UNSW, School of Mechanical and Manufacturing Engineering

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Design for High Volume Manufacturing

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Course Coordinator – David Lyons

Group 22

Jason Clegg	*z5115189*	*z5115189@ad.unsw.edu.au*
Alexander Cunio	*z5204704*	*z5204704@ad.unsw.edu.au*
Joel Davis	*z5215383*	*z5215383@ad.unsw.edu.au*
Mohique Gajdhar	*z5204101*	*z5204101@ad.unsw.edu.au*
Dan Nguyen	*z5206032*	*z5206032@ad.unsw.edu.au*

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Course code: MMAN2130 **Course name:** Design and Manufacturing

Course Convenor name: Mr David Lyons **Assignment:** Assignment 2 – HV redesign

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FAMILY NAME	GIVEN NAME(S)	STUDENT ID	SIGNATURE
Alexander	Cunio	5204704	amcunio
Mohique	Gajdhar	5204101	
Jason	Clegg	5115189	
Joel	Davis	5215383	
Dan	Nguyen	5206032	

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ABSTRACT

The PP175 Vertical Displacement Pump prototype, with its received order of 24000 units from Mega Manufacturing Alpha Industries (MMAI), is redesigned for high-volume manufacturing (HVM) and this feasibility reported concerns the design process which consisted of the HV redesign, material selection process and process planning. The HV redesign saw merges of prototype pump parts, shelling and mechanism changes to reduce cost and assembly time; and implementation of features to reduce manufacturing defects. The material selection process consisted of translation, screening, ranking and documenting of multiple materials with respect to each prototype pump part where the selected material is ABS plastic on the basis of its rigidity, lightness, and cost per mass. The process planning researched and compared five different HVM methods (conventional machining, injection moulding, rotational moulding, resin-transfer moulding, and die casting) with the cost analysis of injection moulding and die casting. The selected HVM method is injection moulding due to its high yield rate of production, ease of manufacture, tolerance control, and overall cheaper total cost of production of $6.60 per unit.

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

1 INTRODUCTION

The purpose of this report is to conduct a feasibility study on the high-volume manufacturing (HVM) of the PP175 Vertical Displacement Pump as specified by Mega Manufacturing Alpha Industries. This report aims to professionally discuss the high-volume (HV) redesign features of the PP175 pump, material selection process and process planning of the pump based on the prototype pump built at Ultimo TAFE utilising hand-manufacturing methods. It is crucial to consider alternative HV designs, materials and manufacturing methods before HVM as it is in the best interest of the client to maximise profit.

The HV redesign process saw significant design changes and implementation of design features. The significant design changes were dependent on the following metrics for the rationale of HVM:

- Cost to manufacture
- Yield rate of manufacture
- Maximised lifetime of 65 million revolutions
- Scalability for higher volume manufacture
- Operation in dry and stable environments at room temperature and pressure (RTP)

The design features aimed to reduce potential manufacturing defects but were dependent on the recommended manufacturing method that is injection moulding and the recommended material that is ABS thermoplastic.

The material selection process identified the functional requirements, constraints, objectives and free variables of each required pump component for the basis of material selection calculations which utilised Ashby charts to screen for potential materials. The screened materials were then ranked depending on the criteria of the part then selected after a comparison of materials. Assumptions were made in the calculations to simplify the material selection process such as the shape of the parts to be modelled as simply supported beams and the fluid mechanics of air to be modelled as a spring.

The process planning researched five potential HVM methods and compared their advantages and disadvantages on the basis of the metrics with the selection of the two most suitable methods for cost analysis. The five potential HVM methods are: conventional machining, injection moulding, rotational moulding, resin-transfer moulding, and die casting. The two most suitable methods to undergo a cost analysis are: injection moulding and die casting. Gross assumptions were made in the cost analysis for the setup, production, material and machine costs as exact quotes on these costs vary greatly.

The HV redesign, material selection process and process planning are intrinsic to each other which is therefore not a linear procedure in the study for HV feasibility. The three processes therefore required extensive communication between each other to determine the optimal redesign features, material and manufacturing method for HVM.

2 HIGH-VOLUME RE-DESIGN

2.1 Rationale of HV Redesign

The PP175 Vertical Displacement Pump was redesigned and proposed for its suitability for the high-volume manufacturing (HVM) method of injection moulding of ABS thermoplastic. The redesign of the pump was to remain under the same functional specifications as the prototype as specified by Mega Manufacturing Alpha Industries [1], permitting the exclusion of GEN_04 and GEN_05 from the specifications; i.e. the pump does not have to contain five parts and the pump does not have to be made from a given material from the material list.

The redesign procedure of the pump consists of the analysis of the features of the prototype for its feasibility of HVM with the suggested manufacturing method and material impacting the result; the discussion of the changes made to the pump with respect to the metrics and dependencies; then the final features of the proposed redesign. These steps are respectively broken into sections 2.2, 2.3, and 2.4 which are discussed below.

2.2 Analysis of Prototype Pump

The prototype PP175 Vertical Displacement Pump was analysed in its advantages and disadvantages with respect to its features and the suggested HVM method in Table 2.1 below.

Table 2.1 – Features & Manufacturing Advantages & Disadvantages

Advantages		Disadvantages	
Feature	HVM	Feature	HVM
Base			
Constant thickness	No warping	No fillets	Warping, poor material flow & stress concentrations
Simple design	Reduces complexity of mould & HVM	Slots & holes	Increases complexity of mould
No undercuts	Easier removal from moulds	Thick section	Sinkholes
House			
Simple design	Reduces complexity of mould & HVM	No fillets	Warping, poor material flow & stress concentrations
No undercuts	Easier removal from moulds	No draft angle on the outside walls	Difficult to remove from mould
-	-	Thick section	Sinkholes
Piston			
Merged piston head and connecting rod	Reduces production of multiple moulds	No draft angle on connecting rod	Difficult to remove from mould
-	-	Slots & holes	Increases complexity of mould
-	-	No fillets	Warping, poor material flow & stress concentrations
-	-	O-ring groove undercut	Difficult to remove from mould
Cover			
Constant thickness	Reduced effect of hotspots	No fillets	Warping, poor material flow & stress concentrations
Simple design	Reduces complexity of mould & HVM	Thick section	Sinkholes
No undercuts	Easier removal from moulds	No draft angle on the outside walls	Difficult to remove from mould
Valve			
No undercuts	Easier removal from moulds	Two-part system	Requires production of multiple moulds

Injection moulding has considerable risk to direct cost expenses when manufacturing defects arise due to inadequate part designs. Hence, it is necessary to achieve the correct design before the first production [2].

Warping, poor material flow and stress concentrations are eliminated through the use of fillets where fillets allow a smoother even flow of the polymer therefore ensuring constant wall thickness around corners. Warping is the twisting of material due to uneven cooling rates. This is typically caused by nonuniform wall thickness and will cause a poorer surface finish, decreased material lifetime, and non-mating assembly. Poor material flow does not allow the mould to be fully filled which can therefore cause burn marks. Stress concentrations decrease the lifetime of the material as material failure typically occurs at the corners of a body. Fillets will be added to every edge and corner where required for even material flow, where the radius of the fillet is dictated by the following formulas [3], where t is the wall thickness (see equations 1, 2).

$$Interior\ Fillet\ Radius = 0.5 \times t\ mm \tag{1}$$

$$Exterior\ Fillet\ Radius = 1.5 \times t\ mm \tag{2}$$

Sinkholes are depressions that form in the material surface due to hotspots which are regions of the part cooling down slower than other regions. This is due to thick cross-sections which causes the same issues as warping. The presence of sinkholes can be eliminated by reducing the thickness of cross-sections or shelling of the body, base and cover.

Draft angles must also be considered when designing the part and mould as it allows the easier ejection of sections from the mould. Draft angles should be added to any vertical walls which will not allow the damage of the mould during ejection. This reduces the chances of manufacturing new moulds therefore saving maintenance time and decreasing unexpected cost expenditures. Draft angles will need to be utilised for the vertical walls of the piston, house and cover and follows the following rule-of-thumb, where h is the height of the wall (see equation 3).

$$Draft\ angle\ (^o) = \frac{h}{25}(mm) \tag{3}$$

The prototype however does have some advantageous features for HVM that will not be changed in the redesign process. The lack of undercuts observed in the base, housing, cover and valve will allow these parts to easily be ejected from the mould. Design simplicity was another desired feature already present in the body parts of the prototype. This decreased the complexity of the mould, and ultimately leads to a less costly manufacturing process. As a result, this aspect of the base, housing and cover did not require any alterations other than the minimisation of the thick section.

2.3 Discussion of HV Redesign Process

This section discusses the significant design changes of the prototype pump. These changes naturally follow on from the analysis of the prototype pump but with more concern on the metrics of the redesign.

To discuss the changes required to be made, the prototype pump is decomposed into systems that were fundamental to its function:

- Pump body
- Compressor
- Air input/output

These systems consisted of subcomponents that were explored in its options for HVM which is tabulated as a morph chart (Table 2.2 below).

Table 2.2 – Morph Chart for HV System Redesign

Subcomponent	Option 1	Option 2	Option 3	Option 4
Pump Body Shape	No change	Cylindrical	-	-
Pump Body Merges	No change	Merge base and house	Merge house and cover	Merge all body parts
Fasteners	No change	Snap fit	Threaded part	-
Compressor	No change	Shelled underside of piston head	Internally shelled piston	-
Valve Mechanism	No change	Flap	No O-ring	No spring & O-ring
Valve Ball Stopper	No change	Pin	Cap	-
Valve Body Merges	No change	Merge bottom valve with cover	Merge top and bottom valve with cover	-
Base Shape	No change	Decreased dimensions	-	-

With the cost of manufacturing as the primary metric for design and yield rate of manufacture as the secondary - parts of the pump body were merged to reduce the number of parts to manufacture reducing the variety of moulds required and decreasing assembly time to mate all the parts. The merged body parts were the: house and base; and cover and valves.

This decision allowed the simplification of the pump to opt for a screw-on lid therefore eliminating the need for off-the-shelf fasteners. The thread dimension to be used is M32x2.0 and is created within the mould. This thread dimension is in between the external diameter of 31mm for the body and the internal diameter of 33mm for the lid. This decreased the cost to purchase off-the-shelf components and further decreasing assembly time.

The original valve system consisted of a top valve to hold the internal ball and spring system inside the bottom valve. With the merge of the valves and cover, a simpler alternative of a pin stopper removed the need for a top valve, along with the off-the-shelf components of the O-rings and springs. This will greatly increase the yield rate of manufacture as valve production is eliminated with only the off-the-shelf components of a pin stopper and ball valve to be purchased.

The prototype pump had lots of excess material at the corners of its body. Therefore, the pump house shape was changed from a rectangular prism to a cylinder and the dimensions of the base minimised while still maintaining the functional specification (BASE_03) for the slots. The house, base and piston was to be shelled to decrease material usage and save cost and time to manufacture.

2.4 Proposed Design

With respect to the analysis of the prototype pump and discussion of changes, the pump body is revised to contain three parts:

- Body
- Lid
- Piston

This simplified the pump to consist of two subassemblies that are the compressor and build and three unique off-the-shelf components as portrayed in the assembly chart of Figure 2.1.

