Project Report

Course: MECH 351 – Thermodynamics II
Section: HI-X
Group: 15

Thermoelectric Generator Challenge Project

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Executive Summary

The project is aimed to design and construct a small-scale electric vehicle powered by a thermoelectric generator (TEG) that converts thermal energy into electricity to propel a DC motor. Utilizing the Seebeck effect, the system operated a Peltier module to generate electrical energy from a temperature gradient maintained by a tea light as the heat source and ice as the cooling agent.

The mechanical design incorporated lightweight 3D-printed components, a gear system to enhance torque, and LEGO mechanical parts for ease of assembly and functionality. Testing involved assessing the performance of individual components and the fully assembled vehicle on flat surfaces and inclined ramps. Results highlighted challenges in optimizing energy transfer, maintaining a temperature gradient, and mitigating mechanical inefficiencies.

The system's overall thermodynamic efficiency was calculated at 0.004%, with mechanical efficiency at 1.62%, and the TEG's thermodynamic efficiency at 0.3%. These results reflect significant energy losses due to thermal and mechanical inefficiencies, limitations inherent in small-scale thermoelectric systems, and the modest thermal gradient achieved.

Despite its limitations, the project successfully demonstrated motion and provided practical insights into thermodynamic principles, emphasizing the importance of efficient thermal management and mechanical optimization for future iterations.

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Objectives

The main objective of the project is to design and construct a small electric vehicle powered by a thermoelectric generator (TEG) that converts thermal energy into electricity to drive a DC motor, allowing the vehicle to travel on flat ground and ascend an inclined ramp. Additionally, the project aims to analyze and document the vehicle's design, testing its thermodynamic efficiency and mechanical performance.

Introduction

The small-scale electric vehicle will be powered by a TEG, specifically a Peltier module, which harnesses thermal energy to produce electricity. This energy will then drive a DC motor to propel the vehicle across a flat surface and up an inclined ramp. By evaluating the thermal efficiency of the system and documenting the design process, the project aims to bridge theoretical thermodynamic concepts with practical mechanical applications.

Thermodynamically speaking, a TEG operates based on the Seebeck effect, which occurs in devices where a temperature difference across materials leads to the movement of electrons, thereby generating an electric current. In fact, the Seebeck effect is a thermoelectric phenomenon where a voltage is generated between two different conductors or semiconductors when a temperature difference exists across them.

In practice, as it can be seen in Figure 1, TEGs consist of multiple thermocouples connected in series or parallel to maximize voltage output. Each thermocouple has two junctions: the "hot" junction, exposed to the heat source, and the "cold" junction, exposed to a cooler environment. When a temperature gradient is applied, a voltage develops across each thermocouple, and by stacking multiple thermocouples in a module, the device amplifies the generated voltage to a usable level for electrical systems, such as powering an electric DC motor.

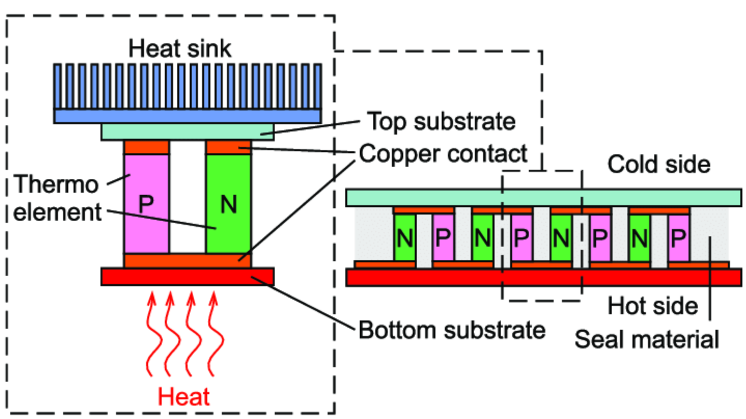

Figure 1: Principle Scheme of a Thermoelectric Generator [1]

In the mechanical setup of this electric vehicle, a gear system will be employed to increase torque output from the DC motor, enhancing its ability to move the vehicle, particularly when ascending the incline. In essence, the gear ratio is determined by the relationship between the driven gear, which is attached to the wheels, and the driving gear connected to the motor. When the driven gear has more teeth than the driving gear, creating a gear ratio greater than 1:1, the speed at which the wheels rotate is proportionally reduced, but the torque delivered to the wheels increases by the same factor. This setup allows the vehicle to trade some of the motor's rotational speed (RPM) for enhanced torque, which is essential for overcoming friction and providing sufficient force to move the vehicle forward and then upwards.

For instance, a gear ratio of 5:1 means that the motor needs to rotate five times to achieve a single rotation of the wheel gear. While this reduces the vehicle's speed, it effectively quintuples the torque at the wheels. This increase in torque is vital when the vehicle encounters resistance, such as starting from a stationary position or climbing an inclined ramp, where more force is required to counteract gravitational and frictional forces.

The efficiency of this setup is governed by both thermodynamic and mechanical principles. The Carnot efficiency sets the theoretical limit for the efficiency, indicating that the efficiency will depend on the temperature differential maintained between the hot and cold sides of the TEG.

Design and Construction

Designing an electric vehicle powered by a TEG required a systematic approach to meet the project objectives. Each component was carefully selected and assembled to create an efficient system capable of exploiting heat energy for propulsion. The following sections detail the choices made for each critical part and the overall design considerations implemented to optimize thermal and mechanical performance.

Overview of System Components

The essential components of the vehicle include a TEG and a DC motor, as well as a structural frame. The Peltier device operates in Seebeck mode, generating voltage when exposed to a temperature differential, while the DC motor translates this electrical energy into motion. The TEC1-12706 Peltier device was chosen based on its compatibility with the project specifications and was obtained from Abra. This Peltier device can produce a maximum power of 72W. The DC motor selected is GA12-N20-3V30, chosen for its low-voltage operational efficiency, making it compatible with the expected voltage range generated by the TEG. Moreover, this motor was the one that provided the most torque between the options, which will help the vehicle get up the ramp.

Additionally, two LEGO gears were utilized to amplify the torque: an 8-tooth gear connected to the motor drives a 40-tooth gear attached to the rear axle, effectively transferring rotational motion to the wheels. Four 62.4 mm diameter LEGO rubber tires and wheels, along with two LEGO axles, were used to mobilize the vehicle. Employing all mechanical components from LEGO ensured compatibility and seamless integration, simplifying assembly. To ensure structural coherence, a CAD model was done to test the assembly, making sure that gears, axles, motor were all perfectly aligned.

To ensure efficient operation, the vehicle’s frame was designed to be lightweight, the chassis and the support structure, that holds the copper plate, TEG module, heat sink, and other thermal components, were 3D printed in PLA. For thermal management, a thin metal plate was placed between the tea light and the hot side of the TEG to avoid direct flame exposure, which could damage the TEG. Aluminum tape was applied to all sides of the TEG support structure to protect it from the flame. TM30 performance thermal paste was applied between the TEG and metal plate to maximize heat transfer by filling any microscopic air gaps. A heat sink was also attached to the TEG’s cold side to promote heat dissipation, helping maintain a stable temperature gradient across the TEG, although ice was the definitive choice. Figure 2 depicts the looks of the fully assembled car.

Note: All technical drawings are provided in the appendices, Figures 3 to 12.

