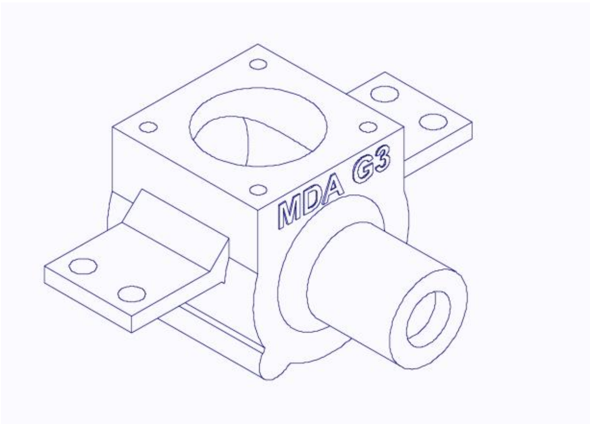
University of Birmingham
School of Engineering

Mechanical Design A

DESIGN FOR MANUFACTURE PROJECT

Assessed by Dr Carol Kong



Group Number	MDA 3
Group Name	MDA 3
Number of Pages (not including preliminary pages and appendices)	13

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i. Feedback	
A: Reflecting on the feedback that I have received on previous assessments, the following issues/topics have been identified as areas for improvement:	
1	We should aim to keep within the set report limit.
2	Methods could be improved by using figures to enable text to be written more concisely, without loss of understanding.
3	Results could be improved by including further narrative to guide the reader through the data presented
B: In this assignment, I have attempted to act on previous feedback in the following ways:	
1	We have carefully read over the design brief to ensure an adequate amount of information is included without breaching the limit of pages.
2	We have shown some data with tables and we have ensured any text is written is a clear, concise form.
3	We have included a description of any data presented in tables and we inserted comments as required explaining any assumptions made or any methods used in our calculations.
C: Feedback on the following aspects of this assignment (i.e. content/style/approach) would be particularly helpful to me:	
1	How well the format of our report suits the specification and how the style can be improved.
2	How we can improve our content, whether its amount included or what we information we have chosen to include.
3	How practical our design is and what we could add to make it more advanced.

ii. Executive summary

The purpose of this study is to analyse our Engine design to make it suited for manufacture. This will involve creating routing sheets and information on how to assemble the product. The environmental impact of the engine will also be analysed. The engine will need to suit an increased production of 10,000 per annum. Therefore, changes have been made to the materials to improve the quality and strength of the design whilst helping minimise the production cost and also still meeting the requirements of the technical specification.

After analysing the materials list, it was found that many of the parts had other materials that were more suitable for the role, therefore changes have been considered for all the parts except for the heatsink. This would drastically improve how well the engine runs and would save a significant amount of production costs.

By altering some assembly processes, the efficiency of the assembly process has improved from 22% to 32% from the semester 1 design to the current updated design (this was evaluated using the design for the assembly index).

A design that eases manufacturing processes was created. By creating a product flow layout, the operations were organized in the most efficient way possible. Processes that were chosen were suitable for each part and suited for the increased batch size. They require lower production and equipment/tooling costs and are also ones that are commonly used in engine manufacturing. The operations chosen are automated therefore have lower overall costs in the long term.

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Material selection

The material analysis will be conducted on the CES Edupack software, Granta design limited, Cambridge,UK,2009 - 2019 version, level 2.

1.1 Methodology used to select material for the conrod:

The function of the conrod is to convert the reciprocating motion of the piston into the rotation of the crankshaft. Conrods are designed to withstand dynamic stresses from combustion and piston movement. To suit the role of a conrod the material is required to be hard, have a high compressive strength and have a high shear strength (Ashby, 2017). It would also be preferred to have a low mass and to be the lowest cost as possible.

Function	Conrod for an IC engine
Constraints	Stroke (length = 16 mm), to not fail from high-cycle fatigue, to have high strength and to have a high stiffness
Objectives	Low cost and mass
Free variable	Material choice

Table 1: Summary of conrod requirements

Objective function (minimise mass): $m = AL\rho$ (Eq.1)

Fatigue constraints: $\frac{F}{A} < \sigma_e$ (Eq.2)

Merge Eq.1 and Eq.2: $m > Fl\,(\frac{\rho}{\sigma_e})$ (Eq.3)

For min m max material index $M1 = \frac{\sigma_e}{\rho}$ (Eq.4)

m = mass
A = cross sectional area
L = length
F = force applied
ρ = density
σ_e = endurance limit

A few materials seem to perform well as shown in **Graph 1- see appendix 1**, therefore, to narrow the choices down, more analysis was performed to see which materials would meet other constraints.

Impact of cross section shape:

Certain cross-section shapes can support loads better e.g. in bending, therefore, to understand how well the material will perform the shape must be considered. The performance will be compared with a square cross section as a reference.

S = stiffness
So = stiffness of square section
E = elastic modulus
I = moment of inertia
Io = moment of inertia for square cross section
b = side length
Z = section modulus

Shape factor due to stiffness: $\frac{S}{S_O} = \frac{EI}{EI_O}$(Eq.5)

Moment of inertia: $I_o = \frac{b^4}{12} = \frac{A^2}{12}$ (Eq.6)

Shape factor $\Phi = \frac{12I}{A^2}$ (Eq.7)

Strength efficiency- ratio of section moduli:$\Phi_f = \frac{Z}{Z_o}$ (Eq.8)

Section modulus: $Z = \frac{b^3}{6} = \frac{A^{1.5}}{6}$ (Eq.9)

Strength efficiency using Eq.9: $\Phi_f = \frac{6Z}{A^{1.5}}$ (Eq.10)

Limiting moment: $M = Z\sigma_e = \frac{\Phi_f}{6}\sigma_e A^{1.5}$ (Eq.11)

Substitute A in Eq.1: $m = (6M)^{2/3}L(\frac{\rho^{1.5}}{\Phi_f\sigma_e})^{2/3}$ (Eq.12)

For best material and shape with respect to max bending strength use

Material index 2: $M_2 = \frac{(\Phi_f\sigma_e)^{2/3}}{\rho} = \frac{\sigma_f{}^{2/3}}{\rho}$ (Eq.13)

See graph 2- refer to appendix 1

For best material and shape with respect to max stiffness use

Material index 3: $M_3 = \frac{(\Phi E)^{0.5}}{\rho} = \frac{E^{0.5}}{\rho}$

See graph 3- see appendix 1

As shown low alloy steels commonly perform well through all the constraints. It has one of the highest fatigue strength, tensile strength and young's modulus that could be seen from the graphs. To decide which low alloy steel, some constraints using the limit function was added to see which material was the best. As described in the specifications, it must have high strength, be hard, be able to withstand shear, tensile and compressive forces and finally have a low inertial mass. Using CES Edupack these constraints were compared for low alloy steels. ***Refer to figure 4- see appendix 1.*** It was decided that Low alloy steel AISI 4340 would be used.

1.2 Crankcase material selection process

Firstly, the function of the crankcase was considered. It must provide an enclosed volume to allow/protect the crankshaft, piston and connecting rods whilst they are moving and in operation. There is understanding that the crankcase would be subjected to radial and axial forces, and forces due to thermal expansion therefore the objective for the crankcase was to be able to support these loads. This information was used to research and determine some constraints, and these constraints were set using the limit function on CES Edupack. The material should have a high yield strength to be able to bear loads and to resist deformation. Whilst bearing loads, the crankcase needs to maintain its structural stiffness. The specifications of the engine also required that the materials should be able to resist thermal expansion forces. The shape and size of the case is fixed as it must fit with the design. The objectives are to keep the cost of the material and the mass to a minimum and that it would be preferred if the material was recyclable. Finally, the material and its suitability to be manufactured to the required design was considered- therefore primary processes were assessed for the ease of shaping the material to the required design. The free variable in this selection is the type of material used. The following table compares the performance of the original material selection to the new chosen material.

Constraints	**Original material: Stainless Steel 304 annealed**	**New material: Aluminium c3550 t6**
Yield strength > 200MPa	Yes (205-310 MPa)	Yes (219-242 MPa)
Stiffness > 20 MN.m/kg	Yes (23.8-25.6 MN.m/kg)	Yes (25.8-27.1 MN.m/kg)
Thermal expansion coefficient< 25 μstain/℃	Yes (13-18 μstain/℃)	Yes (22.3- 23.5 μstain/℃)
Low price	1.99 - 2.23 GBP/kg	1.72 - 1.99 GBP/kg
Low density	7.85e3 - 8.06e3 kg/m^3	2.7e3-2.73e3 kg/m^3
Ease of manufacture	Suitable for forming/welding	Suitable for cast/welding

Table 2: Constraints used in crankcase material selection process

For each constraint the material which shows to perform better for that function has been highlighted. Aluminium c3550 has similar properties as stainless steel in terms of how well it would perform in an Engine. However, it is cheaper and considerably less dense (almost ¼ less dense). Trying to reduce the overall weight of the engine is important as it will help improve efficiency and will reduce fuel costs. Therefore, this led to changing the material selected. Finally, Aluminium is suitable for casting which is considered as the chosen manufacturing method whereas stainless steel isn't suitable for this.