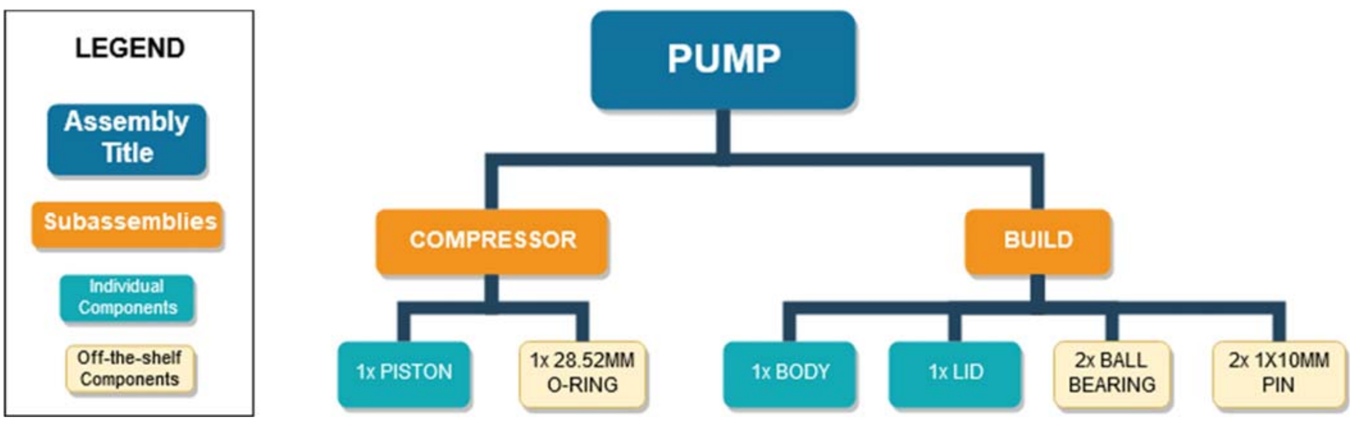

Figure 2.1 – Assembly Chart of HV Redesign

The mating of the pump components is shown as an exploded isometric view in the assembly engineering drawing in Appendix B.

2.4.1 Body

The thickness of the base of the body was at a constant 3mm to reduce the effects of hot spots and warping. To ensure constant thickness at the corner between the base and house, a fillet was added by calculation of equation 1 with the results tabulated in Table 2.3 below. The wall thickness varied between 3-6mm, therefore an approximate lenient wall thickness of 5mm was specified.

Table 2.3 – Fillet Calculations for Body

Fillet Location	Wall Thickness (mm)	Interior Fillet Radius (mm)	Exterior Filet Radius (mm)
Between Base and House	~5.00	2.50	-

No fillets were added to the piston chamber of the body so as to not create wedges for the piston head.

A draft angle was added to the vertical wall of the house of the body by calculation of equation 3. The result is tabulated in Table 2.4 below where the draft angle was rounded up for leniency on the ejection of the part from the mould.

Table 2.4 – Draft Angle Calculations for Body

Draft Angle Location	Vertical Wall Height (mm)	Draft Angle (degrees)
Outside Wall	30	2

The dimensions of the base were decreased from 100x70x10mm to 86.76x55x3mm with the shelling of thick sections to reduce the effects of sinkholes and increase efficiency of material usage. The 10mm hole in the base for the piston shaft was increased to 12 mm to increase the tolerance of the assembly.

The redesigned body of the PP175 pump is shown in drawing number 1 of Appendix A.

2.4.2 Lid

With respect to the mechanism of the valve, only two unique off-the-shelf components were required, that were: two 1x10mm pin stoppers and two 4mm balls. The pin stoppers were inserted into slots to allow the ball valves approximately 2mm of travel. This requires a minimum revolution per minute of 5.4 rpm (refer to Appendix C for the calculation), which means this measurement is suitable for specified motor (60-70 rpm).

The wall thickness of the lid was at a constant 1.5mm where the fillet calculations are tabulated in Table 2.5 below. The mouths of the valves were given 0.5mm radius fillets as to primarily reduce the stress concentration and impact loading due to the ball valve’s motion, therefore increasing the lifetime of the off-the-shelf component and lid.

Table 2.5 – Fillet Calculations for Lid

Fillet Location	Wall Thickness (mm)	Interior Fillet Radius (mm)	Exterior Filet Radius (mm)
Corner of Lid	1.5	0.75	2.25
Between Lid and Input Valve	1.5	0.75	2.25
Mouth of Input Valve	-	0.5	0.5
Between Lid and Output Valve	1.5	0.75	2.25
Mouth of Output Valve	-	0.5	0.5

A draft angle of 1 degree was added to the outside wall of the lid as by calculation of equation 3 and recorded in Table 2.6 below.

Table 2.6 – Draft Angle Calculations for Lid

Draft Angle Location	Vertical Wall Height (mm)	Draft Angle (degrees)
Outside Wall	18	1

The redesigned lid of the PP175 pump is shown in drawing number 2 of Appendix A.

2.4.3 Piston

The piston head diameter was kept the same with the O-ring groove depth of 2.5mm for the off-the-shelf component of a 28.52mm O-ring. The connecting rod of the piston was shortened to save material for a length of 56.5mm while still maintaining support for the stroke length range of 20-35mm.

Fillets (refer to Table 2.7) were added to maintain constant wall thickness except for the exterior corners of the piston head to maximise the volume of air displaced. The bottom of the connecting rod shaft had a radius of 2.67mm, therefore a lenient fillet radius of 4.00mm was added for a dome feature.

Table 2.7 – Fillet Calculations for Piston

Fillet Location	Wall Thickness	Interior Fillet Radius	Exterior Filet Radius
Bottom of Connecting Shaft	-	-	4.00
Piston Head	1.5	0.75	2.25
O-ring groove	1.5	0.75	-

A draft angle of 1 degree was added to both the interior and exterior walls of the connecting rod shaft to allow the easier ejection of the piston from the mould and maintaining a constant wall thickness (refer to Table 2.8). A draft angle of 1 degree was chosen instead of 2 as suggested from equation 3 so as to allow enough width at the bottom of the connecting rod shaft to have a 6mm hole feature whilst minimising the volume of the material.

Table 2.8 – Draft Angle Calculations for Piston

Draft Angle Location	Vertical Wall Height (mm)	Draft Angle (degrees)
Exterior Wall of Connecting Rod	56.5	1
Interior Wall of Connecting Rod	48.5	1

The redesigned piston of the PP175 pump is shown in drawing number 3 of Appendix A.

3 MATERIAL SELECTION PROCESS

This section outlines the material selection for the different components of the pump design. It is desired to merge two identical materials for multiple components as this will reduce manufacturing complexity. Furthermore, by using a single material for all components, only a single set of manufacturing equipment for that material is required to be purchased. As a result, a decrease in price and increase in productivity is predicted as an outcome of merging components.

3.1 Pump Prototype Translation

By looking at the different required components of the pump from the specification [1], Table A 1 in Appendix D provides an overview of the requirements, constraints, objectives, and free variables for each of these parts.

3.2 Cover

3.2.1 Screening

From Table A 1, the cover is required to withstand an internal chamber pressure of 10 666 Pa and endure at least 65 000 000 pressure cycles. From this information, calculations of the material's required Young's modulus (E) have been performed (see Appendix section 11.2). With these primary constraints, the cover's objectives include the cheapest net cost and shortest production time, as well as, to maximise the safety factor. In order to satisfy these objectives, the mass of the cover is desired to be minimised, while the cover's strength is maximised (Note: this desire exists for all components of the pump).

Assuming a cover volume of 4.81×10^{-6} and a maximum cover mass of 50 g, the maximum desirable density (ρ) is 10 386.68 kg/m^3 (found using equation 4). This cut-off density and Young's modulus value is applied to an Ashby chart in Figure 3.1.

$$\rho = \frac{mass}{volume} = \frac{m}{V} \tag{4}$$

This minimum calculated Young's modulus and maximum desired density is displayed by the outline in Figure 3.1, demonstrating the favourable materials for the cover.

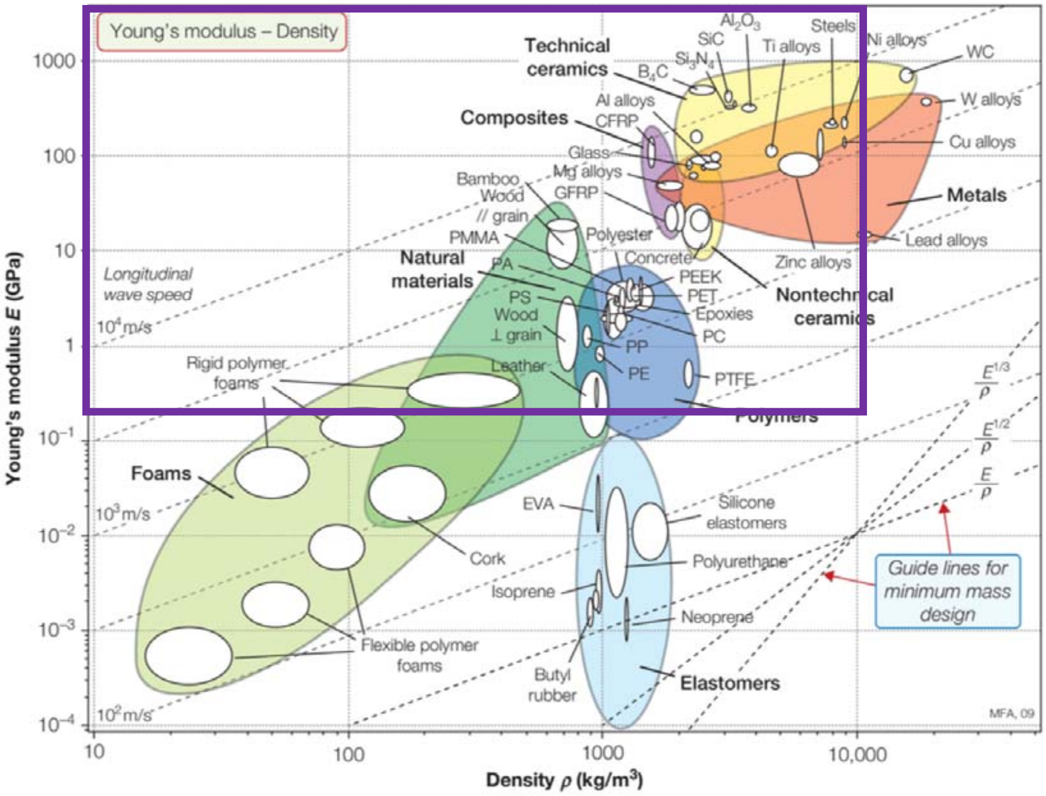

Figure 3.1 – Ashby chart comparing Young's modulus and density with markings for cover

3.2.2 Ranking

The material property index [4] is used to rank the materials identified by the rectangular box in Figure 3.1. By making the assumption that the cover is a beam loaded in bending with a free height, from Table 3.1, the index is $E^{1/3}/\rho$, whereby the specified constraint is stiffness and the objective is to minimise mass. From this, the preferred materials are those which exist in the upper left-hand corner of the rectangular box and at the greatest perpendicular distance from the corresponding line in Figure 3.1. In this case the two material families which best suffice this condition are the Natural Materials and rigid polymer foams.

Table 3.1 – Table of constraints for stiffness limited design for minimising mass[4]

Function and Constraints	Maximize
TIE (tensile strut)	
Stiffness, length specified; section area free	E/ρ
SHAFT (loaded in torsion)	
Stiffness, length, shape specified; section area free	$G^{1/2}/\rho$
Stiffness, length, outer radius specified; wall thickness free	G/ρ
Stiffness, length, wall thickness specified; outer radius free	$G^{1/3}/\rho$
BEAM (loaded in bending)	
Stiffness, length, shape specified; section area free	$E^{1/2}/\rho$
Stiffness, length, height specified; width free	E/ρ
Stiffness, length, width specified; height free	$E^{1/3}/\rho$
COLUMN (compression strut, failure by elastic buckling)	
Buckling load, length, shape specified; section area free	$E^{1/2}/\rho$
PANEL (flat plate, loaded in bending)	
Stiffness, length, width specified; thickness free	$E^{1/3}/\rho$
PLATE (flat plate, compressed in-plane, buckling failure)	
Collapse load, length, width specified; thickness free	$E^{1/3}/\rho$
CYLINDER WITH INTERNAL PRESSURE	
Elastic distortion, pressure, radius specified; wall thickness free	E/ρ
SPHERICAL SHELL WITH INTERNAL PRESSURE	
Elastic distortion, pressure, radius specified; wall thickness free	$E/(1-\nu)\rho$

3.2.3 Documentation

Cover material Pugh's Matrix

Table 3.2 provides an analysis of the possible materials for the pump cover, comparing particle board and ABS thermoplastic through a Pugh's matrix.

