Ryerson University
Faculty of Engineering & Architectural Science

Department of Mechanical and Industrial Engineering

Program: Mechanical Engineering/Industrial Engineering

Course Number	MEC 431
Course Title	Manufacturing System Control
Semester/Year	Fall 2020
Instructor	Dr. Vincent Chan

Design Project

Report Title	Mechanical Calculator

Section No.	1
Group No.	4
Submission Date	December 7, 2020
Due Date	December 7, 2020

Name	Student ID	Signature*
Daniel Volkov	19851	D.V.
Syed Shoaib Hasan	32412	Syed Shoaib Hasan
Parampreet Baryar	10500	PB
Zaid Al-Kayali	35814	Z.A
Maichel Tawdrous	53120	M.T

(Note: remove the first 4 digits from your student ID)

**By signing above you attest that you have contributed to this submission and confirm that all work you have contributed to this submission is your own work. Any suspicion of copying or plagiarism in this work will result in an investigation of Academic Misconduct and may result in a "0" on the work, an "F" in the course, or possibly more severe penalties, as well as a Disciplinary Notice on your academic record under the Student Code of Academic Conduct, which can be found online at: http://www.ryerson.ca/senate/policies/pol60.pdf .*

Table of Content

Table of Content 2

List of Figures 3

List of Tables 4

Introduction (Authored By: Parampreet) 5

Literature Review (Authored By: Shoaib) 6

Design Process 9

Initializing the Project (Authored by: Maichel) 9
Product Design Specification (Authored by: Maichel) 10
Design Characteristics (Authored by: Maichel, Zaid, Shoaib, Parampreet, Daniel) 11
Functional Requirements (Authored by: Maichel, Zaid, Shoaib, Parampreet, Daniel) 11
Physical Constraints (Authored by: Maichel, Zaid, Shoaib, Parampreet, Daniel) 11
Pairwise Comparison Chart (Authored by: Maichel, Zaid ,Shoaib and Daniel) 12
Justification For the Pairwise Comparison Chart (Authored by: Parampreet) 12
Reference Design (Authored by:Shoaib) 16
Re-Design 1(Authored by: Maichel) 17
Re-Design 2 (Authored by: Maichel and Zaid) 18
Weighted Decision Matrix (Authored by: Maichel, Zaid ,Shoaib and Daniel) 19
Justification of Weighted Decision Matrix (Authored by: Zaid) 20

Drawings (Authored by: Zaid and Maichel) 22

MasterCAM (Authored by:Shoaib) 23

Ultimaker Cura (Authored by:Daniel) 26

Process Plan (Authored by:Daniel) 31

Calculations for Gears (Authored by: Maichel) 32

Conclusions and Recommendations (Authored by: Parampreet) 34

References 35

Appendix A: MasterCAM setup sheets for each board being cut (Authored by: Shoaib) 36

Appendix B: annotated G-code from MasterCAM (Solidworks files, MasterCAM files, G-code files, STL files uploaded to D2L) (Solid works: made by: Maichel & Zaid) 37

List of Figures

Figure 1.Pascaline calculator	6
Figure 2.Input and output mechanism	7
Figure 3.Carry over mechanism	7
Figure 4.Annotated Sterling Dial A Matic	8
Figure 5. Sterling Dial a Matic	16
Figure 6. Redesign 1 sketch showing the outline of the design	17
Figure 7.Displaying one of the gears+lever	18
Figure 8.Exploded view of final design	22
Figure 9.MDF board 1 machining operations	24
Figure 10. MDF board 2 machining operations	24
Figure 11. MDF board 3 machining operations	25
Figure 12. Cura isometric view	26
Figure 13. Cura layer 1 view	26
Figure 14: Cura layer 16 view	27
Figure 15: Cura layer 27 view	27
Figure 16: Cura top layer view	28
Figure 17: Cura isometric view of triangles for lever	28
Figure 18: Curalayer 1 view of triangles for lever	29
Figure 19: Curalayer 10 view of triangles for lever	29
Figure 20: Curalayer 15 view of triangles for lever	30
Figure 21:Outline of the Gear	33
Figure 22:Sketch showing gear names definition	34

List of Tables

Table 1.Summary of Design Constraints 10

Table 2.Pairwise Comparison Chart 12

Table 3. Weighted decision Matrix including weight factor 19

Table 3.1. Weighted Decision Matrix Scoring 19

Table 4. Measurements used in the gears 33

Introduction *(Authored By: Parampreet)*

The team has been assigned to design a prototype mechanical adding machine. The mechanical calculator is to be designed with the use of only gears and linkage. The calculator must be able to sum 4 digital numbers and slide ruler type calculators are not allowed, there must be mechanical energy transferred. The team is also constrained to a limited amount and type of materials to build the prototype from.

The project will incorporate the use of three different software programs to accompany the design process.. Which are Solidworks, Mastercam and Ultimaker Cura that will be used to aid. The design is created on Solidworks and there are also solidwork drawings along with video simulation of the gears and linkages in the calculator moving, showing how the calculator works. The drawings are proper engineering drawings with dimensions, title blocks, and both assembly with balloons and callouts. The manufacturing is the machining of the parts out of the MDF boards, Mastercam Files, and generated G-code file as well as a video of the parts being cut out of the MDF boards. The Rapid Prototyping is the G-code that was generated by Cura for the parts being printed. The Final report is the accumulation and summary of the entire project containing multiple sections and appendices.

Literature Review *(Authored By: Shoaib)*

In the world of mechanical calculators, perhaps the most ubiquitous category is the adding machine, first popularized by slide adders, such as the Addiator, newly designed by Carl Kübler in 1920 [1]. While slide adders and it's concept existed before then, its use as a business tool became more prevalent after the industrial revolution. The issue with many of these slide adders was that it required a separate control panel for addition and subtraction, something the rotary adding machines attempted to fix shortly before their demise after the launch of desktop electronic calculators. By having numbers stamped onto a line of gears and connected in such a way that they would automatically carry over digits, they were able to combine the addition and subtraction operations together on one control panel. One of the very first examples of this is the Pascaline calculator, shown below:

Figure 1: Pascaline calculator [2]

Invented by French mathematician-philosopher Blaise Pascal between 1642-1644 [2], it's use is governed by the user changing the input dials with a stylus, and when consecutive numbers are entered, their addition is displayed on the output window. Subtraction occurs by using nine's complement arithmetic as the dials could only rotate one way, and to understand that an assessment of it's internals are needed:

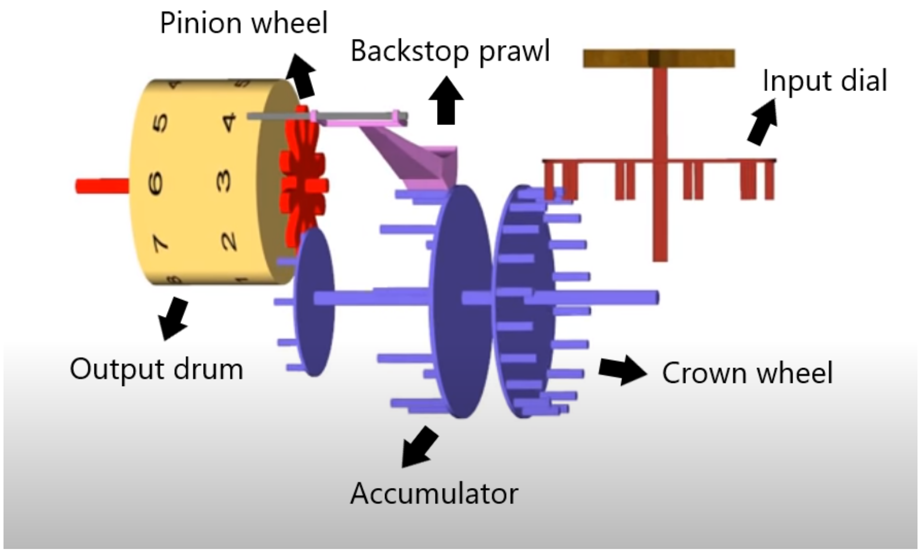


Figure 2: Input and output mechanism[3]

In the figure 2 above of the internals of the pascaline calculator, one can see that the accumulator gear, which actually corresponds to the numbers 0-9, is prevented from going the other way with the backstop prowl. The reason for the gear ratio change between the accumulator and crown wheel is to have enough physical space for the carry lever and spring loaded pawl, which carry the digit once the carry pins on the accumulator push them up, as seen below in figure 3:

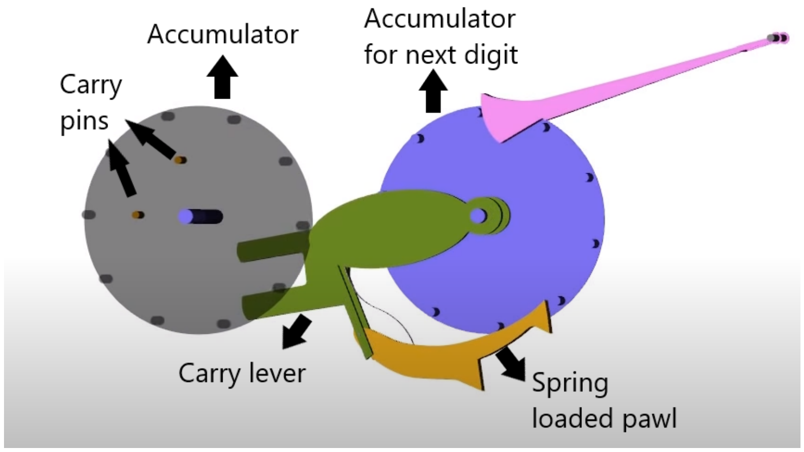


Figure 3: Carry over mechanism[3]

With this many moving parts, it’s clear that it’s a very complicated design, and given that it was machined mostly of brass, it’s not very feasible for mass production. Not that it was made to be anything more than a prototype, as Pascal reportedly only sold about 50. This no doubt helped popularize the much cheaper slide adders such as the krummer adding machine, that was made of inexpensive materials such as cardboard, paper, and ferrous alloys [4].

Thankfully, some redesigns of rotary adding machines, such as the Sterling Dial-A-Matic and Kesling Pocket Adder, addressed the large envelope dimensions of the Pascaline, used rotary gears, and found a way to make it almost completely out of plastic. While a stylus was still needed, the calculator had been redesigned to mass produce, and works as a starting point for our design. Looking specifically at the Sterling Dial-A-Matic clear version, it's clear to see that the input dial is now just a rotary dial with a gear attached. In effect, it replaces the accumulator and input dial as one part, and negates the use of a crown wheel. Furthermore, the spring loaded pawl and carry lever are replaced with a carry gear instead, engaging via a single carry pin on the rotary dial. Finally, the backstop prowl is switched with a lever, not to prevent opposite rotation, but as a countermeasure to prevent carrying more than one unit.

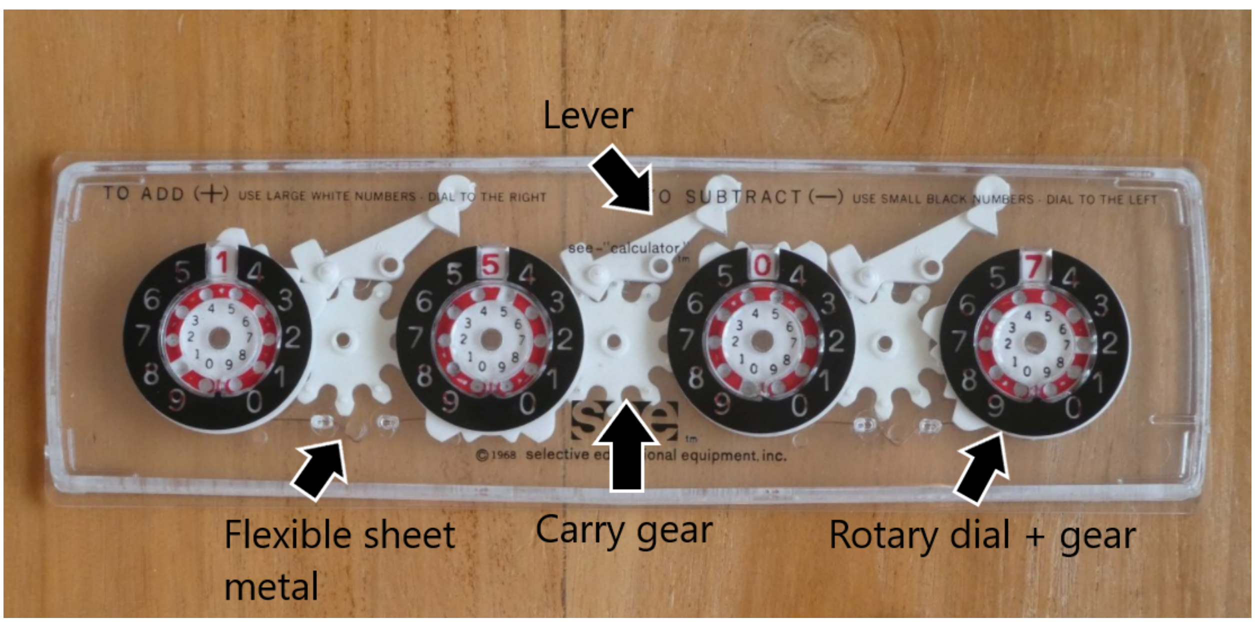


Figure 4: Annotated Sterling Dial A Matic[1]

There's also a flexible metal sheet, which mimics the clicking sound of a mechanical movement, and a number dial on the top outer case to help with addition, while the inner dial helps with subtraction. In effect, the 9 or so parts required per 1 digit in the Pascaline calculator, have been replaced with 3 parts. While that's all very impressive, it's important to know that this is a redesign of a 350+ year old product, and even then, there is some debate over whether or not the transfer digit system from the Sterling design is copied from a "Lightning adding machine" from 1955 [5]. What's more important is that because of the advent of the electronic calculator, this was one of the last design iterations of the affordable rotary adding machines. With the materials given for this project, our goal is to redesign this adding machine to improve the functionality of the product, such as finding an alternative way to change numbers so a constantly broken stylus won't have to be used. We'll also look at finding ways to cut costs by redesigning parts such as the lever to use less material.

Design Process

Initializing the Project *(Authored by: Maichel)*

The main objective of this project is to design a prototype mechanical calculator (mechanical adding machine). Using only gears and linkages, the calculator will be able to sum 4 digit numbers. One of the other objectives is to finish the required product with the given constraints. Which are the limited amount and type of materials to build your prototype from.

Three different softwares will be used to make this project happen. Firstly, a solidworks design is needed with functioning mechanisms of all gears rotating with a carry-on mechanism. After that is done, the files of the parts that are going to be machined will be transferred to Mastercam for machining. Finally, the parts that will undergo 3D prototyping will be transferred to Ultimaker Cura 4.8 for printing (simulation of printing).

Product Design Specification *(Authored by: Maichel)*

This section of the project will discuss the Design process of the project. Firstly, a PDS (product design specification) is required. This will include a design characteristics list which are the characteristics our design will focus on while designing. Moreover, a functional requirement will then be listed and this describes how the product characteristics will be exhibited in the product during the product's term of operation.

The following table (Table 1) summarises the design constraints that were provided by the instructor. These constraints must be followed and shall not be exceeded nor substitute. Furthermore, for the Software constraints it was provided by our instructor that:

- 30 grams of FDM rapid prototyping on the R/P machine

Given These constraints, our group made up the following PDS that will be used to come up with a functioning design that would both satisfy the requirements/constraints and will be better than the reference design.