1.3 Crankshaft material selection process:

The function of a crankshaft is to transform the linear motion of the piston into rotational motion in order to transmit power in the engine. The constraints set for the materials of crankshafts was that it should be easily shaped, have adequate strength, be tough, and have high fatigue strength. Also the shape of the crankshaft must stay the same as has been already assigned. The objectives were to consider the cost and mass. The free variable in this case is the material chosen. The constraints used to choose the material are shown below in ***TABLE 3***.

Constraints	Original material: Stainless steel 340	New material: Carbon steel AISI 1050
Tensile strength > 500 MPa	Yes (510- 620 MPa)	Yes (570 - 705 MPa)
Toughness > 13 Kj/m^2	Yes(15.6 - 25.3 Kj/m^2)	Yes(13.9 - 32.6 Kj/m^2)
Fatigue strength at 10^7 cycles > 200 MPa	Yes(229- 253 MPa)	Yes(288 - 336 MPa)
Young's modulus > 190 MPa	190-203 MPa	208-216 MPa
Recyclable	Yes	Yes
Low density	7.85e3-8.06e3 kg/m^3	7.8e3-7.9e3 kg/m^3
Low price	1.99 - 2.23 GBP/kg	0.57-0.592 GBP/kg

Table 3: Constraints used in Crankshaft material selection process

For each constraint the material which shows to perform better for that function has been highlighted. After analysing the materials, it was deduced that Carbon steel 1050 meets requirements as well as stainless steel does, however it performs slightly better in most functions and it is around ¼ of the price. Reducing costs are important now the production rate has increased, as small savings would lead to a significant reduction in the final costs. Therefore, Carbon steel was considered as the best material for the crankshaft.

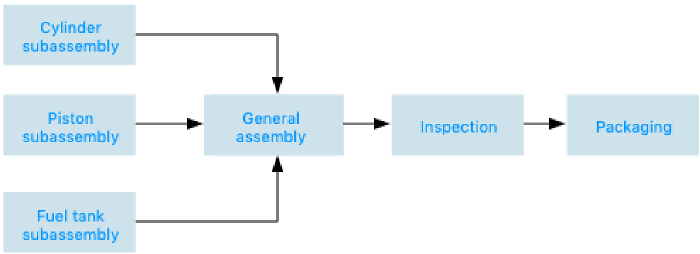
1.4 Revised bill of materials

Engine part	Original material	Revised material
Fuel tank	Aluminium 6061	Aluminium 5052
Crankcase	Stainless steel 304	Aluminium c3550 t6
Cylinder heat sink	Aluminium 6061	Aluminium 6061
Crankshaft	Stainless steel 304	Carbon steel AISI 1050
Bolts	Stainless steel 304	Stainless steel 403
Cylinder sleeve	Stainless steel 304	Cast iron flake graphite
Backplate	Nylon 6	Aluminium 5052
Shaft coupler	Aluminium 6061	Carbon steel AISI 1137

Table 4: Revised bill of materials for 85% of the engine's overall weight

Engine assembly

2.1 Assembly routing sheets



Symbol	*Description*	*Definition*	*Example*
●	Operation	A job or task normally performed at one location	Machine material
➡	Transportation	The movement of an item from one location to another	Moving material by hand, conveyor, etc.
■	Inspection	The determination of acceptability of an item	Examine material for quality or quantity
D	Delay	A pause or interruption in scheduled work	Material waiting to be processed
▼	Storage	Scheduled holding of items before, during or after production operations	Raw material or finished goods stock

Batch assembly, subassemblies are assembled in batches of 500 units before moving to the general assembly station. Diagram above shows the assembly operation sequence and table describes meaning of each symbols used in assembly routing sheet shown below (Crowson, 2010).

Cylinder subassembly				
Steps	Symbol	Description	Tools & Components required	Time (seconds)
1	●	Screw the first 5 threads of contra piston into the center of the heatsink, subsequently use an impact wrench to tighten to 2Nm	Socket ratchet, impact wrench, torque meter	10
2	●	Insert threaded rod into the threaded hole of contra piston, and screw in M3 bolts from either side and screw in 3 rotations	Socket ratchet	10
3	●	Insert cylinder sleeve into heatsink whilst aligning the blocks for a press fit.	Hydraulic press	20
4	●	Place a paper seal on the bottom of the heatsink while aligning bolt holes.	Pliers	5
5	■	Check if the threaded rod is held in place. Check if the outlet port of the cylinder sleeve and heatsink are aligned.	Visual inspection	5
6	▬	Move to subassembly to the general assembly station	Trolley, cylinder subassembly	10

Table 5: cylinder subassembly routing sheet

Piston subassembly

Steps	Symbol	Description	Tools & Components required	Time (seconds)
1	●	Apply a bead the size of a grain of rice of lithium grease on crankshaft, rub excess lubricant with paper towel and press bushing 1 fully onto the shaft with a hydraulic press	Lithium grease, hydraulic press, paper towel, crankshaft	25
2	●	Press-fit bushing 2 and 3 (identical) into the conrod borehole with a hydraulic press. Ensure bushing is flush with conrod	Hydraulic press	10
3	●	Insert gudgeon pin into piston hole and Slide conrod into gudgeon pin.	Hydraulic press	20
4	●	Use a hydraulic press to press the gudgeon pin fully into the piston, ensuring the piston surface is flush with the gudgeon pin.	Hydraulic press	15
5	■	Inspect all components, ensure no excess lubricant, ensure piston can pivot freely around conrod	Visual inspection	5
6	—	Move to subassembly to the general assembly station	Trolley, piston subassembly	10

Table 6: Piston subassembly routing sheet

Fuel tank subassembly				
Steps	Symbol	Operation description	Tools & components required	Time (seconds)
1	●	Put spring through needle thread. Screw needle thread between the two vent holes of the backplate for 3 revolutions.	Spring, needle screw, backplate, needle pliers	8
2	●	Insert PVC tube into backplate inlet	Backplate, pvc tube	5
3	●	Place the copper sheet over the inlet in the fuel tank cylinder, ensure it covers the hole fully and is centered. Press-fit the valve spring over the copper sheet into the notch.	Copper sheet, valve spring, fuel tank cylinder, needle pliers	20

4	●	Place paper seal over the fuel tank cylinder	Fuel tank cylinder, paper seal	5
5	■	Ensure paper seal is aligned with fuel tank, pvc tube is firmly attached to backplate	Visual inspection	10
6	▬	Move to subassembly to the general assembly station	trolley	10

Table 7: Fuel tank subassembly routing sheet

General assembly				
Steps	Symbol	Operation description	Tools & components required	Time (seconds)
1	●	Insert the crankshaft fully into the crankcase's bushing holder. Bushing should be able to rotate freely	Pliers	5
2	●	Press fit conrod with bushing into crankpin	Pliers	10
3	●	Press fit heatsink assembly onto the crankcase, whilst ensuring the exhaust slot is on the left when facing the front of the crankcase. Use bolts and impact wrench to screw heatsink into the crankcase	Impact wrench	15
4	●	Press fit the fuel tank into the back of the crankcase, ensuring bolt holes are aligned. Use 4 bolts to secure the fuel tank into the crankcase. Tighten fully to 2Nm. Check bolts are tightened correctly with torque meter	Impact wrench, torque meter	20
5	■	Ensure the crank shaft can spin freely and motion is linked with the piston, check surface finishing of components with a sample engine, ensure all bolts are present and attached firmly.	Visual inspection	60
6	▬	Move to packaging station	Trolley, general assembly	20
7	▼	Package full assembly in cardboard boxes and put in storage units to prepare for shipping. For every batch of 500 units, take five units for quality control and testing.	Trolley	30