Table 3.2 – Pugh's matrix comparing ABS thermoplastic and Particle Board

Objectives	Relative Weight (%)	Weighting (out of 10)	Particle Board	Datum (Note: datum is ABS Thermoplastic)
Cheapest Net Cost for 24,000 units	40	8	+1	0
Shortest production time	10	2	-1	0
Suitable for HV manufacturing methods	40	8	-1	0
Scalability	10	2	-1	0
Score	-	-	-2	0
Weighted Score	-	-	-4	0

Endurance Limit

Natural Material (e.g. woods): Inexpensive woods such as MDF, OSB, plywood and particleboard, survive over 1 million fatigue cycles at 30% of their respective ultimate tensile strengths. The wood among this group with the lowest ultimate tensile strength is $1.04 \times 10^7\ Pa$ (particleboard), which is significantly above the predicted maximum bending stress (see Appendix section 11.3). However, the predicted maximum bending stress for the cover is approximately 70% of the ultimate tensile strength of particle board. From the above statement of particleboard achieving 1 million fatigue cycles at 30% of its ultimate tensile strength, this greater stress allows for the inference that it will not achieve the full 65 million fatigue cycles.

Polymers (ABS): An example of polymers are the thermoplastics ABS and PC-ABS, which are especially common in high-volume manufacturing [5]. At standard temperature and pressure, both these two thermoplastics can endure infinite cyclic loading below 11 MPa [6], which is much greater than the maximum predicted bending stress of the cover.

Ultimately the polymer family's superior endurance limit properties, as well as, high volume manufacturing advantages, making them a better option than natural materials. By looking at Figure 3.2, the higher upper stiffness of ABS over PC provides it as the best choice.

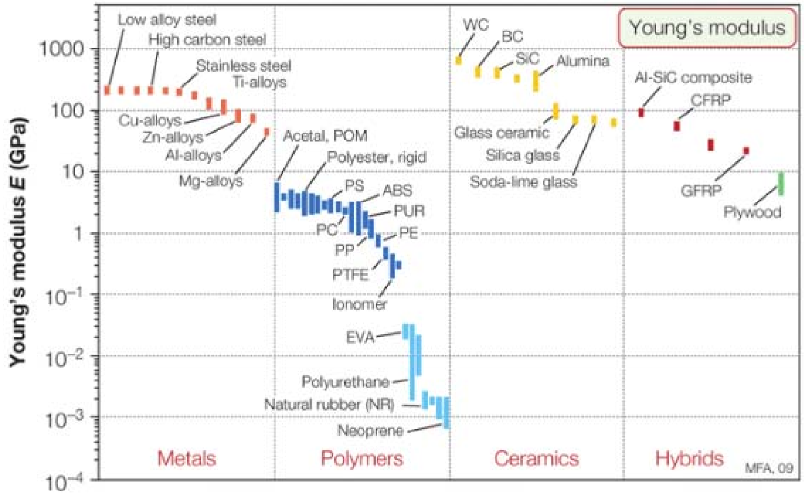

Figure 3.2 – Bar chart of material Young's modulus [4]

3.3 Housing

3.3.1 Screening

Similar to the pump cover, Table A 1 demonstrates that the housing should be designed to have a minimum mass and greatest safety factor. From Appendix section 11.4, the maximum predicted hoop stress of the housing is 86280.2 Pa. The desired density should be similar to that of the cover (10386.7 kg/m^3) which has been identified as a reasonable value to ensure low mass.

Using this information, a stress versus density Ashby chart has been implemented to identify potential housing materials in Figure 3.3.

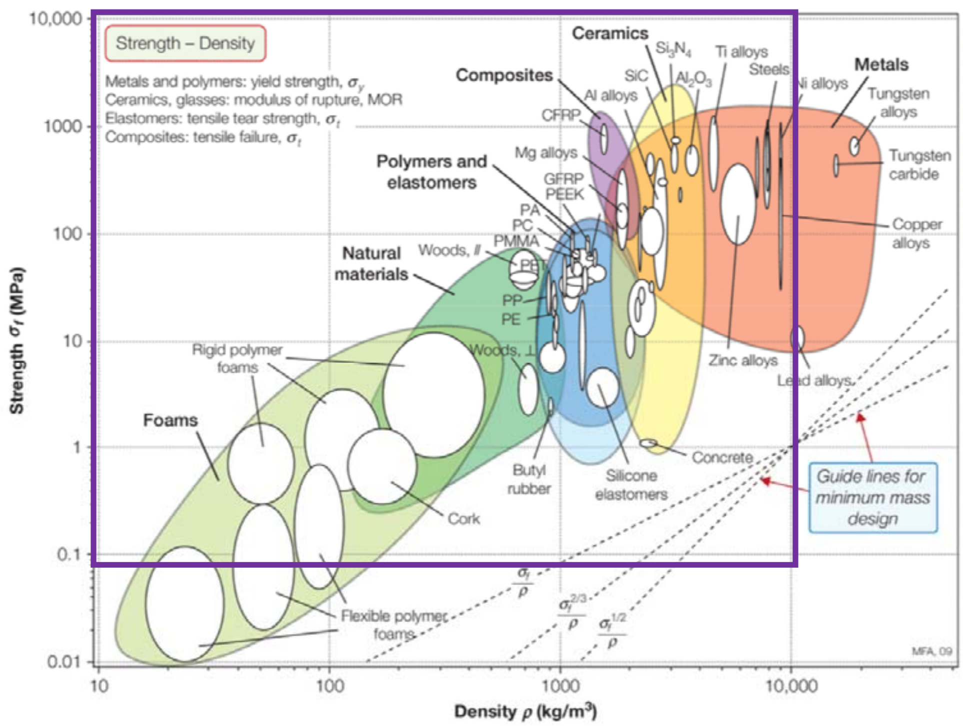

Figure 3.3 – Ashby chart comparing strength and density with markings for cover

3.3.2 Ranking

As identified in Figure 3.3, the families of polymers and natural materials appear once again within the bounded region. These can be seen as the superior alternatives (above others within this region) by looking at the material indices. The housing is estimated as a cylindrical pressure vessel, having a specified inner radius and a free variable of wall thickness. This provides a minimising factor of ${\sigma_f}/{\rho}$ (see Table 3.3).

Table 3.3 – Material indices for minimising mass for strength-limited design [4]

Function and Constraints	Maximize
TIE (tensile strut)	
Stiffness, length specified; section area free	σ_f/ρ
SHAFT (loaded in torsion)	
Load, length, shape specified; section area free	$\sigma_f^{2/3}/\rho$
Load, length, outer radius specified; wall thickness free	σ_f/ρ
Load, length, wall thickness specified; outer radius free	$\sigma_f^{1/2}/\rho$
BEAM (loaded in bending)	
Load, length, shape specified; section area free	$\sigma_f^{2/3}/\rho$
Load length, height specified; width free	σ_f/ρ
Load, length, width specified; height free	$\sigma_f^{1/2}/\rho$
COLUMN (compression strut)	
Load, length, shape specified; section area free	σ_f/ρ
PANEL (flat plate, loaded in bending)	
Stiffness, length, width specified; thickness free	$\sigma_f^{1/2}/\rho$
PLATE (flat plate, compressed in-plane, buckling failure)	
Collapse load, length, width specified; thickness free	$\sigma_f^{1/2}/\rho$
CYLINDER WITH INTERNAL PRESSURE	
Elastic distortion, pressure, radius specified; wall thickness free	σ_f/ρ
SPHERICAL SHELL WITH INTERNAL PRESSURE	
Elastic distortion, pressure, radius specified; wall thickness free	σ_f/ρ
FLYWHEELS, ROTATING DISKS	
Maximum energy storage per unit volume; given velocity	ρ
Maximum energy storage per unit mass; no failure	σ_f/ρ

From Figure 3.3, it can be observed that the material family perpendicularly furthest from the drawn line of gradient ${\sigma_f}/{\rho}$ (towards the upper-left hand corner) are natural materials. However, as discussed in section 3.2, economic natural materials are likely not to have adequate endurance limits. Thus, with the desire to converge to a single material, the knowledge that ABS plastic is suitable as a cover, it is decided that further inquiry should be performed into the usage of the polymer family to serve as the housing material.

3.3.3 Documentation

There are numerous thermoplastics which are very applicable to HV manufacturing. These include HDPE, PVC, PP, Nylon, PC/ABS, ABS and PC (see comparison of these in Figure 3.4).

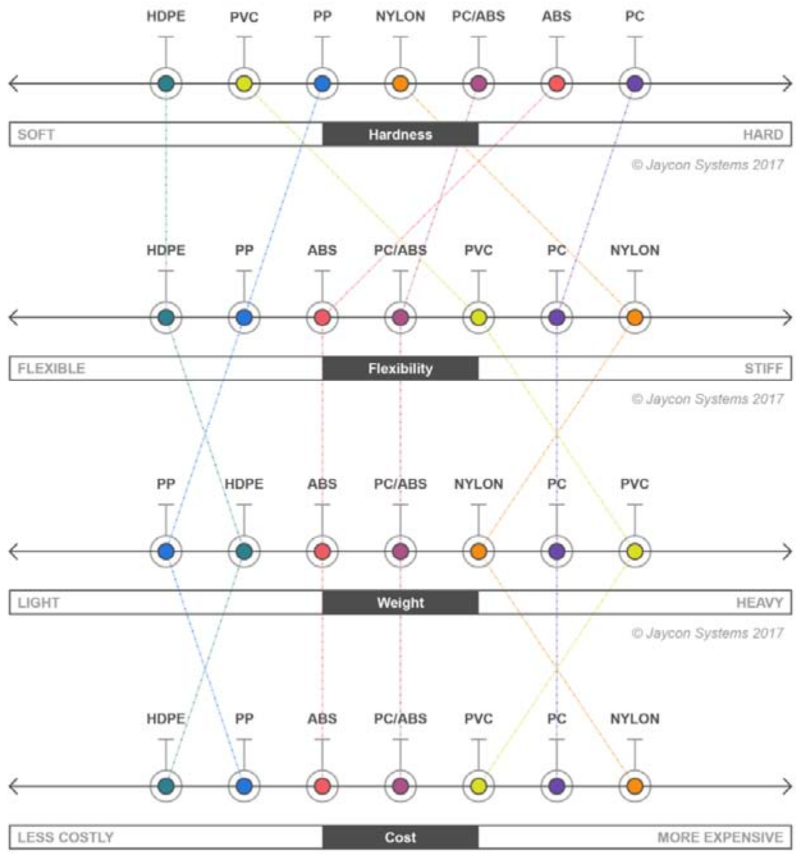

Figure 3.4 – Comparison of advantages and disadvantages of common polymers [7]

From this comparison, as it is desired that the housing thickness is minimal, a relatively stiff material is preferred, ruling out HDPE and PP due to their flexibility. All of PVC, Nylon, and PC are potentially suitable materials due to their stiffness, though being heavier and more expensive than ABS they are not as suitable.

Ultimately, all thermoplastics discuss share disadvantages and advantaged over ABS. However, no thermoplastic addressed is overwhelmingly more beneficial over ABS in respect to the objectives of the housing. Thus, ABS is chosen as the superior housing material.

Cracking

A strong concern of the pump is loss of air pressure due to cracks. This is most critical for the housing as it is the largest and hence, most expensive component of the redesigned pump. A fracture analysis has been performed on the housing in order to investigate whether ABS plastic is resistive to failure by cracking under the specified pump conditions (see Appendix section 11.5).

The maximum stress experienced by the housing is $86\ 280.22\ Pa$ (see Appendix section 11.4), which is much less than the above calculated stress required to fail the housing due to fracture failure ($13\ 498\ 841.14\ Pa$). Thus, it can be observed that the ABS plastic housing will not experience a stress that will cause unstable fracture propagation if a 2mm crack were to appear in the housing.

3.4 Valves

3.4.1 Screening

A similar screening process can be carried out from the pump metrics in Table A 1, having similar objectives to decrease mass (and hence cost) and maximise the safety factor between maximum stress experienced by the valves and yield stress of the chosen material.

From the calculations in Appendix section 11.6, the maximum stress exerted on the valves is shear stress of magnitude 12 443.7 Pa. Along with the desire to retain a similar density material as in 1.1, materials are screened using a stress versus density Ashby chart (Figure 3.5 – Ashby Chart comparing strength and density – purple line encloses desired material property), demonstrating minimum requirements.