Table 1: Summary of Design Constraints

Item	Quantity	Dimension
Sheets of medium density fiberboard MDF	3	4”x 7”x. 1/4” (nominal)
Rubber bands	5	Size #64
Wooden dowel	1	¼” diameter and 12” long
Paper clips	4	NA
long pan head screws & nuts	10	#6-32 by 3/4”
Sheets of photocopying paper	1	8-1/2” x 11”

Design Characteristics *(Authored by: Maichel, Zaid, Shoaib, Parampreet, Daniel)*

- Cost efficient: The product must be affordable to all users
- Durability: The product should last without breaking
- Safety: The product should be safe for usage
- Portability: The product should have light weight and should be small in size
- Functionality : The product should meet all functional requirements
- Usability: The product should be easy to use.
- Manufacturability: The product must be made from the constraints provided by the instructions that are mentioned in the physical constraint section.

Functional Requirements *(Authored by: Maichel, Zaid, Shoaib, Parampreet, Daniel)*

- Product must display legible whole numbers as output
- Product must be able to perform 4 digit additional operations
- Machined parts of the product must be machined from MDF
- Rapid prototyped parts must use FDM
- Product must have mechanical gears
- Numbers inserted in the calculator must be inserted using a wooden dowel.

Physical Constraints *(Authored by: Maichel, Zaid, Shoaib, Parampreet, Daniel)*

- Product must weigh less than 350 grams (based on density of MDF, and weight of FDM)
- Product must be machined from a maximum of 3 sheets of MDF with dimensions of 4" x 7" and a thickness of 1/4"
- Product must use no more than 4 paper clips
- Products must have a clearance diameter for a diameter of 0.25 inches should be made so that the dowel fits.

Pairwise Comparison Chart *(Authored by: Maichel, Zaid ,Shoaib and Daniel)*

Table 2: Pairwise Comparison Chart

Product Characteristic		**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Totals**	**%Weight**	**Ranking**
Cost Efficient	**A**	-	B	C	A D	E	F	G	1	4.35	5
Durability	**B**	-	-	C	D	E	F	G	1	4.35	5
Safety	**C**	-	-	-	C	E C	C	C	6	26.00	1
Portability	**D**	-	-	-	-	E	F	G	2	8.70	4
Functionality	**E**	-	-	-	-	-	E	E	6	26.00	1
Usability	**F**	-	-	-	-	-	-	F	4	17.39	2
Manufacturability	**G**	-	-	-	-	-	-	-	3	13.04	3
									23	100	-

Justification For the Pairwise Comparison Chart *(Authored by: Parampreet)*

Cost Efficient vs. Durability

Comparing the importances of cost efficient and durability, durability is seen as more important. The product must definitely be more durable, it should not break or malfunction after some time of use, it should last many uses.

Cost Efficient vs. Safety

When comparing the two attributes of cost efficiency and safety the more important design characteristic is seen to be safety. It is more important for the user to feel safe with the product as opposed to the costing of the product.

Cost Efficient vs. Portability

Both cost efficiency and portability are equally important in the design of the product. The product must be able to be moved around from place to place and at the same time it should also not be excessively priced.

Cost Efficient vs. Functionality

The product must meet all of its functional requirements before the cost effectiveness of the product can be judged and evaluated. It is much more important for the product to perform its intended functions.

Cost Efficient vs. Usability

Much like functionality, usability is also a very important attribute for a product which weighs heavier than the cost efficiency. The product must feel easy for the user during its use before the cost effectiveness of the product can be looked at.

Cost Efficient vs. Manufacturability

It is more important for the product to meet all its production requirements and constraints as compared to its affordability. The product must be in line with its manufacturing requirements and should be easily producible.

Durability vs. Safety

The product must make the user feel safe and secure during its use. The user should feel comfortable and not have to worry about harm during the use of the product. The safety the product has is therefore greatly more important that its durability.

Durability vs. Portability

The product must be lightweight and small in size for it to be able to move around easily from place to place given the user's preference. It is more important for the product to be portable than for it to be durable in this instance.

Durability vs. Functionality

The product must meet all of its functional requirements before the durability of the product can be evaluated and analyzed. It is much more important for the product to perform its intended functions than to be durable.

Durability vs. Usability

Usability is a very important attribute for a product which is much more important than the durability of the given product. The product must feel easy for the user during its use before the durability of the product is assessed.

Durability vs. Manufacturability

It is more important for the product to meet all its production requirements and constraints as compared to its durability. The product must be in line with its manufacturing requirements and should be easily producible.

Safety vs. Portability

Safety is one of the most important aspects of a product. The product must be safe and should not be harmful in any way to the user or its environments. That is why safety is one of the most important attributes, more important than portability for the product.

Safety vs. Functionality

Although safety is extremely important, in this case it was determined that safety is equally as important as functionality. The product being able to perform its intended functions is very important, just as important as its safety.

Safety vs. Usability

Ease of use of the product is very important but the safety of the product is more vital and weights more than the safety. The product must be safe and show no harm to its user before the usability is evaluated.

Safety vs. Manufacturability

Safety is one of the most important aspects of a product. The product must be safe and should not be harmful in any way to the user or its environments. That is why safety is one of the most important attributes, more important than manufacturability of the product.

Portability vs. Functionality

The product must meet all of its functional requirements before the portability of the product can be evaluated and analyzed. It is much more important for the product to perform its intended functions than to be portable.

Portability vs. Usability

Usability is a very important attribute for a product which is much more important than the portability of the given product. The product must feel easy for the user during its use before the portability of the product is assessed.

Portability vs. Manufacturability

It is more important for the product to meet all its production requirements and constraints as compared to its portability. The product must be in line with its manufacturing requirements and should be easily producible.

Functionality vs. Usability

The product must meet all of its functional requirements before the ease of use of the product can be examined. It is more important for the product to perform its intended functions than it to be easy to use.

Functionality vs. Manufacturability

The product must meet all of its functional requirements before the manufacturability of the product can be judged and evaluated. It is much more important for the product to perform its intended functions than for it to be producible.

Usability vs. Manufacturability

The product must be easy to use and at the same time be easy to produce as well. Although both are important, the ease of use plays a much greater role in a successful product and design therefore usability is more important.

Reference Design *(Authored by:Shoaib)*

The original Sterling Dial-A-Matic calculator was focused mostly on cost efficiency and usability, given its plastic build and instructions which were written on top of the board. While portable, the design was meant for children to learn basic math, or accountants to do simple calculations. There was even a design built specifically for Chevrolet dealerships, to help the car salesmen find the total price of the car for a customer. There were also some models that included a decimal system, along with a resetting mechanism, but only counted upto 3 units. Some durability issues, such as the stylus being grinded off or broken after some use did exist, but were indirectly addressed by using a pencil instead. Of course, that small stylus could be a choking or poking hazard for small children, so using a longer and thicker pencil could be safer. Lastly, the manufacturability of the product goes hand in hand with it's cost; the simple top down assembly made of plastic means that this product could be mass produced cheaply.

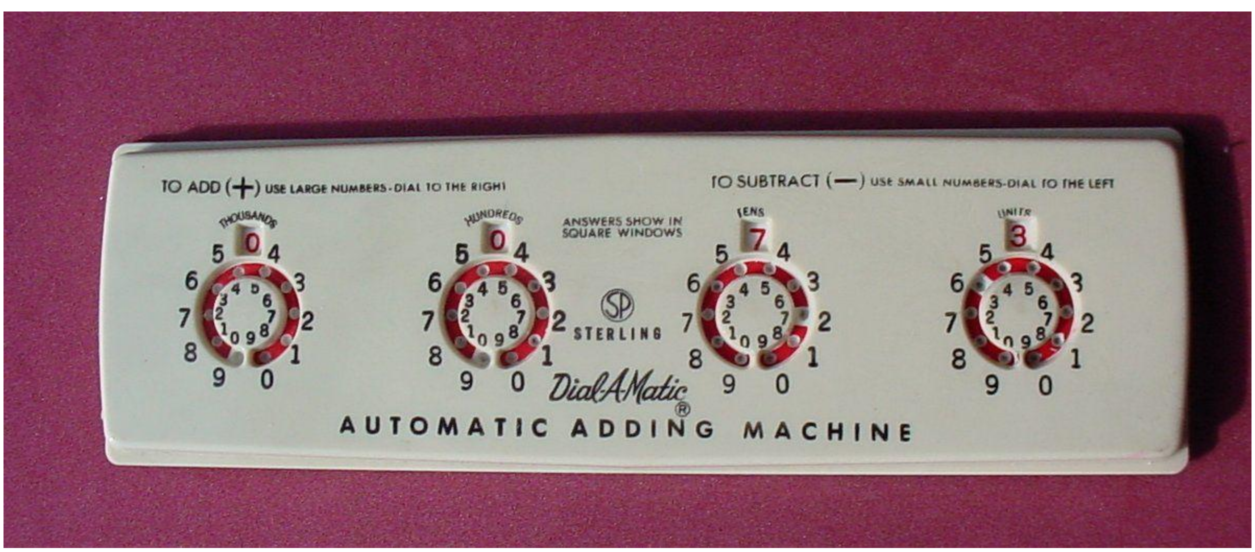


Figure 5: Sterling Dial a Matic[1]

Re-Design 1(*Authored by: Maichel)*

This design is made with the motive of improving and performing minor changes to the pascaline famous mechanical calculator. Pascaline is made up by the great french scientist Blaise Pascal that was for a long time considered as the first mechanical calculator in the world [7]. The pascaline follows the principle which almost all mechanical calculators follow nowadays which is: When a gear with ten teeth makes one rotation (tens) a second gear shifts one tooth until that gear rotated ten times (hundreds) that shifts another gear (thousands) etc. This principle is still used in odometers in cars, pumps of petrol stations, and your electricity meters at home[8]. The way this design works is by having 7 gears attached together in the order shown in figure 6. Numbers are written on each gear, rotation of each gear is done manually using hands. Each 2 gears are connected by another gear which is responsible for the carry on mechanisms The value of the output is then displayed and shown from the numbers on the bottom gears. Moreover, there is an arrow at the bottom of the gear to point at the inputted/outputted value. Levers made on the upper gears are made with alternating thickness in order to avoid any collision with the bottom gears.

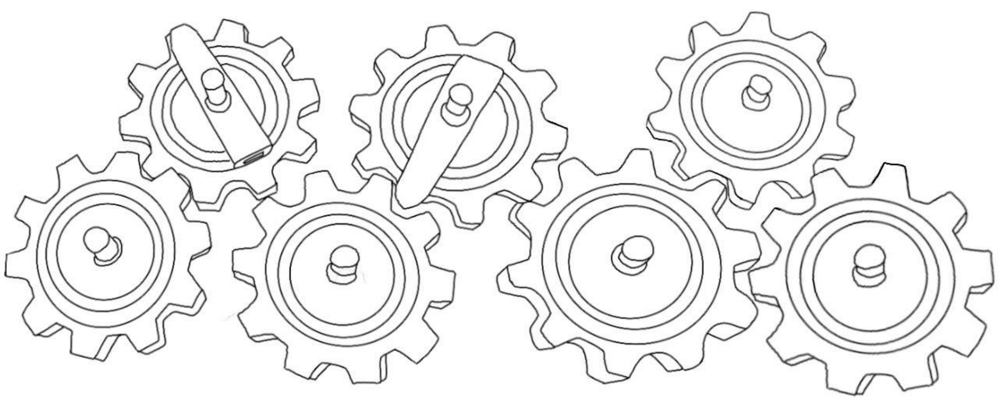


Figure 6: Redesign 1 sketch showing the outline of the design

Re-Design 2 (*Authored by: Maichel and Zaid)*

The redesign process started with the motive in mind of improving the reference design to better enhance the functionality, safety and manufacturability of the product. To begin with, the lever's design got changed to be smaller in size thus improving the cost of the product and making it affordable for all users. Moreover, the edges of the lever were made less sharp to be easily manufactured considering that this part was 3D printed. Moreover, the pins on the sides of the gear were changed from a gear to the other meaning their dimensions were altered as well their shape in order to help the carryon mechanism to the neighbour gear in case a value greater than 10 was inserted. The changes that were performed on the gear differed from alternating its dimensions as well as its location to avoid the situations where the pin gets stuck to the gear beside it. Also, another addition that was made to the existing design is that there will be no ratcheting/clicking mechanism in the redesigned product. Furthermore, The screws attaching the top casing will be removed, this will improve the costing of the product without affecting its functionality. The method of attaching the case together will be using glue that is strong and relatively cheaper and this was one of the provided materials in the project manual by the instructor. Finally, the re-designed product will use a different mechanism to input the numbers, the mechanism will involve a dowel which is again, one of the permitted materials to be used as per the project manual. The wooden dowels will be used in order to rotate the main gear with the needed numbers. Finally, The numbers on the top casing will be printed/written on the casing using ink or regular pen to be sort of a sticker add on it instead of machined to lower the costing of the product.

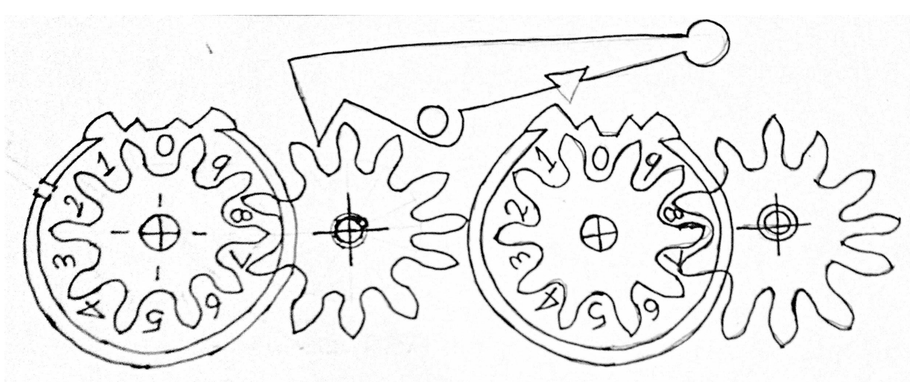


Figure 7: Displaying one of the gears+lever

By observing the sketch illustrated above, it can be seen that the changes made on the original design revolve around its functioning mechanism. The purpose of these additions/alterations is to include a wider group of end users and provide a better user experience, reduce the cost and ensure the product is safe to use even when used by young children. Screws attaching the casing are replaced with the snap fitting mechanism. Similarly, the 10 holes made in each gear are also removed for the purpose of replacing the clicking mechanism with the dowel insertion mechanism. Concept 2 is also built on solidworks where each part is made with careful measurements and with accordance to the requirement in the project manual. Assembly construction and assembly drawings are also included for a better understanding of how the design works. A video stimulation has been incorporated to present the product while in use and guide the user on how to handle the product. Drawings are provided in Appendix B.

Weighted Decision Matrix *(Authored by: Maichel, Zaid ,Shoaib and Daniel)*

A weighted decision matrix (WDM) is a simple tool that is very useful in making complex decisions, especially in cases where there are many alternatives and many criteria of varying importance to be considered. The following WDM will be used in order to determine which design is better.

Table 3.0: Weighted decision Matrix including weight factor

Product characteristics	Wgt (%)	Original Design		Concept 1		Concept 2	
		Rating	Score	Rating	Score	Rating	Score
Functionality	4.35 %	0	0	+1	0.0435	+1	0.0435
Cost	4.35 %	0	0	+1	0.0435	+1	0.0435
Manufacturability	26.00 %	0	0	+1	0.26	+2	0.52
Portability	8.70 %	0	0	0	0	0	0
Safety	26.00 %	0	0	-1	-0.26	+1	0.26
Usability	17.39 %	0	0	+1	0.1739	+1	0.1739
Durability	13.04 %	0	0	-1	-0.1304	0	0.1304
Total	100 %	0	0	2	0.1305	+6	0.9982
Rank		3		2		1	

Table 3.1. Weighted Decision Matrix Scoring

Rating				
-2	-1	0	1	2
Very Poor	Poor	Same as Reference	Good	Very Good

Justification of Weighted Decision Matrix *(Authored by: Zaid)*

This initial decision matrix is used to compare the proposed redesign concepts with the original design with respect to the criteria suggested in the Pairwise Comparison Matrix. The weight percentages in the PDS represent the importance of the criteria. The original design is the reference design which comparisons will be made against. The design with the highest score will be chosen as our final selection. Results are shown in Table 3 above.

