Design Project

Mech 323 Machine Design (Winter 2020)

Group Number	**301**

Phase Number	**# 4**

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Mark	

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1.0 Introduction

The following document is the final phase of the MECH 323 design project. It involved the development of a housing structure and finalizing dimensions for shafts, gears and other parts of the system. These final dimensions ensure that there will be no failures when attempting to print the gearbox. Also, minor changes were made to the shafts to ensure sound operation. These changes include the addition of a D-Profile to the input and output shafts (used to secure timing pulleys) and splines to mate with the inner race of each gear. Lastly, bushings were selected to fit the newly designed shafts and to support the given loading. Once these changes were made the overall system was assembled. It is shown below in Figure 1.

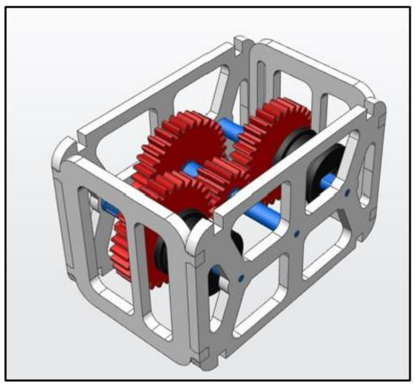


Figure 1: Assembled CAD gearbox view including housing.

2. 0 Gearbox Design

2. 1 Gear Ratio Development and Design

The gearbox was designed to achieve the best results for both a top speed event and a hill climb event, with a primary focus on the hill climb event. The speed event requires maximum angular velocity of the output shaft while the hill climb requires maximum output torque and small angular velocity. Due to the opposing requirements of the events, a two-stage sliding gear box design was selected. The second stage design adds complexity to the design and increases the overall manufacturing time, but it’s added benefit in comparison to a single stage gearbox is that it allows a gear ratio larger than 3:1 to be achieved within the constrained dimensions of the gearbox. Furthermore, the second stage sliding gearbox with three shafts allows the gearbox to easily be re-arranged to achieve diverse gear ratios, depending on the event. A single stage sliding gearbox can also achieve different gear ratios, but with only two shafts the ratios obtainable are limited to be inversely proportional and smaller than a 3:1.

A primary focus was put on the hill climb event because with a second stage sliding gearbox design, two gear sets will always be involved in the transmission of torque. As a result, these gears were designed to have an optimal performance in the hill climb set-up because the tangential loading in this event will be greater due to the torque manipulation across the first pinion and gear. Reviewing the vehicles power and torque requirements in conjunction with the power and torque motor curve provided, a gear ratio of 4.27 was chosen for the hill climb event which results in a motor torque of 1.91 Nm. Any gear ratio lower would have resulted in a torque above the warning line, causing the outputs to be unpredictable as the motor would be operating too close to the stall torque.

Due to gearbox design constraints, the focus on achieving hill climb performance caused the second and third gears to be overdesigned for the top speed event. Regardless, the shaft angular velocity could be maximized with gear ratios of either 1 or 1.1. Therefore, the simpler gear ratio of 1 was selected for the speed event which allowed some of the hill climb gears to be re-used for the speed event, saving both design and printing time. This ratio resulted in an operation torque of 1.25 Nm.

To avoid energy loss in the transmission of torque between gears, spur gears where used for all gears in the gearbox since the transmission direction was strictly perpendicular to the axis of rotation. A total of five gears were used for the design, all possessing pressure angles of 20 degrees and a module of 1.5 mm. There are three larger 48 mm pitch-diameter gears, and two smaller 22.5 mm pitch-diameter gears. The larger gears have face widths of 10 mm and the smaller gears varied with face widths of 11 mm and 15 mm, depending on the situation. The 11 mm face width was used to prevent rubbing of non-active gears when the system is set for hill-climb, and the 15 mm face width was designed to increase the strength of the second pinion gear (which was initially failing by AGMA standards). The inner race of all gears depends on their respective shafts and are designed to have an interference fit with the mating splines. A schematic of the gearbox can be seen in Figure 2, where the 1C, 2C, 3C and 4C represent the gearbox configuration used for the hill climb event and the 1S, 2S and 3S represent the configuration for the speed event.

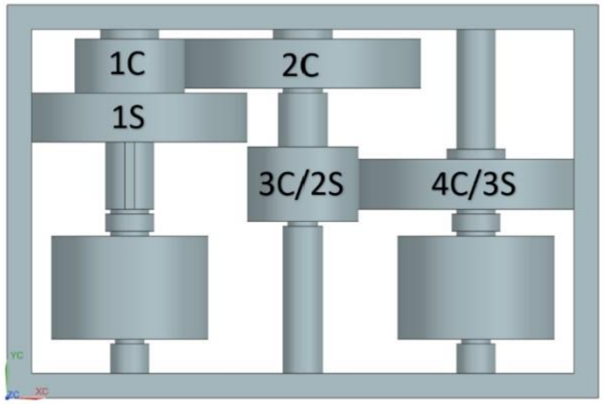


Figure 2: Overhead view of the final pitch diameters chosen and the gear placement.

2.2 Shaft Design

The shaft design revolved around constraints identified both by the group and within the project handouts. The largest issue the group experienced was trying to fit a timing pulley and two sliding gears along a 70 mm shaft while still considering the eventual assembly. A 2D sketch was drafted on paper which helped to visualize the placement of each of the components, and to determine whether it was possible. From here, an array of shaft diameters (8,10 and 12) in millimeters were used to create constraining shoulders and splines with a transitional fit were used to hold the gears in place. It is likely that after printing some sanding will be performed to ensure the gears fit and slide as desired.

In this last phase, a D-profile was also added to the ends of both the input and output shafts to secure the pulleys. To prevent stress concentrations stemming from the addition of this feature, a lofted surface was used to blend this cut-out into the adjacent circular diameter. Also, after deciding upon ¼" bearings to support the shafts, minor adjustments were required. The end diameters were decreased from 5 mm to 1/8" to ensure a secure fit with the inner bearing diameters. The shaft safety factor calculations were re-evaluated to validate this change and each of the ends still acquired safety factors above 2. The design of the middle shaft below in Figure 3 displays how the splines and shoulders will be used to secure gears.

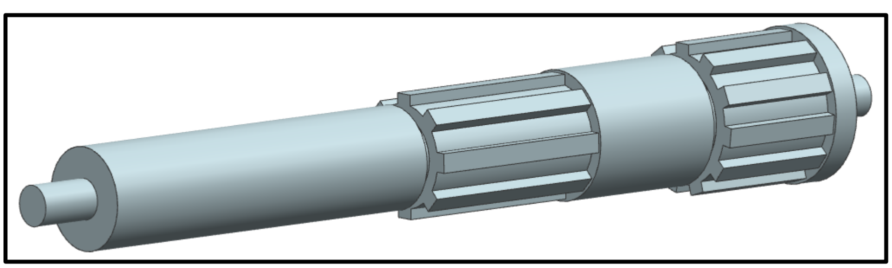


Figure 3: The final middle shaft highlighting the use of shoulders and splines to secure gears.

2.3 Housing Design

The housing of the support shafts and gears was designed to ensure that every constraint within the project handout was met. The purpose of the housing is first to restrain the shaft and gears during operation, but also to act as a chassis, holding together the front and rear of the electric vehicle. The cross-sectional dimensions were 80X80mm which was required specifically to accommodate the locking-pin mechanism and the length was 120.5 mm. This was determined by the center-to-center distances of the shafts and the required 25 mm distance between the input/output shaft and their adjacent wall.