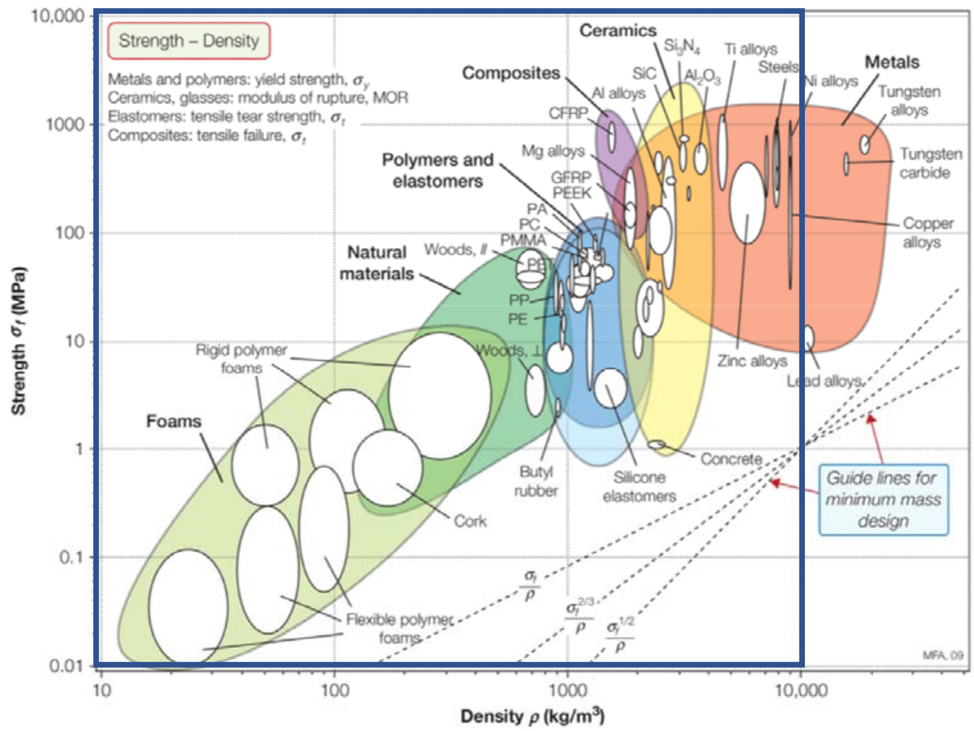

Figure 3.5 – Ashby Chart comparing strength and density – purple line encloses desired material property

3.4.2 Ranking

From the Figure above, it is evident that many material families pass the screening process. The property index used to rank these material families is σ_f / ρ (using the assumption of the valves as a cylindrical pressure vessel). It is apparent that the Polymers and elastomers family are is a suitable material as it exists perpendicularly furthest from the property index function and within the allowable materials boundary.

3.4.3 Documentation

Refer to section 3.2.3 for justification of using ABS Plastic for the valves as oppose to other thermoplastics.

3.5 Base

3.5.1 Screening

It can be seen from Appendix section 11.7 that the minimum Young's Modulus (E) of the base to ensure all constraints are met is 0.885 GPa. Again, the mass of the base is desired to be minimal to satisfy objectives regarding cost and production time. Using the density value of 10 386.68 kg/m^3, the Ashby chart in **ss** can be used to identify suitable materials for the base.

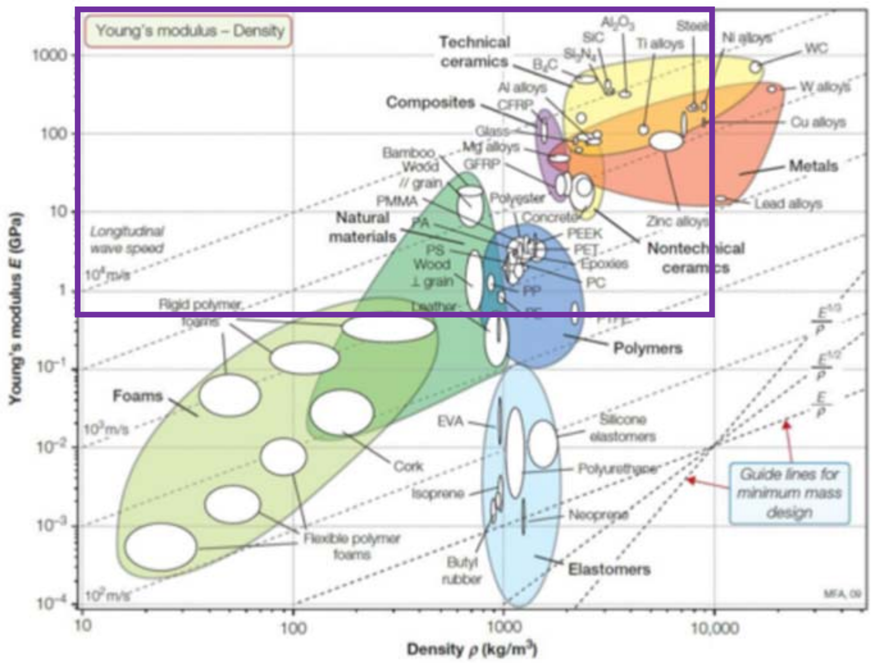

Figure 3.6 – Ashby Chart comparing Young's modulus and density – purple line encloses desired material property

3.5.2 Ranking

The property index for minimising mass for strength-limited design (Table 3.3) used to rank these material families inside the purple box in Figure 4.2.1 is $\frac{\sigma^{\frac{1}{2}}}{\rho}$. This correspond to the approximation of a beam loaded in bending with a stiffness constraint, minimising mass with a free variable of section area. The polymers and natural material appear as the best suited materials as they exist perpendicularly far from the property index function and towards the top left-hand corner of the allowable materials boundary box.

3.5.3 Documentation

Refer to section 3.2.3 for justification of using ABS Plastic for the base as oppose to other thermoplastics or natural materials. In addition, using ABS as the base material is desirable as it allows for the merging with other components.

3.6 Piston

3.6.1 Screening

Again, Table A 1 demonstrates the requirement for the piston to endure at least 65 000 000 pressure cycles, as well as experiencing the pressure from the air pressure, however it must also withstand additional pressure from the compression by the motor. The objectives include the cheapest net cost and shortest production time, as well as, to maximise the safety factor. It has been calculated that the maximum allowable stress exerted on the piston is to be $0.639\ MPa$ (Appendix section 11.8). Using the desired density of $10\ 386.68\ kg/m^3$, an Ashby chart in Figure 3.7 has been utilised to screen for viable materials.

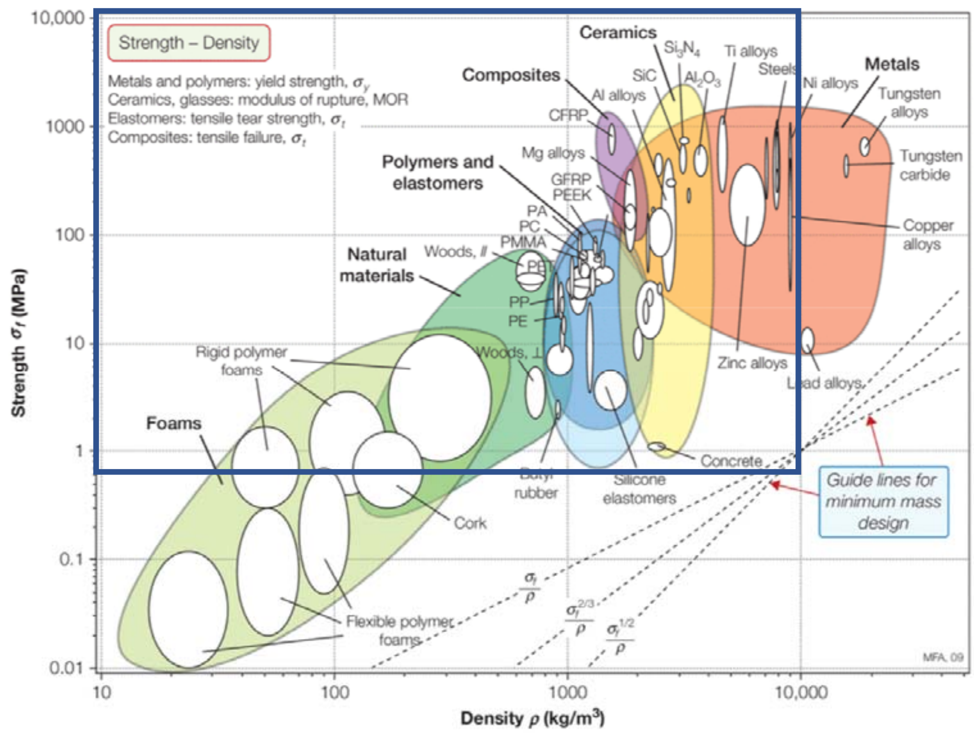

Figure 3.7 – Ashby Chart comparing strength and density – purple line encloses desired material property

3.6.2 Ranking

As similarly found in previous components, there are a plethora of materials which pass the screening process. As the piston is the only moving component, it will experience the greatest wear, which is linked to the hardness of the material (related to Young's modulus) [8], with this relationship shown in Figure 3.8.

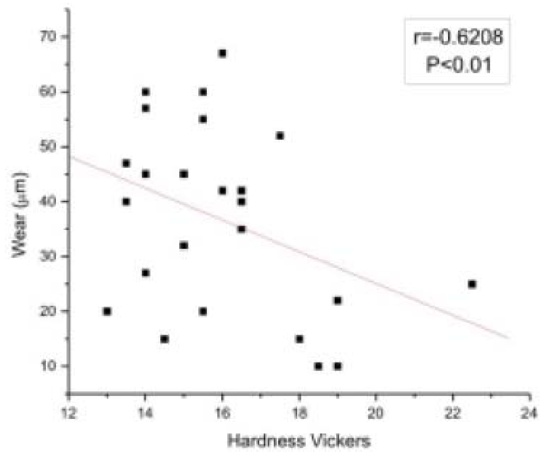

Figure 3.8 – Scatter plot of relationship between material hardness and wear

As a result of this relationship, the strength of material and Young's modulus should be maximised. Using property indices in Table 3.3, this provides the relationship σ_f/ρ, corresponding to the approximation of the piston as a column loaded in compression. Once again, Polymers, metals, and metal alloys are suitable materials, since these families exist perpendicularly far from the property index function and within the allowable materials boundary.

3.6.3 Documentation

While metals are a valid choice for the piston, their increased mass and price compared to thermoplastics along with the desire to have components of similar material, means it would be ideal for polymers to be used for the piston.

Refer to section 3.2.3 for justification as to why ABS is chosen for piston material over other thermoplastics.

3.7 Additional Information

Friction

The maximum relative coefficient of dynamic friction of ABS compared to metals does not reveal any strong reason to use metals over ABS in order to reduce frictional forces. To elaborate the coefficient of dynamic friction of ABS, steel, aluminium and copper are 0.5, 0.57, 0.47 and 0.36. Thus, the small variance of these values, as well as, noting that the side forces of the piston with the base are assumed to be similar in the case of both an ABS and metal piston, suggests that there is no strong benefit in using metals over ABS in order to reduce frictional forces [9]. Additionally, since dry rubbing between components of similar coefficients of kinetic friction can be an issue for binding, lubricant will be added to avoid this.

Economics

From all material property charts documented in this section, it is apparent that the metals family have good material properties in respect to the pump component functions. The only noticeable drawback when observing the Ashby charts is that the metals are high in density, thus are unreasonably heavy. The predominant reason why metals such as aluminium were not chosen as the piston material is the extra cost this choice would incur. It has been previously decided for all other pump components that the plastic, ABS, is viable. This decision has the effect of allowing the merging of components, however, it also means that a single thermoplastic injection moulding machine needs to be purchased. If the piston was chosen to be made of aluminium, another production (die casting) machine will need to be acquired which will increase costs.

3.8 Conclusion

ABS (Acrylonitrile butadiene styrene) thermoplastic is a suitable material for all pump components. As a result, merging of components is possible. It has been decided that the two valves and cover will be merged, the housing and base will be merged, and piston remain as an individual component. While the base, housing, cover, and valves could all have been combined, the requirement to insert the piston into the pump body means that there must be a separation, with this resulting in the design in 2. Ultimately, this smaller number of components will result in fewer moulds required to be designed and a simpler assembly line, thereby decreasing costs and increasing productivity.

