Dear José,

I apologise in advance that I am using Word to send you this document. To compensate, I am writing this in Bahnschift SemiCondensed.

Yours truly,

Zion

Research Findings:

This section had been split into nine sections to simplify the findings made for comparing 3D-Printing PLA (3D-P PLA) and 6061-T6 Aluminium.

* Tensile Strength
* Elasticity
* Surface Quality
* Thermal Properties
* Precision
* Cost
* Time Consumption
* Complexity in Manufacturing Process
* Environmental Impact

**Tensile Strength**

A key attribute that determines a material’s capacity to resist pulling forces without breaking is its tensile strength. A number of differences were found when 3D printed PLA (polylactic acid) and 6061-T6 aluminium were compared, emphasising the distinctive mechanical properties of each material.

PLA is a bioplastic composed of renewable resources like corn starch and from a technical data sheet made by BCN3D Technologies, an ultimate tensile strength of 70 MPa was reported from them (link). The value shown is the highest possible stress PLA can withstand before breaking down to tension. Due to PLA having a relatively lower tensile strength, being a polymer and having a layer-by-layer deposition while 3D printing, it can result in the formation of weak areas along the contact points. Despite its lower tensile strength compared to metals, PLA can be used in situations where mechanical strength is not as important and instead can be used when specified component have to be made. Examples on what components were made through 3D printing are shown below.

**[insert images of Chassis Body Corners, Suspension Rocker & Boogie, Chassis-Rocker Connector]**

On the other hand, according to a material data sheet published by ASM International (link), 6061-T6 aluminium, a commonly used alloy in several industrial applications, showed a significantly greater ultimate tensile strength of 310 MPa. The composition of the alloy and the T6 tempering process, which includes heat treatment and artificial ageing to improve the mechanical properties of the alloy, are responsible for its high tensile strength. For structural components and applications that need high amounts of strength, 6061-T6 aluminium is the ideal material due to its better tensile strength. A good example can be the motor-wheel shaft which transmits torque from the motor to the wheel hub and from the wheel hub to the wheel. In addition, there is the motor cover which supports the weight of the rover. This can be shown below.

**[insert images of Shaft and Motor Cover working (can be an image from Fusion360)]**

The wide range in tensile strengths between PLA and 6061-T6 aluminium shows the need for choosing a material according to the particular requirements of a given application. PLA has advantages in terms of manufacturing and environmental impact (mentioned in Section ….), but its mechanical limits restrict its application to less demanding structural tasks. Whereas, when mechanical strength is crucial, 6061-T6 aluminium’s durability and reliability make it essential. This comparison emphasises how important it is for engineering and industrial projects to consider both mechanical qualities and application requirements when choosing materials.

**Elasticity**

The Young’s Modulus and Elasticity between PLA and 6061-T6 aluminium showed differences when compared to one another, which suggests their different uses and stress-resistance.

Based on BCN3D Technologies’ datasheet o PLA (link), the material has a Young’s modulus of 3120 MPa (or roughly 3.2 GPa). The fact that PLA is a semi-crystalline polymer that was intended to be flexible and simple to produce can be seen in its low modulus score (link). The elasticity of PLA was moderate, meaning that it could deform under stress and return to its former shape when the load was released. However, with certain components the 3D-printed PLA could make it brittle. Therefore, it was appropriate for low-stress applications and prototyping where high rigidity was not a requirement. Elasticity in a material helped so that it could absorb some impact without permanent deformation, making it useful for lightweight and less structurally demanding parts.

6061-T6 aluminium had a much greater Young’s modulus of 68.9 GPa (link). Compared to PLA, 6061-T6 aluminium was stiffer and had a smaller chance to deform under stress, as shown by its higher modulus. The material was applicable in instances where rigidity and endurance were required due to its decreased elasticity, which allowed it to bear larger loads without experiencing significant deformation.

The contrast in elasticity and Young’s modulus between PLA and 6061-T6 aluminium showed the different uses for which each material was appropriate. PLA was made for the use of rapid prototyping and scenarios where it required some flexibility because of its lower modulus and increased elasticity. Whereas with 6061-T6 aluminium’s higher modulus and low elasticity, it made it useful in high-stress situations where strength and durability were expected.

**Surface Quality**

For 3D printed PLA, the noticeable layer lines on the surface were a result of the layer-by-layer deposition used in FDM (Fused Deposition Modelling) technology (link). The print resolution determined how smooth the surface was; surfaces with thinner layers at higher resolutions were smoother while at lower resolutions, layer lines were more apparent. To smooth and minimise roughness, post-processing methods like coating and sanding (link) were used. Despite these initiatives, 3D printed PLA had rougher surfaces than machined metals.

**[have 3x images of the Motor-Wheel Shaft to compare the smoothness / MK3 printed vs MK4 printed vs MK4 printed then sanded] ………. Possibly also having a physical survey for people to touch each one and compare?**

Next, components made of 6061-T6 aluminium, which had a smoother surface and very little roughness (commonly at Ra 0.4 μm). The components were produced with a certain degree of surface consistency and homogeneity die to the machining process. Moreover, surface quality could be improved by applying anodizing and polishing treatments, which would add a layer of protection and improve the appearance. 6061-T6 Aluminium has a glossy natural finish and could possibly be polished even more to get a mirror-like surface, which makes it appealing and ideal for higher-end applications.