Since a two-stage gearbox design was chosen, this complicated the design of the side walls of the housing. Like with the shaft design, a sketch was first produced on paper to have some sort of guide to base the 3D model off. From here, a solid wall was created with the initial 3 bearing holes (to support the shafts) and slowly material was cut until producing the desired volume of material, ensuring a print-time of under 9 hours and minimizing costs. The front and rear walls were similar in process but had their own unique constrains. Since the input and output shafts a hold gears with a diameter of 48 mm but are only placed 25 mm from their closest wall, there are evident spacing issues. To mitigate the problem, cut-outs were made on the front and rear walls to allow the gears to 'spin-through' at the required locations. Furthermore, 15 mm wide holes were also created to allow for the timing belts to pass through at their respective locations. To secure the four walls together, dovetail joints were used. When the structure is assembled alone, it is constrained in two directions due to these joints. However, once it is placed within the electric vehicle, the locking pins add the final constraint and the gearbox is secure in all directions.

As a group, it was decided to neglect the design of a floor or ceiling for the housing. It was deemed unnecessary since each of the components are already well constrained and anything more would be excessive. Also, it leaves a clear access point for straightforward shifting of the gears between events.

Overall, the gearbox design is complex, but is designed for strength and maximum performance in the hill-climb event. After developing a momentum-update model able to predict the exact outcome of any gear ratio, the team knew we should take advantage of our situation and strive for quality. If presented to a consumer, the assembly would appear daunting, but this is a false speculation. While designing each of the components this was considered and alleviated with a slide on approach of all parts. The process will be described in the following section. Figure 4 below shows how cutouts were used to reduce print time on the side housing of the gearbox.

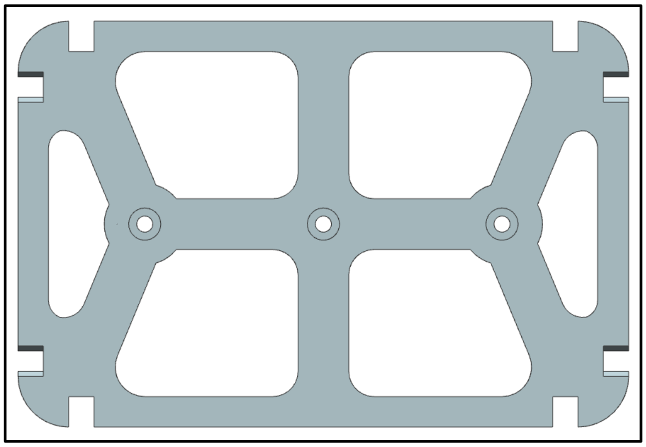


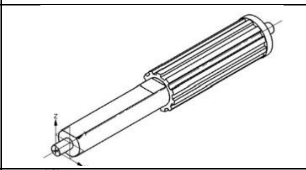
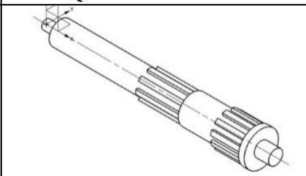
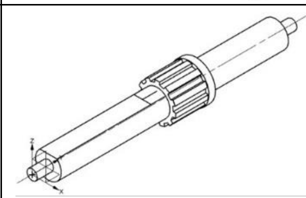
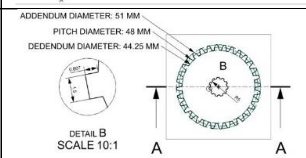
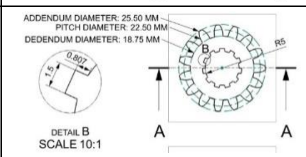
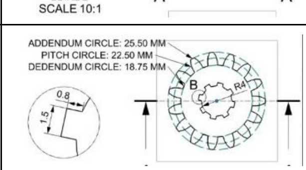
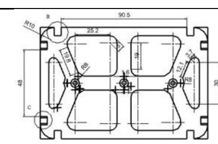
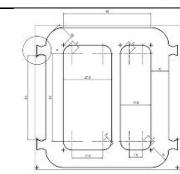
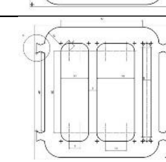
Figure 4: Final sidewall of the gearbox housing. Cutouts were made to ensure strength, cost and manufacturability.

3.0 Technical Specifications

3.1 Part List

Table 1 shown on the following page displays the manufacturing parts list for the gearbox design. For additional drawing details, refer to the complete drawing package in Appendix A.

Table 1: Gearbox part list.

Part #	Quantity	Name	Description	Drawing
1	1	Input Shaft	Holds and transfers torque to/from the timing sprocket, 48.0mm pitch diameter and 22.5mm pitch diameter, 11mm face width gears	
2	1	Middle Shaft	Holds and transfers torque to/from the 48.0mm pitch diameter gear and 22.5mm pitch diameter, 15mm face width gear.	
3	1	Output Shaft	Holds and transfers torque to/from the timing sprocket and 48.0mm pitch diameter gear	
4	3	Gear, 48.0mm Pitch	Transmits torque to from the input, middle and output shafts	
5	1	Gear, 22.5mm Pitch, 11mm Face Width	Transmits torque from the input shaft to the middle shaft	
6	1	Gear, 22.5mm Pitch, 15mm Face Width	Transmits the torque from the middle shaft to the output shaft	
7	2	Side Housing	Houses bushings for the three shafts and provides structural support	
8	1	Front Housing	Prevents gear box from disassembling and provides added structural support	
9	1	End Housing	Prevents gear box from disassembling and provides added structural support	
10	6	¼" Bearing	Support shafts and facilitate the desired angular motion.	N/A

3.2 Assembly and Reconfiguration

The gearbox was designed for a straightforward assembly and an easily adjustable gear configuration between events. The required tools to achieve this include some rough and fine grit sandpaper for obtaining final part dimensions and a rubber mallet for any interference fits.

After manufacturing is complete the parts must be submerged in water to allow the soluble supports to dissolve. Once each of the part dimensions have been finalized, the following procedure outlined below can be used to assemble and reconfigure the gearbox between events. Gears and pulleys will always be slid onto the shafts from the small diameter side first.

3.2.1 Assembly

1. On the input shaft, first slide on the 22.5 mm pitch diameter pinion with a face width of 11 mm, followed by one of the 48 mm pitch diameter gears. Ensure that the splines align and apply some force due to the transitional mating fit.
2. On the middle shaft, slide on the 48 mm pitch diameter gear followed by the 22.5 mm pitch diameter gear with a 15 mm face width.
3. On the output shaft, slide on the 48.0 mm pitch diameter.
4. Slide the timing sprockets onto the D-profile ends of the input and output shafts
5. Thread the timing chains through the end housings and connect them to the timing sprockets on the input and output shafts
6. Insert the 6 bushings into the cut outs on the side housing (3 per side).
7. Insert the ends of the 3 shafts into the side housing and attach the front and rear walls using the dovetail joints.

3.2.2 Configuration Adjustment

A. To set up the gearbox for the hill climb event, slide the 22.5 mm pitch diameter, 11 mm face width gear on the input shaft so that it is in contact with the 48.0 mm pitch diameter gear on the middle shaft. At the same time position the 48 mm pitch diameter gear on the input shaft such that it is against the smaller pinion gear. This will prevent the inactive gear from obstructing any motion of the system.

B. To set up the gearbox for the speed event, slide the 48.0 mm pitch diameter gear on the input shaft so that it is in contact with the 22.5 mm pitch diameter, 15 mm face width gear on the middle shaft. Again, slide the inactive gear on the input shaft (pinion gear for hill-climb) with the larger gear such that it does not block any motion.

3.3 Gearbox

Table 2 displays the gearbox specifications. The values seen below have been calculated assuming a lifetime of 5 straight years and that the gear box is made from AISI 4130 steel.

Table 2: Summary of gearbox design technical specifications.