4 PROCESS PLANNING

4.1 Research on Relevant HV Manufacturing Methods

4.1.1 Conventional Machining

Background

Machining is any of the various processes in which a piece of raw material is cut into a desired final shape and size by a controlled material-removal process. It is a part of the manufacture of many metal products, but it can also be used on materials such as wood, plastic, ceramics and composites. Conventional machining involves direct contact of tool and work-piece. Almost all engineering components, whether made of metal, polymer, or ceramic, are subjected to some kind of machining during manufacture. Metals differ greatly in their machinability, a measure of the ease of chip formation, the ability to give a smooth surface, and the ability to give economical tool life. Poor machinability means higher cost [4].

Process

There are a variety of techniques and forms of conventional machining that are able to be used (see Figure 4.1). In turning and milling, the sharp, hardened tip of a tool cuts a chip from the workpiece surface. In drawing, blanking, bending and stretching, a sheet is shaped and cut to give flat and dished shapes. In electro-discharge machining, electric discharge between a graphite electrode and the workpiece, submerged in a dielectric such as paraffin, erodes the workpiece to the desired shape. In water-jet cutting, an abrasive entrained in a high speed water-jet erodes the material in its path [4].

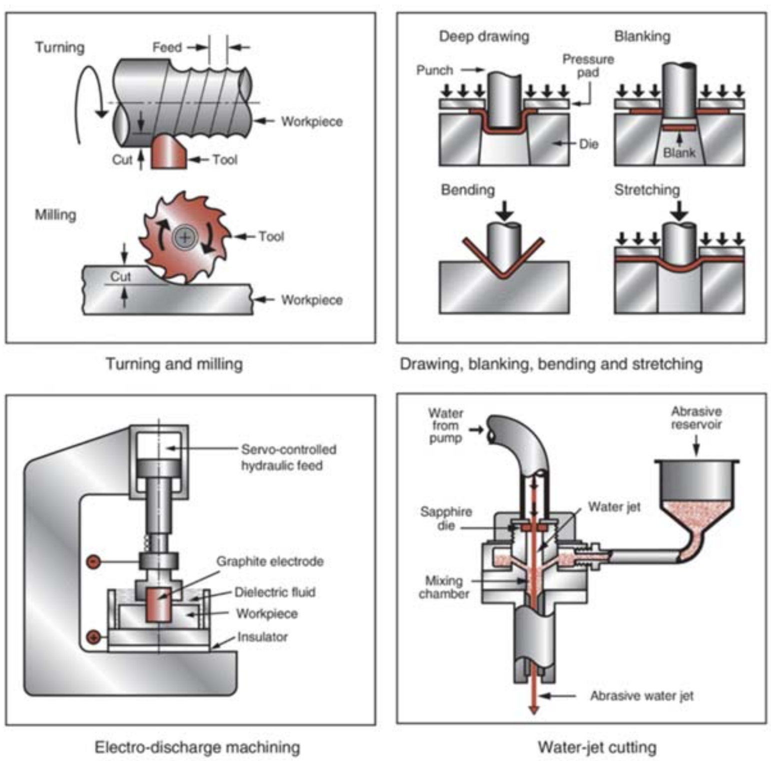

Figure 4.1 – Machining processes [4]

Advantages [4]

- A high surface finish can be obtained
- Good dimensional accuracy
- Lower capital cost
- Easy set-up of equipment

Disadvantages [4, 10]

- Conventional machining of fibre-reinforced composites is difficult due to diverse fibre and matrix properties, fibre orientation, inhomogeneous nature of the material, and the presence of high-volume fraction of hard abrasive fibres in the matrix.
- The accuracy of the components produced is dependent on the efficiency of the operator
- The consistency in manufacturing is not present
- Frequent design changes in the component cannot be incorporated in the existing layout
- Tool life is less due to high surface contact and wear
- Higher wastage of material
- Operation time is longer

Pump Components

Conventional Machining can also be used to produce any of the three parts of the HV pump.

ABS can easily be machined with common machining techniques which include turning, drilling, milling and sawing. It can be cut with standard shop tools and line bent with heat strips. Machining will particularly be easy for making the lid as it is a complex shape (see drawing 2 of Appendix A). The requirements of machining fibre reinforced plastics include a sharp cutting edge to shear effectively the fibres, low material removal rates, and lower temperatures than those encountered in metal machining [11]. Hence, machining is not as feasible due to the longer operational time while generating high material waste.

4.1.2 Injection Moulding

Background

The injection-moulding process has been in use for nearly 150 years. Reciprocating screw injection-moulding machines were introduced in the 1960s and are still used today [12]. It is a technology for manufacturing complex, precision, net-shape components for use in medical, automotive, industrial, firearms, and consumer industries. The potential of injection moulding lies in its ability to capture the shaping advantage offered by injection moulding by using a starting mixture of fine metal powder and organic binder. This technology provides advantages of cost-reduction at volumes ranging from a few thousand to over millions of parts per year due to its ability to hold close tolerances [13].

Process

The injection-moulding machine (see Figure 4.2) comprises an injection unit, where the material is prepared for injection into the mould, and a clamping unit, where the injected plastic is captured in the mould under conditions of temperature and pressure to form the finished product. In the early machines, the injection unit was a piston travelling in a heated cylinder. The raw material was fed into a cylinder, and the material came to process temperature by thermal conduction. Modern machines use extrusion technology. The screw uses geometry and drive motor power to do work on the material, generating frictional heat. This provides rapid and effective heating, and mixes the material [12].

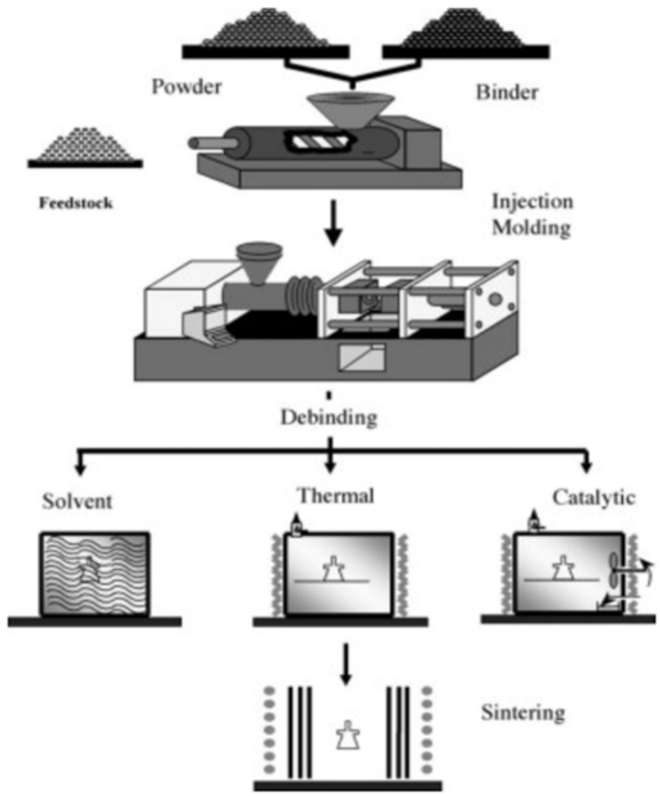

Figure 4.2 – Process schematic of injection moulding [13]

Advantages [14]

- High efficiency - faster production
- Ability to handle complex part design
- Enhanced strength
- Flexibility - material and colour
- Reduced waste
- Low labour costs
- Smoother finish
- Good dimensional control
- Can be used to produce smaller parts

Disadvantages [12, 14]

- High initial tooling and machinery cost
- Not economical for lower volumes
- Part design restrictions

Pump Components

Injection moulding is suitable to manufacture our pump because of its ability to handle complex part design. ABS can easily be injection moulded. It will result in a smoother finish with a good dimensional control. It has high initial tooling and machinery cost, but after that its economically viable (as 24000 units are being produced).

4.1.3 Rotational Moulding

Background

Rotational moulding is a process of production used for forming elastomers, thermoplastics, thermosets, and polymer foams into dished sheets or hollow three-dimensional shells (see Figure 4.3, Figure 4.4) [4]. While primarily used for hollow objects, these shells are able to contain complex forms without the seams or joins present in other processes [15]. This method of production does not rely on pressure for the insertion of molten material into the mould (unlike other processes, including injection moulding), not producing a high degree of accuracy in tight corners, instead relying simply on heat and the rotation of the mould for the material to be taken up by the mould [16].

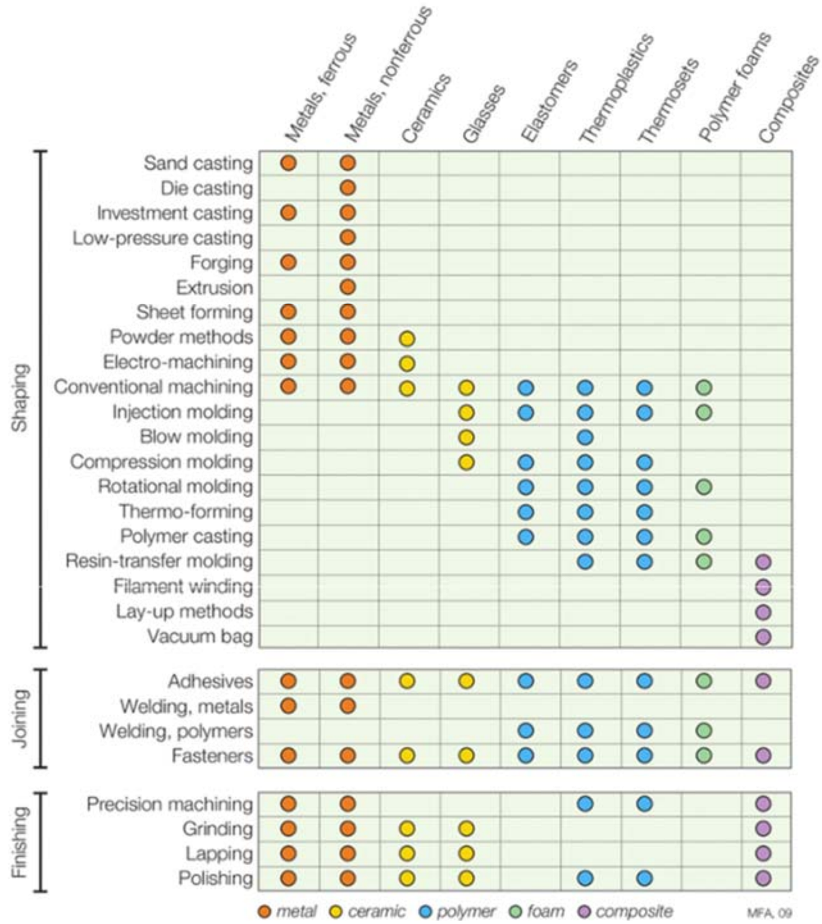

Figure 4.3 – Process-material matrix [4]

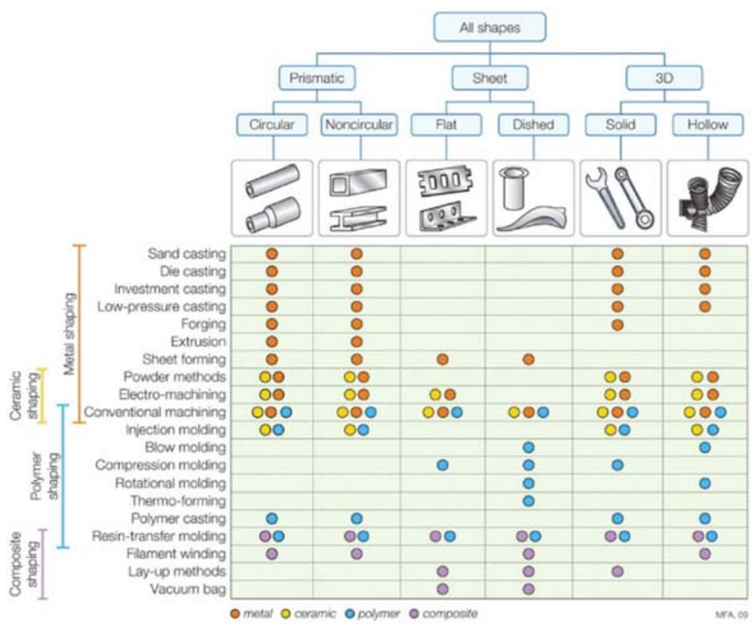

Figure 4.4 – Process-shape matrix [4]

Process

Rotational moulding involves four major steps, where the machining is conducted with the raw materials (as a powder, granules, or a viscous liquid) and a mould (usually aluminium, steel, or nickel chosen for their rigidity with heating cycles and good thermal conductivity) placed within a moulding machine [15, 17, 18]. The first step involves loading a measured amount of the raw material into the mould, which is sealed within the machine. This is heated externally in order to melt the material, while simultaneously being rotated so that it is distributed around the inner walls of the mould, forming a thin-walled vessel. Following this, the mould is allowed to cool, with the mould continuing to rotate, so that the shape is solidified. During the cooling the product will also shrink by some amount, helping to release it from the mould. The final stage of production is removing the part from the mould. Care must be taken in the choice of temperatures and rotation speeds about two different axes so that the desired properties are produced. A summary of this production process can be seen in Figure 4.5.