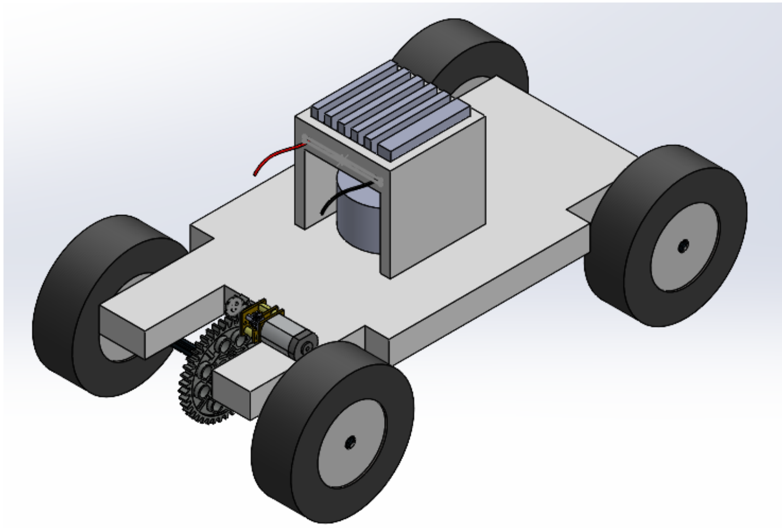

Figure 2: 3D Model of the Thermoelectric Car

Testing Procedures and Observations

After assembling the vehicle, a series of tests were conducted to evaluate the functionality of individual components and assess the vehicle's overall performance. The TEG and motor were tested independently to confirm their suitability and behavior under different conditions before assembling the final vehicle. Detailed observations from these tests are described in the sections below.

Initial Testing of Individual Components

1. **Peltier Device Testing:** The TEG was first connected to a 1.5V battery to observe its behavior in thermoelectric cooler (TEC) mode, where it showed a clear temperature difference across its surfaces. This confirmed the device's integrity and functionality. Subsequent tests involved using a hot water bath to create a temperature differential across the TEG, resulting in diverse output voltages, depending on the water temperature.

2. **Motor Testing:** Testing the motor involved connecting it to different power sources to observe its torque and speed. Around 1.2V, the motor rotated smoothly and demonstrated sufficient torque, confirming it would operate effectively within the voltage range expected from the TEG.

Assembled Vehicle Testing

With the components successfully tested, the vehicle was then assessed in its fully assembled form. Tests were conducted on flat ground as well as on an inclined ramp with a 20° slope. The vehicle's performance on each surface was recorded and analyzed. The following Table 1 presents key data values obtained during the tests.

Table 1: Testing Data Sheet

Condition #	Hot Sources	Condition	Voltage [V]	Current [mA]	Speed [cm/s]
1	Tea Light	TEG + Copper Plate	0.164	30	0
2		#1 + Heat Sink	0.300	60	0
3		#1 + Ice	1.150	165	0.526
4		#3 + Copper Plate (Cold side)	1.100	152	0.500
5		#4 + Thermal Paste (Hot Side)	1.200	150	0.595
6	Hot Bath	TEG + Copper Plate	0.090	17	0

During the testing phase, several scenarios were tested, as seen above. Voltage and current were measured using a digital multimeter. On the other side, speed was determined based on the time it would take the car to travel a sample distance of 1 metre, for example.

The ideal configuration based on the analysis made is having a tea light as a hot source, along side a copper plate on each side of the Peltier device. The cold source would be ice instead of a heat sink, because the heat sink didn’t show convincing results.

Sample Calculation for Speed

$$v = \frac{Distance}{Time} = \frac{50\ cm}{(60 + 24)\ s} = 0.595\ cm/s$$

Results

To evaluate the vehicle's performance, theoretical calculations were performed to predict its behavior, followed by a comparison with the actual data gathered during testing. This section discusses these calculations and presents an analysis of the key findings from the tests.

Theoretical Calculations and Expectations

In this sub-section, some theoretical expectations related to the performance of the thermoelectric car will be made in order to compare with actual results.

Energy Input to Tea Light

Paraffin wax, the wax used in tea lights, typically has an energy content of about 41.5 MJ/kg [2]. By weighing the tea light before and after testing, it is possible to determine the mass of wax burned during operation.

$$Mass\ Burned = 21\ g - 19.8\ g$$
$$= 1.2\ g$$
$$Mass\ Burned = 0.0012\ kg$$

Note: These masses are averages of multiple trials.

Considering the energy content of paraffin was determined earlier, the energy released by burning this amount of paraffin wax is:

$$Q_{in} = Mass\ Burned \times Energy\ Cotent$$
$$= 0.0012\ kg\ \times 42\frac{MJ}{kg}$$
$$Q_{in} = 50\ 400\ J$$

This energy is released over the burn time. The maximum burn time for this test was determined to be 15 minutes (900 seconds), the power input can be calculated as follows.

$$Power\ Input = \frac{Energy\ Input}{Burn\ Time}$$
$$= \frac{50\ 400\ J}{900\ s}$$
$$Power\ Input = 56\ W$$

This is the total thermal power generated by the tea light. However, only a fraction of this energy flows through the TEG and is converted into electrical power.

Heat Transfer Through TEG

Assuming that only a portion of the tea light's heat reaches the TEG, due to heat losses, a conservative estimate would be to assume 10 % of the total thermal energy is effectively transferred to the TEG [3].

$$Heat\ Input\ to\ TEG = 56 \times 0.1 = 5.6\ W$$

This gives an estimated 5.6 W of thermal power available to the TEG.

Maximum Climbable Height

Using this heat input of 5.6 W and assuming 4% thermoelectric efficiency for the TEG, the net electrical power output can be calculated as seen below [4], [5].

$$Electrical\ Power\ to\ Motor = 5.6\ W \times 0.04 = 0.224\ W$$

The maximum climbable height can then be calculated based on this electrical power output.

$$\begin{aligned} h_{max} &= \frac{P \cdot t}{m \cdot g} \\ &= \frac{0.224\ W \times 900\ s}{0.400\ kg\ \times 9.81 \frac{m}{s^2}} \\ h_{max} &= 51.38\ m \end{aligned}$$

where:

- h_{max} is the maximum height achievable
- P is the power available to the motor
- t is the time elapsed
- m is the mass of the vehicle
- g is gravitational acceleration (9.81 m/s^2)

So, under optimal conditions, the maximum height the vehicle could theoretically achieve with this setup would be around 51.38 meters. However, this is an idealized value assuming perfect conditions and no losses outside of the TEG's conversion efficiency. This estimation is probably far from the actual maximum height to which the car can go.

Expected Maximum Velocity

Given the specifications of the motor used and the mechanical assembly of the gears, the maximum velocity can be estimated as follows:

$$
\begin{aligned}
v_{max} &= n_{motor} \times r \times \varnothing_{tire} \\
&= (30\ rpm)\left(\frac{2\pi\ rad}{1\ rev}\right)\left(\frac{1\ min}{60\ sec}\right)\left(\frac{1}{5}\right)(0.0624\ m) \\
&= 0.0392\frac{m}{s} \\
v_{max} &= 3.92\frac{cm}{s}
\end{aligned}
$$

where:

- v_{max} is the maximum velocity of the car
- n_{motor} is the rotational speed of the motor
- r is the gear ratio used (5:1)
- $\varnothing_{tire}$ is the diameter of the tires

Thus, the expected maximum velocity on a flat surface is 3.92 m/s. Comparing with the experimental values obtained in Table 1, these values look plausible. Experimental velocity is less than the theoretical one, since no losses outside of the TEG's conversion efficiency was calculated, such as friction, power transmission, etc.

Expected Height on Ramp

Considering the inclination of the ramp and the theoretical maximum absolute height the thermoelectric car can climb; the following formula provides the expected height on an infinite ramp of the same inclination:

$$
\begin{aligned}
h_{ramp} &= \frac{h_{max}}{\sin(\theta)} \\
&= \frac{51.38\ m}{\sin(20°)} \\
h_{ramp} &= 150.23\ m
\end{aligned}
$$

Therefore, theoretically speaking, the car would definitely climb the ramp provided at the laboratory and would also travel a total distance of 150.23 m along a ramp of the same inclination, if its length would've permitted. Again, it is worth noting that this theoretical value does not account for losses other than the TEG's conversion efficiency.