Gearbox Technical Specification	Value	Unit
Gearbox Type	2-Stage Sliding Spur Gear	-
Gearbox Design Lifetime	43,800	Hours
Design Output Torque for Motor	1.91	Nm
Safety Factor – Gear, 48.0mm Pitch	2.06	-
Safety Factor – Gear, 22.5mm Pitch, 11mm Face Width	3.15	-
Safety Factor – Gear, 22.5mm Pitch, 15mm Face Width	4.36	-
Input Shaft Lowest Safety Factor	7.70	-
Middle Shaft Lowest Safety Factor	1.61	-
Output Shaft Lowest Safety Factor	2.51	-
Gearbox Footprint (Length x Width x Height)	120.5 x 80 x 80	mm
Print Time	7:36	Hours

3.4 Manufacturing (CatalystEX)

As shown below in Figure 5, using the standard orientation for 3D printing and soluble supports, the gearbox print time was approximated by CatalystEx [1] to 7:36 hours. Soluble supports were selected because complex parts can easily be internally support and they result in the best surface finish after removal. Even though the dissolving times are long, the process can be sped up with the addition of temperature and agitation. The total model and support material used is 9.03 in^3 and 2.99 in^3.

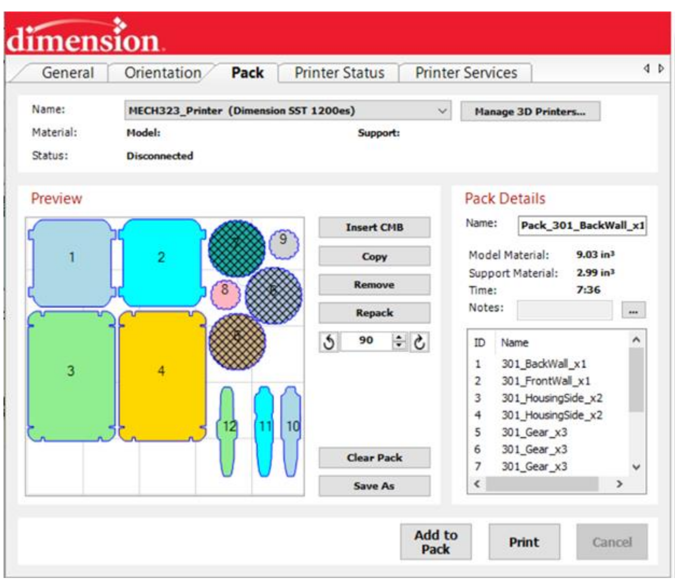


Figure 5: 3D print time, pack orientation and material used estimates with CatalystEx.

4.0 Future Work Recommendations

Prior to manufacturing, additional modeling should be performed using the anisotropic properties of the 3D plastic material. All past design calculations have been using AISI 4130 steel properties which have very different characteristics and performances compared to 3D plastic. Most notably is the strength, which means that the failure torque for the 3D plastic will be lower than the steel. In order to accommodate for this discrepancy, the shaft diameters were increased by a safety factor of 10 – 20% [2]. This design adjustment ensures that the gearbox will operate safely throughout both events, but is not precise. Any excess increase in shaft diameter increases the risk of a gear rim failure and the overall manufacturing time.

Structural analysis should be completed on the housing design since this will account for more than 50% of the total gearbox print time [3]. Therefore, an analysis to maximize the cut-outs available and minimize the housing thickness would ensure sufficient strength for the events but reduce part volume and thus print time. Additionally, part orientation should be optimized prior to printing because factors such as nozzle changes, nozzle path, required support material and excessive acceleration and deceleration due to an overly complex print path will increase the print time. Gearbox performance is strongly related to printing quality and tolerances, so reducing printing time will allow more time in the manufacturing process for quality assessment and control.

Provided with a larger project budget, the bushings should be replaced with ball bearings. Bushings are a lining that act to reduce friction and are designed to wear and fail such that the housing or shaft does not wear or experience damage. For the scope of this competition wear of the bushings is not relevant but over an extended period of operation, the loss of material results in tolerances, reduced strength and torque transmission and lower gearbox efficiencies. Ball bearings still work to protect the shaft and housing in the same way and do experience wear, but they achieve substantially less friction resulting in better performance and longer operating lifetimes. Ball bearings achieve this friction reduction through the rolling of the balls between the inner and outer rings. The balls in the bearing are manufactured to have a much lower surface roughness and friction coefficient than the shaft and housing. This allows bearings to support loads perpendicular to the centroid much better than bushings.

If the design specifications and scope of the project ever changed, it would be recommended to further consider the manufacturing material used and explore the ability to adjust the shaft locations within the gearbox between events. The 3D print material and method has varying tolerances and strengths which means the design requires an added safety factor and additional time sanding the parts to correct dimensions. In comparison, cast iron is a very common material used to manufacture gears due to its strength and tolerances but it's substantially heavier which is not suitable for this application. Therefore, a material such as aluminum is lighter than cast iron, transmits torque better than 3D plastic and is very easily machined with high precision. Additionally, the design specifications constrain the input and output shafts to a set distance from the walls of the housing. Therefore, in a first or second stage sliding gearbox the achievable ratios are still limited because the sum of the gear diameters, regardless of the configuration, must remain constant. If there was an allowable variance with the input and output shaft location, there would be more flexibility in ratios achievable.

5.0 Conclusion

A sliding two-stage gearbox design was the chosen final design. A gearing ratio of 1 will be used for the speed event and a gearing ratio of 4.27 for the hill climb event. This design was chosen as the sliding allows for a variety of gearing ratios (including those above a 3:1) and permits optimization for each event individually. The team is content with the final design developed and are dispirited that it will never be seen competing against other solutions.

References

[1] D. I. Y. Kim, "MECH323_Project - Phase_4_CatalystEX_Tutorial," Queen's University, 2020. [Online]. Available: https://onq.queensu.ca/d2l/le/content/382355/viewContent/2217177/View. [Accessed 4 April 2020].

[2] D. I. Y. Kim, "MECH323_Project - Phase_4_Instructions_2020_REVISED," Queen's University, 2020. [Online]. Available: https://onq.queensu.ca/d2l/le/content/382355/viewContent/2260422/View. [Accessed 2 April 2020].

[3] D. I. Y. Kim, *MECH323_Lecture_Slides_2020,* Queen's University, 2020.