Table 8: General assembly routing sheet

Process planning

3.1 Part drawings

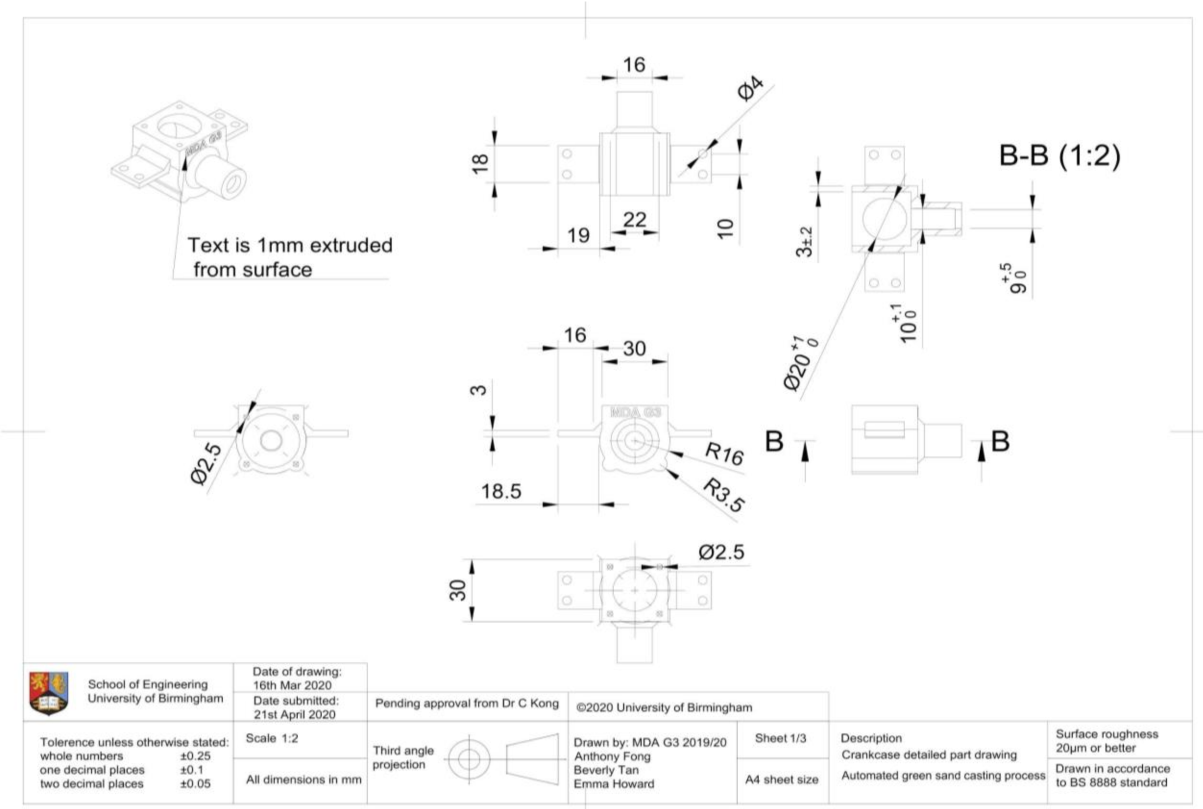


Figure 1: Detailed part drawing of crankcase

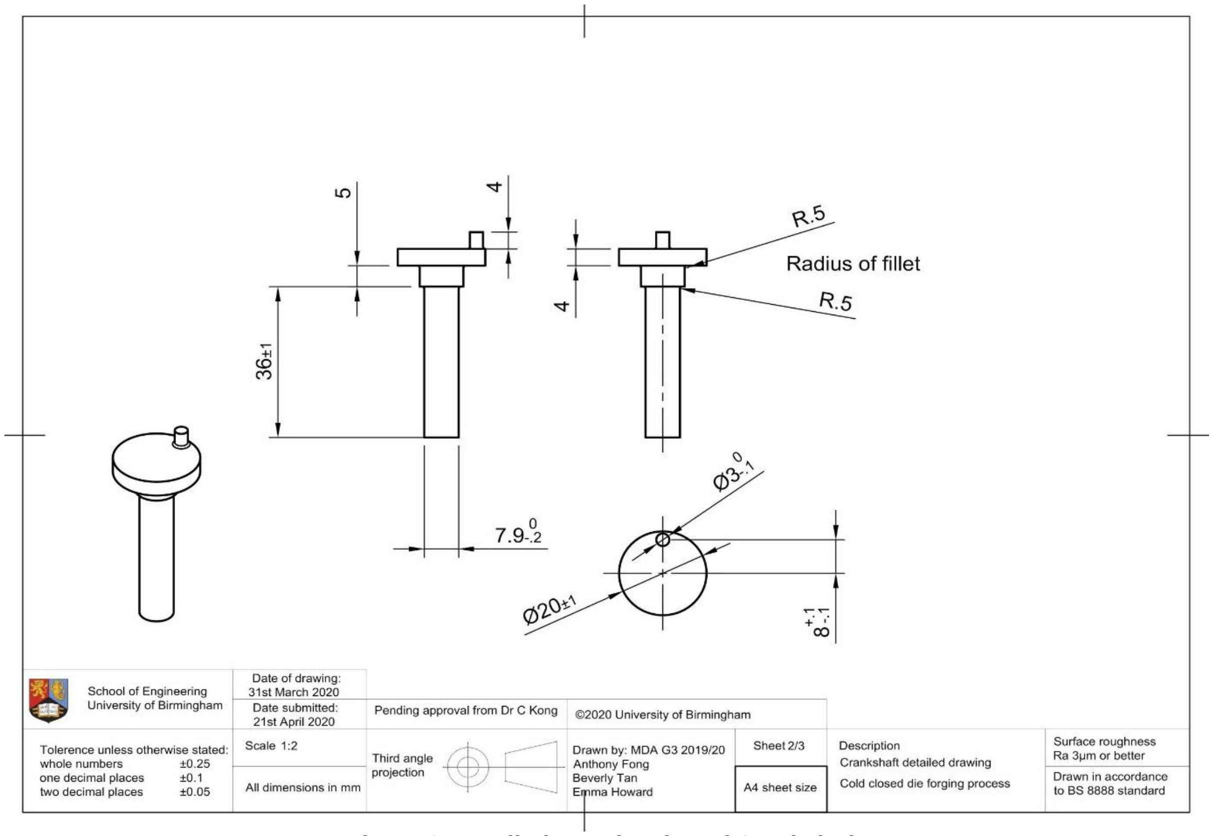


Figure 2: Detailed part drawing of Crankshaft

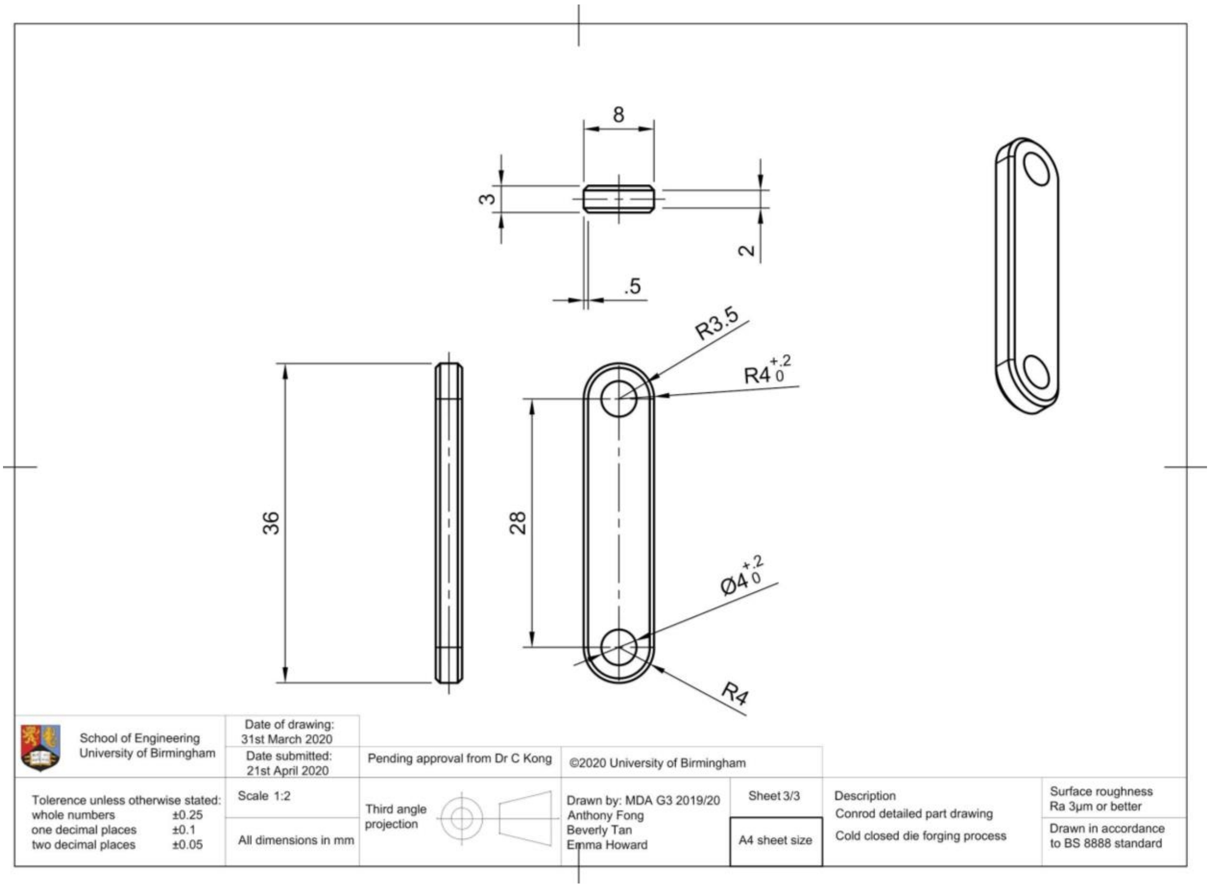


Figure 3: Detailed part drawing of Conrod

3.2 Summary of process selection

As the manufacturing grounds are producing identical batches of a specialized product, the engine, the production type will be based on mass production. As an automated assembly line has preset parameters, this increases efficiency and lowers labour costs (Mass Production Definition, 2020). Automated machinery also allows for a higher rate of assembly, again increasing efficiency and lowering human labour (Mass Production Definition, 2020). The product flow layout organizes fixed workstations based on the manufacturing processes and arranges them sequentially. Specialized labour dedicated for each workstation decreases training costs and increases output volume as each worker is tasked with highly standardized and repetitive tasks (Mass Production Definition, 2020). In this layout, the primary processes include automated sand casting and cold closed die forging. The secondary process include work done on a milling machine such boring, drilling and chamfering. The operations to enhance physical properties include induction hardening, and the final process is chemical polishing.