With respect to functionality, both concepts achieved a score of 1. The first concept included alternating the thickness of the lever arm providing a push to the adjacent gears in order to prevent any collisions or misalignment from occurring. Similarly, concept 2 enhances the functionality of the design by alternating the thickness and dimensions of each gear to provide smoothness of movement and prevent collisions of parts, which may lead to product failure. Another change added to the second concept is the substitution of the clicking mechanism with a dowel. Using a dowel does not require as much force needed to input numbers like the clicking mechanism would. Although the original design is marked to have no choking hazards, our team has decided to get rid of the screw used in the outer casing to prevent any potential loosening and fall in hands of young kids, which may lead to such hazards.

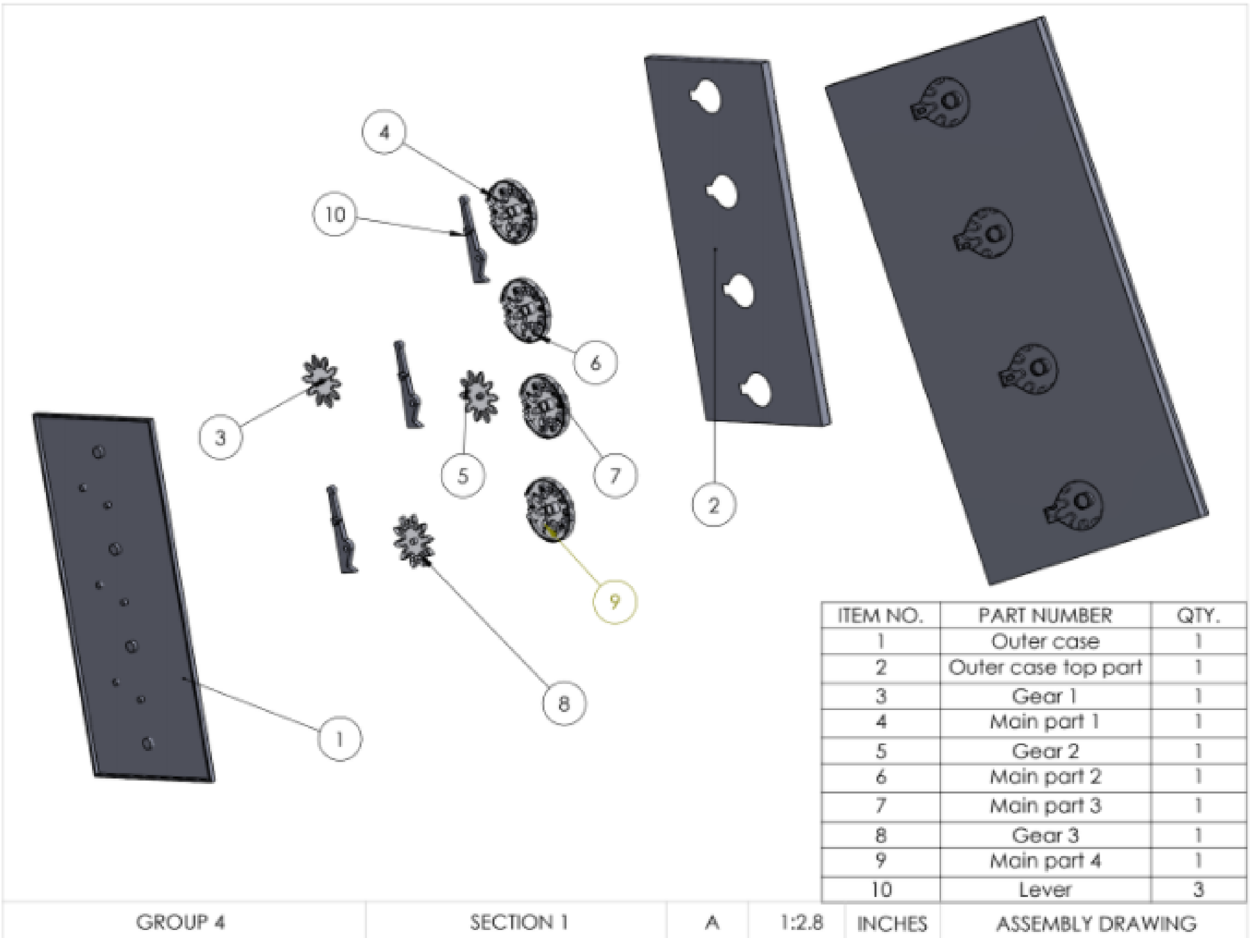
In regards to cost, concept 1 has a less variety of parts used to build the product, which could reduce the manufacturing cost. Concept 2 reduced the size of lever arms used to rotate the gears in contact with them. It also excludes the screws used to attach the casings together. As a result, both concepts achieved a score of .

In terms of manufacturability, concept 1 achieved a score of 1 due to the fact that there is a less variety of the parts used to design and assemble the product which eases the process of manufacturing. on the other hand, concept 2 achieved a score of 2 due to multiple reasons. The 2nd concept replaces the clicking mechanism with a dowel mechanism. The clicking mechanism requires making 10 holes in each gear in order to input numbers. The dowel mechanism achieves the same goal by just using a wooden dowel to rotate the gears for inputting numbers. This can reflect on the manufacturing process and manufacturing costs as aforementioned.

Durability remained unchanged for both concepts as the changes made to both concepts have no impact on the portability of the product and thus achieved a score of zero. On the other hand, usability achieved a score of one as the change in inputting mechanism has changed in both concepts allowing for improvements on the usability from the user's end. Similar to portability, durability also remained zero for the same reasons mentioned above.

Drawings *(Authored by: Zaid and Maichel)*

A full set of working drawings can be found in Appendix B



ITEM NO.	PART NUMBER	QTY.
1	Outer case	1
2	Outer case top part	1
3	Gear 1	1
4	Main part 1	1
5	Gear 2	1
6	Main part 2	1
7	Main part 3	1
8	Gear 3	1
9	Main part 4	1
10	Lever	3

Figure 8.: Exploded view of final design

MasterCAM *(Authored by:Shoaib)*

The parts being machined were the outer case, outer case top part, and the 3 levers without the triangle edge, as they were being 3d printed due to their thickness bringing the overall part thickness to 0.26 inches. The process to get the .dxf files was to use the sketches of the Solidworks part files, and copy them onto a 4" x 7" x ¼" block, and then convert to a .dxf file. This would leave 3 .dxf files of blocks, all with the origin centered at them, so MasterCAM doesn't have to guess where the stock material is. As a side note, the .dxf files also come with a Solidworks watermark, which unfortunately was not removable.

The first MDF board was used in its entirety as ⅚ of the outer case, with the second MDF board containing the remaining ⅙ of the outer case, and ½ of the outer case top part. This outer case top part was machined on its back, as it's thickness is the same as the MDF board given. Lastly, the third MDF board had the other half of the outer case top part, and the three levers. Note that before machining the outer case and levers, the MDF board had to be machined down in thickness, which will take a long time. Thankfully, because the levers don't take the entire width of the board, a trapezoidal envelope shape was created using the CAD tools in MasterCAM for the face milling operation, but is not present in the .dxf file.

The reason these parts were chosen and not the gears, is simply because of the limitations of a 0.5" endmill, and the wide arching shape of the gears themselves. In terms of the fraction of outer casing parts being split among MDF boards, those were done so they'd be stuck together at different intervals. Meaning if one were to apply force on the outer case top part in the middle, the bottom outer case isn't affected as it's adhered along a parallel, but separate axis. Also, there was no thought put into clamping positions, as it was advised that double sided tape would've been used to adhere the board to a CNC machine. An isometric view of the MDF boards being machined out on MasterCAM are shown below, and the 3 sets of files containing the MCX-6, .dxf, .ncl and .mp4 files per MDF board will be submitted with the report.

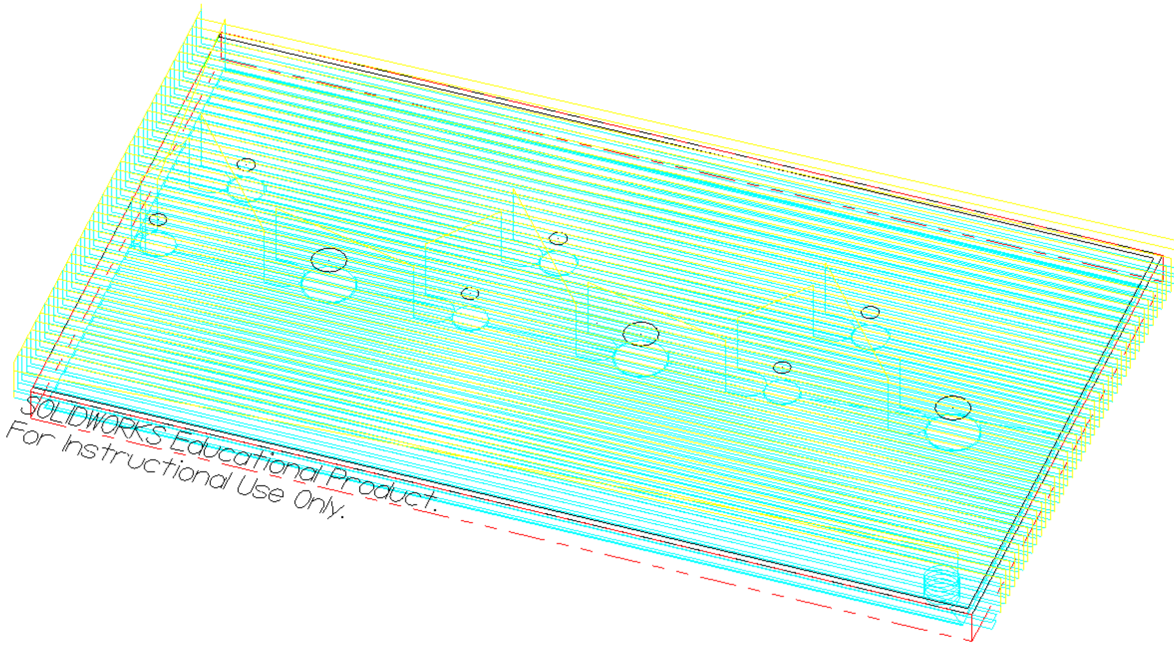


Figure 9: MDF board 1 machining operations

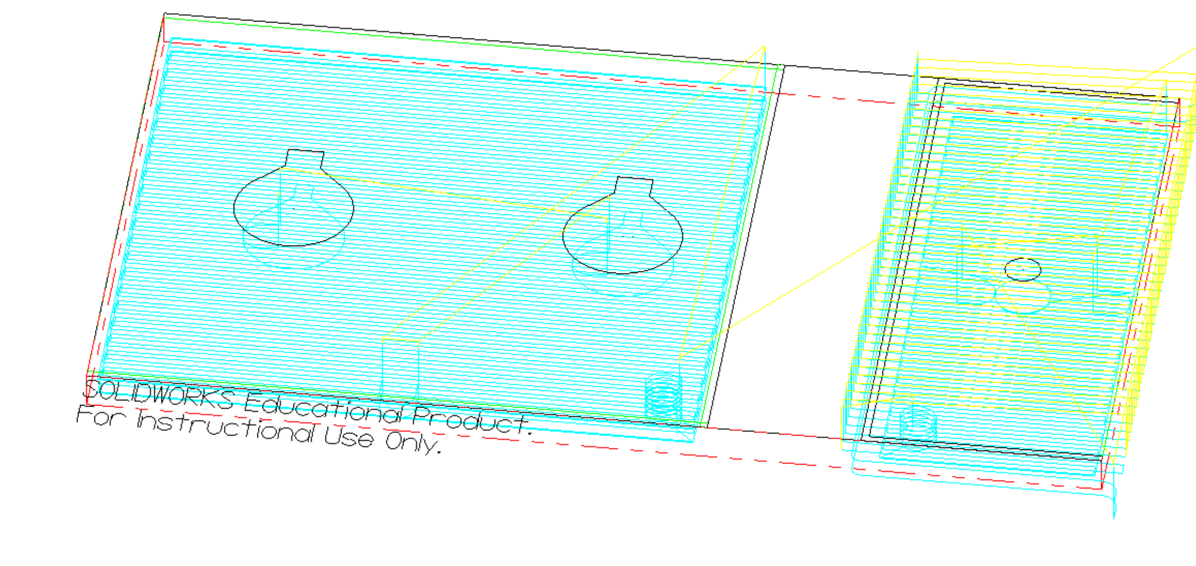


Figure 10: MDF board 2 machining operations

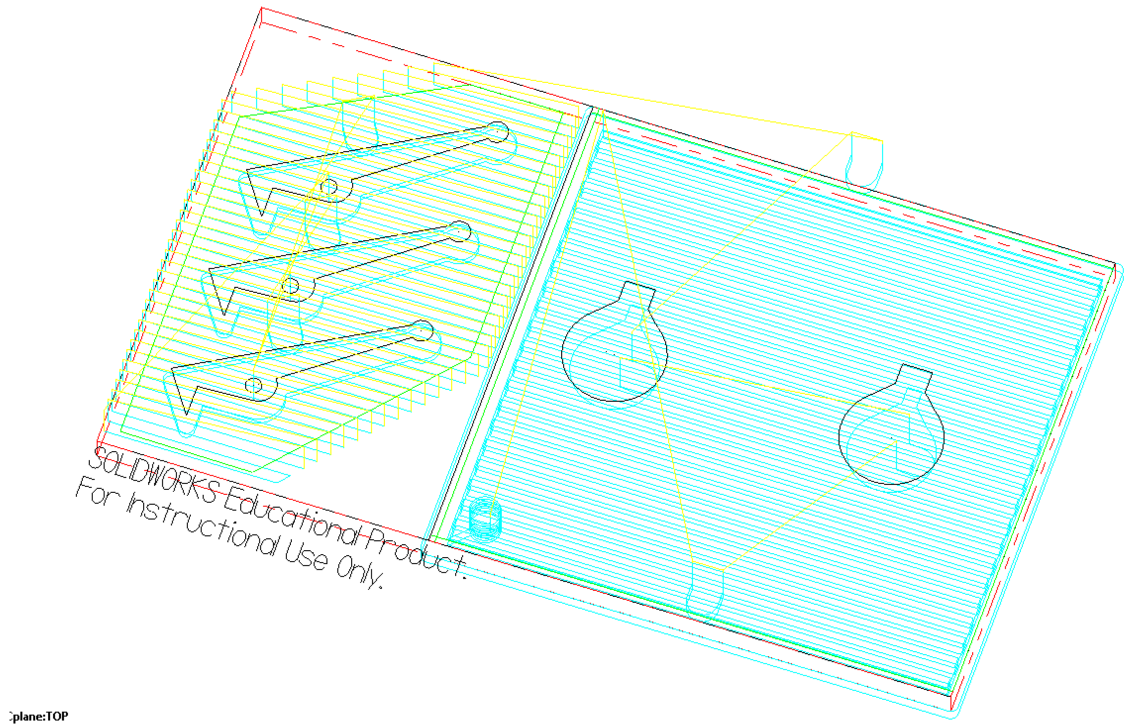


Figure 11: MDF board 3 machining operations

Ultimaker Cura *(Authored by:Daniel)*

Once the Solidworks files were created the required parts were saved as .stl files and then imported and placed on to the print bed in Cura as can be seen in in the figures below. Once the parts were positioned the parts were sliced and a G-code was generated. This G-code can be saved to an SD card and transferred to the printer for printing. In total it will take 2 hours and 22min to print all the parts using 7.23m of filaments which will weigh 21g.