In terms of aesthetics, 3D printed PLAA parts could have had a matte to semi-glossy appearance, and depending on the filament used, there were a wide range of colour options available, from typical white or transparent to a number of different colours available on the market.

However, the components that were made from 6061-T6 aluminium had a silver-grey, natural glossy finish. This could have also had the possibility to be anodized in several colours, increasing the components’ adaptability (get a link form MS chapters). If necessary, aluminium can be polished to a shinier finish which could increase the visual attractiveness and enables it for uses where performance and aesthetics are equally important.

**Thermal Properties**

When choosing a material for a specific application, especially one where changes in temperature are active, its thermal characteristics are important. Several differences between the thermal characteristics of 6061-T6 aluminium and 3D printed PLA are apparent. Compared to metals, PLA has a lower melting point of 145 °C to 160 °C, which makes it acceptable for low-temperature applications. PLA components are also more prone to dimensional changes with temperature variations, which could impact its stability and precision in some applications. The coefficient of thermal expansion (CTE) for PLA ranges from 68 to 100 × 10⁻⁶/ °C. In addition, it loses its mechanical qualities and structural integrity due to thermal breakdown, which starts at temperatures higher than 200 °C. (link)

6061-T6 aluminium, on the contrary, has a much higher melting point – between 582°C and 652°C - making it ideal for high temperature applications. Approximately 23.6 x 10⁻⁶ /°C is the coefficient of thermal expansion of 6061-T6 aluminium, which is significantly lower than that of PLA and indicates a higher dimensional stability during temperature fluctuations. Furthermore, 6061-T6 aluminium retains its mechanical qualities and structural integrity across many circumstances and does not breakdown at normal operational temperatures. This comparison between the two materials emphasises how important it is to choose the correct thermal requirements for an application. (link)

**Precision**

An analysis of the precision of parts manufactured from PLA using a Prusa MK4 3D printer and from 6061-T6 aluminium using CNC machining or milling demonstrated differences in the two materials and processes in terms of dimensional accuracy, repeatability, complexity, and customisation potential.

With the Prusa MK4 dimensional accuracy for 3D printed parts usually varied between ±0.1 and ±0.2 mm, depending on variables which included: layer height, print speed, nozzle diameter, and printer calibration. The overall precision of the items was impacted by the inherent unpredictability introduced by the layer-by-layer deposition process of 3D printing. On the other hand, components made from 6061-T6 aluminium that were CNC machined or milled showed much better dimensional precision, with tolerances usually ranging from ±0.02 mm to ±0.005 mm. The machining procedure, equipment calibration, tool wear, and thermal expansion could have been variables that affected this precision.

Another important factor was repeatability, or the ability to consistently make the same parts. When applying the same print parameters, the Prusa MK4 showed good repeatability, though small differences could happen due to environmental factors and the grade of the filament. Even though they are small, these differences could affect the way parts made in large quantities turn out. In contrast, high precision was provided by CNC machining of 6061-T6 aluminium, guaranteeing almost identical parts within predetermined tolerances. This constancy would be essential for applications that needed accuracy and consistency between different units.

Additionally, there were also notable differences in each manufacturing method’s complexity and customisation. Complex interior structures and geometries that were difficult or impossible to machine might be produced using the Prusa MK4. This feature, along with simplicity and affordability of modifying and improving designs, enabled 3D printing a compelling choice for specific components and prototypes.

Nevertheless, the CNC machining could have had limitations and frequently be needed for specialised equipment, despite its ability to handle complicated geometries. In conventional manufacturing, customisation would be more costly and time-consuming as it required much more labour and funds to change designs after tooling was put up.

In summary, the complexity, repeatability, and accuracy of producing parts made of 6061-T6 aluminium and PLA showed the advantages and disadvantages of each process. Fr high-stress, high-volume applications, CNC and milling machining offered a greater degree of customisation with good accuracy and consistency. The specified requirements, which balance the demands of precision, repeatability, and design complexity, determined which of the approaches above was to be used.

**Cost**

**Made from 3D Printing PLA:**

* 4x Motor-Wheel Shaft: €0.76
* 2x Rocker Axle: €1.92
* 2x Boogie Axle: €1.48

Total: €4.16

**Made from 6061 T6 Aluminium:**

* 4x Motor-Wheel Shaft
* 2x Rocker Axle
* 2x Boogie Axle

Total: €201.28

When comparing the price of parts produced of 6061 T6 Aluminium and PLA printed by a Prusa MK4, there was noticeable price difference. The same components – 4x motor-wheel shafts, 2x Rocker Axles, and 2x Boogie Axles – were made with both materials. The entire cost of employing PLA 3D printing to produce these components was €4.16. The motor-wheel shafts cost €0.76, the rocker axles €1.92, and the boogie axles €1.48 according to the breakdown. This is a visible difference to the same components made out of 6061-T6 aluminium which came to a total cost of €201.28.