Automated Green Sand Casting are relatively cheap for a 10000-batch size as it has medium labor costs (CES EduPack 2016, 2017). Having it automated instead of manual reduces labor as well as making it ideal for larger batch size (Die Casting Process, Defects, Design, 2020). It is a common process for molding engine parts (CES EduPack 2016, 2017).

Cold Closed Die-Forging is also cheap for large batch sizes of 10000 due to its low labor intensity (CES EduPack 2016, 2017). It does not require extensive finishing work which would in turn reduce production costs. Cold forging is chosen over hot forging as this process increases the strength due to strain hardening (Cold Forging vs. Hot Forging – Considerations, Benefits and Drawbacks, 2020). It hardens metals and is again commonly used in engine parts (CES EduPack 2016, 2017).

Induction hardening increases hardness, wear resistance and fatigue resistance, ideal for parts that are constantly under stress (CES EduPack 2016, 2017). The process requires low labor intensity, while the tooling and equipment cost at a medium price (CES EduPack 2016, 2017).

Chemical Polishing has cheap equipment, tooling and labor cost (CES EduPack 2016, 2017). It is used for colouring, decorating, reflectivity and surface texture (CES EduPack 2016, 2017). The glossy finish helps eradicate minor imperfections. Ideal for increasing the aesthetics of the engine.

Detailed operation details can be found in the appendix (Table 14).

3.3 Component Routing Sheet

Routing sheet			
Part Name: Crankcase		Material: Aluminum c3550 t6	
Quantity: 10,000	Date:		Page: 1 of 1
Op. no.	Description		Machine tool
10	Mix sand mixture of 90% sand, 3% water, 7% clay		Mixer
20	Prepare pattern		Pattern
30	Fill both halves of molding box with sand mixture. Create the core using sand mixture. Clamp the mold		Casting machine, Core making machine
40	Melt Aluminum at 660°C, fill mold cavity and wait to cool		Static pour, Furnace
50	Remove sandcast		Vibrating table, Shot blast
60	Trim excess metal		Trimming press
70	Prepare polishing bath with 77.5% H_3PO_4, 16.5% H_2SO_4, 6% HNO_3		Polishing Bath

80	Immerse work piece in bath for 90s at 85°C	Polishing Bath
0	Rinse work piece in water at 50°C for 60s	Water Bath

Table 9: Routing sheet for Crankcase

Routing sheet			
Part Name: Crankshaft		Material: Carbon steel AISI 1050	
Quantity: 10,000	Date:		Page: 1 of 1
Op. no.	Description		Machine tool
10	Place steel billet between upper and lower die		
20	Bring upper and lower die together with a force of 16MN to compress the billet at room temperature		Hydraulic press
30	Place crankshaft in alternating magnetic field at 10Kw maintaining at 850-900°C with dwell time of 0.1s		Induction hardening machine
40	Quench with water at 10 liters/min		Quenching machine

Table 10: Routing sheet for crankshaft

Routing sheet			
Part Name: Con rod		Material: Low Alloy Steel AISI4340	
Quantity: 10,000	Date:		Page: 1 of 1
Op. no.	Operations Description List		Machine tooling
10	Place steel billet between upper and lower die		
20	Bring upper and lower die together with a force of 16MN to compress the billet at room temperature		Hydraulic press
30	Drill 3.97mm diam. Holes through the workpiece. 5mm from each end of the workpiece X2		Milling machine
40	Bore 3.97mm drilled holes to 4mm diam. holes		Milling machine

50	Use a 45° chamfer to create peripheral cut on all edges of the workpiece inc. holes	Milling machine
60	Place Con-rod in alternating magnetic field at 10Kw maintaining at 850-900°C with dwell time of 0.1s	Induction hardening machine
70	Quench with water at 10 liters/min	Liquid jet

Table 11: Routing sheet for Conrod

Operations List						
Part Name: Con-rod			Material: Low Alloy Steel AISI4340			
Quantity: 10,000			Date:		Page: 1 of 1	
Op. no.	Description	Machine Tool	Tooling	Speed (RPM)	Feed (mm/min)	Op. Time (min)
30	Drill radial holes 3.97mm diam	Milling Machine	DeWalt DW1163 5/32" Drill Bit	3000	35	2.25
40	Bore holes from 3.97mm to 4mm diam.	Milling Machine	Iscar #56527583 4mm Bore Bar	180	20	3.20
50	45° chamfer to on edges	Milling Machine	TCMT C20-25-110L 45-degree chamfer end	180	25	4.25

Table 12: Routing sheet for Conrod

Life cycle analysis

4.1 Eco Audit of the updated engine design

The following eco audit summary has come from data with the following assumptions:

- The product is made in Birmingham and shipped to London (distance approx. 220 km) in a 40-tonne (6-axle) truck
- The country of use is the UK
- Certain standard components are shipped from China (Bolts), travelling 7872 Km on a long-haul air freight- a considerable contribution to the transport phase
- The product life is expected to be 5 years- majorly impacting the USE phase
- It has been assumed that the engine will be used 100 days a year for 1 hour each time- It is not expected to be in use every day and the spec states a 1-hour flight time
- The power rating of the engine is 372 W- as stated by our spec
- All the materials used were recyclable so it was assumed that all materials will be recycled after use- this is to show all the EOL potential however, this may be optimistic
- The energy input comes from fossil fuels (diesel) which is converted to mechanical output (internal combustion)

It can be seen from ***Graph 4-see appendix 3*** that the USE phase of the product predominates all other phases of life in terms of its energy consumption and CO2 footprint. From ***Table 15-see appendix 3*** the data shows the energy consumption in the USE phase contributes to 97.9% of energy consumption and it contributes to 98% of the CO2 footprint. The MATERIAL PRODUCTION phase is the second most significant phase as it contributes to 1.5% of energy consumption and 1.4% of the carbon footprint. The TRANSPORT phase has a slight impact predominantly due to shipping parts from China, however the overall impact seems insignificant as it only contributes to 0.5% of the energy consumption and carbon footprint. The impact of MANUFACTURE and DISPOSAL in this case are negligible due to the high impact of the USE phase.

4.2 What-if eco audit

The following data assesses the impact of using the original materials for the Engine. The original materials had less analysis and had many materials which were very dense and maybe were less suitable for their role, therefore the new engine is suspected to be more efficient than the old one. The materials in the old design all differ to the new design except for the heatsink which it was chose to keep the same. All the same assumptions and manufacturing process were used in this eco audit.

Like the new design the USE phase has the greatest environmental impact as it contributes to 98% of energy consumption and contributes to 98.1% of the carbon footprint which can be seen from ***Table 16-see appendix 3***. The second most significant phase is the MATERIAL PRODUCTION phase contributing to 1.4% of the energy consumption and 1.3% of the carbon footprint. The TRANSPORT phase has little contribution as it contributes to 0.5% of energy consumption and 0.6% of the carbon footprint. Again, the MANUFACTURE and DISPOSAL have negligible effects.

Eco-audit comparison

Graph 6-see appendix 3 and ***Graph 7-see appendix 3*** compare the environmental impact of the new and old engine design. As seen, the impact of changing the materials in this instance has very little effect. Again the values found in ***Table 15-see appendix 3*** and ***Table 16 -see appendix 3*** can be compared and the total energy consumption and CO2 footprint are the same (2.28e3 MJ and 162 kg), which is most likely due to that fact that the same assumptions were used. On the contrary, the new Engine has more end of life potential which is 27.7 MJ of energy and 1.8 kg of Carbon footprint being saved compared to 22.9 MJ and 1.47 kg for the old engine.

5.1 Conclusion

CES Edupack has allowed comparison between material properties. Upon revising material selection, alternative materials were found that outperformed original material choice in different criteria, such as density, yield strength and lower costs per kg. The aluminum heatsink was the only material choice which did not change. The revised material selection resulted in lower overall weight, which can lead to increased flight time or fuel carrying capacity. The engine is also more durable as materials with higher yield strength was used.

The efficiency of the assembly process can be evaluated using the design for the assembly index. (Boothroyd, Dewhurst and Knight, 1994). The index improved from 22% to 32% after optimisation **(*see Table 13).*** The improvement comes from simplifying assembly alignment by adding fillets to gudgeon pin, threaded holes and backplate for easier part insertion. Adding notches to the fuel tank inlet, backplate and heatsink for easier valve assembly. Overall, modularity was prioritised over part count, despite understanding part count plays a major role on assembly efficiency, the user experience was prioritised. As the market for UAV engine of this size are primarily hobbyists, which value upgradability, reliability, and room for custom modifications.

The design can be easily manufactured with an assembly line. The product flow layout is highly efficient, and by automating parts of the production line, both labour and training costs will be reduced, while precision and speed of manufacturing will improve. The primary, secondary and final processes were chosen due to their low production and tooling costs. and are commonly used in manufacturing. The product flow layout is suitable for high volume output in a short time frame which is the ultimate goal for this design.