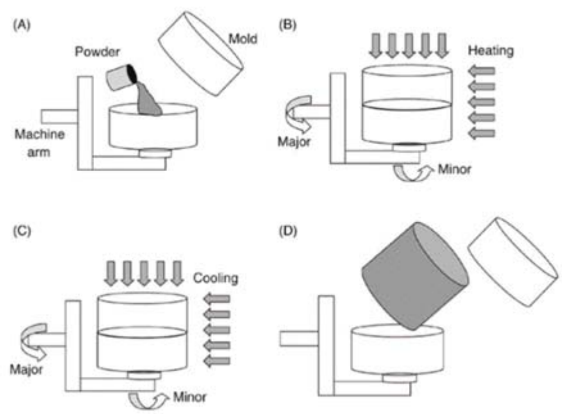

Figure 4.5 – Four steps of rotational moulding (Loading, Heating and rotating, Cooling, Unloading) [15]

Advantages [15-18]

- Ideal for the production of larger hollow shells, not requiring a seam or fill point
- Low-cost moulds as they do not need the rigidity of those for other methods which function under high pressure
- Easy to produce uniform thin-walled vessels, with the ability to vary this thickness by changing parameters for the production process
- Limited scrap material/wastage as all material added to moulds is used to form final part
- Easy to make colour changes
- Moulds can be changed out within a single machine easily and quickly to allow multiple parts to be made
- Can be used to produce parts with a large range of sizes
- Low pressure required for production

Disadvantages [15-18]

- Amount of material for each part must be calculated and carefully measured each time the process is run to ensure consistency
- Process is relatively time consuming with a slow cycle time taking significant amounts of time to heat and cool for each part, meaning that it is most economical for low quantity production
- Higher material costs (must be made into a powder)
- Intricate shapes and solid objects cannot be produced
- Limited range of production materials
- Reasonably labour intensive (needing to load and unload moulds with each piece)
- Additional release agents required so part doesn't stick to mould, increasing operator involvement and costs
- Large, flat surfaces warp when produced
- Lower accuracy in final dimensions as part can shrink when cooling

Pump Components

Rotational moulding would not be ideal for the production of the pump body because, although it provides uniform parts without the need for fill points and does not require high pressure adding additional stress to the components, the method is only used for the production of hollow shells. While this part does contain some features that are a hollow shell (the upper housing), the entire part is not a single shell meaning that it would not be suitable.

Both the piston and lid could be produced through rotational moulding as they could be designed as hollow components with a constant wall thickness, however there are other production methods that could provide better alternatives stemming from the increased production time for this process along with the increased cost due to increased labour and its ideal purpose for larger flatter surfaces.

4.1.4 Resin-transfer moulding

Background

Resin-transfer moulding (RTM) is a process of manufacturing thermoplastics, thermosets, polymer foams, and composites to form a wide variety of shapes including circular prismatic, non-circular prismatic, flat sheets, dished sheets, 3-d solid, and 3-d hollow shapes (see Figure 4.3, Figure 4.4) [4]. This eco-friendly process involves the use of catalysed resin injected under pressure into a mould, whose physical properties can be altered to affect the final product [19].

Process

Resin transfer moulding has four primary steps for the production of a particular part. Once heated, the resin to be used is loaded into a container that applies pressure by compressing this material with a plunger. An opening allows this pressurised resin to be moved into the enclosed mould where it forms to the carved shape in order to produce the desired part. After allowing this to cool, it is removed from the mould. Changes can be made to material temperature and through the addition of fibres within the resin or sheets within the mould to alter the properties of the final part [16, 20].

Advantages [16, 21, 22]

- Good surface finish
- Good tolerance to the specified dimensions
- Preferable mechanical properties (strength within a particular thickness) through the use of fibres to reinforce part within the mould
- Allows for the strong production of complex shapes
- Variations within a single part can be produced (including a changing wall thickness)

Disadvantages [16, 21, 22]

- Mould does not always completely fill due to the presence of fabric (differing materials)
- Extended cycle time and increased labour requirements (resulting in higher cost) due to the need to cut and place fibres within mould
- Excess material remains in intake, making this less efficient
- Requires additive catalyst and reinforcing fibres, increasing raw material cost
- Increased cost of moulds as they must withstand high pressures

Pump Components

Resin transfer moulding could be used for the production of any of the three parts as it allows for making both hollow and solid three-dimensional parts. Particularly, rigidity could be added to the piston which experiences greater stresses and wear during the pump cycle, however it might not be worthwhile due to the increased labour and cost that are added with this process.

For the pump body and lid, this process could be beneficial in that it allows for the production of more complex shapes with a good tolerance, which is important due to the design decision to attach the two parts together through a thread and to tight fit required between the piston and housing to make an air tight seal. However, this comes with inherent disadvantages, particularly the increased cost with the increase in labour, material additives, and lost material, especially comparing to other similar processes like injection moulding.

4.1.5 Die Casting

Background

Die casting is a process used for the production of (nonferrous) metals (most commonly aluminium) to produce prismatic (circular and non-circular) beams as well as solid and hollow three-dimensional structures (see Figure 4.3, Figure 4.4) [4]. The process involves the use of high pressure and velocity to inject liquefied metal into a mould (die), where it solidifies into the cast object and ejected from the mould [16].

Process

For the process of die casting, a liquid metal is added to a cavity, where a plunger creates high pressure so this metal is injected into a clamped mould at high velocity. This pressure is maintained until the metal is solidified. Once hardened, the die is opened (it splits into two halves) and ejection pins are used to remove the cast object [16, 23].

Advantages [16, 23, 24]

- A good proportion of the production process can be automated (injection of material, removal of part from die) increasing the overall productivity and profitability of the process
- Good accuracy in tolerances/dimensions
- Ability to cast more complex shapes (including holes, slots, and depressions)
- Smooth surfaces on cast
- Production of consistent parts
- No need for post-machining
- Fast cycle time
- Once produced, the mould can be reused for one or more full production runs (unlike other process where each part requires a new mould)

Disadvantages [16, 23, 24]

- High die cost compared to other forms of machining
- Not very profitable for small production runs (due to the high cost of tooling/dies)
- High stress for dies
- Excess material (flash) must be removed (can be automatically done by a trim die)
- Difficult to use with metals of high melting point (e.g. steel)

Pump Components

Die casting differs from the production alternatives above, rather producing in metal than plastic, which provides an important alternative that can take higher stresses and a different material so that two rubbing surfaces to not wear too much. The advantages of the material possibilities play into favour particularly for the piston which has the greatest stress and wear of any of the components.

The decrease in labour and other costs is beneficial for all parts manufactured with die casting that comes from the automation of the process. However, the increased die and material costs mean that this is not necessarily as feasible where the greater strength of parts is not required including for the pump body and lid.

4.1.6 Most Suitable Production Methods

From the above analysis of the different possible methods of production applying to the high-volume manufacturing of the vertical displacement PP175 Pump, a conclusion has been made that the best alternatives are the injection moulding and die casting. There were a number of factors that impacted this decision, the primary ones being the ability to largely automate both of these, including the addition of material, removal of parts from mould, and the ability to add more tools for more functions like unscrewing threaded parts and removing additional flash. This will help in reducing costs through labour and time to deliver the customer's parts as well as increasing the yield of the project. While resin-transfer moulding provided a similar outcome to injection moulding, it was decided that the increase in time and material/fibre additives outweighed the increase in rigidity that could be made

Other reasons that led to the final process decision, included their ability to mould a wide variety of shapes, even complex ones, allowing not only shells (which are required by rotational moulding), but also three-dimensional solid shapes. Additionally, these methods are additive production methods (as against conventional machining which is subtractive), significantly decreasing the amount of waste material.

Finally, these methods of production allow for the production to be further scaled for further unit orders as the greatest production price, the moulds, will only need to be made once and can be reused.

4.2 Cost-Analysis of HV Manufacturing Methods

This section provides an insight into the setup costs used for each chosen production method (injection moulding and die casting), particularly the price of the machine for use and the shipping cost to Sydney.

4.2.1 Costing Charts

Initial Costs

The following costing charts cover the direct and indirect costing involved in the production of the parts, looking at the costing for both injection moulding with ABS plastic and die casting for aluminium. Table 4.1 summarises the initial setup costs are sourced using a variety of available machines and shipping costs from Alibaba.com [25], providing a comparison of the start-up costs.

Table 4.1 – Costing for initial costs for injection moulding and die casting

	Injection Moulding	Die Casting
Machine Cost ($)	25000	70000
Shipping Cost ($)	800	1000

Individual Part Costing

Table 4.2, Table 4.3, and Table 4.4 provide the cost outline for each of the individual pump components, looking at the setup costs (cost of tooling and mould/die production). The production costs are calculated from estimations of cycle time at 15 seconds per part for injection moulding and 30 seconds per part for die casting [26-28], with labour costing coming from fair work Australia [29]. Additionally, the defect rate was estimated to be approximately 5% for production, which increased the required manufacturing of 24000 final units to 25264 parts produced. Additional costing was initially sought using custompart.net [30], which allowed for the input of a variety of parameters, providing a cost overview. This quote was compared to check for similarity in price (its reliability) with another quote from 3D hubs [31].

Table 4.2 – Pricing table for pump body

	Injection Moulding	Die Casting
Setup cost		
Labour cost – mould production ($/hr)	45	45
Initial setup cost ($)	25000	25000
Decreased surface roughness for moderate finish ($)	3000	3000
Additional features – unscrewing component containing threads, removal of flash ($)	15000	15000
Total setup cost ($)	43000	43000
Production Costs		
Quantity Required	24000	24000
Defect Rate (%)	5	5
Run Quantity	25264	25264
Cycle time (seconds)	15	30
Production time (hours)	110	220
Labour cost – machining ($/hr)	25	25
Operating cost ($)	2750	5500
Material cost		
Defect Rate (%)	5	5
Run Quantity	25264	25264
Mass per part (kg)	0.017	0.04
Material cost ($/kg)	4.5	6.2
Total material cost ($)	2000	6250
Final Cost		
Total cost ($)	47750	54750

From the cost comparison in Table 4.2, it is evident that the production of the pump body is significantly cheaper (around 15 % cheaper) through the use of injection moulding rather than die casting. This provides a benefit in a greater feasibility of the high-volume manufacturing, meaning this would be the recommended production technique. While the production of the mould/die has a similar costing, the material cost for the ABS rather than aluminium and the difference in operation cost does not outweigh the advantages provided by the aluminium's increased stiffness and durability.

