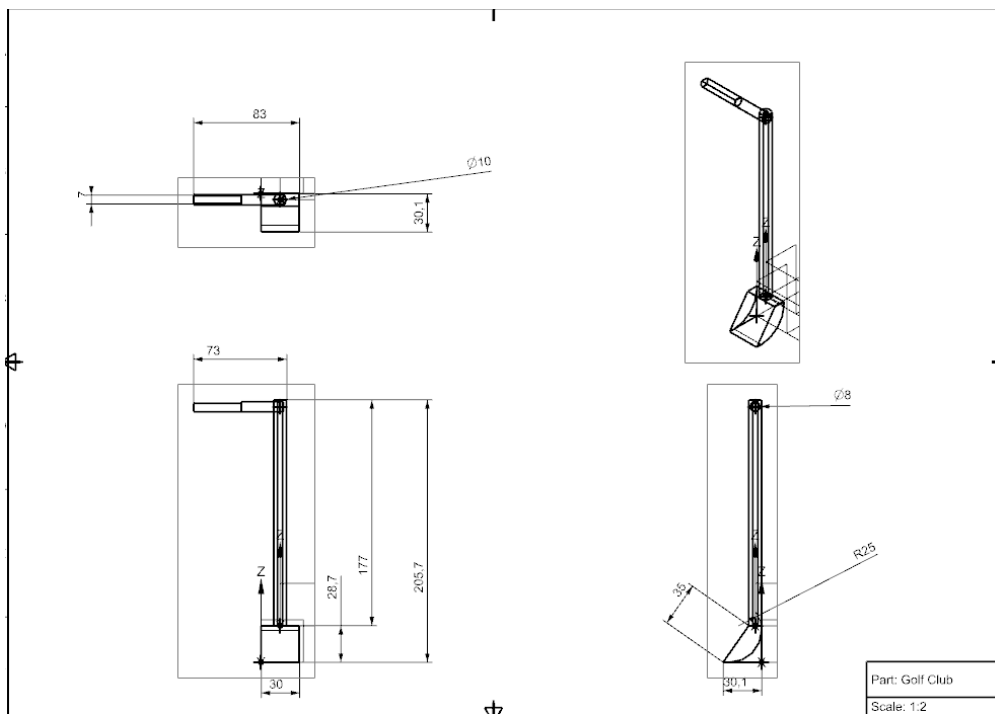


Figure 10.16: Technical Drawing: Golf Club

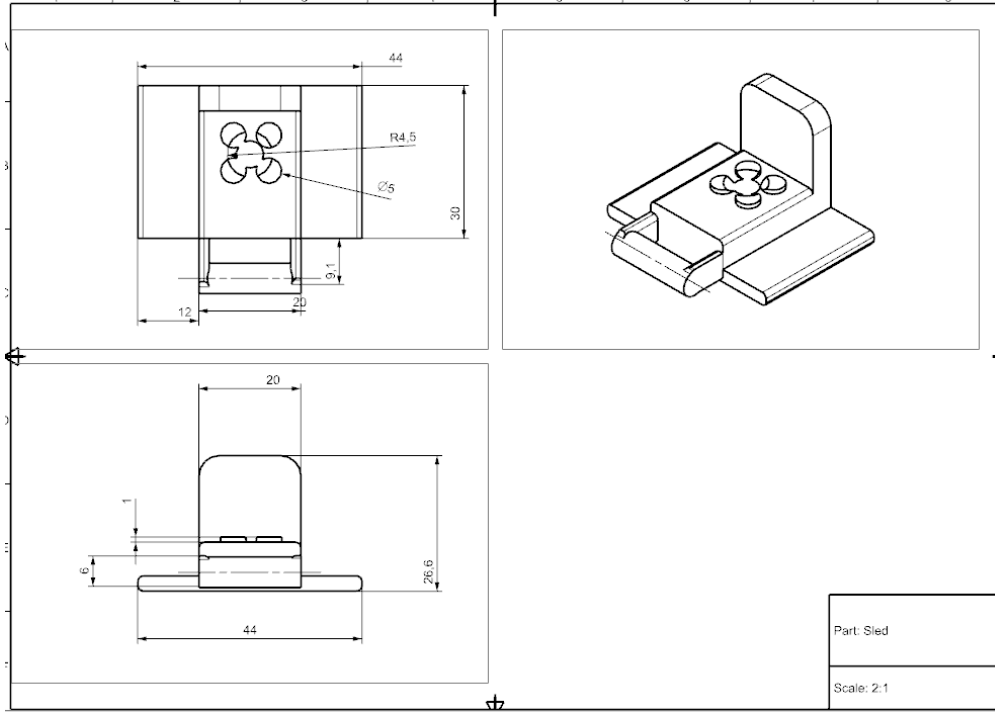


Figure 10.17: Technical Drawing: Sled

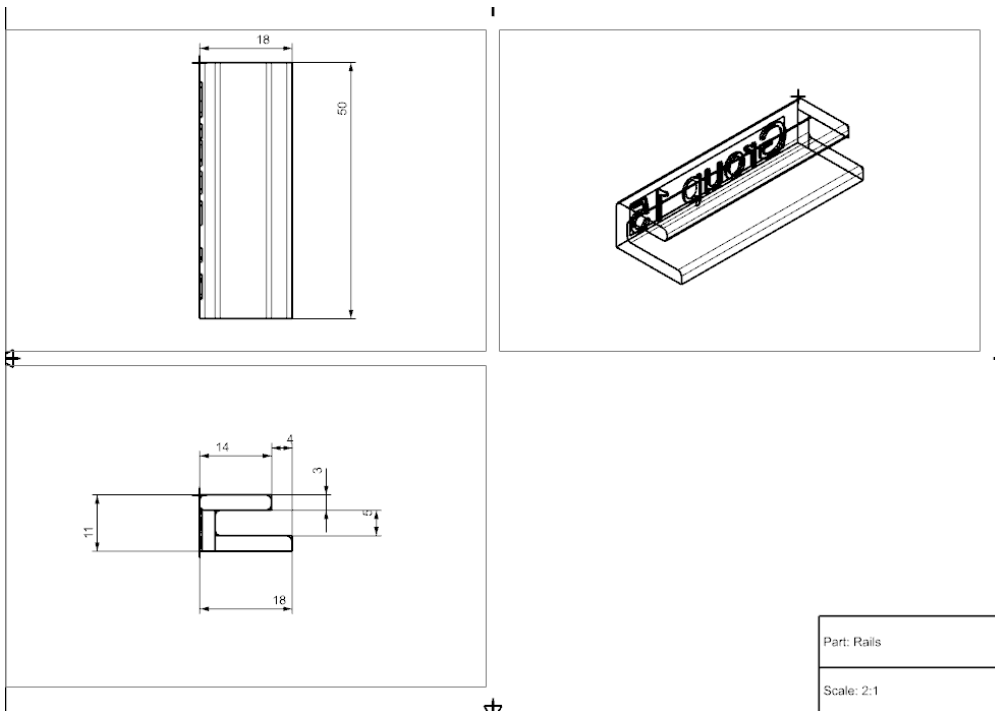


Figure 10.18: Technical Drawing: Rail

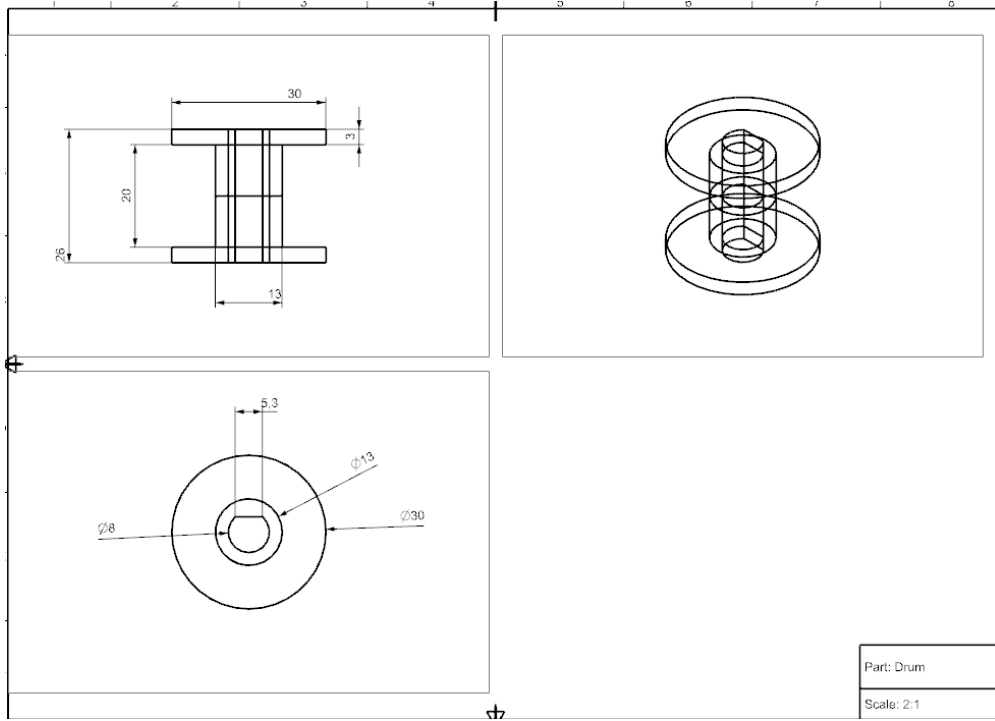


Figure 10.19: Technical Drawing: Drum