The energy consumption for the new engine design is predicted to be 2.28e03 MJ in its lifetime and the carbon footprint is estimated to be 162 kg. With an average life span of 5 years, the largest energy consumption is during its USE phase. Selected materials were critically analysed for high yield strength and endurance limit to maximise the engine's life span and justify the energy consumption and carbon footprint during the MANUFACTURE stage. Changing the materials selection did not show significant reduction in energy consumption or carbon footprint as majority of emissions produced is during the USE phase.

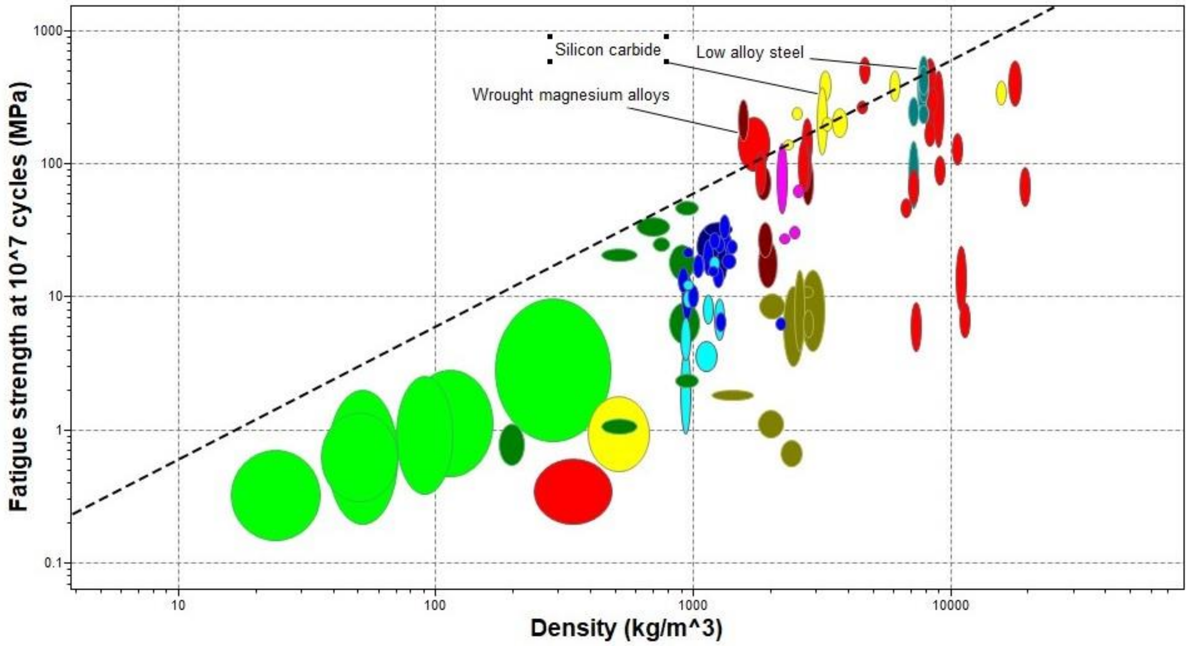
It is believed that this design is suited for the increased production since all materials have been critically selected in order to optimized for both performance and costs. Small cost savings in materials will be critical when manufacturing in large batches. The engine design is refined to be more suitable for large scale manufacturing, optimizing material choice with different constraints which resulted in improved performance, longer life span and lower cost. Small cost savings is especially critical in manufacturing to maximise profit margins.

Recommendations

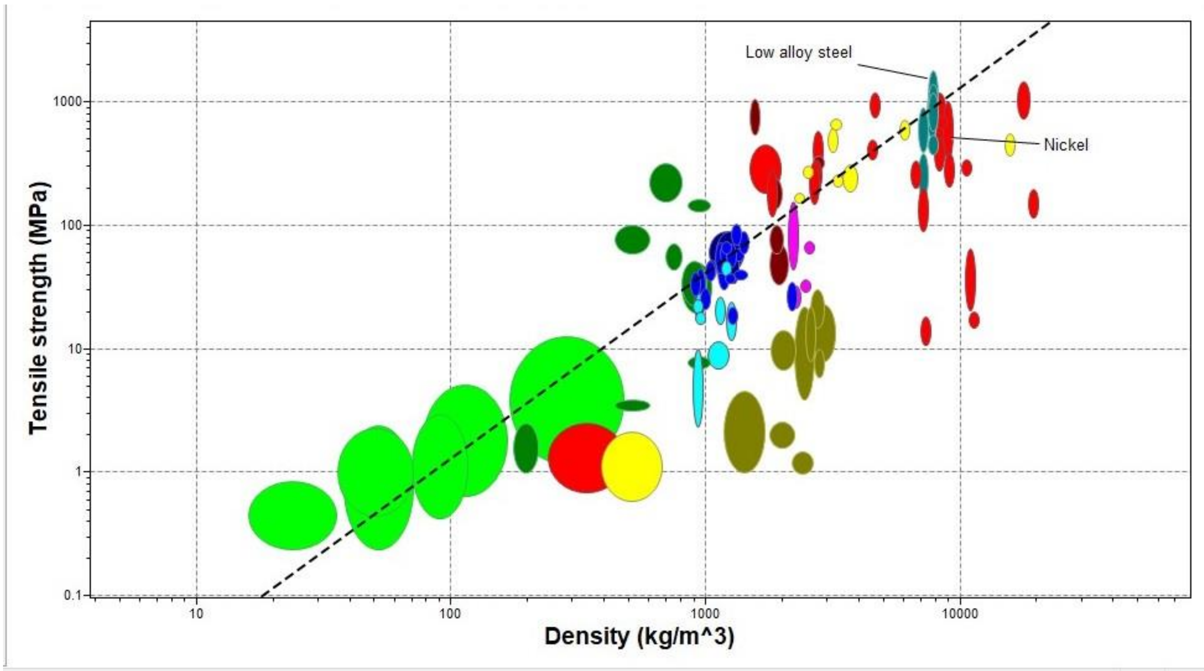
- Reduce weight, primarily the fuel tank weight, as it does not have to be made of aluminum
- Do not use the reed valve, extra point of failure, could use a more reliable rotary valve instead (which many engines of this size use) or an integrated tesla valve
- Add deflector on piston to encourage scavenging
- Seal ring around piston to improve seal and compression ratio
- Use bearings instead of bushings to reduce friction

Appendix

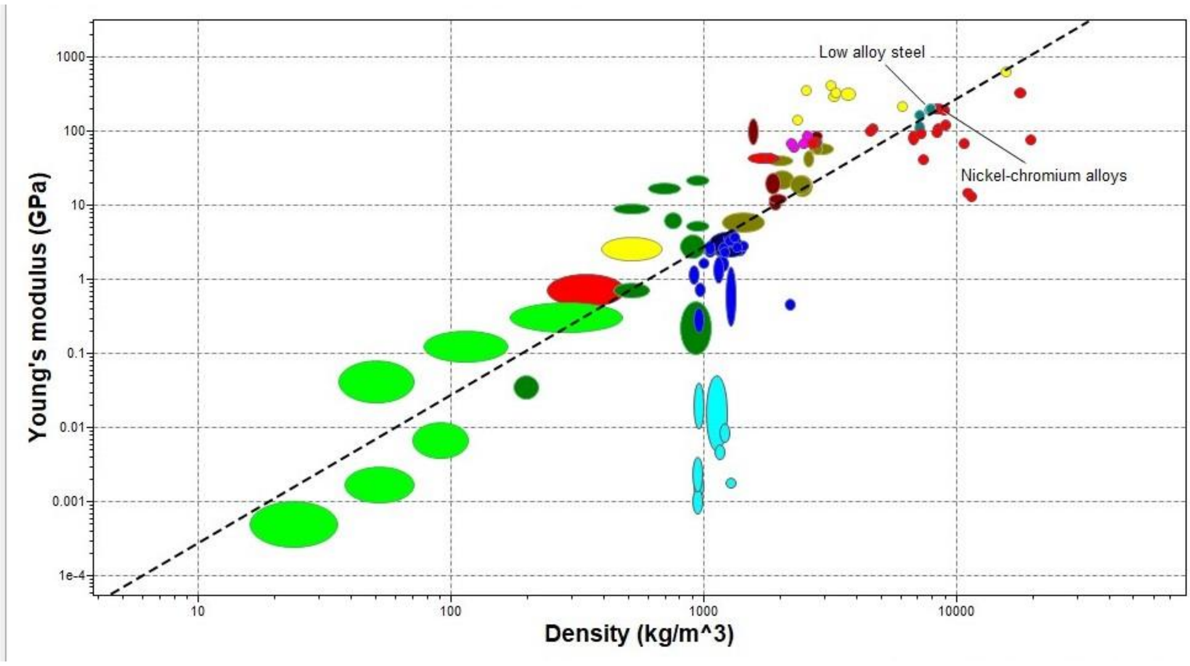
6.1 Material selection appendix



Graph 1: Fatigue strength against density with slope of 1, using CES edupack Level 2 database