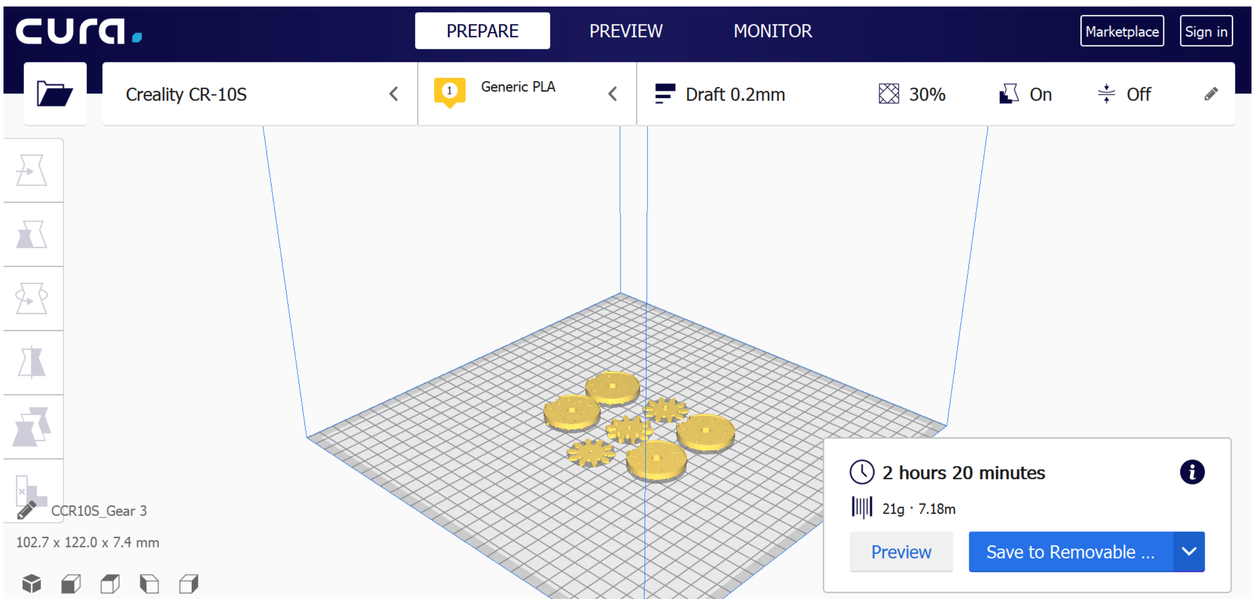


Figure 12: Cura isometric view

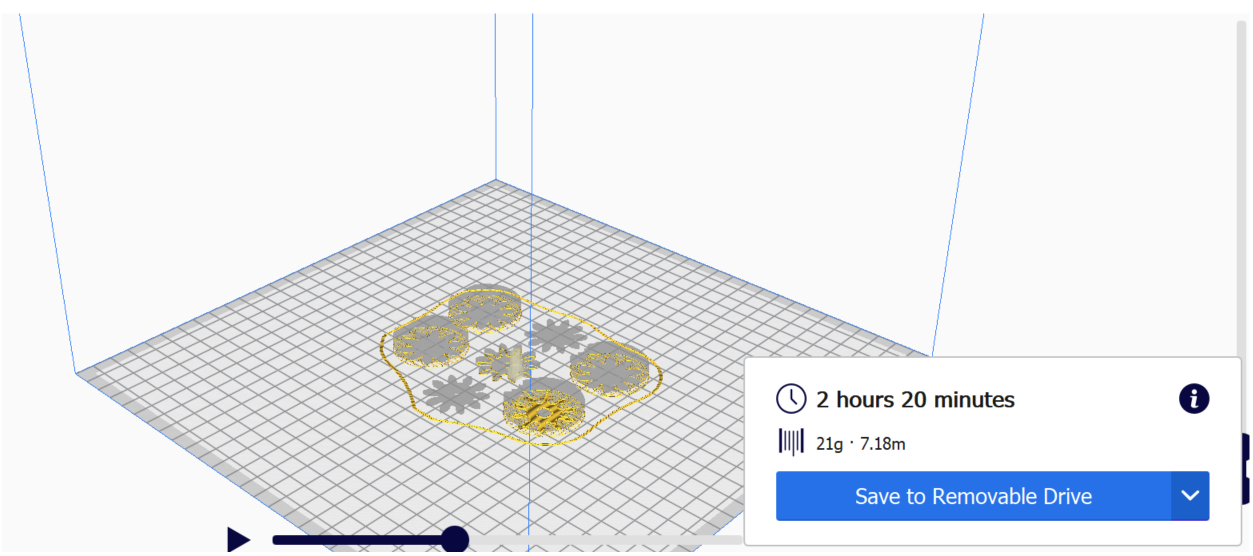


Figure 13: Cura layer 1 view

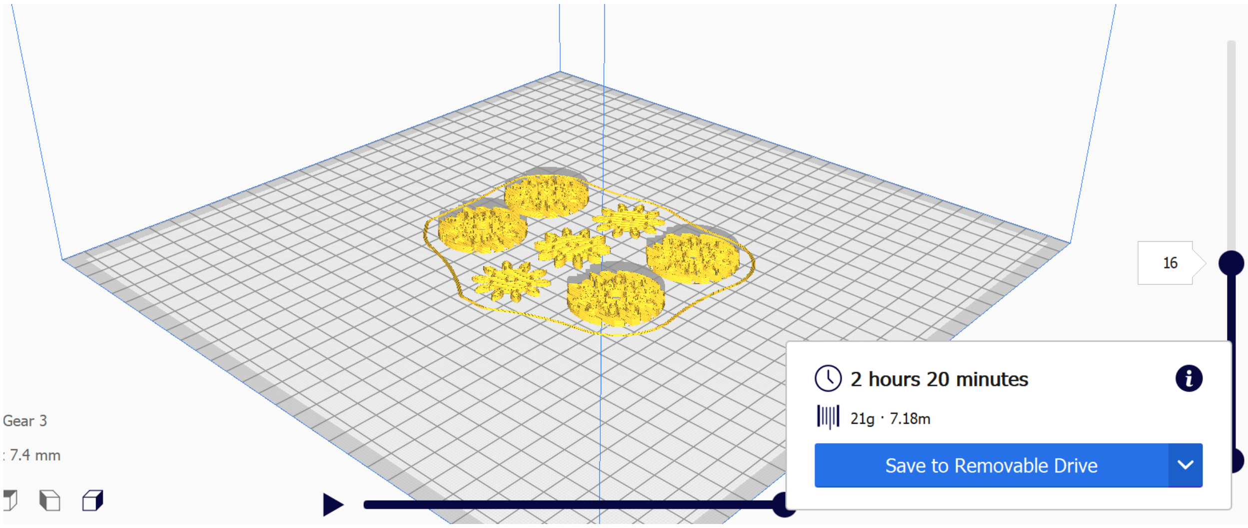


Figure 14: Cura layer 16 view

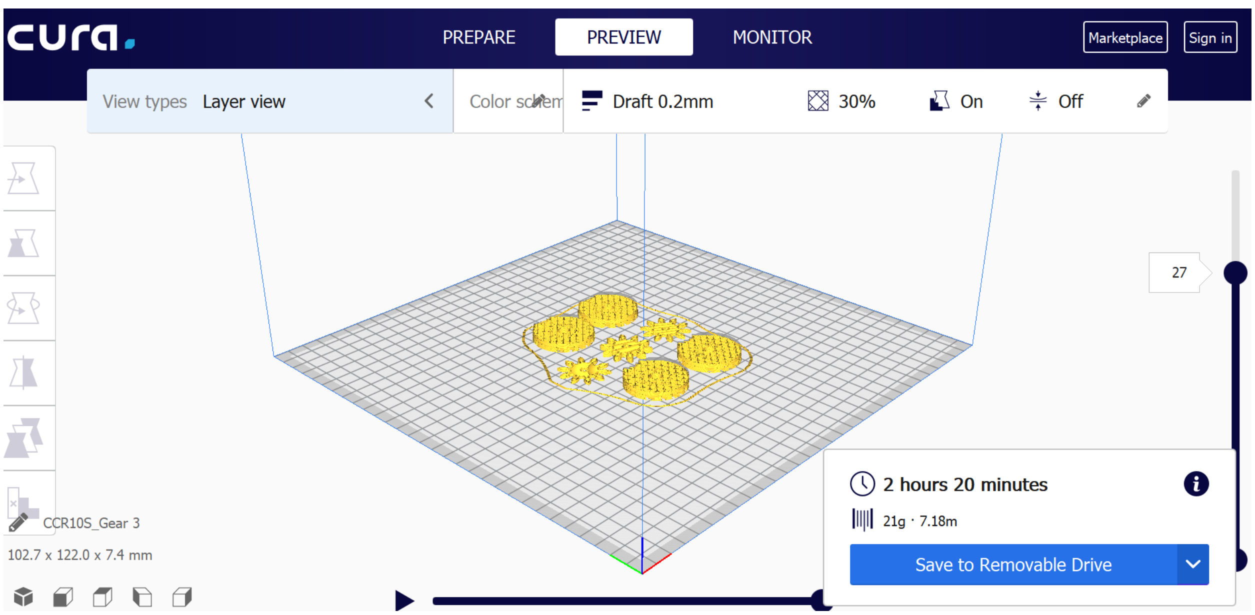


Figure 15: Cura layer 27 view

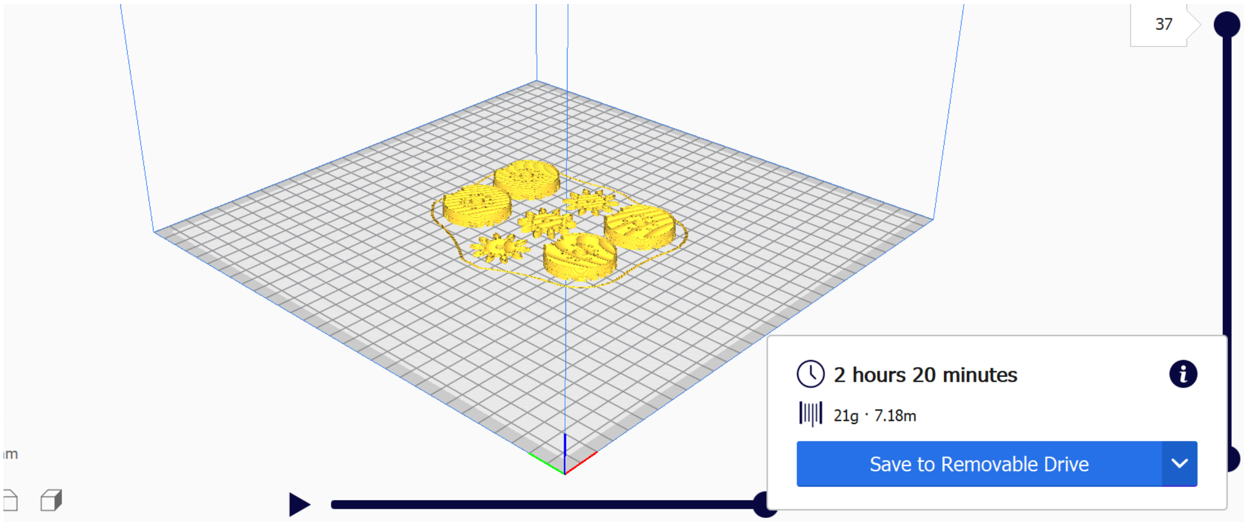


Figure 16: Cura top layer view

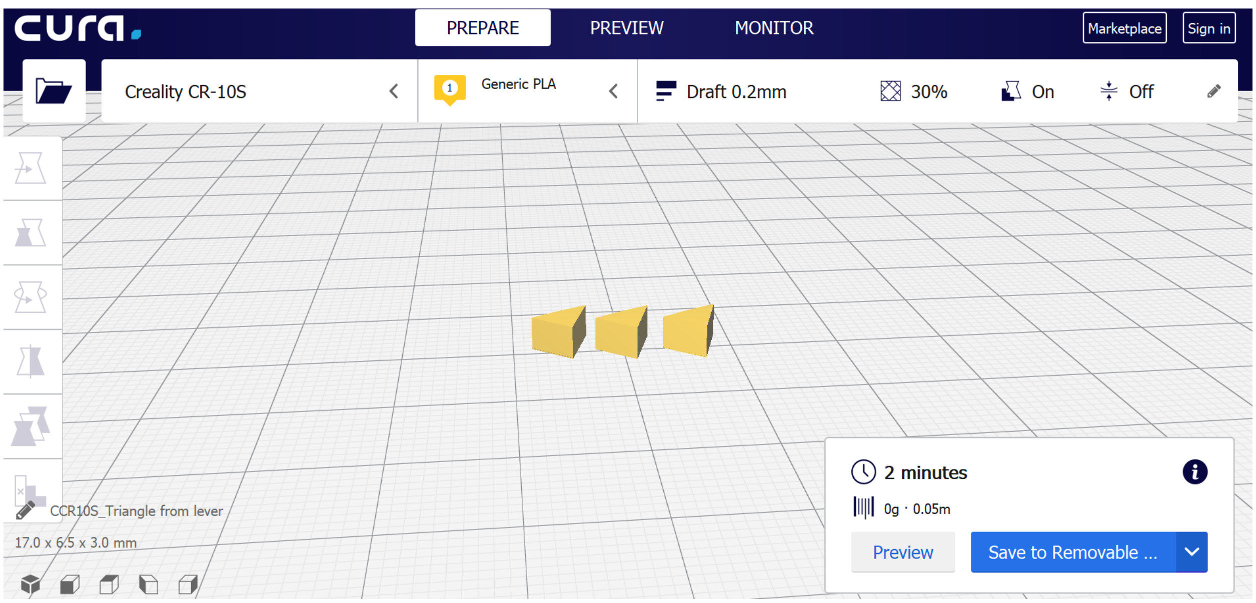


Figure 17: Cura isometric view of triangles for lever

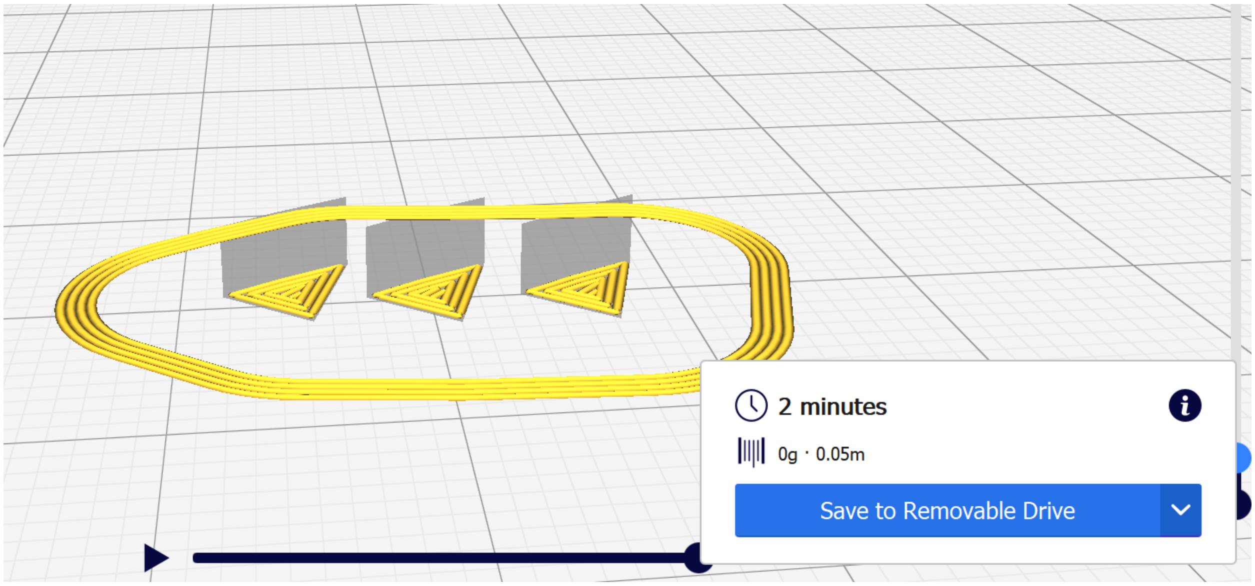


Figure 18: Curalayer 1 view of triangles for lever

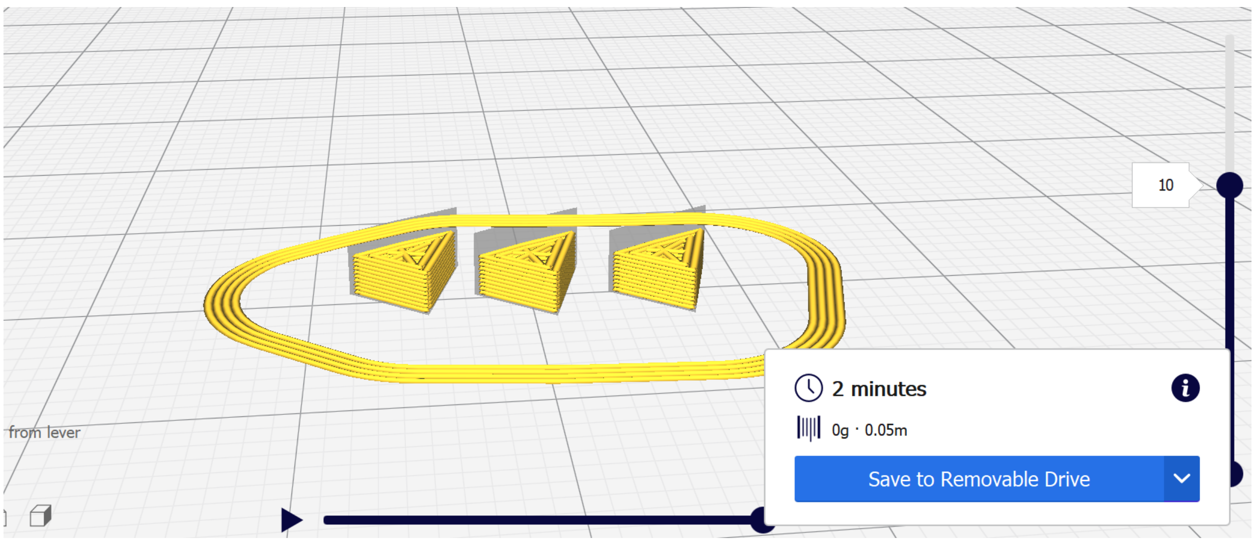


Figure 19: Curalayer 10 view of triangles for lever

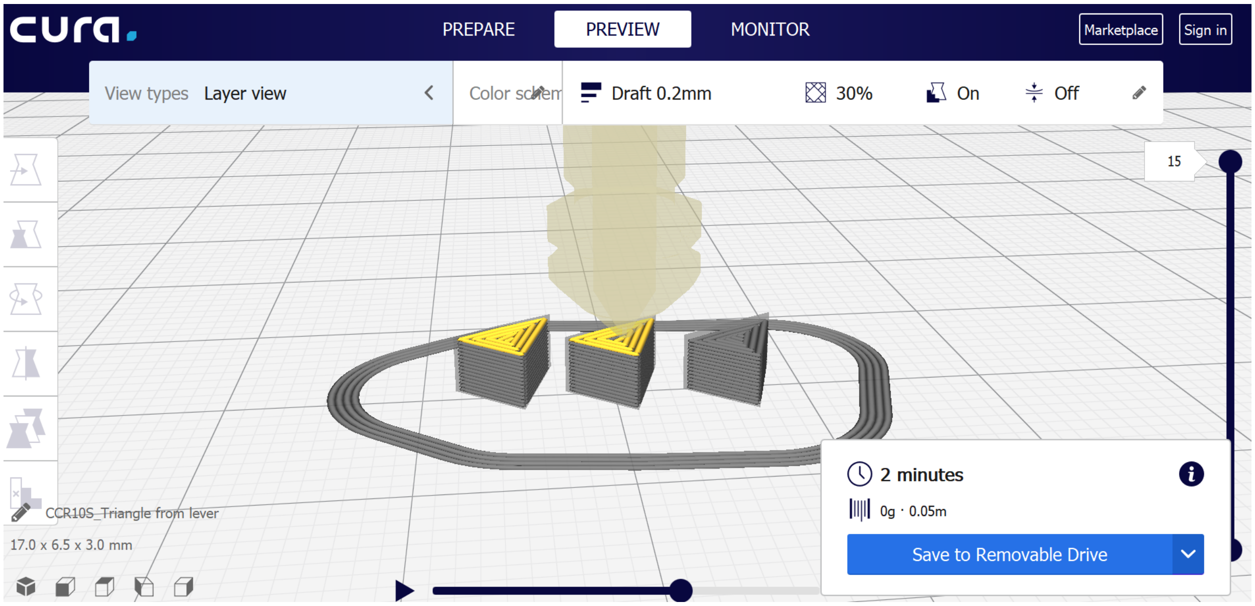


Figure 20: Curalayer 15 view of triangles for lever

Process Plan *(Authored by:Daniel)*

The process plan will describe in detail the manufacturing and assembly process in detail including software design, machining, 3D printing and assembly. To start the process of designing a machine that adds two four-digit numbers. Solidworks was used to create an accurate 3D model of our design. Each part would then be converted into the required file format .dxf for MasterCAM and .stl for Cura. Which are the respective softwares that were used to generate the G-code for the CNC end milling and 3D printing.

The first step in manufacturing the CNC end milling of the required components from the medium density fibreboard (MDF). This process must comply with all of the material design restrictions and equipment design restrictions. Since the diameter of the end mill bit is ⅛” it needs at least a ⅛” gap between each of the pieces being machined so that the bit can fit. Given the limited amount of MDF board provided the positions of each piece were optimized to minimize wasted material.

After making the parts by CNC machining process, the parts are assembled using glue to obtain the desired geometry in terms of height. Mating of the components is a critical step in achieving the desired thickness of MDF panels. The case will be made from the MDF board whereas the internal “mechanics” of the calculator would mostly be 3D printed excluding part of the lever. This is the most efficient way to achieve a design that encloses the interior of the mechanical calculator. The different orientations for printing were analyzed using Cura to see which one requires less material and lower production times. Ultimately the one that was chosen used the least amount of support material since the amount of PLA filament that was provided was limited. Whereas there was no maximum time on the 3D printer. The reduced amount of material for the supports to print the components was preferred since there was a maximum of 30g of PLA. Installing the components in the housing would be the next step in project design. The pieces of wooden dowel were then cut to length using a small hand saw. Although this could be done on a CNC mill it seemed excessive and impractical. The alignment of the shafts with the case was designed such that it would press fit together with a little bit of glue and not require any other fastening devices such as screws or bolts.

Calculations for Gears *(Authored by: Maichel)*

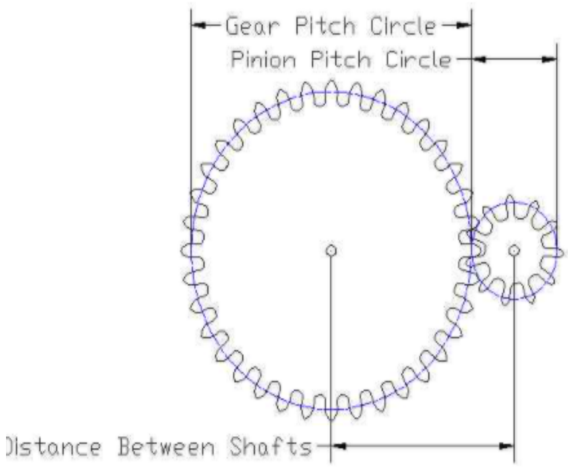


Figure 21:Outline of the Gear [6]

This section will focus on the calculation process involved in the gear design portion. The design required the usage of both gears and linkages in addition to other constraints. (refer to the constraints section) . For the sake of this project, the gears of a diametral pitch of 10 will be used.

$$Gear\ pitch\ diameter\ = \frac{10\ teeth}{10\ diametral\ pitch} = 1"$$

$$Pinion\ \ pitch\ diameter\ = \frac{10\ teeth}{10\ diametral\ pitch} = 1"$$