Efficiency Calculations

To evaluate the vehicle's performance, three efficiencies were calculated based on actual test data.

Overall Thermodynamic Efficiency

The overall thermodynamic efficiency of the vehicle measures how effectively the system converts the heat energy from the tea light into mechanical work to advances the car. This efficiency can be calculated as follows:

$$\eta_{overall} = \frac{W_{out}}{Q_{in}}$$
$$= \frac{m \cdot g \cdot l \cdot \sin(\theta)}{Mass\ Burned \times Energy\ Cotent}$$
$$= \frac{0.400\ kg \cdot 9.81 \frac{m}{s^2} \cdot 0.9144\ m \cdot \sin(20°)}{0.0006\ kg\ \times 42 \frac{MJ}{kg} \frac{1\ 000\ 000\ J}{MJ}}$$
$$\eta_{overall} = 0.004\ \%$$

To calculate the overall thermodynamic efficiency, only the ramp part of the experiment was considered. It was assumed that this part of the experiment uses around half of the total energy input to the system by the candle. Also, the work output was determined as the potential energy given to the system, which length is three feet (0.9114 m), along a 20° incline.

The result showed a very low 0.004 % overall efficiency of the system, which will be discussed in the discussion.

Mechanical Efficiency

The mechanical efficiency of the system assesses how effectively the mechanical components, such as the motor, gears, wheels, convert the electrical energy into mechanical work, driving the car. It is represented by the following equation:

$$\eta_{mechanical} = \frac{W_{mechanical}}{E_{electrical}}$$
$$= \frac{m \cdot g \cdot l \cdot \sin(\theta)}{V \times I \times t}$$
$$= \frac{0.4\ kg \cdot 9.81 \frac{m}{s^2} \cdot 0.9144\ m \cdot \sin(20°)}{1.2\ V \times 0.150\ A \times 420\ s}$$
$$\eta_{mechanical} = 1.62\ \%$$

To calculate the mechanical efficiency of the system, again, only the ramp part of the experiment was considered. For the electrical energy, the data obtained during testing in Table 1 was used. It was assumed that it would take a maximum time of 7 minutes (420 seconds) for the car to climb the ramp.

Thermodynamic Efficiency of the Peltier Device

The thermodynamic efficiency of the Peltier device (TEG) evaluates how effectively it converts heat energy provided by the tea light into electrical energy. Thermodynamic efficiency is calculated using the following equation:

$$\begin{aligned}
\eta_{TEG} &= \frac{E_{electrical}}{Q_{in}} \\
&= \frac{V \times I \times t}{Mass\ Burned \times Energy\ Cotent} \\
&= \frac{1.2\ V \times 0.150\ A \times 420\ s}{0.0006\ kg\ \times 42\,\frac{MJ}{kg}\frac{1\ 000\ 000\ J}{MJ}} \\
\eta_{TEG} &= 0.3\ \%
\end{aligned}$$

To calculate the thermodynamic efficiency of the TEG, once again, only the ramp part of the experiment was considered. For the electrical energy, the data obtained during testing in Table 1 was used. On the other side, the energy input is the same input energy used in the overall efficiency, it accounts for approximately half of the total quantity of was used. It was assumed that it would take a maximum time of 7 minutes (420 seconds) for the car to climb the ramp.

Note: All results will be discussed in further detail in the discussion.

Discussion

The construction and testing of the thermoelectric vehicle provided practical insights into thermodynamic principles and efficiency constraints in small-scale applications. Throughout this project, several challenges were encountered in transferring sufficient thermal energy through the Peltier device to generate the required voltage for motor operation. Thermal resistance between interfaces was mitigated by applying thermal paste, though limitations in maintaining a consistent temperature gradient across the TEG resulted in lower-than-expected energy output.

Testing revealed that achieving sufficient cooling on the TEG's opposite side was essential to prevent thermal equilibrium, where both sides of the TEG approached similar temperatures, reducing voltage output. Various cooling methods were explored, including the addition of a heat sink and the use of ice. Despite these improvements, the thermoelectric efficiency was lower than anticipated, indicating that the TEG's performance heavily depends on the effectiveness of the cold side. At the end, it was decided that using ice cubes on the cold side of TEG was the best option to create an ideal temperature gradient.

Efficiencies

The results of the efficiency calculations provide critical insights into the performance of the system and the various limitations inherent in its design and operation. Each efficiency metric (overall thermodynamic efficiency, mechanical efficiency, and the thermodynamic efficiency of the Peltier device) shows where energy losses occurred and the system's ability to convert heat into motion.

The overall thermodynamic efficiency, calculated to be a mere 0.004%, underscores the significant energy losses throughout the system. This low efficiency is not unexpected, given the fundamental inefficiencies in small-scale thermoelectric systems and the use of a relatively weak heat source like a tea light and a poor cooling such as ice, that melts. The calculation assumes that only half of the energy produced by the tea light is utilized during the ramp test, while the rest is used to cross the meter flat. The work output, measured as the potential energy gained by the vehicle climbing a 20° incline, reflects the limited energy that is effectively converted into motion. The low overall efficiency is largely attributed to the inefficiencies in the thermal coupling between the tea light, the TEG, and the ambient cooling system, as well as the inefficiency of the TEG itself in converting heat to electricity.

The mechanical efficiency of 1.62% reveals the system's performance in converting the electrical energy produced by the TEG into mechanical work to move the vehicle. This efficiency is higher than the overall thermodynamic efficiency, as it does not account for the losses occurring during the thermal-to-electrical conversion process. However, it still highlights significant energy losses, primarily due to friction in the motor, gear train, and wheels. Additional losses may have occurred due to imperfect alignment of components and slippage on the ramp surface. The relatively low electrical output of the TEG further limits the motor's ability to produce torque, resulting in reduced mechanical efficiency. The assumption of a maximum time of 7 minutes for the vehicle to climb the ramp is reasonable based on observed data but may introduce minor inaccuracies depending on experimental conditions.

The thermodynamic efficiency of the Peltier device, calculated at 0.3%, specifically evaluates the TEG's ability to convert heat energy into electrical energy. This metric directly reflects the limitations of the TEG, which is known for its low efficiency under small temperature gradients. The tea light as a heat source and the ice as a cold source represents a relatively modest temperature gradient produced across the TEG, which further reduces this efficiency. Heat losses at the interfaces between the TEG and the heat source, as well as between the TEG and the cooling system, exacerbate this inefficiency. While thermal paste was applied to improve heat transfer, the system still suffered from significant heat dissipation into the environment, reducing the amount of energy available for conversion.

In practice, improvements could be achieved by addressing the thermal management system to minimize heat losses and maximize the temperature gradient across the TEG. For instance, better insulation around the heat source and enhanced cooling mechanisms for the cold side of the TEG could increase its output. Similarly, refining the mechanical components, such as reducing friction in the drivetrain and improving traction on the ramp, would enhance the system's mechanical efficiency. These adjustments, while challenging, could raise the overall efficiency of the vehicle drastically. However, the innate limitations of thermoelectric devices suggest that even with significant improvements, the overall efficiency would remain relatively low compared to conventional energy conversion systems.

Conclusions

In conclusion, the thermoelectric-powered vehicle project demonstrated practical thermodynamic and mechanical limitations when attempting to power a system with minimal thermal inputs. While the project succeeded in generating motion and the vehicle climbed the entire incline ramp, the anticipated speed was not fully realized due to limited power output from the TEG under the conditions tested. The experiment underscored the critical impact of maintaining a long-lasting temperature gradient across the TEG.