Table 4.3 – Pricing table for pump lid

	Injection Moulding	**Die Casting**
Setup cost		
Labour cost – mould production ($/hr)	45	45
Initial setup cost ($)	3500	20000
Decreased surface roughness for moderate finish ($)	1500	2000
Additional features – unscrewing component containing threads, removal of flash ($)	20000	20000
Total setup cost ($)	25000	42000
Production Costs		
Quantity Required	24000	24000
Defect Rate (%)	5	5
Run Quantity	25264	25264
Cycle time (seconds)	15	30
Production time (hours)	110	220
Labour cost – machining ($/hr)	25	25
Operating cost ($)	2750	5500
Material cost		
Defect Rate (%)	5	5
Run Quantity	25264	25264
Mass per part (kg)	0.005	0.01
Material cost ($/kg)	4.5	6.2
Total material cost ($)	550	1600
Final Cost		
Total cost ($)	28300	49100

The cost analysis in Table 4.3 demonstrates that there is a very large difference in the costing between injection moulding and die casting for the pump lid, leading to the decision of injection moulding for ABS as the superior production process choice for the pump lid, aligning with section 3, which suggested ABS as the best material.

Table 4.4 – Pricing table for pump piston

	Injection Moulding	Die Casting
Setup cost		
Labour cost – mould production ($/hr)	45	45
Initial setup cost ($)	12000	20000
Decreased surface roughness for moderate finish ($)	2500	2000
Additional features – removal of flash ($)	10000	10000
Total setup cost ($)	24500	32000
Production Costs		
Quantity Required	24000	24000
Defect Rate (%)	5	5
Run Quantity	25264	25264
Cycle time (seconds)	15	30
Production time (hours)	110	220
Labour cost – machining ($/hr)	25	25
Operating cost ($)	2750	5500
Material cost		
Defect Rate (%)	5	5
Run Quantity	25264	25264
Mass per part (kg)	0.004	0.01
Material cost ($/kg)	4.5	6.2
Total material cost ($)	450	2000
Final Cost		
Total cost ($)	27700	39500

Aligning with the concluding produced by the material selection process, the cost analysis in Table 4.4 demonstrates that the superior production alternative is producing ABS parts through the use of injection moulding. There is a significant difference in price between the two methods, meaning a clear choice for the method of making the piston.

Off-the-shelf Component Pricing

The pricing for the additional components sought as off-the-shelf components is shown in Table 4.5. These prices were sought using aliexpress.com [32, 33] as an estimate for this costing.

Table 4.5 – Pricing for off-the-shelf components

Part	Quantity per pump	Units	Cost ($)
28.52 mm O-ring	1	24000	1600
Springs	2	48000	3200
4 mm bearing balls	2	48000	900
1 mm x 10 mm pins	1	24000	2500
Lubricant	0.1 mL	24000	35

It is cheaper to outsource off-the-shelf components. The cheapest Rubber O-ring making machine costs $3000 and with the overall cost increasing with the inclusion of labour wages. Alternatively, purchasing 24000 O-rings costs approximately $1600. Hence, outsourcing the materials is the most economical option.

Assembly Costs

The pricing for the assembly of the completed pump is shown in Table 4.6, which uses the data in the above tables and an estimate of 1 minute to assemble each pump.

Table 4.6 – Pricing for assembly

Cost	Price
Labour cost ($/hr)	25
Time per pump (minutes)	1
Total time (hrs)	400
Total cost ($)	10000

4.2.2 Costing summary

From the sections above, a conclusion was drawn that each individual component should be produced through injection moulding. While these conclusions were drawn individually, it also provides an additional advantage for all parts to be produced through the same production method as it means that only a single machine is required. If a second were needed for an alternate production method, this would also greatly increase the overall cost.

Without considering the indirect costs, the total cost for injection moulding comes to $154950 and the cost for die casting comes to $232585 (which is significantly larger).

Looking at the production times estimated in Table 4.2, Table 4.3, Table 4.4, and Table 4.6, it is seen that the total production time is approximately 730 hours (about 5 months using a standard 40 hour work week). During this time a factory would be required as a space for production, so taking an average rental price of $750 a month for suitable warehouses [34].

From the above costing sections, it can now be estimated that the total cost for the production of the vertical displacement pump would be approximately $158700, taking into account material, labour, die, off-the-shelf component, assembly, and warehouse costs. This means that the production cost per pump comes to $6.60, which could provide a good profit if sold for $10-20.

4.3 Routing Chart

The routing chart for the production of an individual pump is shown in Appendix . This provides an outline of the steps taken for the production of each component and the assembly of these with the off-the-shelf components. This outline provides approximated times, however for the large-scale production material addition is done in bulk, rather than for individual parts and all units for an individual part produced together. This decreases the overall production time and means that moulds do not have to be inspected and inserted for each individual part.

5 CONCLUSION

This report studied on the feasibility of the manufacture of 24000 units of the PP175 Vertical Displacement Pump as specified by Mega Manufacturing Alpha Industries. This was achieved through discussing and optimising its high-volume redesign features, material selection process and process planning of the pump based on the prototype pump built at Ultimo TAFE [35] utilising hand-manufacturing methods. A wide selection of HV designs, materials and manufacturing methods were considered to ensure the most profitable options were selected.

The HV redesign process took numerous factors into account, maximising profit and efficiency throughout the manufacturing process. The prototype parts were merged to reduce the number of moulds and material required, and decrease the assembly time to mate all the parts. Off-the-shelf fasteners were eliminated for preference of a screw-on lid and the valve's pin-stopper system allowed an increase in mating simplicity and minimising the need for off-the-shelf materials. The manufacturing defects that would arise with injection moulding were addressed and redesigned features such as draft angles, shelling and fillets were implemented. Ultimately, the HV redesign process aimed to decrease the cost to manufacture, manufacture time, chance of manufacturing defects and increase the yield rate of manufacture by reducing assembly time, number of parts to manufacture, and number of off-the-shelf components to purchase.

The material selection process considered each part separately, focusing on their respective functional requirements and aimed to find materials that met these criteria, whilst also factoring the metrics of cost and production time. By calculating the forces and stresses each part had to withstand, as well as their required rigidities, Ashby Charts and other material selection techniques were utilised to determine the most suitable material. This process led to the decision that ABS plastic was the most suitable for every part. ABS plastic is strong, rigid, light and low-cost. In addition to this, selecting the same material for every part meant allowed for a single manufacturing method to be used for the entire pump, massively impacting the overall cost of the product.

Process planning included the comparison of five different HV manufacturing methods: rotational moulding, resin-transfer moulding, die casting, conventional machining and injection moulding. Injection moulding and die casting were favourable HVM methods due to their higher yield rate of production, ability to mould complex part designs, and greater ease of manufacture. These two HVM methods were further compared under a cost analysis where the total cost of the injection moulding process was $154950 and total cost of die casting was $232585. Therefore, injection moulding is recommended as the superior HVM method for the PP175 pump.

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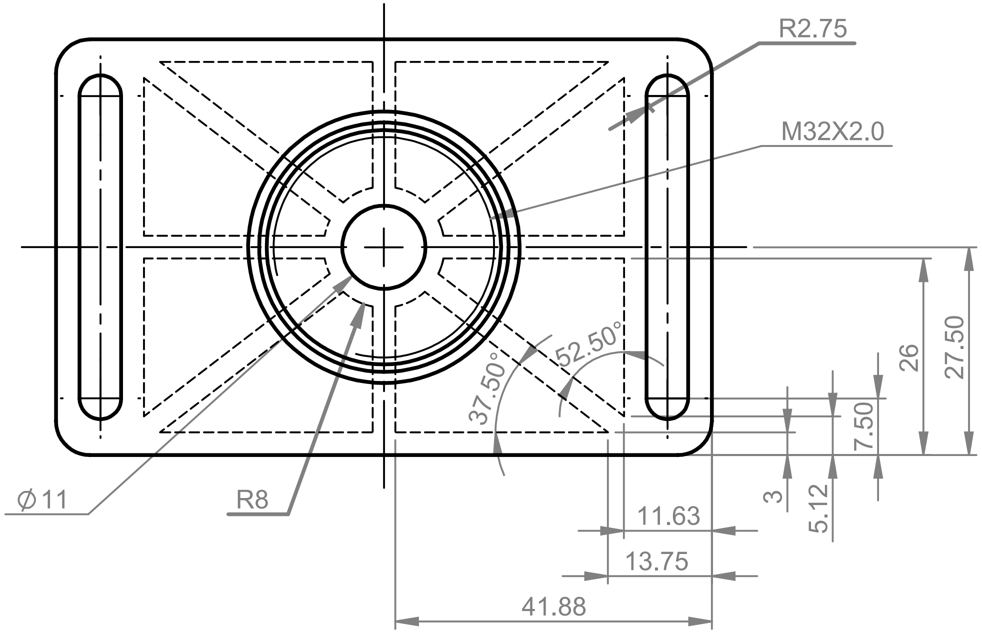
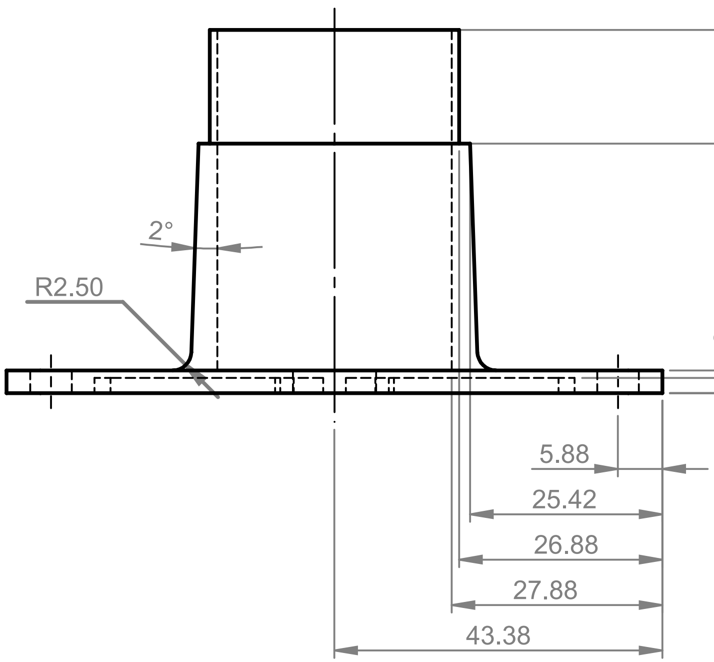
7 APPENDIX A

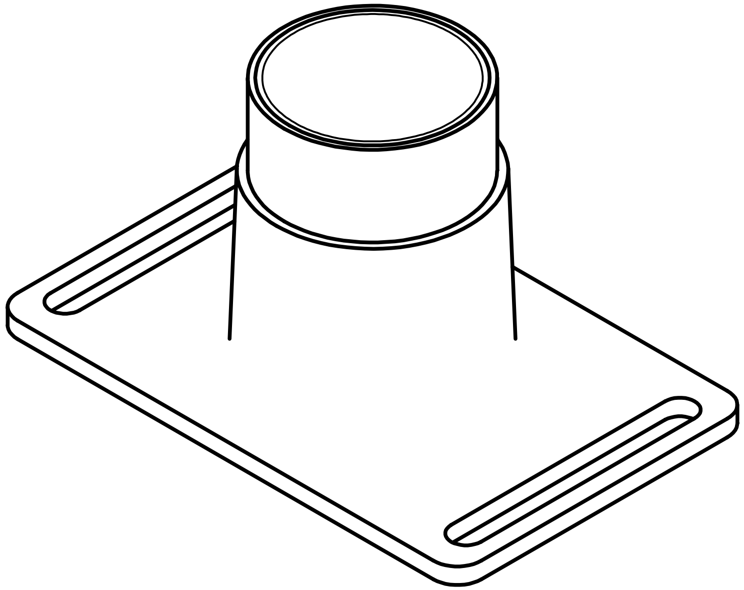
This appendix contains the engineering drawings for the high-volume pump design over the following pages (drawing one-three). Each drawing contains a different part (drawing one is the body, drawing two is the lid, and drawing three is the piston).