$$Shaft\ to\ shaft\ distance\ = \frac{1}{2} + \frac{1}{2} = 1"$$

For the above gear train,each revolution of the tooth pinion will of course move the tooth 10 gear :

$$\frac{10}{10} = 1\ of\ a\ revolution\ or\ 360°$$

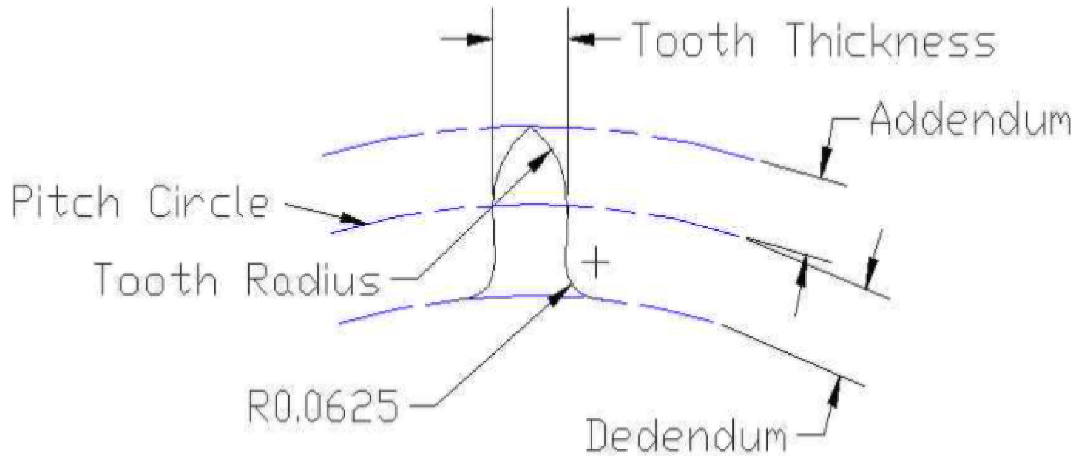


Figure 22:Sketch showing gear names definition[6]

Table 4: Measurements used in the gears

# of teeth	10
Addendum	0.135"
Dedendum	0.157"
Tooth Radius	0.157"
Tooth Thickness	0.157"

Conclusions and Recommendations *(Authored by: Parampreet)*

Throughout the project the team performed multiple tasks and used different methods of analysis in order to complete the final design. The team was assigned with the task of creating a mechanical sum calculator using specific parts and tools with certain constraints. After a literature review was performed and a reference design was acquired, the redesign process started for the mechanical calculator. The team used the aid of the Product Design Specifications along with comparison charts in order to complete the redesign process. Two different redesigns concepts were constructed and then compared to the original design (reference design) using a weighted decision matrix. Justifications were made for the choices in the weighted decision matrix and ultimately Redesign 2 scored the highest and was chosen as the final design moving forward.

For the final design the product was created on Solidworks along with all the engineering format drawings. The parts for the final design were then machined on MasterCAM. The gears were not chosen to be machined using MasterCAM due to the limitation of the endmill provided. The Solidworks files were saved and then imported and placed onto the print bed in the Ultimaker Cura software. The parts were positioned and were then sliced, generating a G-code which was saved and transferred to the printer for printing.

Overall, the group's suggested and final redesign overcame most of the issues claimed and noticed in the original design of the mechanical calculator. Nevertheless, product re-designs will never be perfect and there will always be faults in addition to improving areas. Like for example sustainability was not a factor of the redesign. Because, there were limited material constraints that our group had to follow.

References

[1]"Mechanical slide and rotary adders", Sliderulemuseum.com, 2018. [Online]. Available: https://www.sliderulemuseum.com/Adders.htm#RotaryAdders. [Accessed: 04- Dec- 2020].

[2]P. Freiberger, "Pascaline | technology", Encyclopedia Britannica, 2020. [Online]. Available: https://www.britannica.com/technology/Pascaline. [Accessed: 04- Dec- 2020].

[3] J. Scherphius, "Dial-A-Matic / IBM Hexadecimal Adder / The see "calculator"", Jaapsch.net, 2020. [Online]. Available: https://www.jaapsch.net/mechcalc/dialamatic.htm [Accessed: 04- Dec- 2020].

[4] "The adding device of Kummer", History-computer.com. [Online]. Available: https://history-computer.com/MechanicalCalculators/19thCentury/Kummer.html [Accessed: 04- Dec- 2020].

[5] Detlev Bölter, "The carry over of tens in disc adders" [Online]. Available: http://www.boelter.rechnerlexikon.de/Zehneruebertrag/ten_carry_mechanism.html [Accessed: 04- Dec- 2020].

[6] V. Chan, *cycloid gear cutting*. [Online]. Available: https://people.ryerson.ca/v7chan/cncproject/cycloid.html. [Accessed: 29-Nov-2020].

[7] History-computer.com. 2020. *Pascaline - Complete History Of The Pascaline Calculator*. [online] Available at: <https://history-computer.com/MechanicalCalculators/Pioneers/Pascal.html> [Accessed 6 December 2020].

[8]Thocp.net. 2020. *Pascaline*. [online] Available at: <https://www.thocp.net/hardware/pascaline.htm> [Accessed 6 December 2020].