Despite the higher expense associated with 6061-T6 aluminium, it came down to the quality of the components that were produced. Aluminium was stronger, more resilient, and more durable than PLA, which when it came to specific components, was generally weaker than what was needed and was more prone to deterioration over time. Long-term cost-effectiveness was ensured by the superior performance and fewer replacement needs of aluminium components, which nearly made up for their higher original cost. This study demonstrated the trade-off between short-term cost reductions and long-term value, highlighting the scientific proof that material quality has a major impact on lifespan costs as well as performance.

**Time Consumption**

**3D-P PLA:**

* On Prusa MK4
* 2x Rocker Axle
* 2x Boogie Axle
* 4x Motor-Wheel Shaft
* All components were also made in one print (which means they all fit on the board)

**Total time (in hrs): 11 hours and 30 minutes**

**6061 T6 Aluminium:**

* Went to Muharraq Engineering located in Manama, Bahrain
* Made the order on 25.05.2024 at 11h30
* Received all components 29.05.2024 at 15h30

**Total time (in hrs): 100 hours**

There was an evident difference in the time efficiency when the production durations of the components made from 6061-T6 aluminium and PLA were compared. Using a Prusa MK4, the parts – which included 4x motor-wheel shafts, 2x rocker axles, and 2x boogie axles – were created in a total of eleven hours and 30 minutes. This quick processing time and useful efficiency of 3D printing technology was shown by the rapid output that was achieved in a single print run. When it came to manufacturing the same components out of 6061-T6 aluminium, it took much longer. The parts were manufactured by Muharraq Engineering located in Manama, Bahrain and took a total time of around 100 hours for the components to be produced. The order placement was made on May 25, 2024, at 11:30, and the component delivery was made on May 29, 2024, at 15:30.

According to this comparison, the 3D printing method using PLA produced the components 8.7 times faster than the conventional manufacturing method using aluminium. 3D printing is a very useful technique for projects that have a tight deadline because of its speedy manufacturing capabilities, which enable quicker prototyping and shorter lead times. It should be mentioned nonetheless that the manufacturing time for the 6061-T6 aluminium components may change depending on the engineering firm and the particulars of the order. The aluminium components provide better strength and durability despite the longer production time, highlighting the balance between material quality and speed. This study acknowledged the advantages of 6061-T6 aluminium in applications demanding durable and sturdy components, while also showing the effectiveness of 3D printing PLA for quick production needs.

**Complexity In Manufacturing Process**

The process of process of producing a component using 3D printing PLA was considerably more straightforward compared to manufacturing the same component from 6061-T6 aluminium. The Prusa MK4 was simply loaded with an STL file to initiate the 3D printing process. Since no further technical procedures were needed to translate the digital content into a physical thing, this method required minimal preparation.

In contrast, making a component out of 6061-T6 aluminium required a far more involved and repetitive procedure. The design had to be created in Fusion360, where detailed technical drawings were drawn up. For both accuracy and operation to be guaranteed, certain tolerances had to be finished and sent to an engineer for assessment. Several rounds of comments and revisions were frequently made during this review process. The developer would put in the improvements into place after the engineer reviewed the drawing and made any necessary suggestions; occasionally, this might need multipe iterations before final permission was given.

In the final stages, the component would be approved and then put in a manufacturing queue to wait to be made. Compared to the process of 3D printing with PLA, the procedure of design, review, correction, and approval, followed by scheduling for production, added a significant amount of time and complexity. This thorough comparison brought to light the advantages of 3D printing’s speed and ease of use over traditional manufacturing methods for the aluminium components, which are more complex and time-consuming.

**Environmental Impact**

Since the introduction of 3D printing and the use of PLA, it had gained a number of environmentally beneficial characteristics along the way. PLA had a sustainable material source as it was made from renewable resources like sugarcane and corn starch (as mentioned in Section [Tensile Strength]) In general, 3D printing PLA required less energy than conventional manufacturing techniques for small quantities. Moreover, there was very little waste produced by additive manufacturing technique. PLA has low biodegradability in ordinary landfill sites, but it could be biodegraded under industrial composing conditions when its lifespan comes to an end.

Conversely, the ecological impact of manufacturing with 6061-T6 aluminium was different. Bauxite ore was extracted to provide the raw material for aluminium, a process that is extremely energy-intensive during the mining and processing stages. As a result, the energy required to produce 6061-T6 aluminium was much higher because of the machinery and energy it required for both mining and refining. Additionally, substantial amounts of waste was produced by subtractive manufacturing techniques often used to produce aluminium, including shavings and off-cuts. But 6061-T6 aluminium was highly recyclable at the end of its lifespan without losing any of its qualities. Aluminium recycling used just around 5% of the energy needed to make new aluminium from ore, making it a very energy-efficient process.

Under certain circumstances, PLA was recyclable and biodegradable, but its actual recyclability was constrained by the capabilities of infrastructure. However, the recycling process for 6061-T6 aluminium was well-established and resulted in notable energy savings while preserving the material’s characteristics. This comparison reinforced the necessity for sustainable practices in material selection and production processes by highlighting the importance of also choosing materials based on the environment and potential to be recycled.