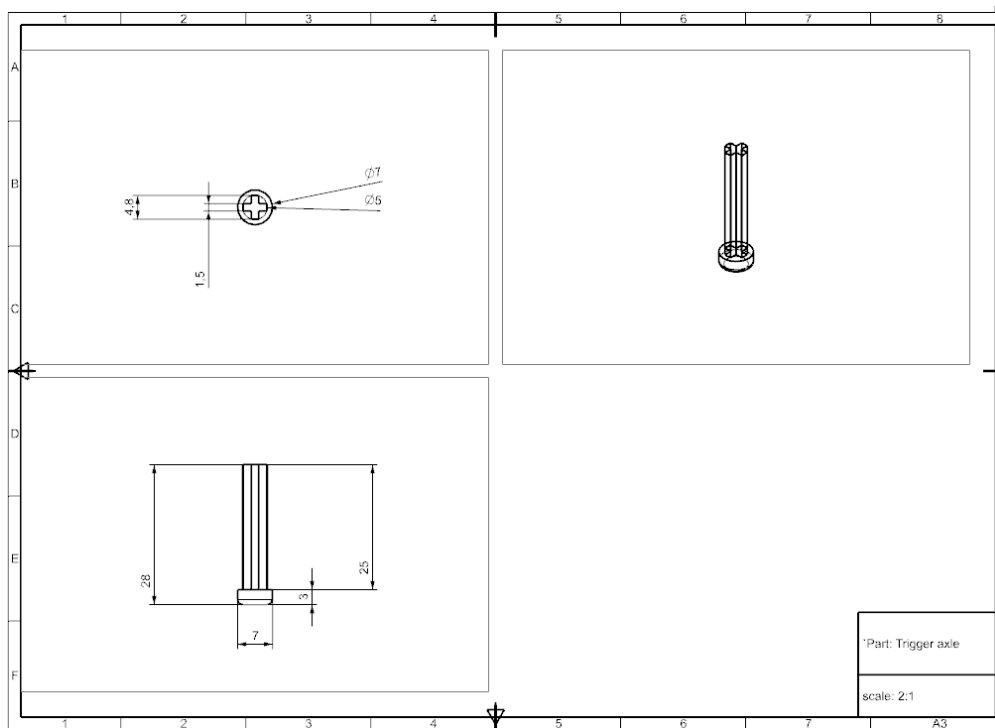


Figure 10.20: Technical Drawing: Trigger Axle

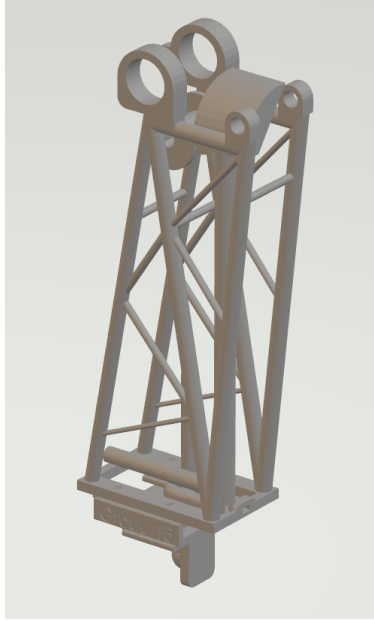


Figure 10.21: Printing assembly

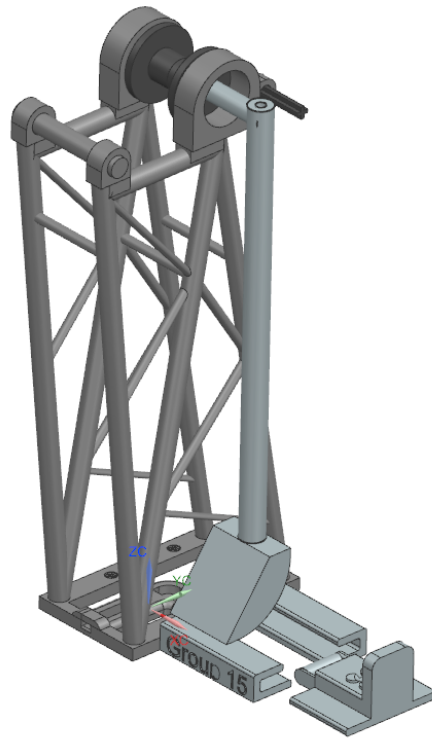


Figure 10.22: Assembly

11 Appendix Chapter 6

11.1 Step-by-step guide to constructing the assembly

Due to the fact that all the parts of the assembly arrive attached together by 2mm pins, each part will have to be detached from each other. Furthermore, some parts may have to be sanded down using sand paper. Refer to Figure 11.1 and Figure 11.2 for the nomenclature of the design used in the instructions below.

Step 1: Screw the frame into into the given base plate using 4, M5 screws.