The actual thermodynamic efficiency of the vehicle was below the calculated expectations, attributable to energy losses in heat transfer and mechanical friction. This discrepancy highlighted the challenges of utilizing thermoelectric power for low-voltage applications. Future improvements could include exploring alternative heat sinks to enhance thermal dissipation, increasing the TEG's thermal efficiency, or pairing the TEG with auxiliary energy sources. Overall, this project offered valuable insights into the practical limitations and potential of thermoelectric power in small-scale vehicle applications.

References

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Appendices

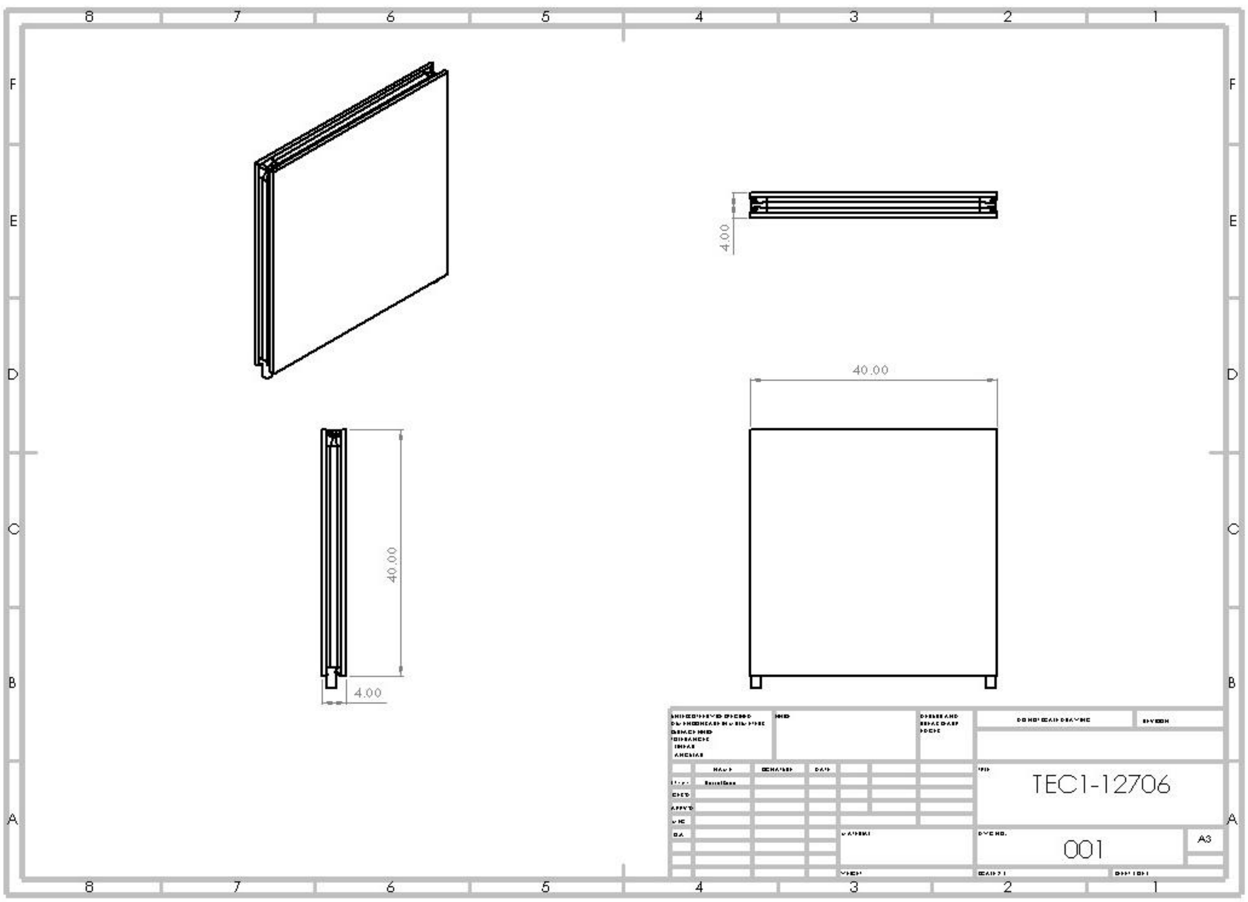

Figure 3: TEC1-12706 Drawing [6]

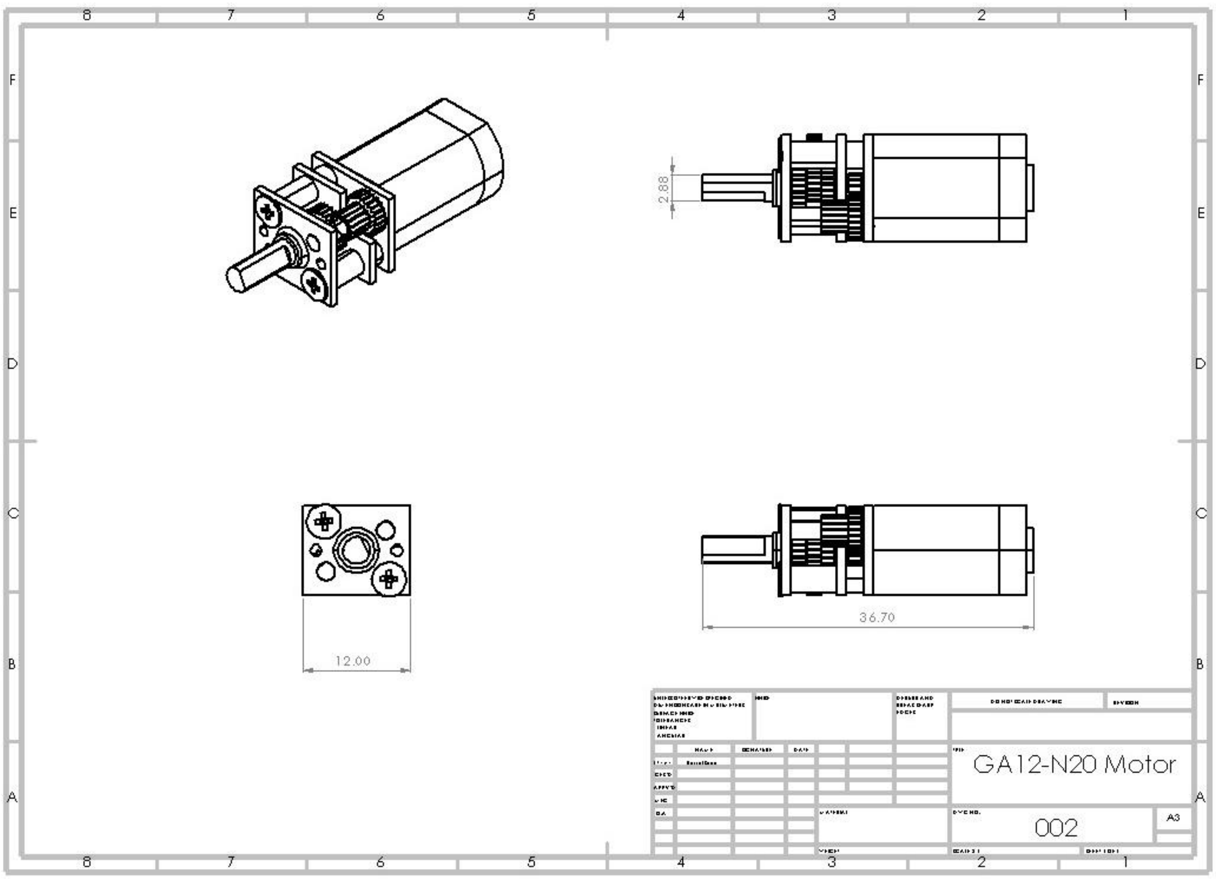

Figure 4: GA12-N20 Motor Drawing [7]