Appendix A: MasterCAM setup sheets for each board being cut *(Authored by: Shoaib)*

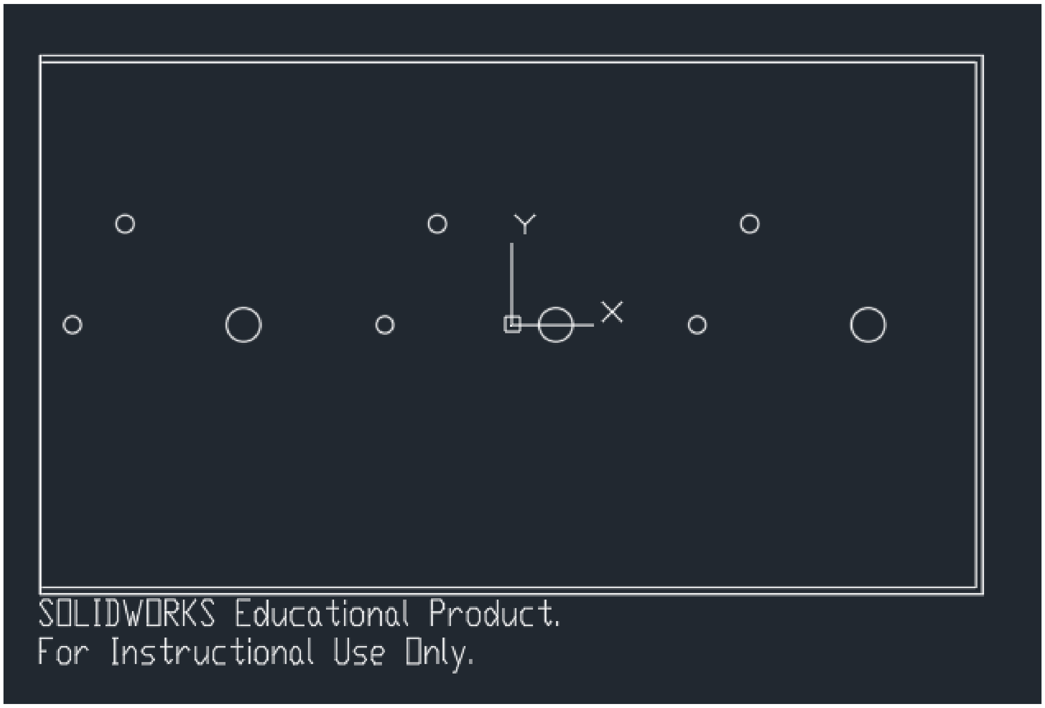


Figure 23: MDF board 1 setup in .dxf file

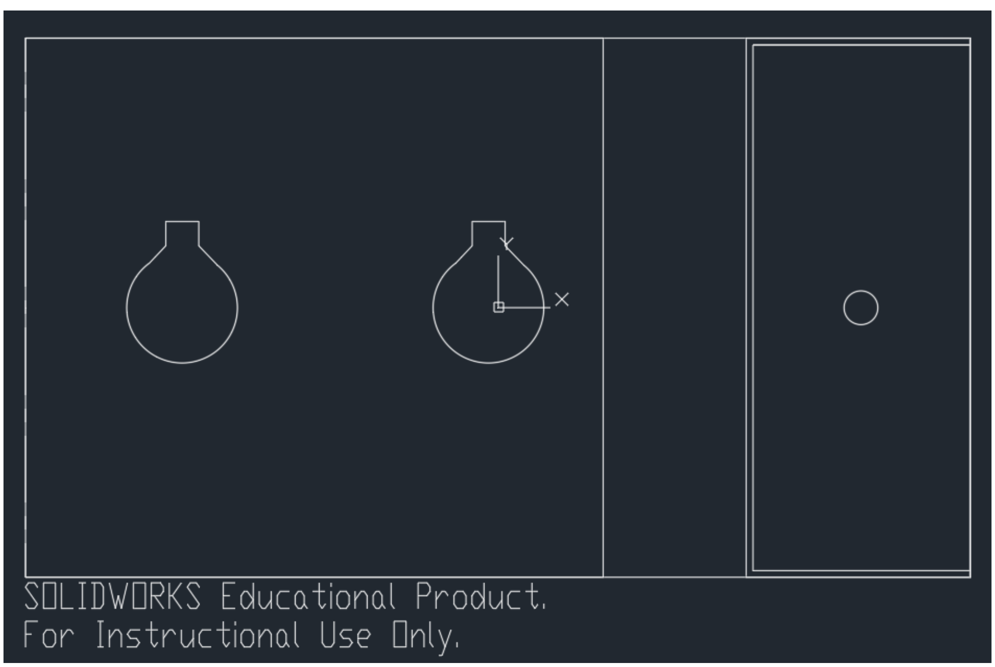


Figure24: MDF board 2 setup in .dxf file

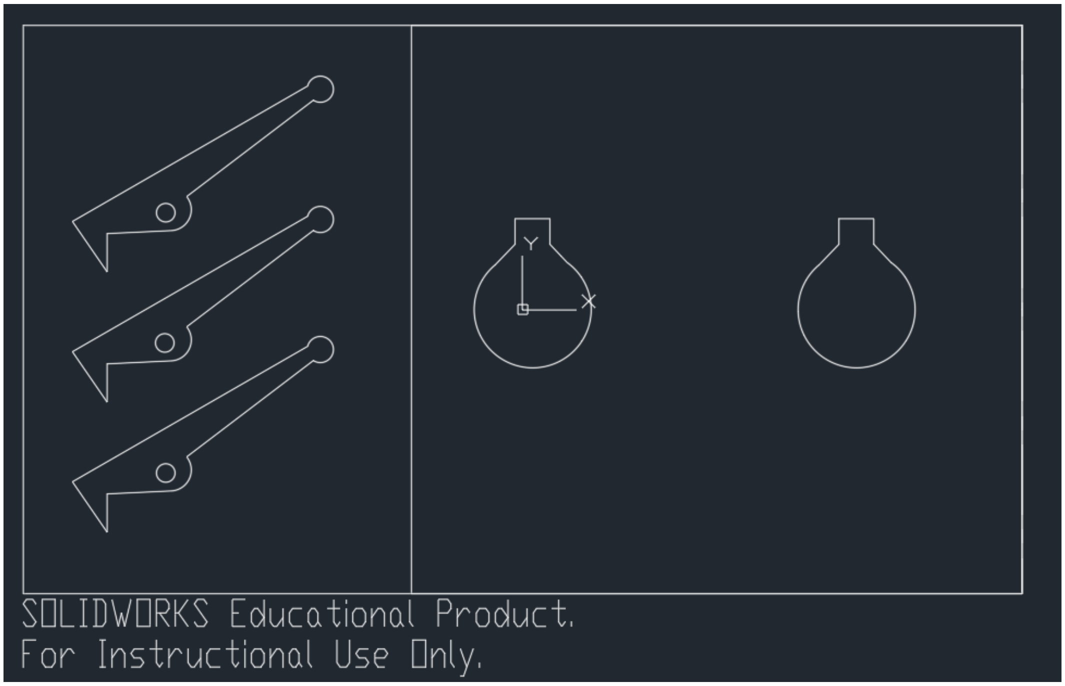
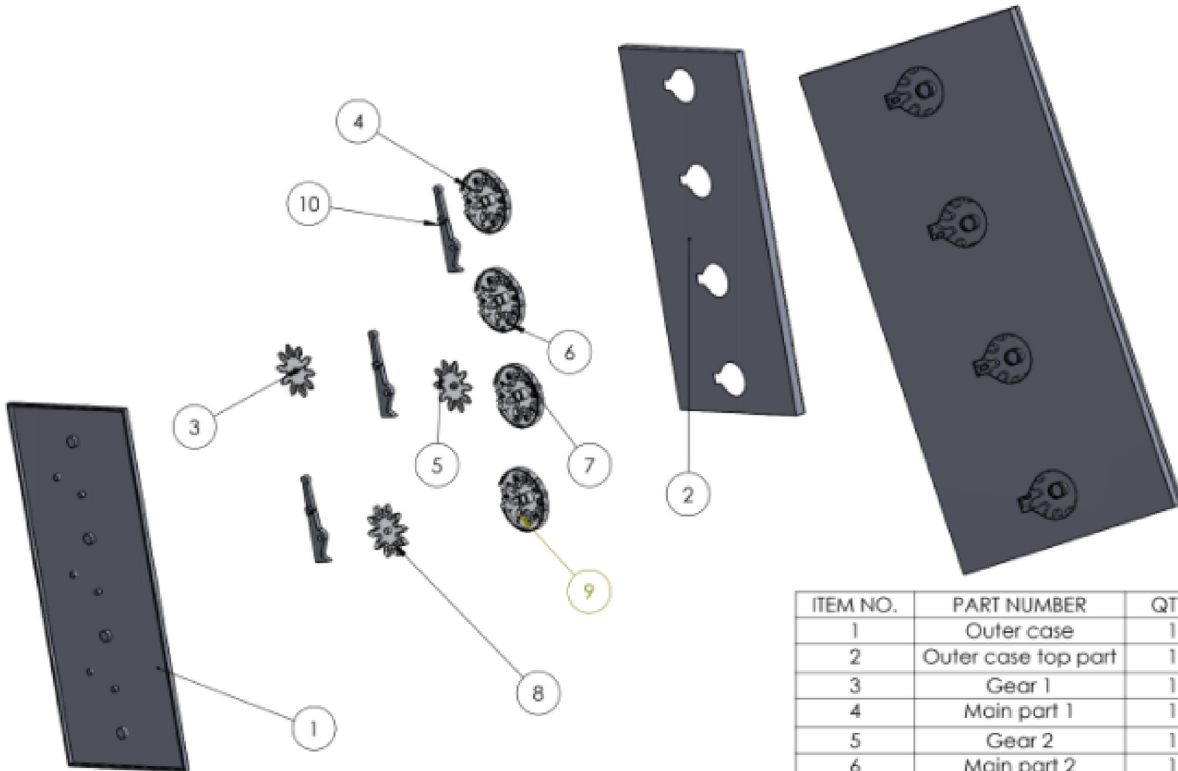


Figure 25: MDF board 3 setup in .dxf file

Appendix B: annotated G-code from MasterCAM (Solidworks files, MasterCAM files, G-code files, STL files uploaded to D2L) *(Solid works: made by: Maichel & Zaid)*

The annotated G-code for MasterCAM is already present in the .NC files submitted with the report. The reason it's not here is because Google docs has repeatedly crashed trying to insert 3500+ lines. The annotations are simply pointing out the beginning of each operation or when a new part is just starting to be machined. Also note that the annotations are written in () and not // like in lecture, simply because that specific syntax is what the ncviewer accepted.



ITEM NO.	PART NUMBER	QTY.
1	Outer case	1
2	Outer case top part	1
3	Gear 1	1
4	Main part 1	1
5	Gear 2	1
6	Main part 2	1
7	Main part 3	1
8	Gear 3	1
9	Main part 4	1
10	Lever	3