Graph 2: Tensile strength against density with slope of 3/2, using CES edupack Level 2 database



Graph 3: Young's modulus against density with slope of 2, using CES Edupack Level 2 database

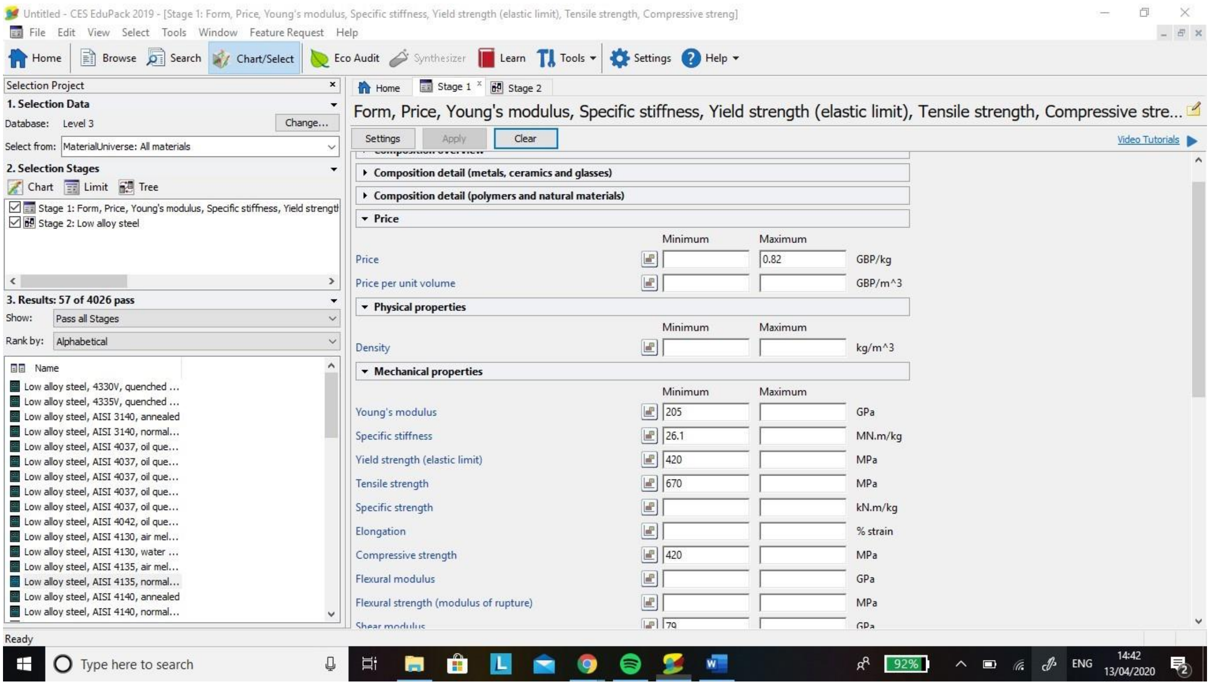


Figure 4: Stages used to decide most suited low alloy steel

6.2 Process planning appendix

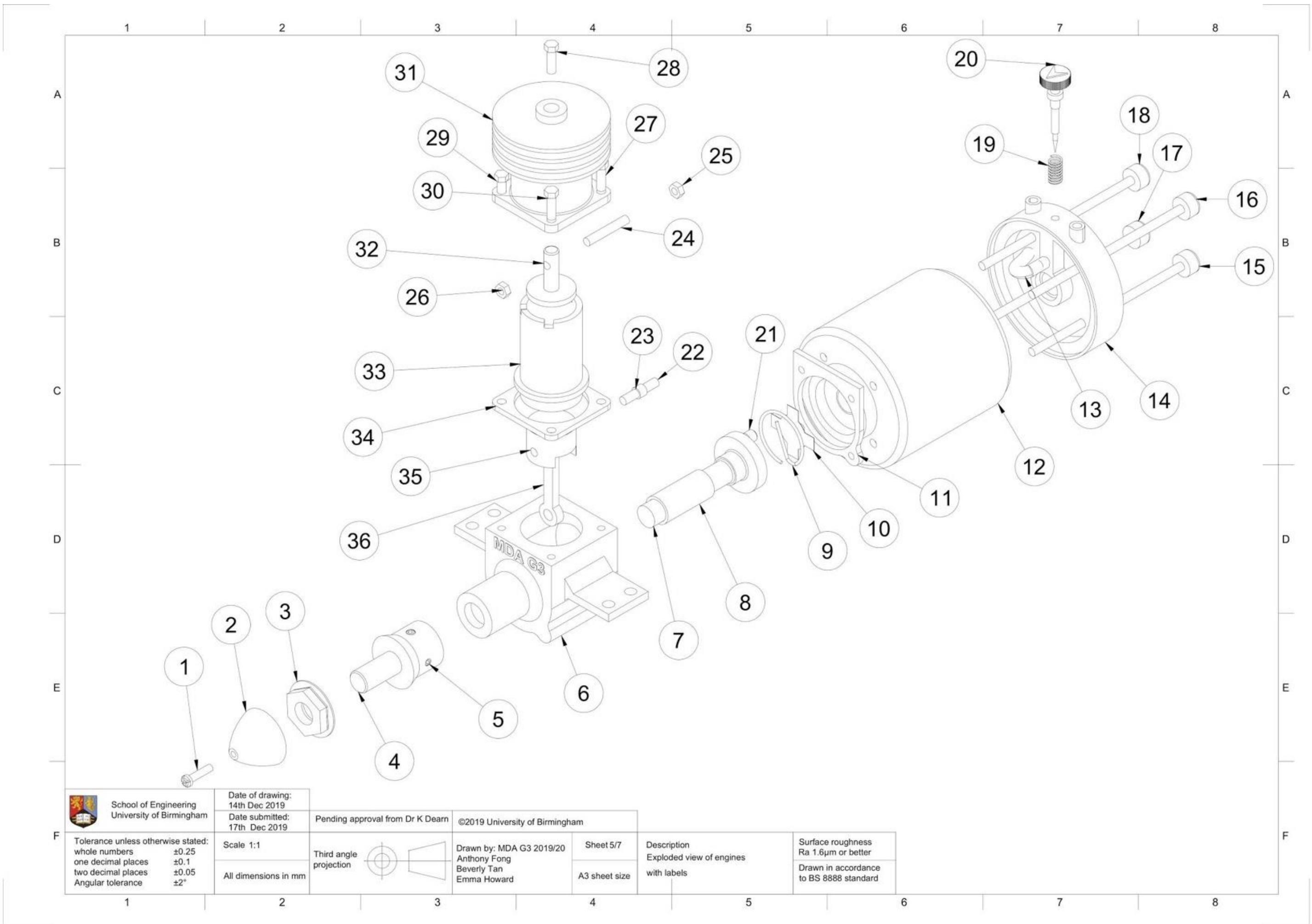


Figure 5: exploded view of whole engine

Design for Assembly Principles

- Minimal Number of Parts
- Parts with Obvious Locations or Self-locating features
- Parts with self-fastenings
- Minimal amount of reorienting components or complete body
- Smooth assembly design for retrieving, handling and inserting parts.
- Emphasis on Top-Down designs
- Standardized parts
- Modular Design
- Frame or base part for components
- Symmetry

MANUAL HANDLING-ESTIMATED TIMES (s)

Key: One hand; One hand with grasping aids

			Parts are easy to grasp and manipulate					Parts present handling difficulties (1)				
			Thickness >2 mm			Thickness ≤2 mm		Thickness >2 mm			Thickness ≤2 mm	
			Size >15 mm	6 mm ≤ size >15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm	Size >15 mm	6 mm ≤ size ≤15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm
			0	1	2	3	4	5	6	7	8	9
Parts can be grasped and manipulated by one hand without the aid of grasping tools	(α+β) < 360°	0	1.13	1.43	1.88	1.69	2.18	1.84	2.17	2.65	2.45	2.98
	360° ≤ (α+β) < 540°	1	1.5	1.8	2.25	2.06	2.55	2.25	2.57	3.06	3	3.38
	540° ≤ (α+β) < 720°	2	1.8	2.1	2.55	2.36	2.85	2.57	2.9	3.38	3.18	3.7
	(α+β) = 720°	3	1.95	2.25	2.7	2.51	3	2.73	3.06	3.55	3.34	4

				Parts need tweezers for grasping and manipulation								Parts need standard tools other than tweezers	Parts need special tools for grasping and manipulation
				Parts can be manipulated without optical magnification				Parts require optical magnification for manipulation					
				Parts are easy to grasp and manipulate		Parts present handling difficulties (1)		Parts are easy to grasp and manipulate		Parts present handling difficulties (1)			
				Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm		
				0	1	2	3	4	5	6	7	8	9
Parts can be grasped and manipulated by one hand but only with the use of grasping tools	α ≤ 180°	0 ≤ β ≤ 180°	4	3.6	6.85	4.35	7.6	5.6	8.35	6.35	8.6	7	7
		β = 360°	5	4	7.25	4.75	8	6	8.75	6.75	9	8	8
	α = 360°	α ≤ β ≤ 180°	6	4.8	8.05	5.55	8.8	6.8	9.55	7.55	9.8	8	9
		β = 360°	7	5.1	8.35	5.85	9.1	7.1	9.55	7.85	10.1	9	10