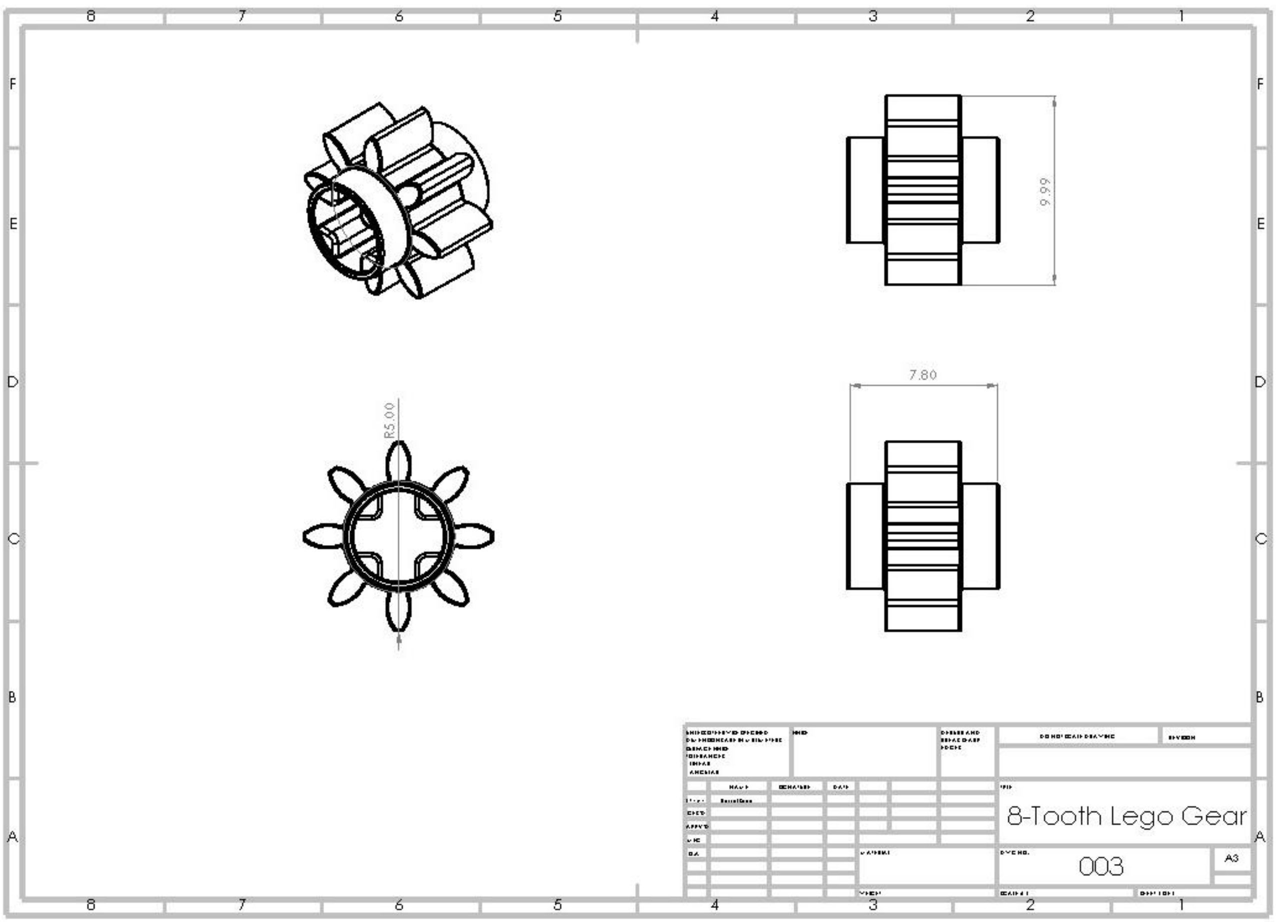

Figure 5: 8-Tooth Lego Gear Drawing [8]

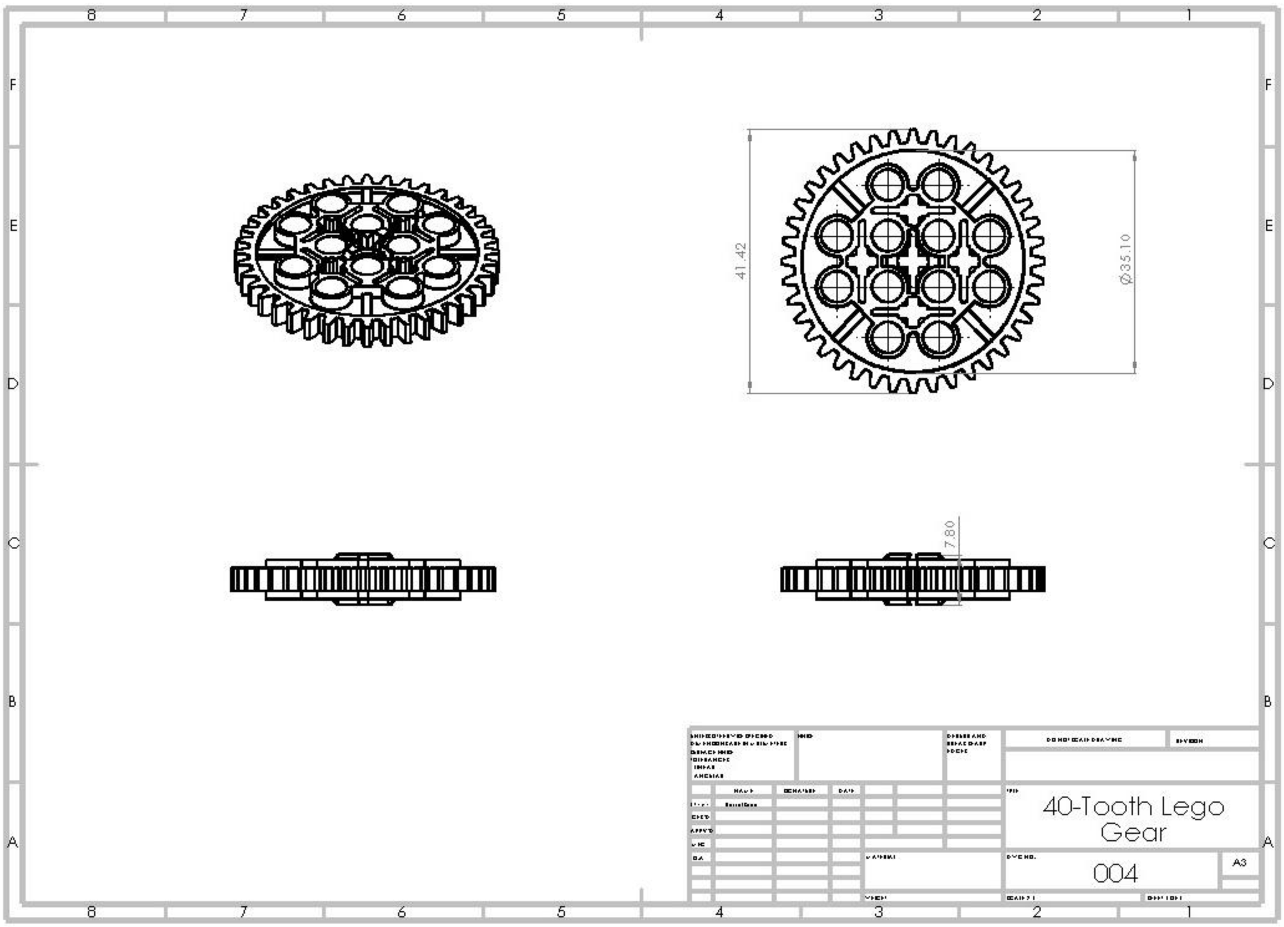

Figure 6: 40-Tooth Lego Gear Drawing [8]