Appendix A - Drawing Package

Exploded View

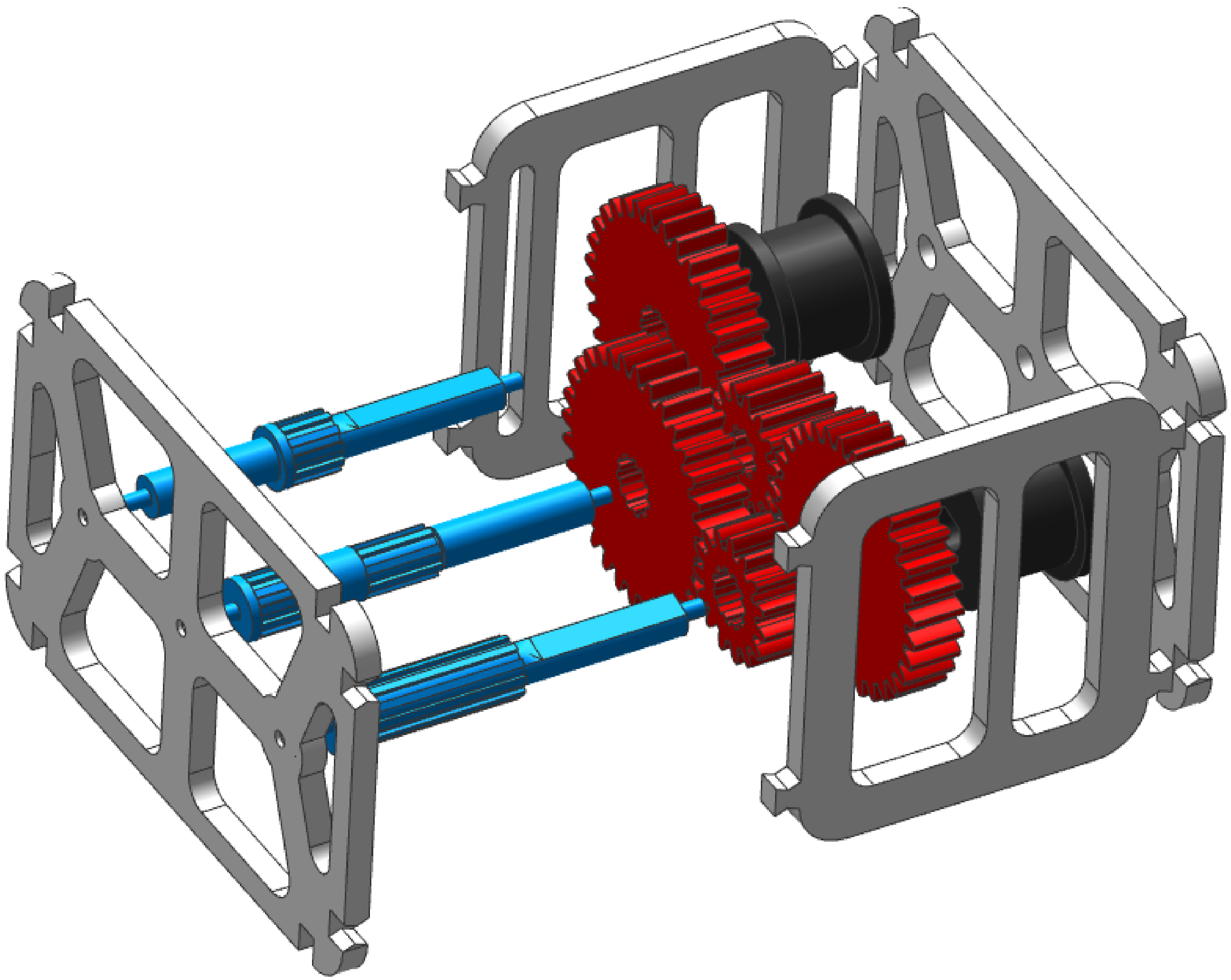


Figure 6: Exploded CAD view of complete gear box.

Input Shaft

Quantity: 1

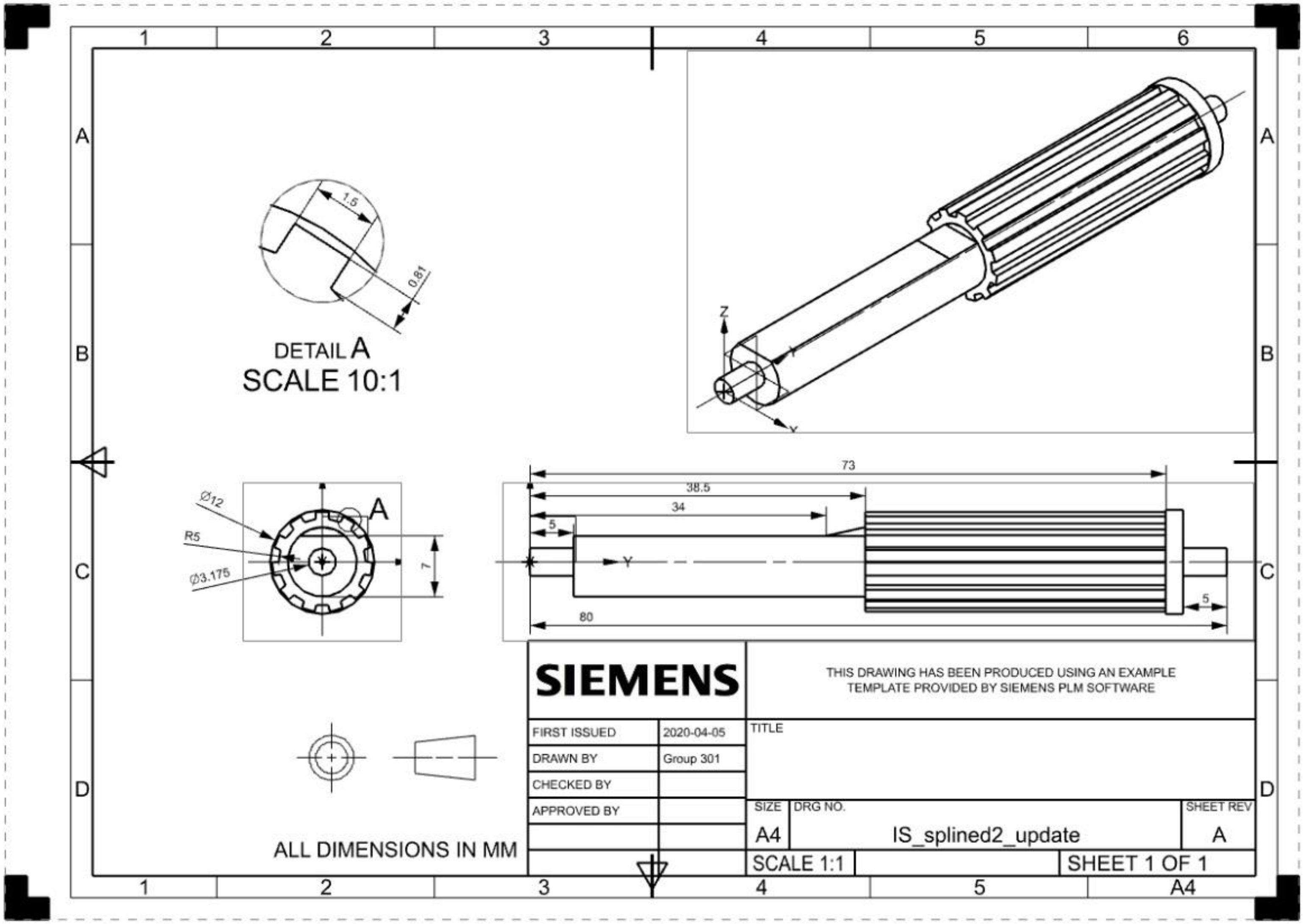


Figure 7: Detailed drawing of the Input shaft.