Figure 7: Estimated time for assembly requiring one hand

Key: Two hands for manipulation; Two hands or assistance required for large size

		Parts present no additional handling difficulties					Parts present additional handling difficulties (e.g. sticky, delicate, slippery, etc.) (1)				
		α ≤ 180°			α = 360°		α ≤ 180°			α = 360°	
		Size >15 mm	6 mm ≤ size ≤15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm	Size >15 mm	6 mm ≤ size ≤15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm
		0	1	2	3	4	5	6	7	8	9
Parts severely nest or tangle or are flexible but can be grasped and lifted by one hand (with the use of grasping tools if necessary) (2)	8	4.1	4.5	5.1	5.6	6.75	5	5.25	5.85	6.35	7

		Parts can be handled by one person without mechanical assistance									Two persons or mechanical assistance required for parts manipulation
		Parts do not severely nest or tangle and are not flexible								Parts severely nest or tangle or are flexible (2)	
		Part weight < 10 lb				Parts are heavy (>10 lb)					
		Parts are easy to grasp and manipulate		Parts present other handling difficulties (1)		Parts are easy to grasp and manipulate		Parts present other handling difficulties (1)			
		α ≤ 180°	α = 360°	α ≤ 180°	α = 360°	α ≤ 180°	α = 360°	α ≤ 180°	α = 360°		
		0	1	2	3	4	5	6	7	8	9
Two hands, two persons or mechanical assistance required for grasping and transporting parts	9	2	3	2	3	3	4	4	5	7	9

Figure 8: Estimated time for assembly requiring two hands

Part no.	Name	Theoretical part count	Assembly time	Revised assembly time
1	Case	1	50	20
2	Crankshaft	1	10.2	10.2
3	Main shaft bushing	1	7.4	3
4	Reed valve spring	1	8.9	6.7
5	Copper valve	1	7.5	5.2
6	Fuel tank seal	1	6.7	3.7
7	fuel tank cylinder	1	3	3
8	PVC tube	0	4.5	4.5
9	Backplate	1	3	3
10 to 13	M3x70 bolt	0	20.8	20.8
14	Spring	1	5.2	5.2
15	Needle	1	5.2	5.2
16	Crankshaft bushing	1	3	3
17	Gudgeon pin	1	20	7.5
18	M3 threaded rod	0	3.7	3.7
10 to 20	M3 Nut	0	7.4	7.4
21 to 24	M3x20 bolt	0	14.8	14.8
25	Cylinder heatsink	1	9.7	3
26	contrapiston	0	15	3
27	Cylinder sleeve	1	5.2	5.2
28	Cylinder seal	1	6.7	3.7
29	Piston	1	7.5	7.5
30	Conrod	1	9.7	9.7
	Total	17	235.1	159
	DFA index		21.7	32.1

Table 13: Calculation table for Design for Assembly Index, comparison between semester 1 and 2 The equations for DFA index is (Theoretical part count x 3)/ assembly time. The assembly time is based on estimates from figure 7 and 8

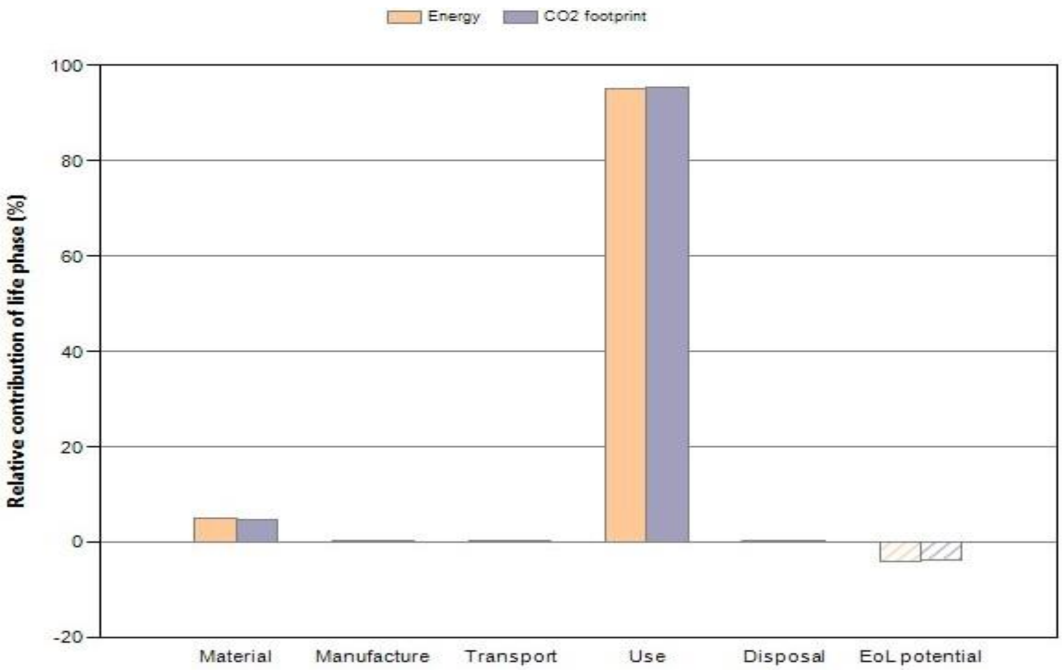
Process	Task No.	Description	Operations List
Primary Processes	1	Green Sand Casting, Automatic	(1) Creating the mold: Sand is molded around the pattern surrounded by a box, which is divided into two halves (top and bottom). Machinery is used to compress the sand to increase production rates. A cavity will form once the pattern is removed. The core used to create the internal surface is also made in a similar manner and placed in the cavity before the molten metal is poured.
			(2) Clamping: This prepares the sand mold for the molten metal. Lubrication is applied in the cavity and the cores are secured before the top and bottom halves of the mold are joined at the parting line. Molten metal will leek out if not clamped securely.

			(3) Pouring: Metal is heated in a furnace at constant temperature until molten. The molten metal is then poured into the clamped sand cast. The cast is filled to the brim to ensure all channels are covered. There is a short time frame before the molten steel solidifies. This is done using machinery.
			(4) Cooling: Depending on the wall thickness of the metal and the temperature, cooling times may vary. Once cooled, the metal will solidify.
			(5) Removing: The sand mold is broken and the core molding is shake out of the metal flask using a vibration machine. Remaining particles stuck on the metal surface is removed by shot blasting
			(6) Trimming: Excess metal solidified during the cooling process is removed through using a trimming press. (Die Casting Process, Defects, Design, 2020)
	2	Cold Closed Die Forging	A metal billet is placed between the upper and lower die. The die are brought together using a hydraulic press, and the metal billet is compressed into the contours of the die. The die is much like a mold that takes the shape of its intended form. The process is conducted at room temperature to increase the strength of the workpiece and the quality of the surface finish.
Secondary Processes	3	Boring, Drilling, Chamfering	The work piece is placed on the workspace of the milling machine. The boring/drilling/chamfering tool is attached to the mill and the cutting parameters are set. (Machining – Material removal processes, 2020)
Operations to Enhance physical Properties	4	Induction Hardening	The workpiece is held in place within an induction coil of suitable size. The workpiece is then heated by eddy currents produced by the high frequency electromagnetic fields. It is heated to its austenitic phase region and then cooled rapidly by gas or liquid jets. This produces a martensitic layer around the workpiece. The amount of hardening depends on the electromagnetic frequency applied.

Finishing Operations	5	Chemical Polishing	The workpiece is submerged in a phosphate based bath solution before being placed in a water bath to remove any remaining solution off the workpiece.

Table 14: Detailed manufacturing operations descriptions

6.3 Eco audit appendix



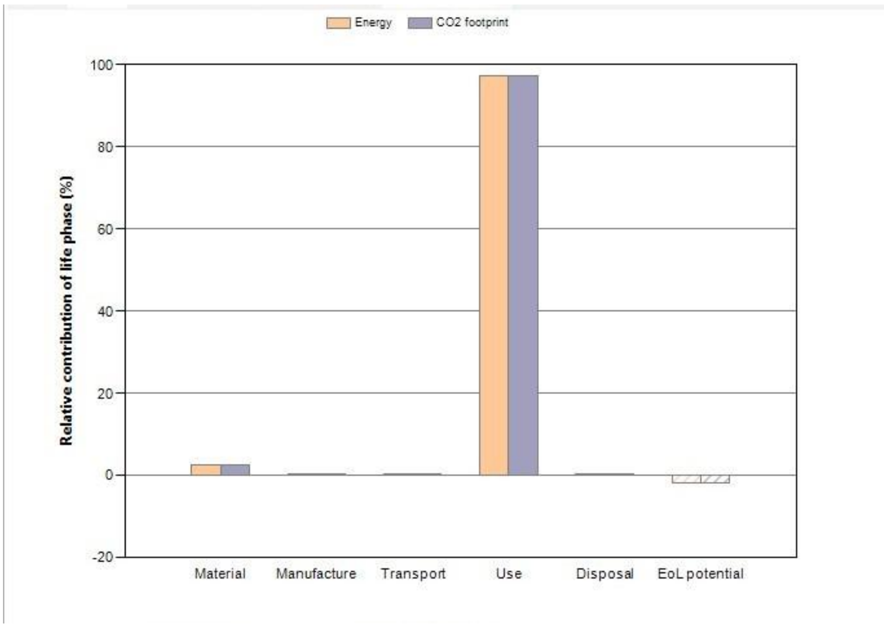
Graph 4: Energy consumption and CO2 footprint for each phase of life for the new Engine design with updated materials.