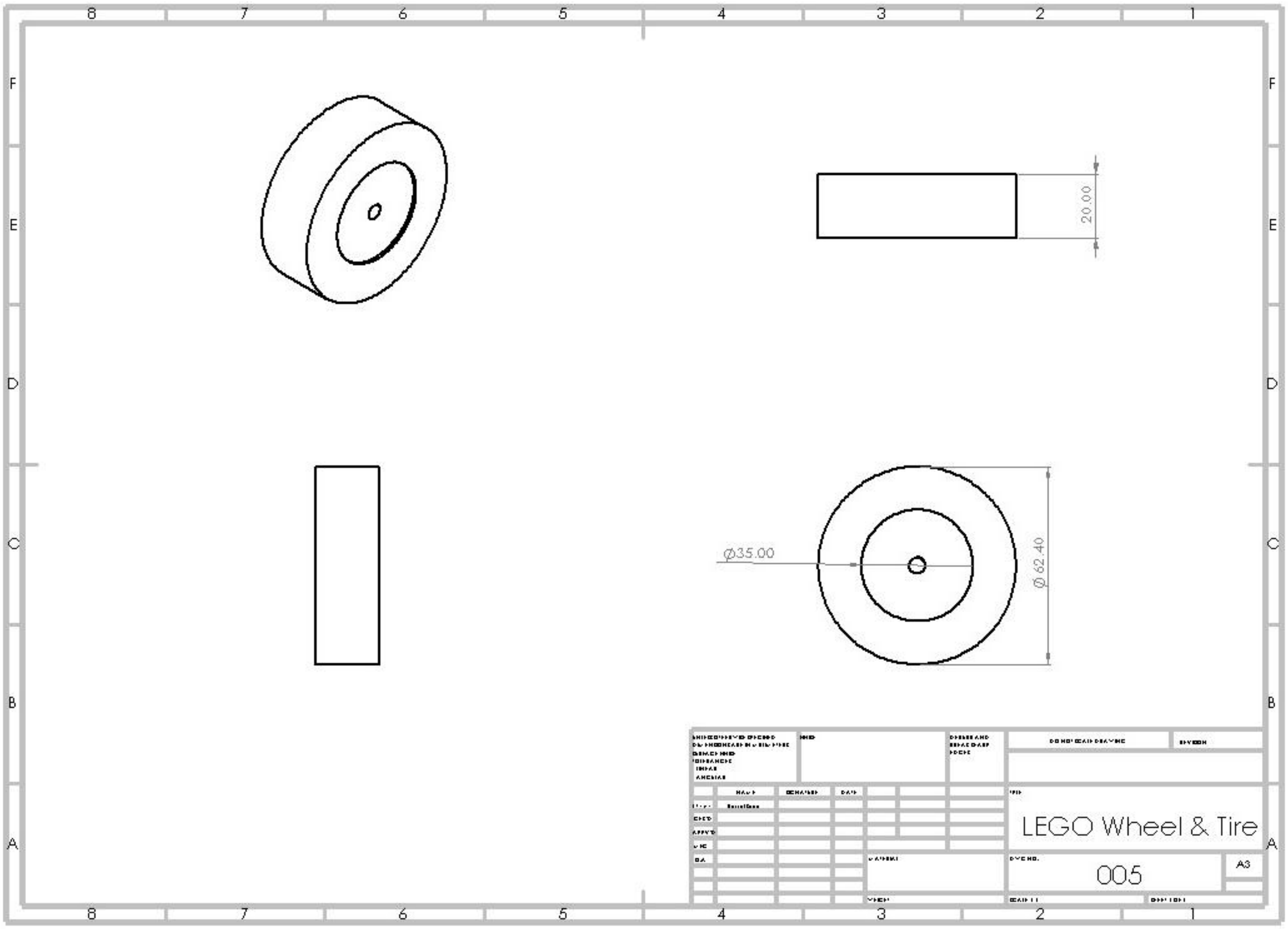

Figure 7: LEGO Wheel & Tire Drawing

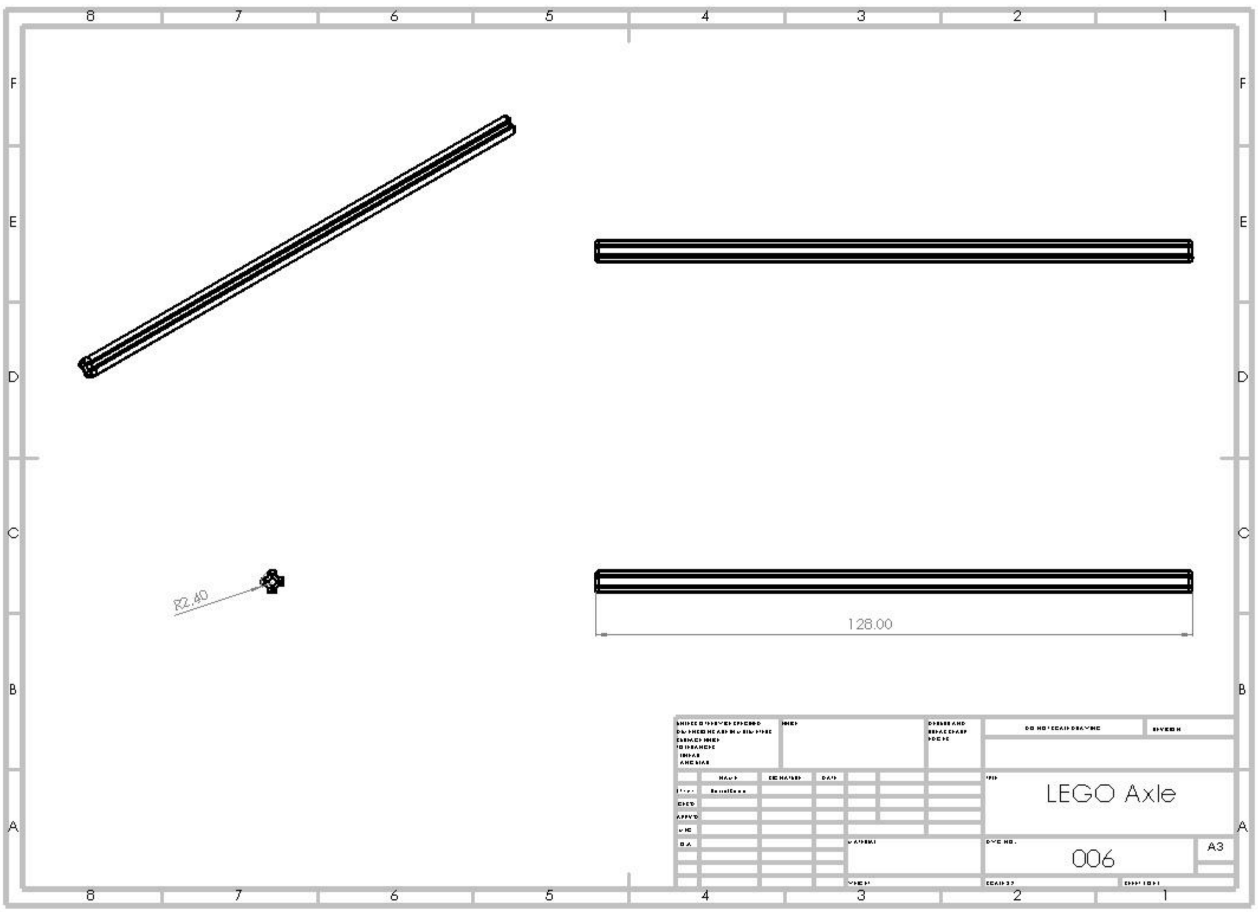

Figure 8: LEGO Axle Drawing [9]