Middle Shaft

Quantity: 1

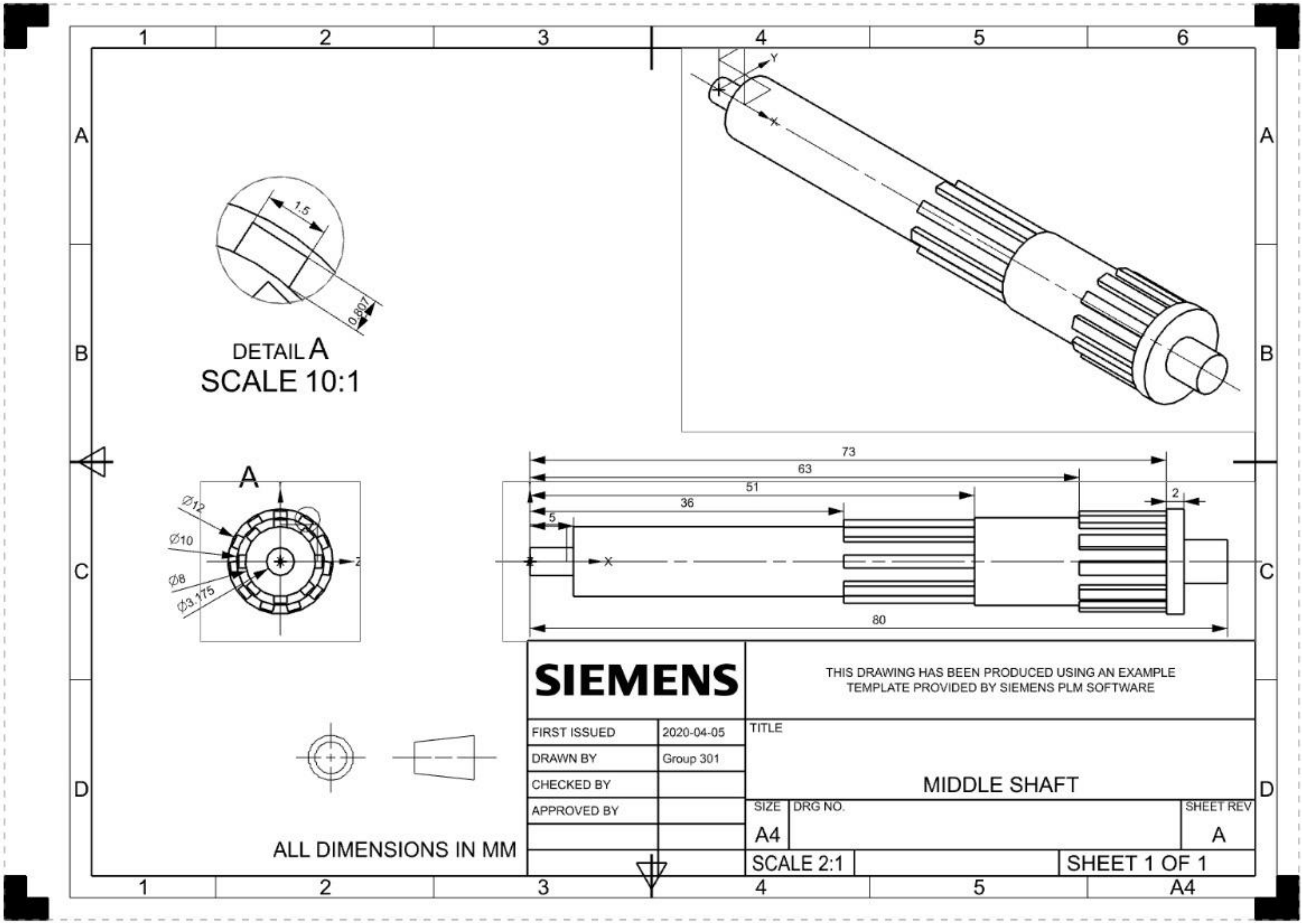


Figure 8: Detailed drawing of the middle shaft.

Output Shaft

Quantity: 1

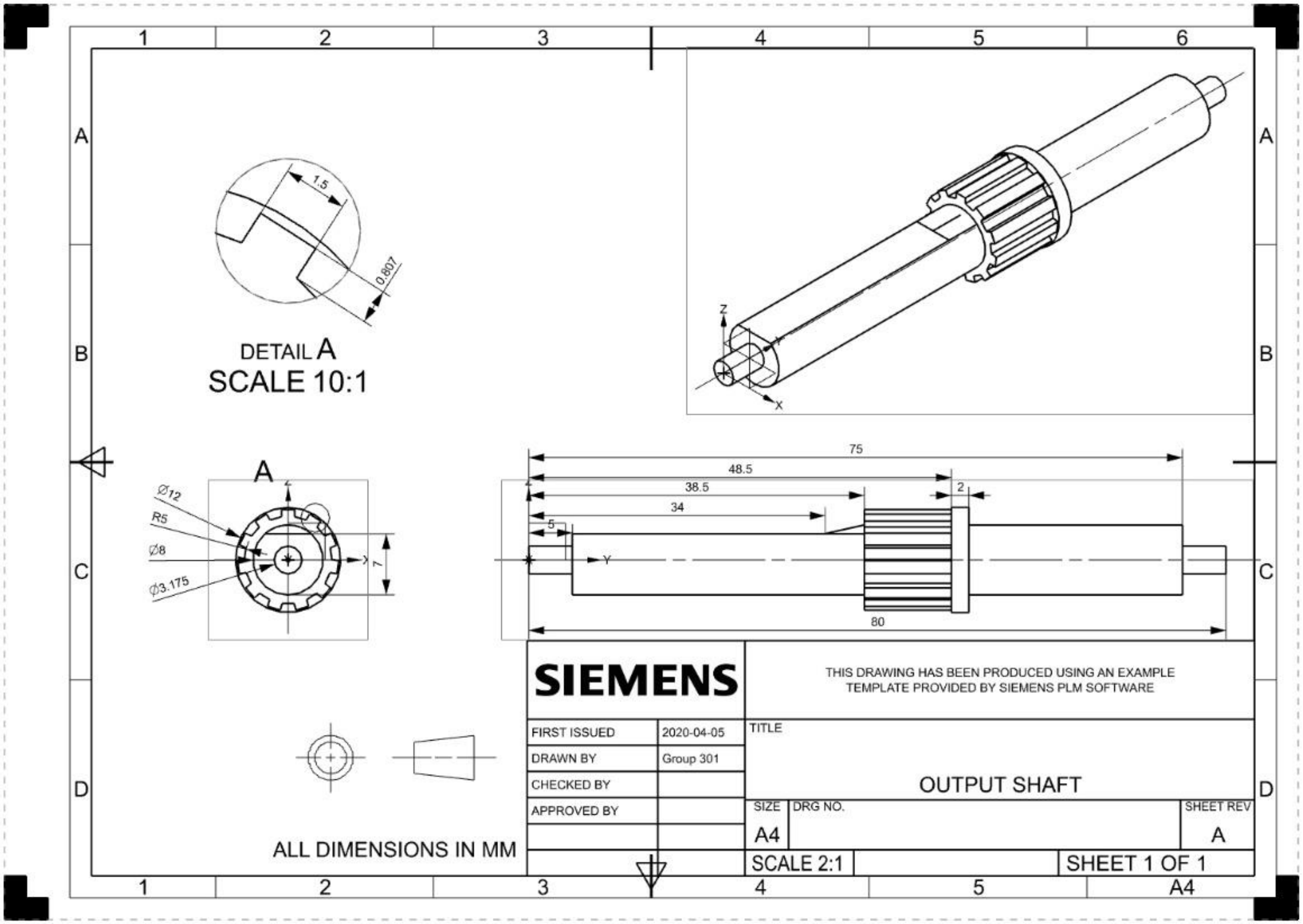


Figure 9: Detailed drawing of the output shaft.