GROUP 4	SECTION 1	A	1:2.8	INCHES	ASSEMBLY DRAWING

Figure 26: Assembly-Exploded View Drawings and BOM

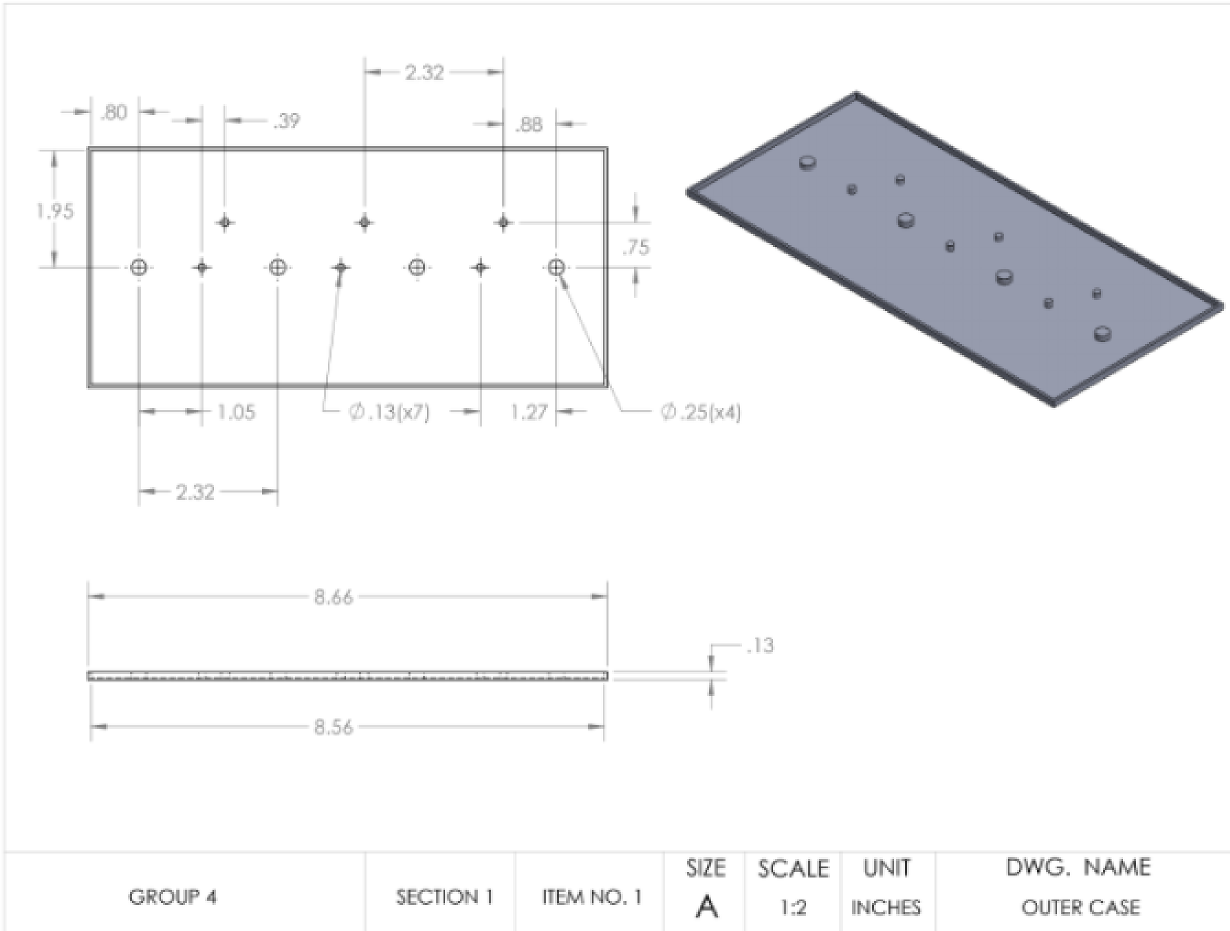


Figure 27: Outer Case Drawing

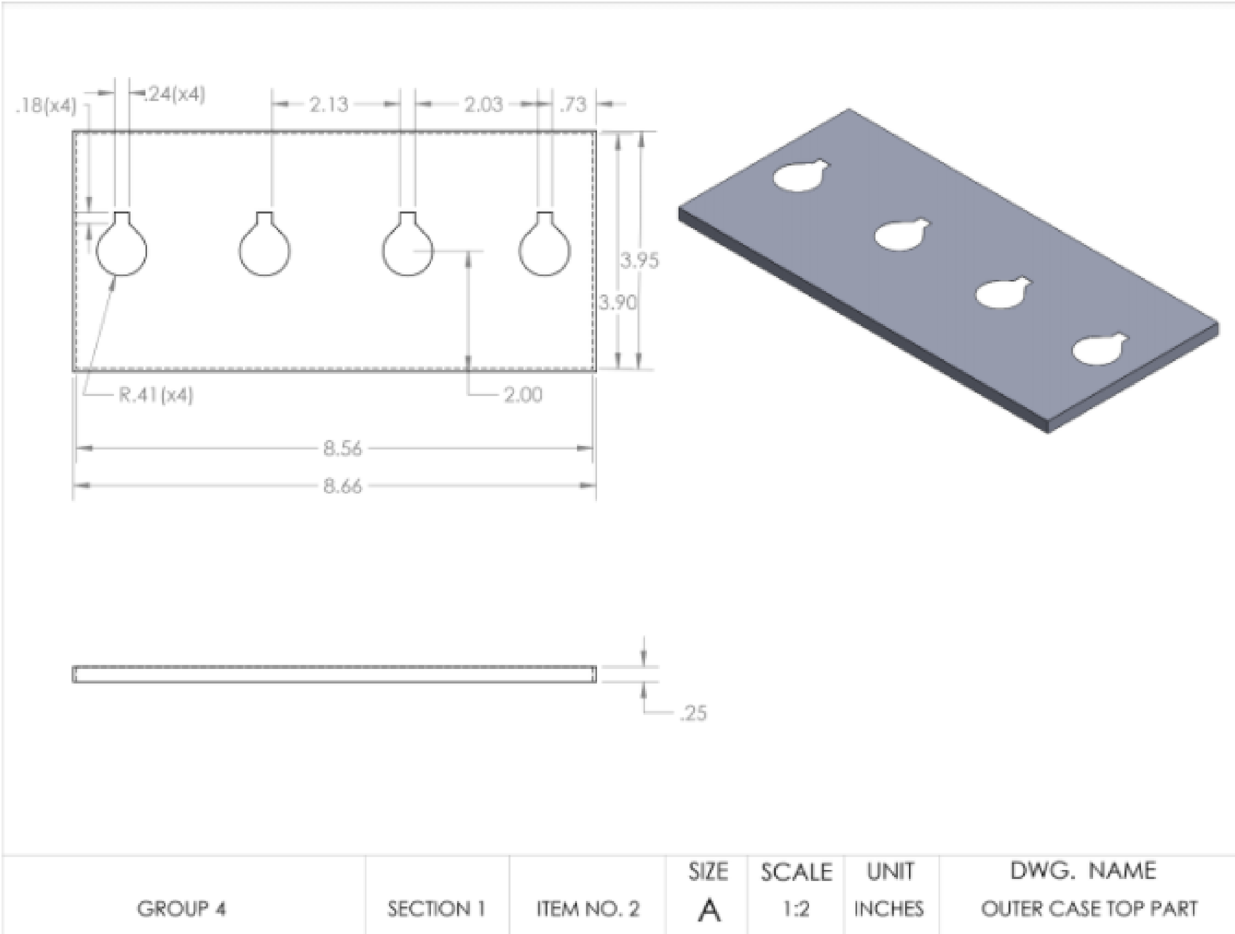


Figure 28: Outer Case Top Part Drawing

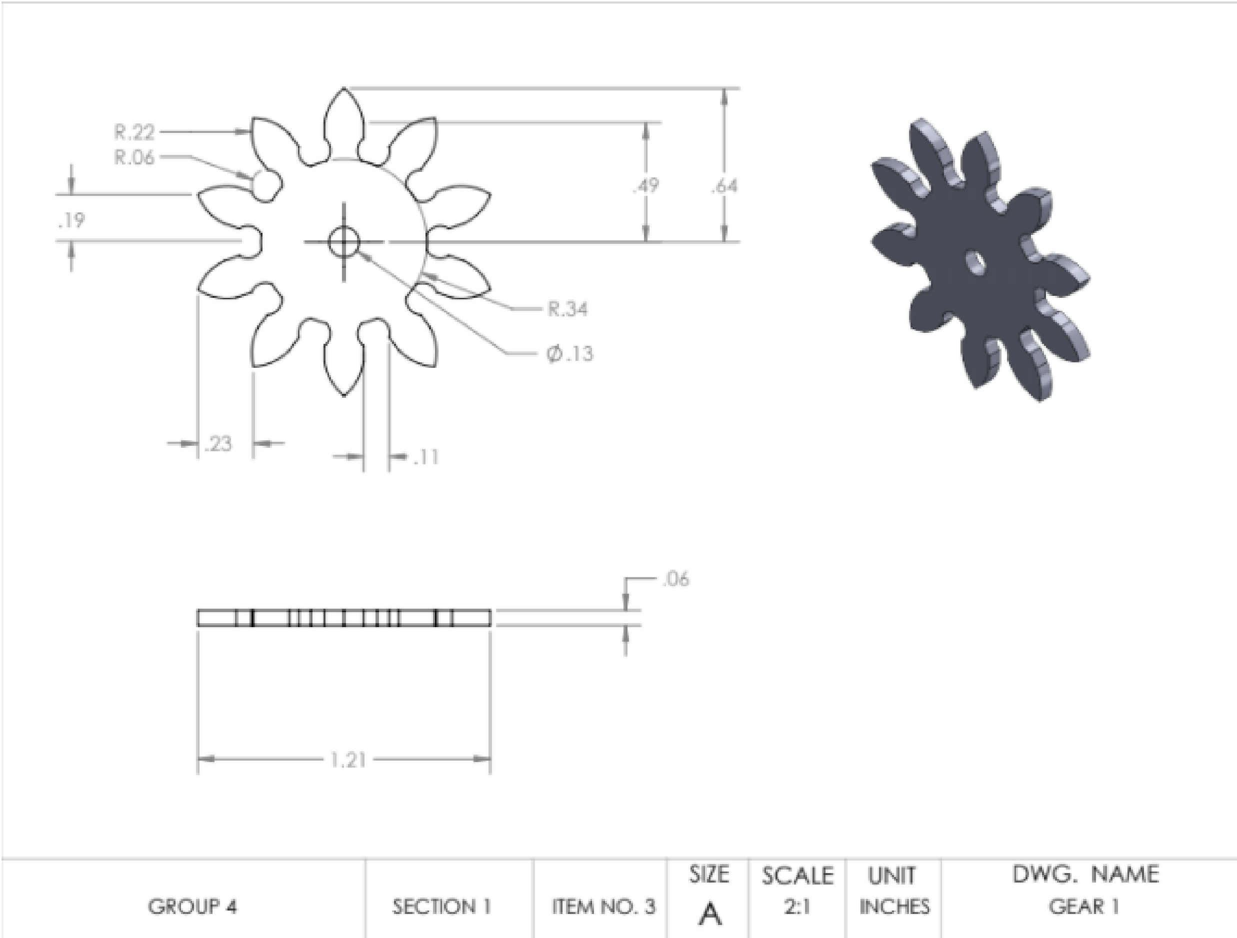


Figure 29: Gear 1 Drawing

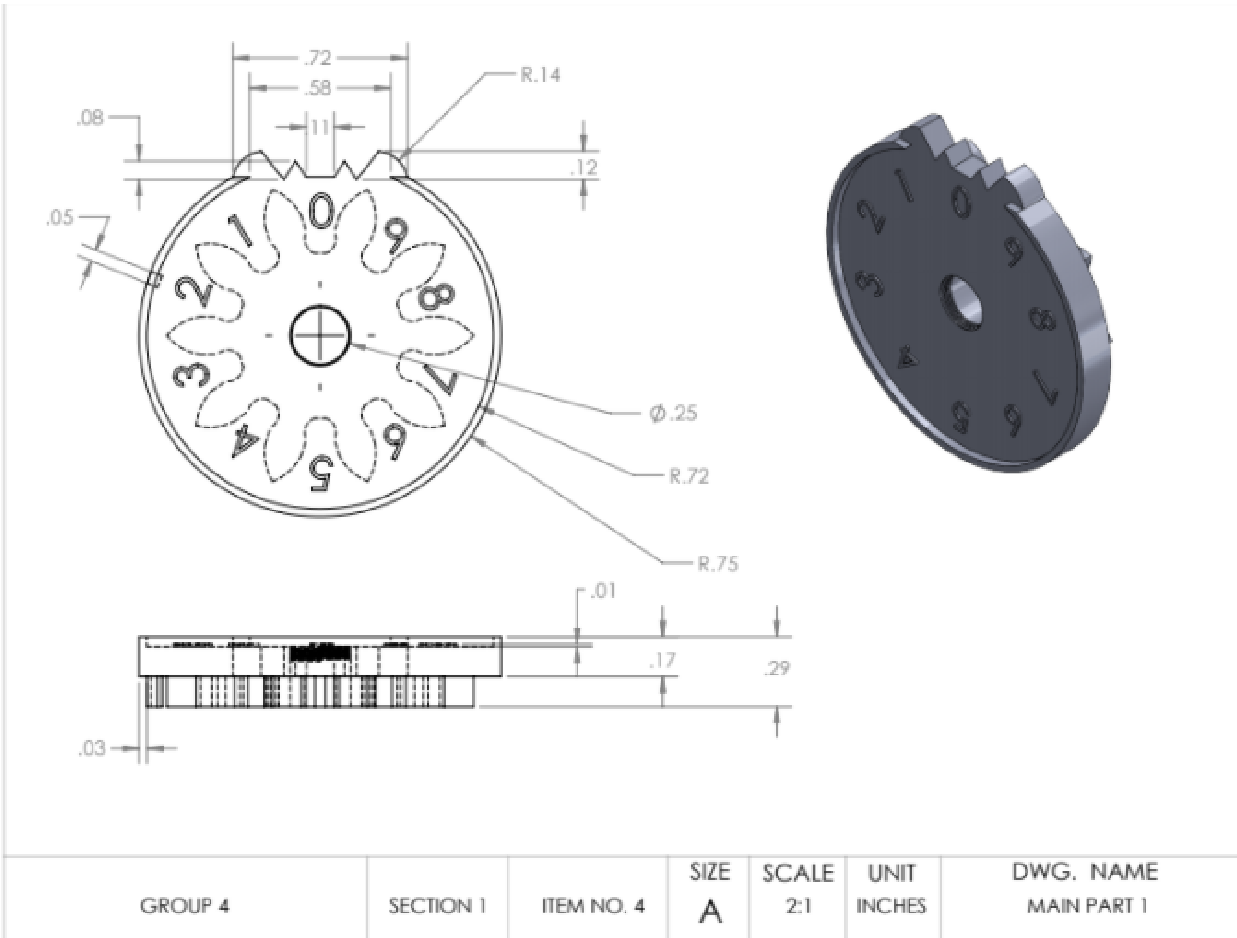


Figure 30: Main Part 1 Drawing