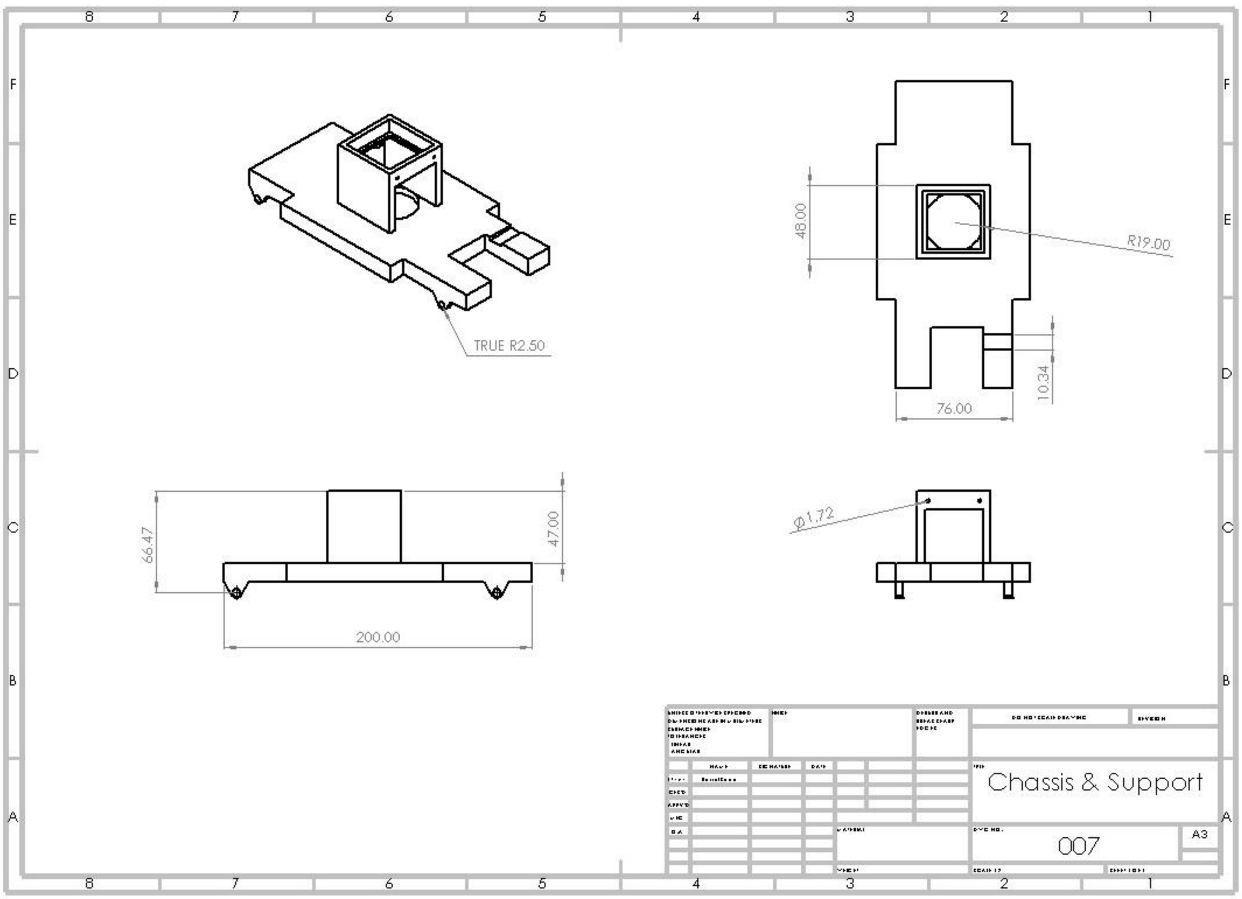

Figure 9: Chassis & Support Drawing

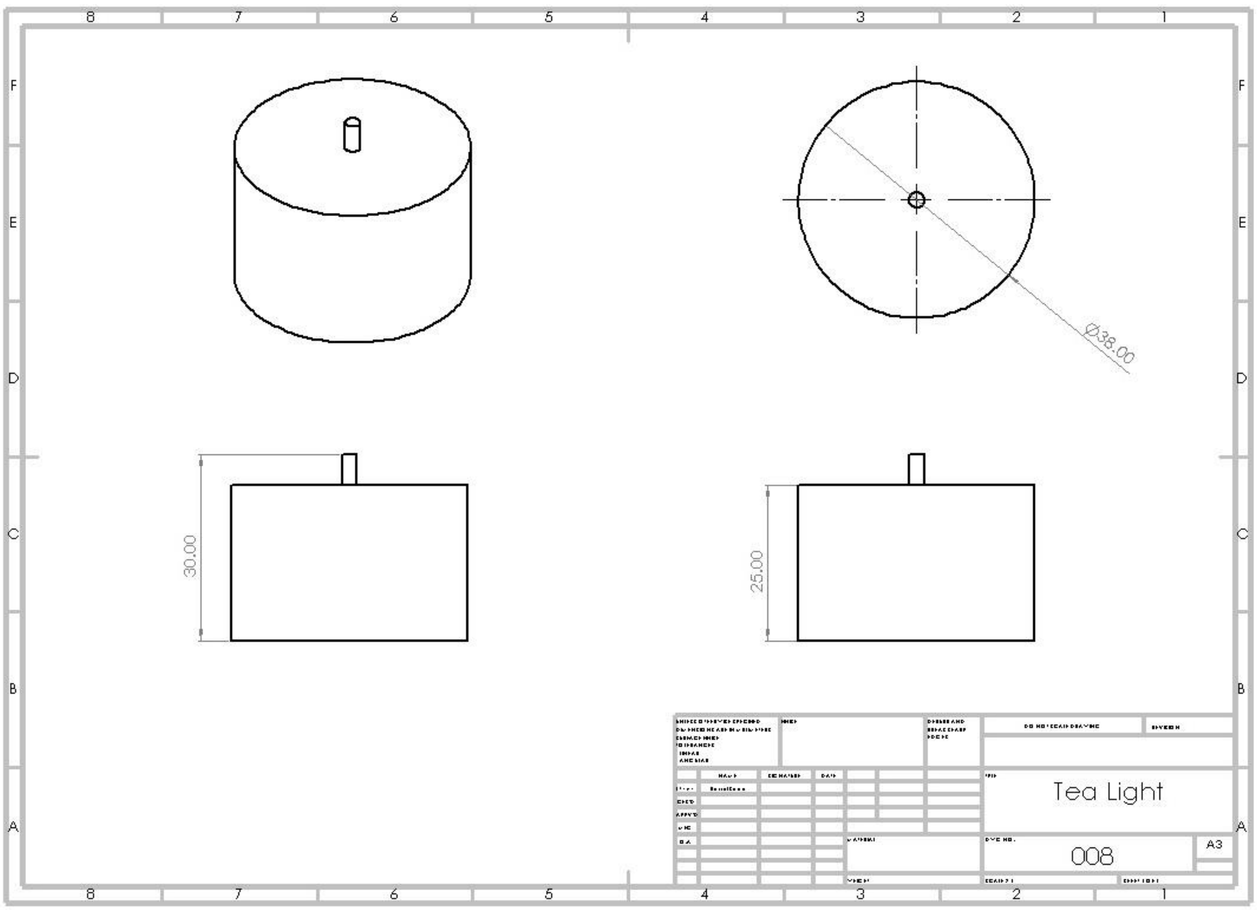

Figure 10: Tea Light Drawing