Gear, 48 mm Pitch Diameter

Quantity: 3

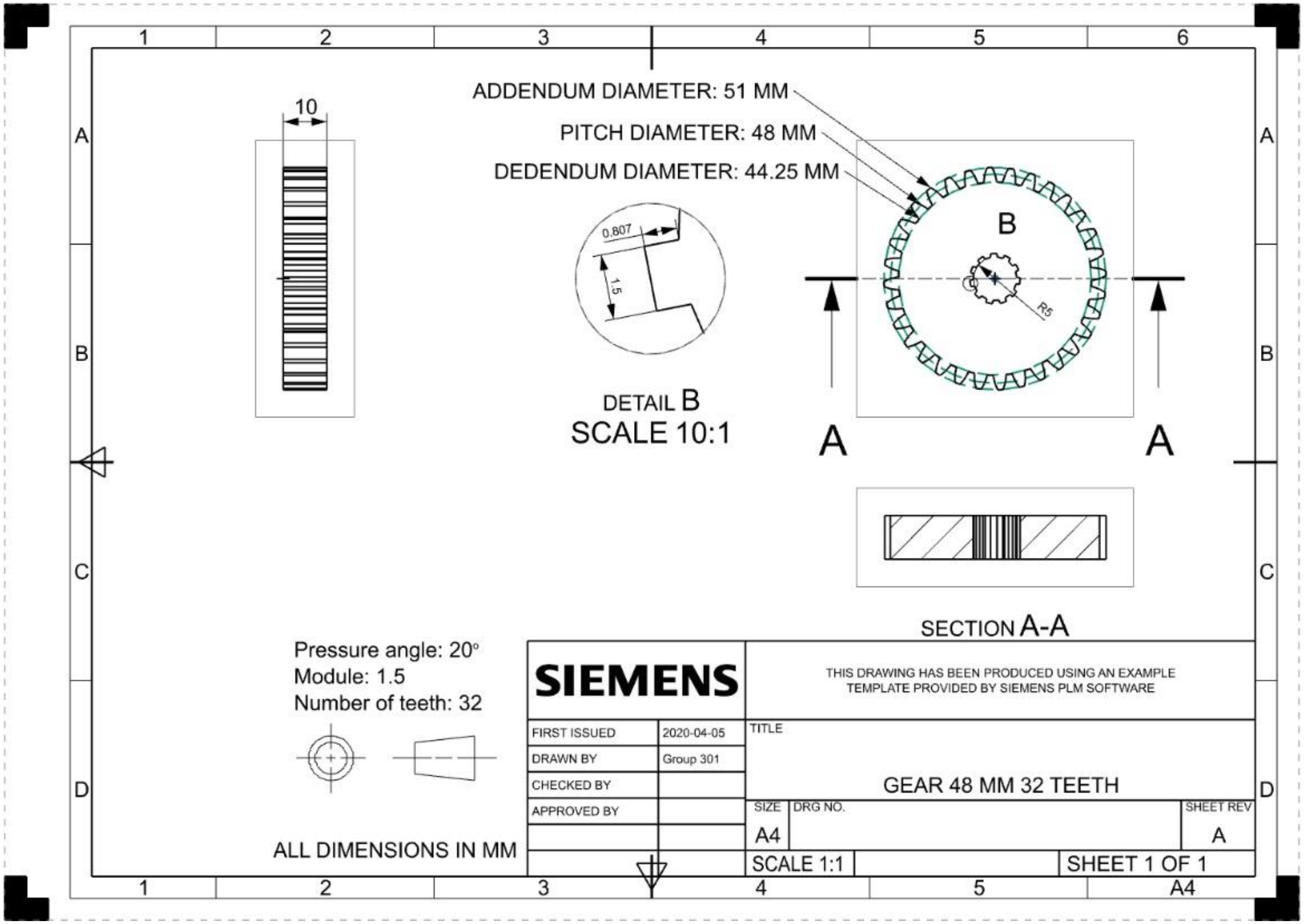


Figure 10: Detailed drawing of the 48.0 mm pitch diameter gear.

Gear, 22.50 mm Pitch Diameter, 11 mm Face Width

Quantity: 1

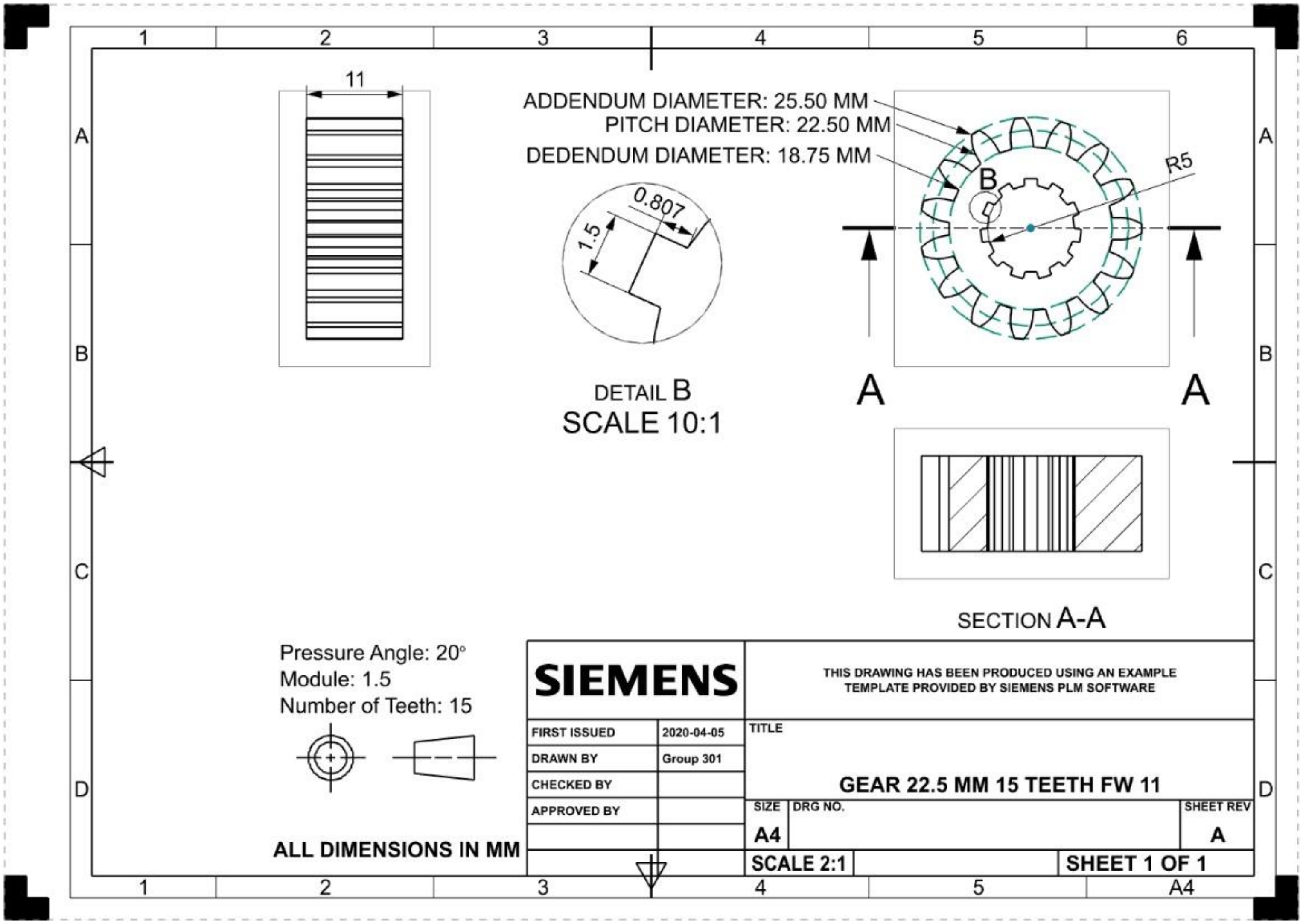


Figure 11: Detailed drawing of the 22.5 mm pitch diameter, 11 mm face width gear.