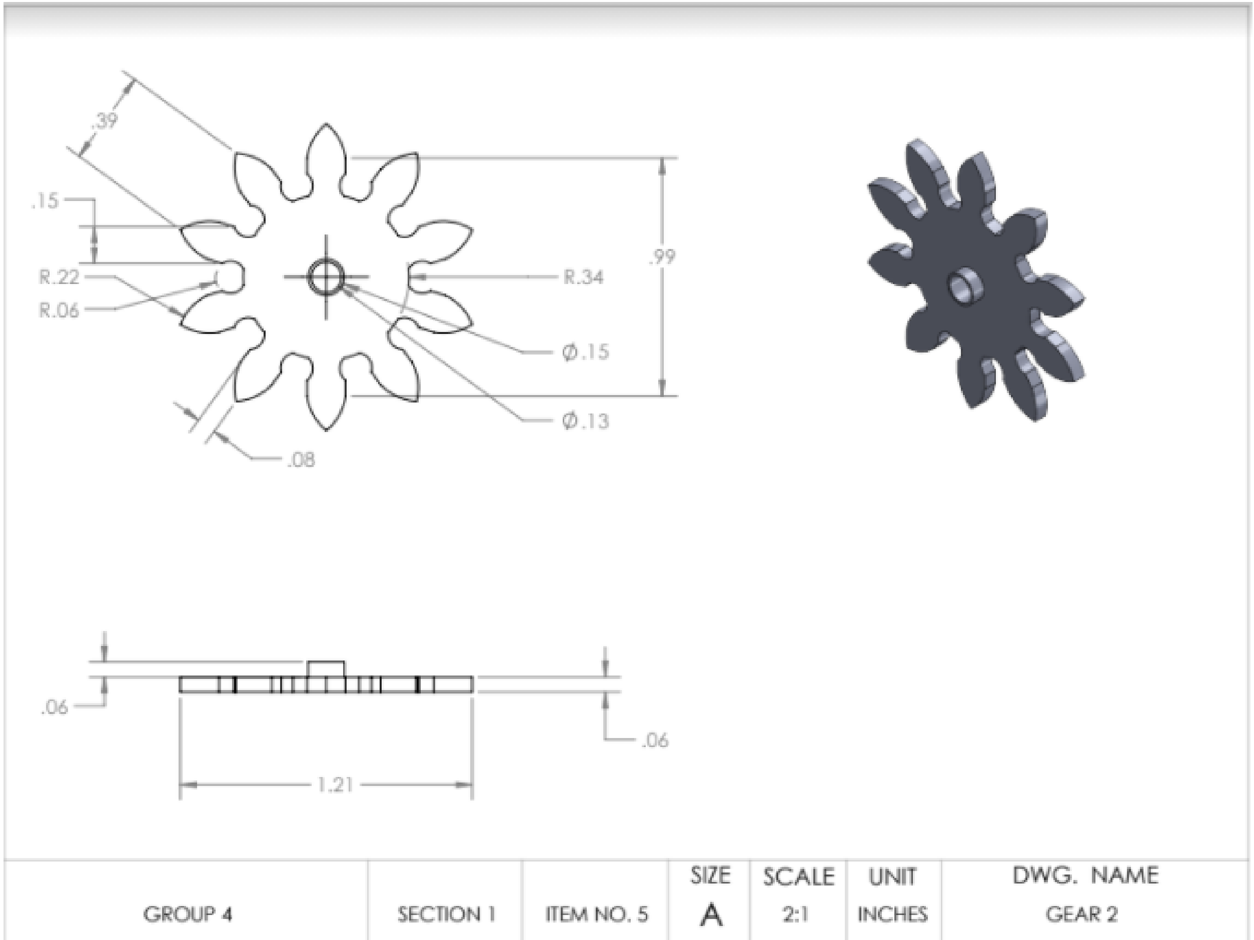


Figure 31: Gear 2 Drawing

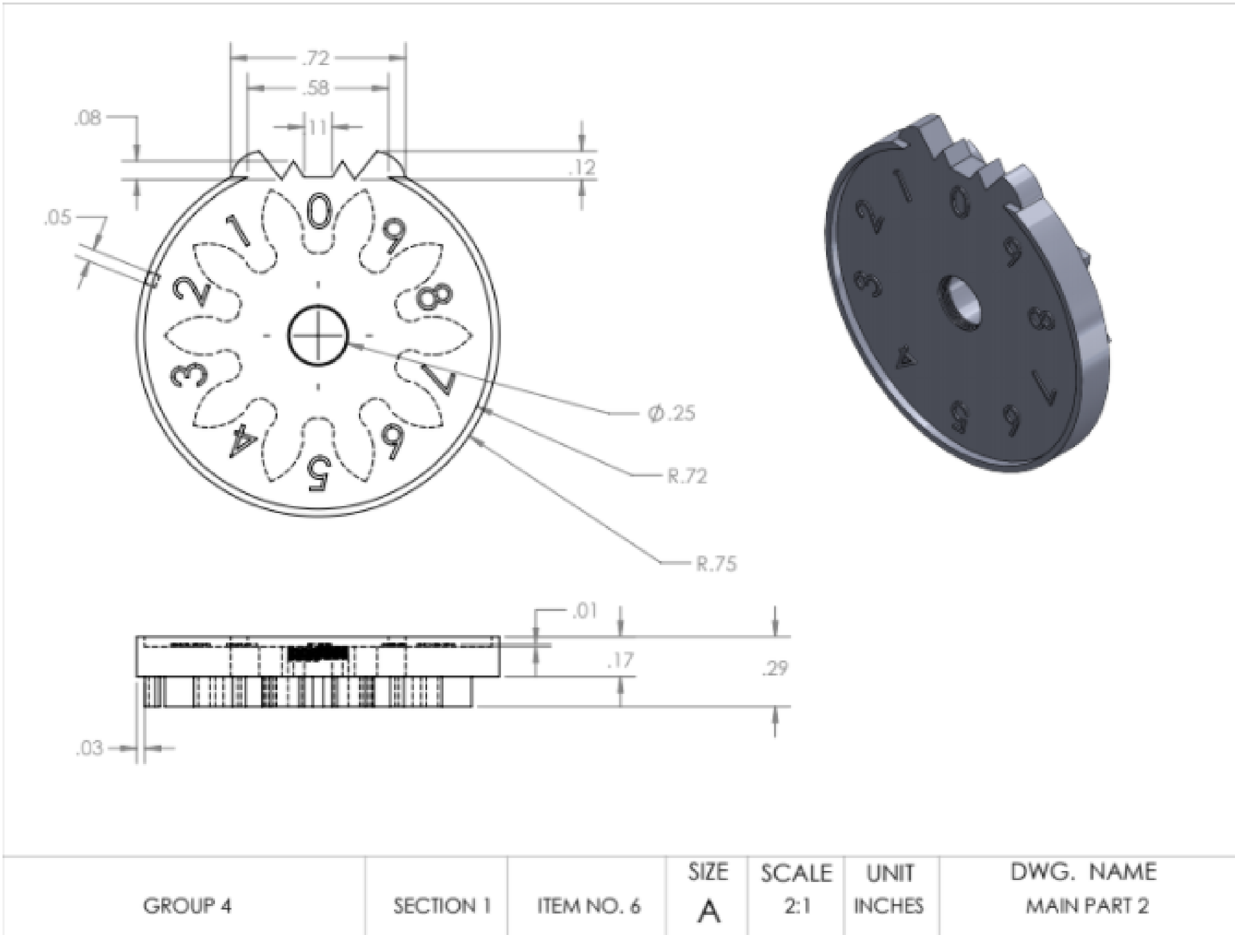


Figure 32: Main Part 2 Drawing

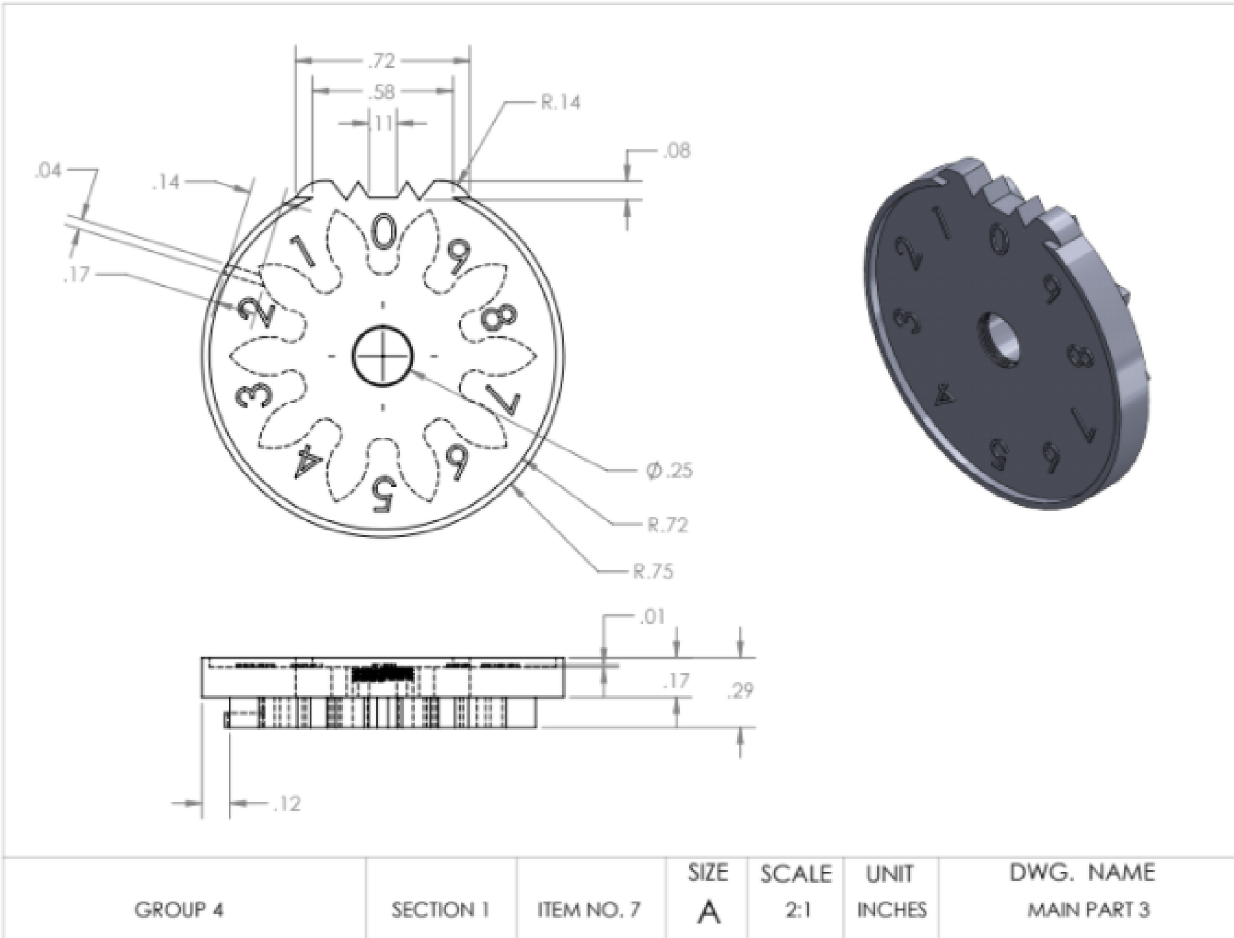


Figure 33: Main Part 3 Drawing

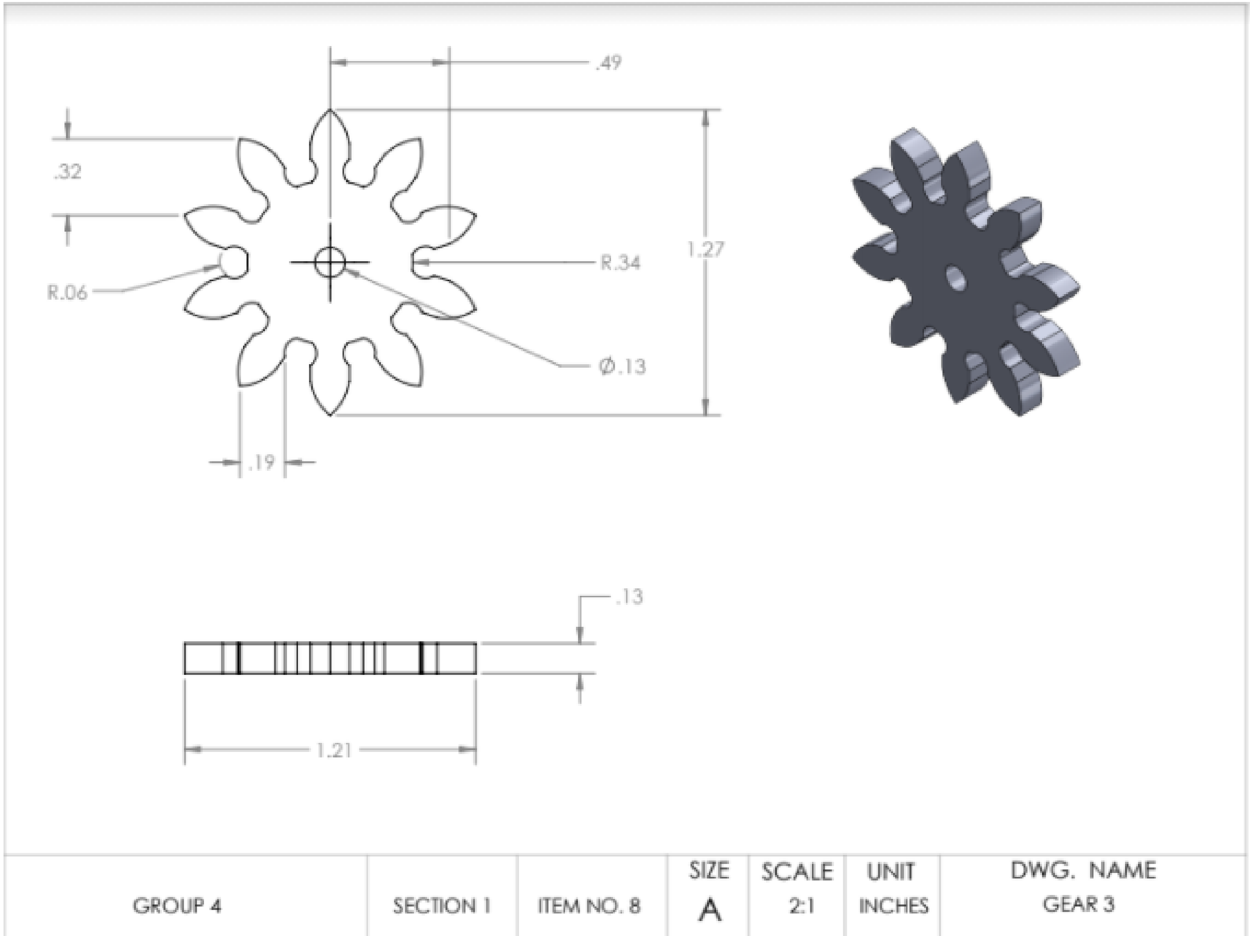


Figure 34: Gear 3 Drawing

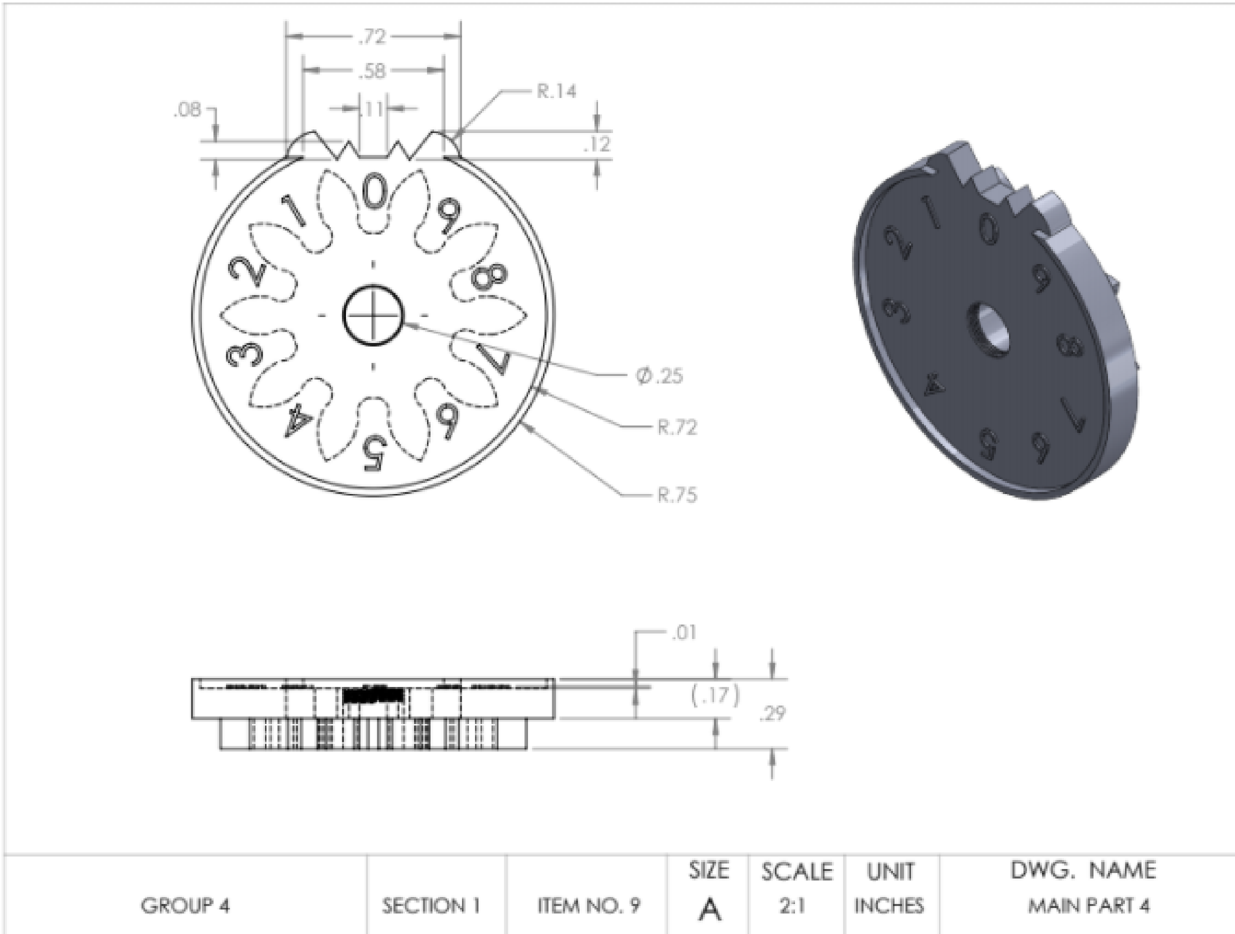


Figure 35: Main Part 4 Drawing

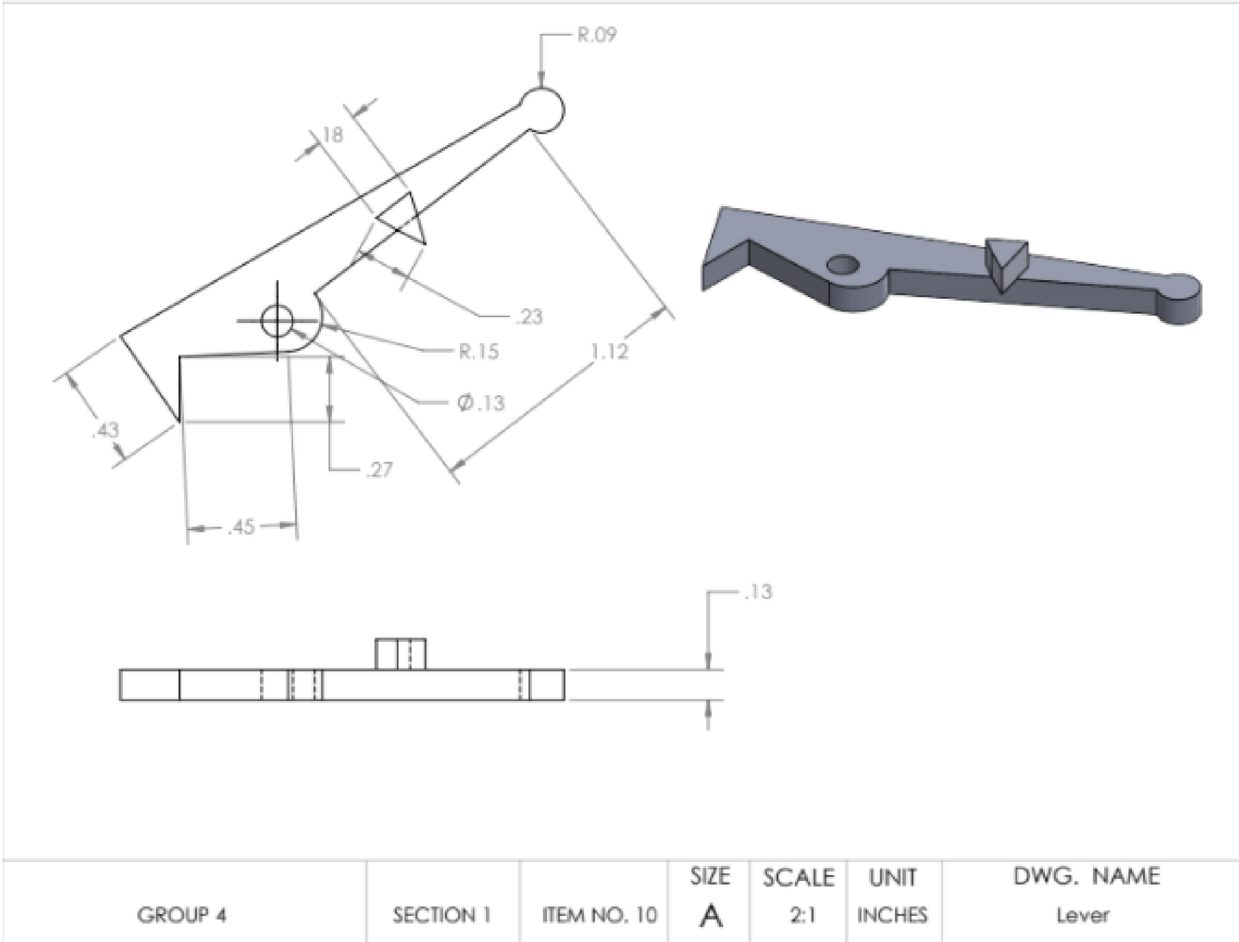


Figure 36: Lever Drawing