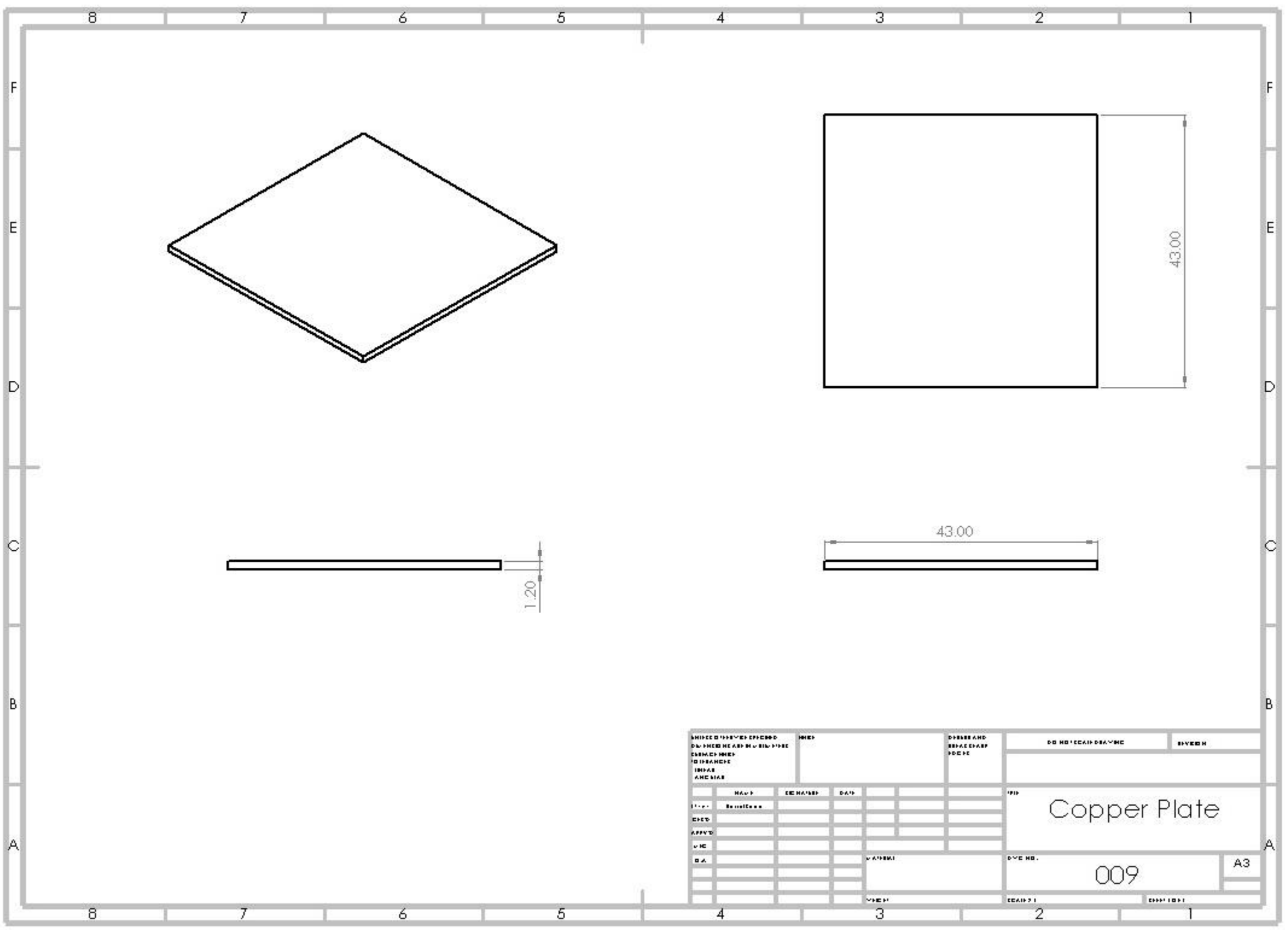

Figure 11: Copper Plate Drawing

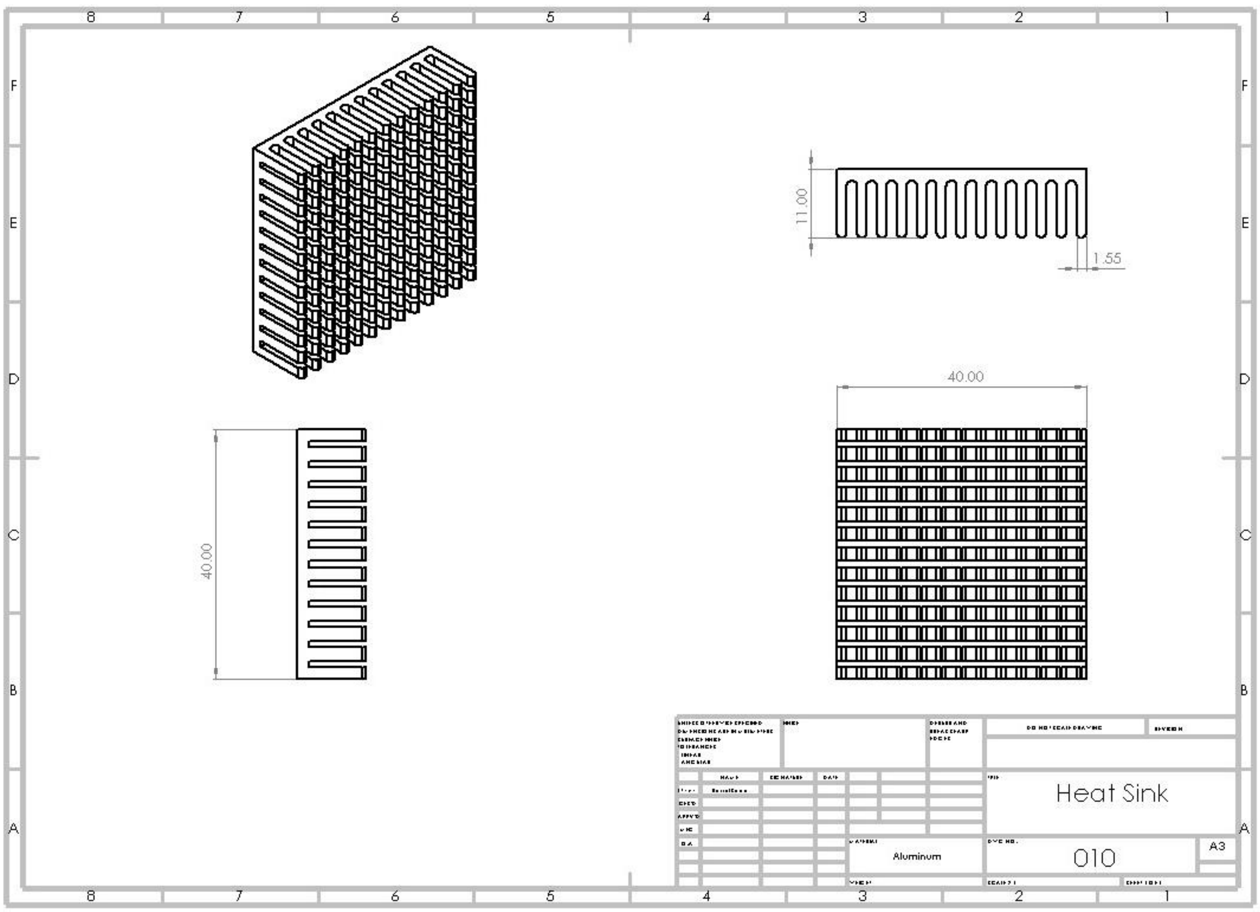

Figure 12: Heat Sink Drawing [10]