Gear, 22.50 mm Pitch Diameter, 15 mm Face Width

Quantity: 1

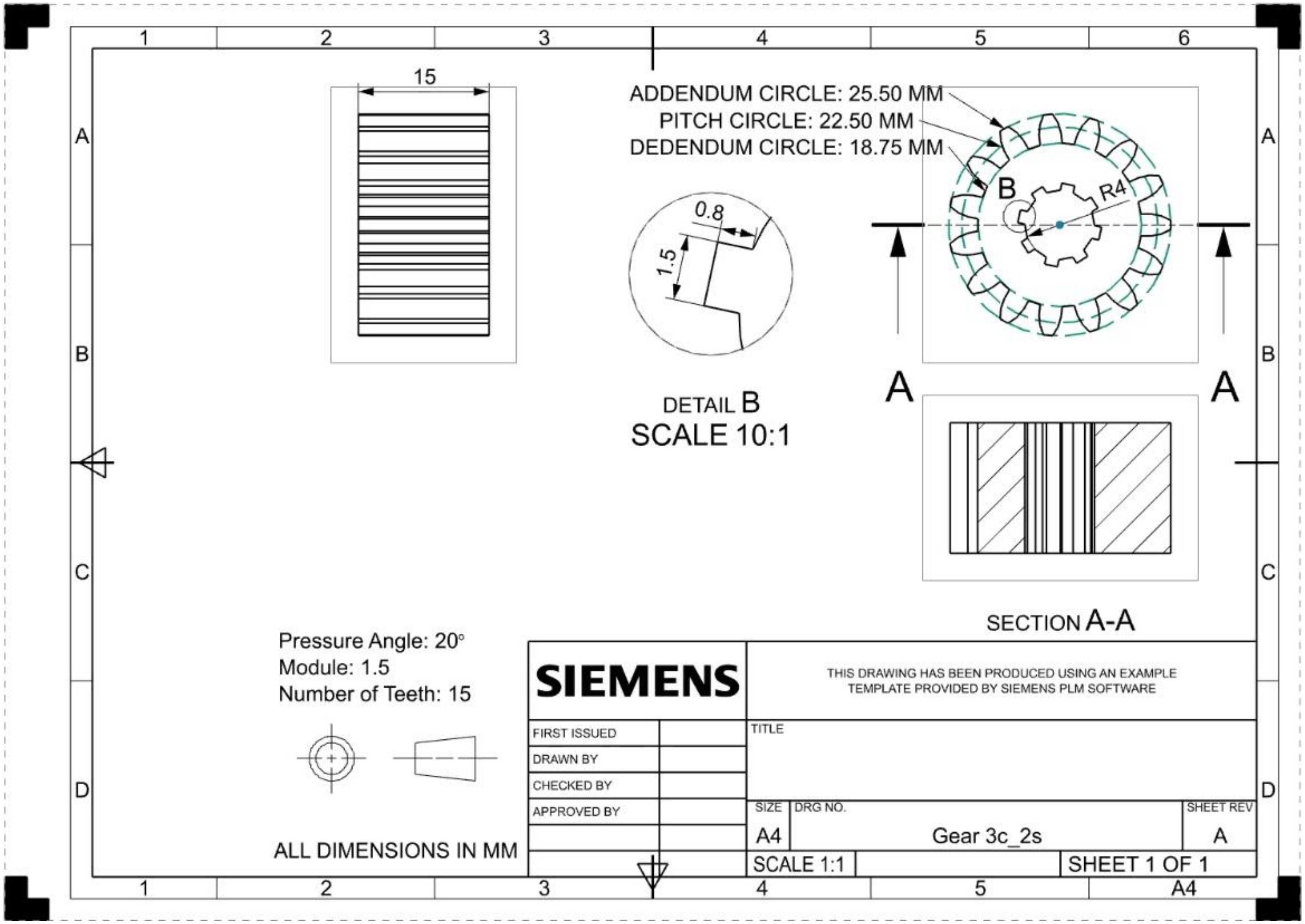


Figure 12: Detailed drawing of the 22.5 mm pitch diameter, 15 mm face width gear.

Front Housing Wall

Quantity: 1

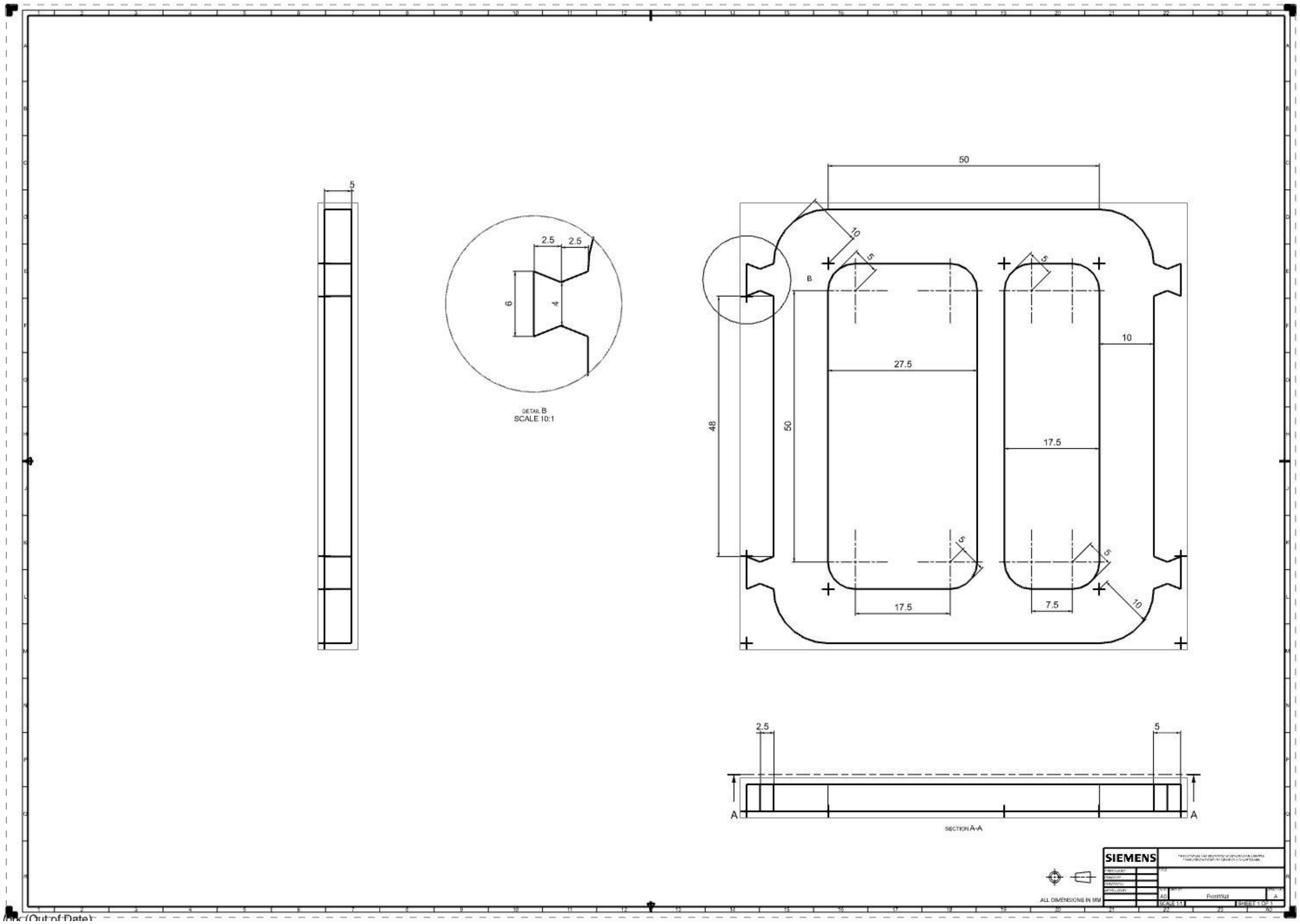


Figure 13: Detailed drawing of the gearbox front housing wall.