Step 2: Insert a bearing type:608 into the bearing sleeve. This will be called Bearing 1.

Step 3: Insert the front axle through the first front hole at the top of the frame. Then insert Bearing 1 onto the front axle. Lastly, push the Front axle fully through into the other front hole on the top of the frame.

Step 4: Insert 2 bearings type:608 into the larger, back holes at the top of the frame. These bearings will be labeled Bearing 2 and 3.

Step 5: Hold the drum between Bearings 2 and 3 while sliding the golf club shaft through the bearings and the drum.

Step 6: Attach the rails to the side of the frame with the rope tunnel entrance using small amounts of superglue.

Step 7: Attach 85cm of rope to sled. Then slide the sled into the rails and feed the rope through the rope tunnel.

Step 8: Attach 115cm of rope to the counterweight. Then attach the other side of this rope to the drum with a knot. Make sure to insert the rope into the groove of the bearing sleeve.

Step 9: Attach the 85cm rope to the counterweight.

Step 10: Place the trigger axle into the trigger hole.

Step 11: Place the projectile onto the sled.

11.2 Arming and firing the mechanism

Step 1: Wind the golf club shaft in the direction opposite to its firing direction. Make sure the rope stays on the drum and does not get tangled.

Step 2: Place the trigger axle in its trigger hole to stop the mechanism from firing.

Step 3: Pull the sled out of the path of the golf club shaft.

Step 4: The mechanism is now armed.

Step 5: To fire the mechanism, simply pull the trigger axle.

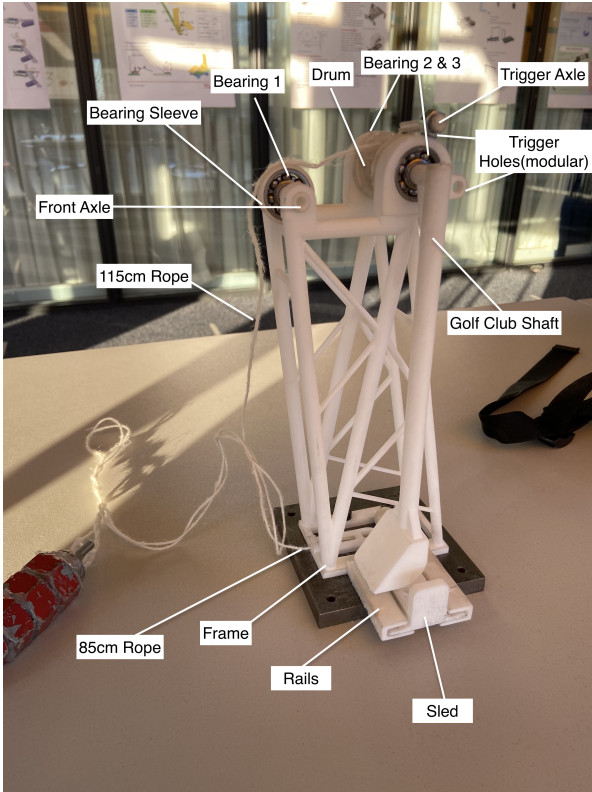


Figure 11.1: Nomenclature of the design

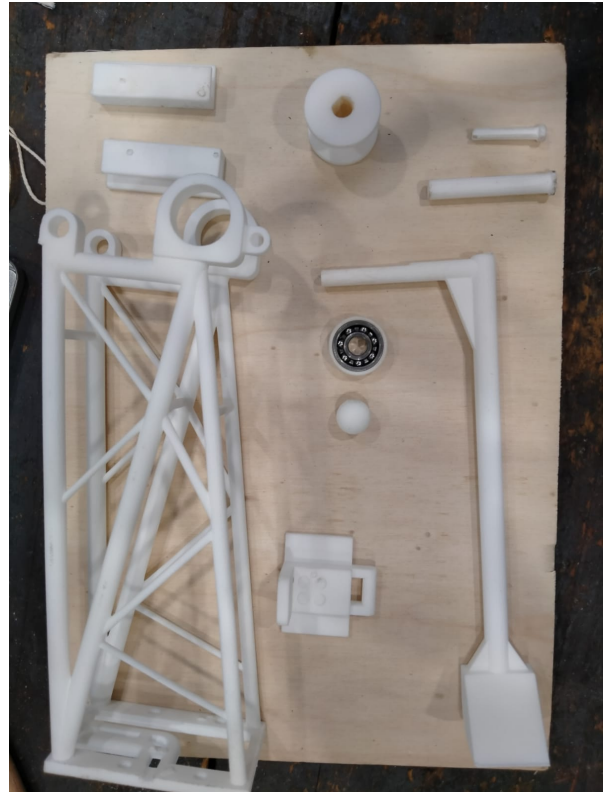


Figure 11.2: Individual parts laid out