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	33.8	1.5	2.28	1.4
Manufacture	0.806	0.0	0.0604	0.0
Transport	12.3	0.5	0.888	0.5
Use	2.23e+03	97.9	158	98.0
Disposal	0.168	0.0	0.0118	0.0
Total (for first life)	**2.28e+03**	**100**	**162**	**100**
End of life potential	-27.7		-1.8	

NOTE: Differences of less than 20% are not usually significant. Page 1 / 3

See notes on precision and data sources. 17 March 2020

Table 15: Energy consumption and CO2 footprint values for each phase of life for the new Engine design with updated materials



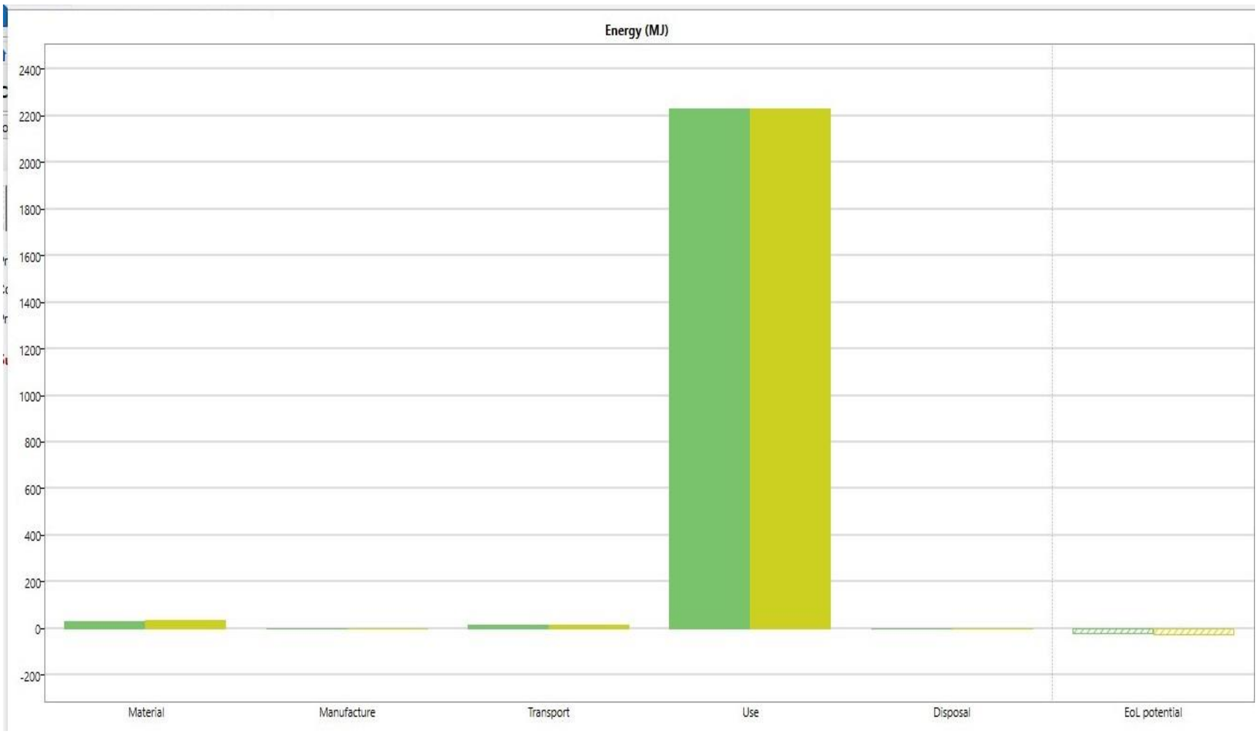
Graph 5: Energy consumption and CO2 footprint for each phase of life for the old Engine design

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	31.1	1.4	2.08	1.3
Manufacture	1.01	0.0	0.0755	0.0
Transport	12.3	0.5	0.888	0.6
Use	2.23e+03	98.0	158	98.1
Disposal	0.161	0.0	0.0112	0.0
Total (for first life)	**2.28e+03**	**100**	**162**	**100**
End of life potential	-22.9		-1.47	

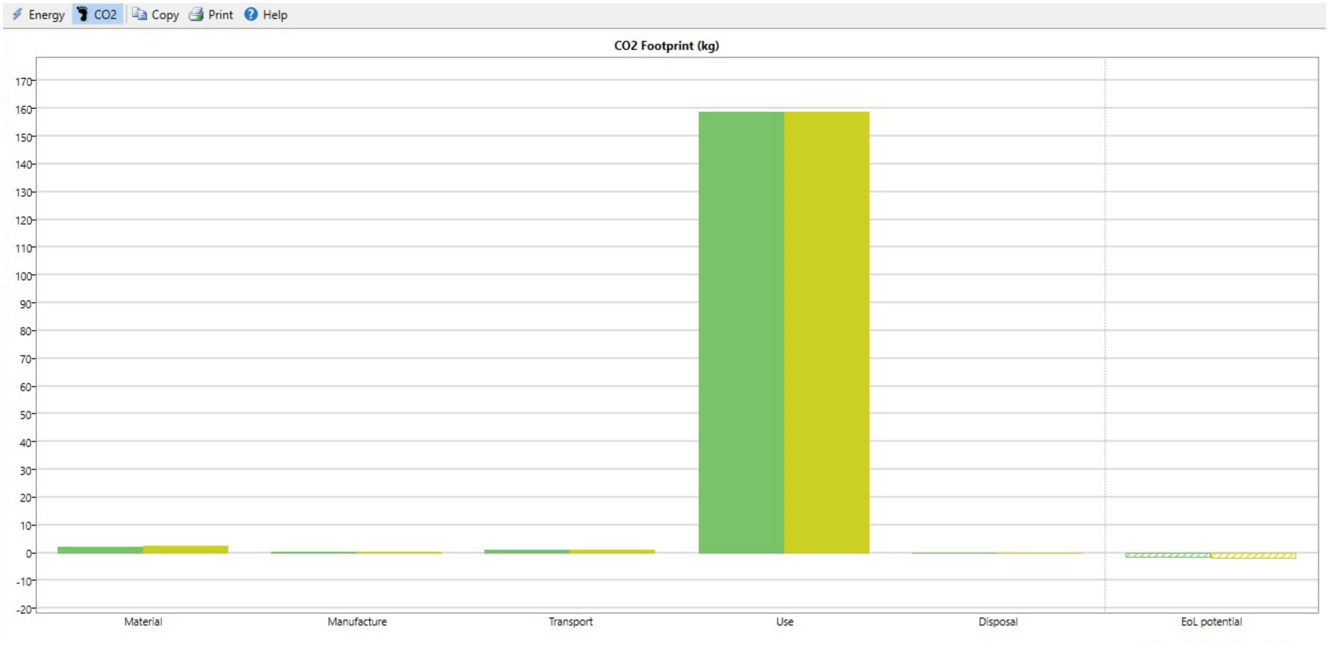
NOTE: Differences of less than 20% are not usually significant. Page 1 / 3

See notes on precision and data sources. 17 March 2020

Table 16: Energy consumption and CO2 footprint values for each phase of life for the old Engine design



Graph 6: Comparisons of the energy consumption for each phase for the original and new engine design



Graph 7: shows comparisons of the CO2 footprint for each phase for the original and new engine design

6.4 Conclusion appendix

Semester 1 features	Semester 2 features optimized for assembly
Lip on backplate to align with fuel tank cylinder	Lip with notch to align fuel tank with cylinder, so bolt holes will align
Lip on fuel tank valve when helping with insertion to crankcase	Lip with notch on fuel tank valve, ensure bolt hole align
Alignment notches of cylinder sleeve with heatsink, align exhaust ports	Added notch on valve to allow spring valve to press fit into slot
Contra piston is circumferential located using a thread on the heatsink	Added non threaded section to contra piston to aid assembly, hand threading
Bushing is held by shoulder on crankcase and crankshaft	Made the paper seals circular instead of square to allow it to align easier

Table 17: Engine assembly features in semester 1 and semester 2 models

7.1 Peer review table

Name	Contribution in their own words	Contribution level agreed with group with respect to the group average (high/normal/low/none)
Emma Howard	Compiled report, Critically analysed materials using Ces Edupack and made revised bill of materials. Conducted Eco audit reports.	high
King Fong	Part drawings, assembly drawings, section 2 assembly planning, conclusion design recommendations	high
Beverly Tan	Created parts routing sheet and operations list including machine, tooling, process parameters. Wrote summary of process selection and process description.	High

8.1 References

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