Back Housing Wall

Quantity: 1

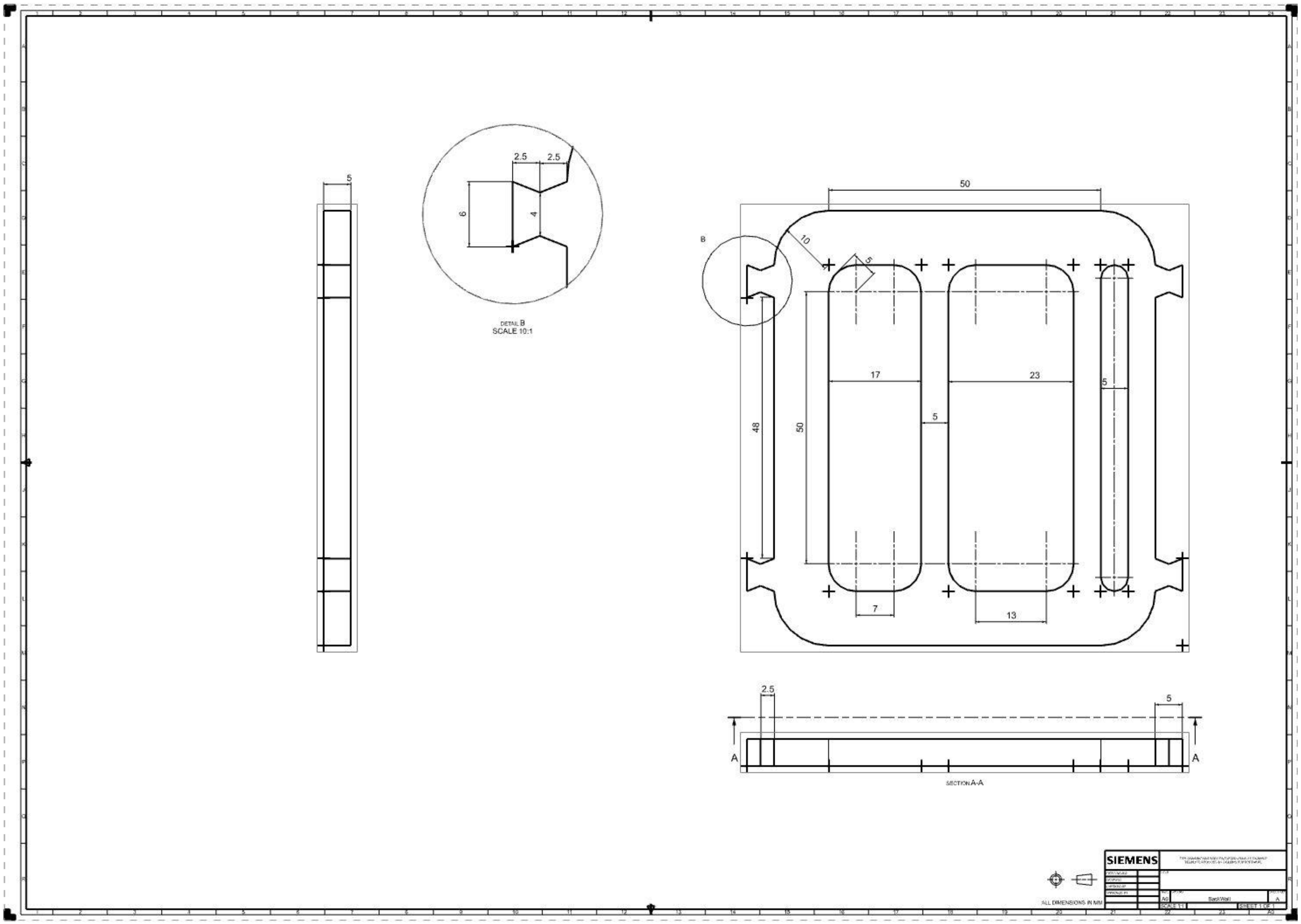


Figure 14: Detailed drawing of the gearbox back housing wall.

Side Housing Wall

Quantity: 2

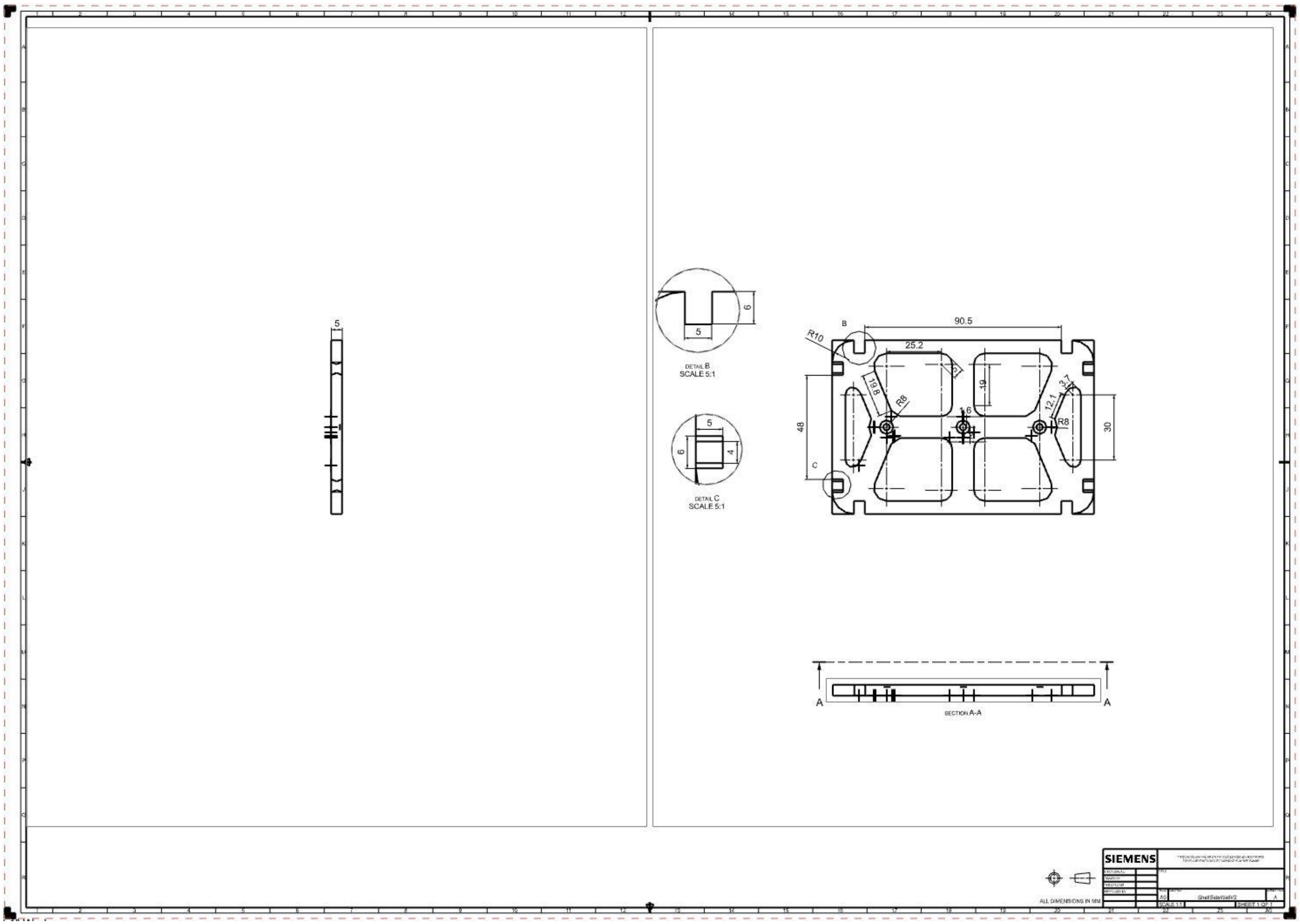


Figure 15: Detailed drawing of the gearbox side housing wall.

Appendix B – Order Form

McMaster-Carr Order Form

Group Number	301

McMaster-Carr Part Number	ID (shaft diameter)	OD (outer diameter)	Length	Price/Unit	Quantity
2868T31	1/8 in	1/4 in	1/8 in	0.53	6
			Total Price:	**3.18$ (USD)**	

Phase 4
Summary Page

(Attach to the end of your Phase 4 Report on a separate page)

Group Number	**301**

Phase Number	**4**

Global Design Characteristics		
Gear Box Parameters	**Number of Stages**	2
	Speed Gear Ratio	1
	Hill Climb Gear Ratio	4.27
Vehicle Weights	**Number of Weights Added**	2

Predicted Event Performance		
Speed Event	**4m Time (s)**	6.1
	Top Speed (m/s)	0.643
	Motor Operating Torque (Nm)	1.25
	Motor Operating Speed (rpm)	97.5
Hill Climb Event	**Distance (m)**	7.84