TOP VIEW



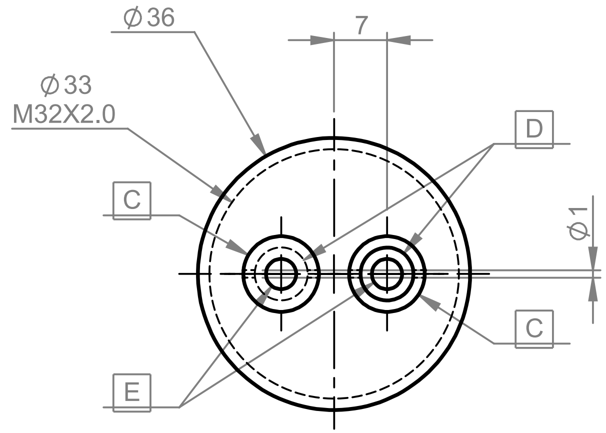
FRONT VIEW



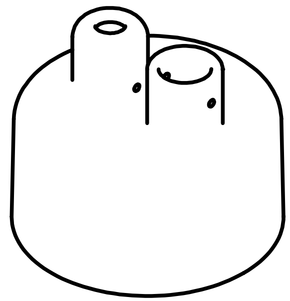
ISOMETRIC VIEW

AS1100

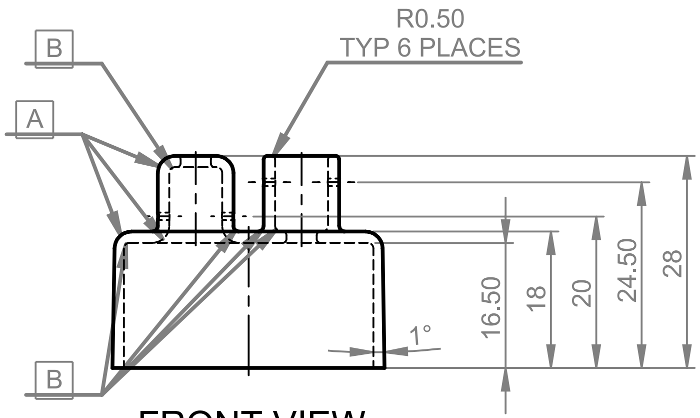
SCHOOL OF MECHANICAL AND MANUFACTURING ENGINEERING - UNSW						
DIMENSION IN MILLIMETRES	SURFACE FINISH UNLESS NOTED OTHERWISE 1.6	DRAWN BY DAN (Z5206032)			TITLE BODY	
DO NOT SCALE		CHECKED BY ALEXANDER (Z5204704)			DRAWING NUMBER 1	
	TOLERANCE UNLESS NOTED OTHERWISE ±0.1	APPROVED BY MOHIQUE (Z5203101)			FIRST RELEASE DATE 24/11/2019	
		QTY 24000	MATL ABS PLASTIC	SCALE 1:1	REV 1	DATE 24/11/2019	A4



TOP VIEW



ISOMETRIC VIEW



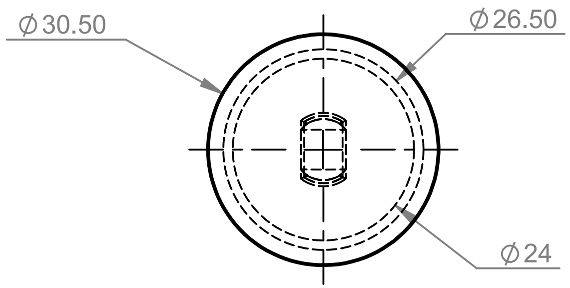
FRONT VIEW

NOTE:

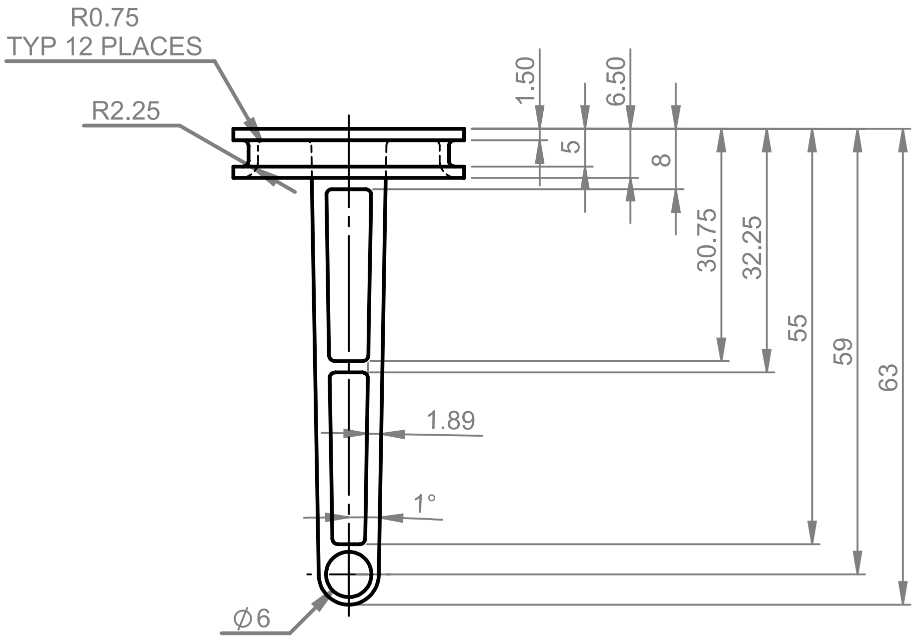
A	R2.25
B	R0.75
C	∅10
D	∅7
E	∅4

AS1100

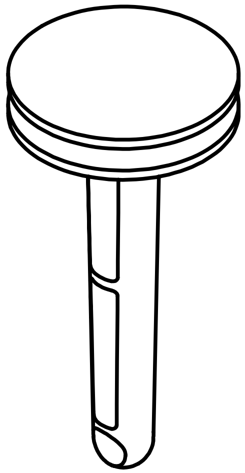
SCHOOL OF MECHANICAL AND MANUFACTURING ENGINEERING - UNSW					
DIMENSION IN MILLIMETRES	SURFACE FINISH UNLESS NOTED OTHERWISE 1.6	DRAWN BY DAN (Z5206032)		TITLE LID	
DO NOT SCALE		CHECKED BY ALEXANDER (Z5204704)		DRAWING NUMBER 2	
	TOLERANCE UNLESS NOTED OTHERWISE ±0.1	APPROVED BY MOHIQUE (Z5203101)		FIRST RELEASE DATE 24/11/2019	
		QTY 24000	MATL ABS PLASTIC	SCALE 1:1	REV 1 · DATE 24/11/2019 · A4



TOP VIEW



FRONT VIEW



ISOMETRIC VIEW

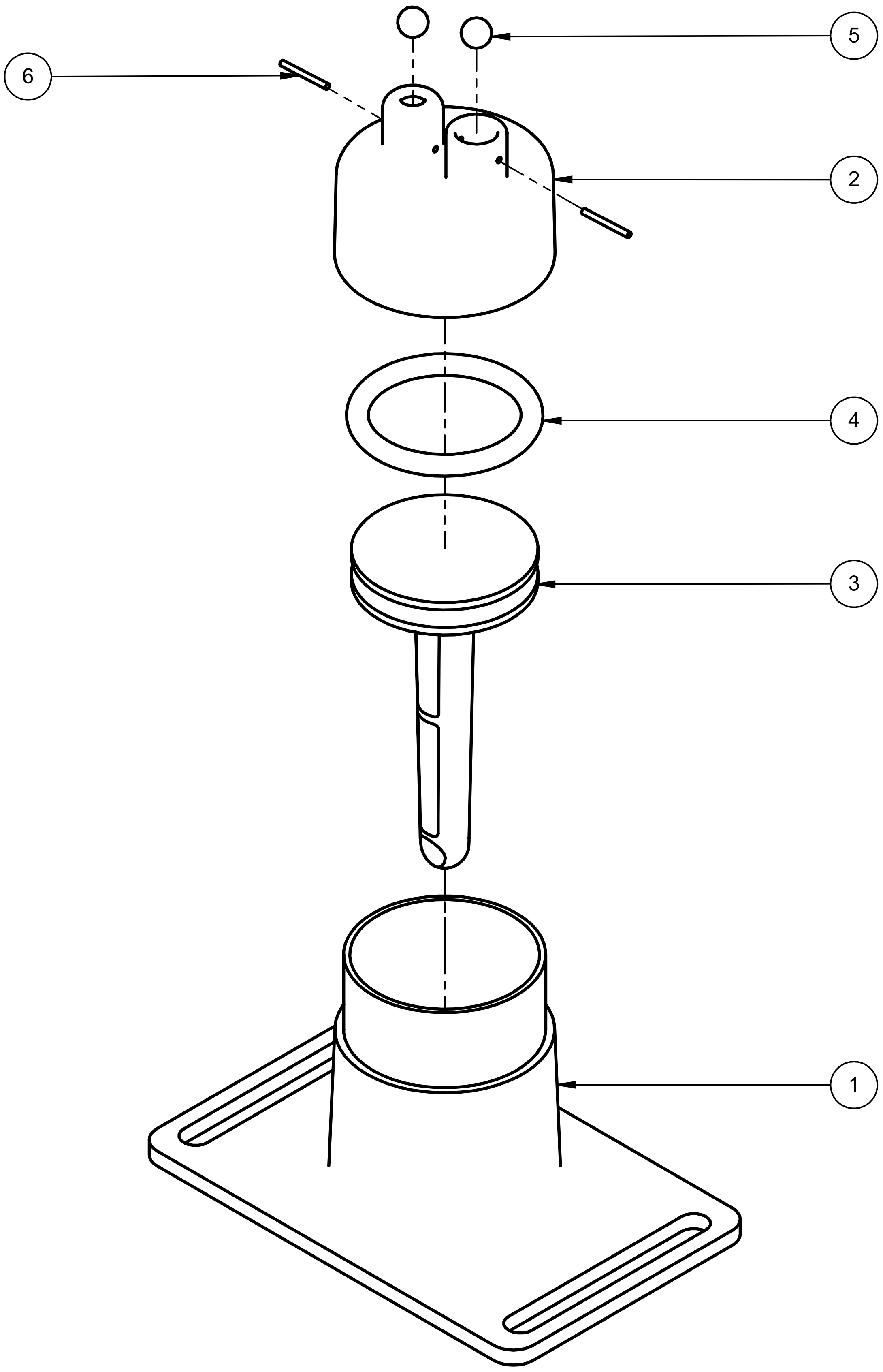
AS1100

SCHOOL OF MECHANICAL AND MANUFACTURING ENGINEERING - UNSW						
DIMENSION IN MILLIMETRES	SURFACE FINISH UNLESS NOTED OTHERWISE 1.6	DRAWN BY DAN (Z5206032)		TITLE PISTON		
DO NOT SCALE		CHECKED BY ALEXANDER (Z5204704)		DRAWING NUMBER 3		
	TOLERANCE UNLESS NOTED OTHERWISE ±0.1	APPROVED BY MOHIQUE (Z5203101)		FIRST RELEASE DATE 24/11/2019		
		QTY 24000	MATL ABS PLASTIC	SCALE 1:1	REV 1	DATE 24/11/2019

A4

8 APPENDIX B

This appendix includes the assembly drawing for the component assembly demonstrating how the pump will go together.



AS1100

6	-	1X10MM PIN	STEEL	2
5	-	4.00MM BALL	STEEL	2
4	-	28.52MM O-RING	RUBBER	1
3	3	PISTON	ABS PLASTIC	1
2	2	LID	ABS PLASTIC	1
1	1	BODY	ABS PLASTIC	1
ITEM NO.	PART NO.	DESCRIPTION	MATERIAL	QTY.

SCHOOL OF MECHANICAL AND MANUFACTURING ENGINEERING - UNSW

DIMENSION IN MILLIMETRES	SURFACE FINISH UNLESS NOTED OTHERWISE 1.6	DRAWN BY DAN (Z5206032)	TITLE PP175 PUMP
		CHECKED BY ALEXANDER (Z5204704)	DRAWING NUMBER 4
DO NOT SCALE		APPROVED BY MOHIQUE (Z5203101)	FIRST RELEASE DATE 24/11/2019
	TOLERANCE UNLESS NOTED OTHERWISE ±0.1	QTY 24000 / MATL ABS PLASTIC / SCALE 1:1	REV 1 / DATE 24/11/2019 / A3

9 APPENDIX C

This appendix contains the calculation for valve constraints on minimum motor RPM.

Considering the ball over the travel distance of 2 mm from rest to the mouth of the valve where the ball seals it. To find the time taken for the ball to fall over this distance of 2 mm (where the initial velocity is zero and the acceleration due to gravity is approximated as 10 m/s^2), we can use the kinematic equations for the ball falling as in equation 5. The negative solution is disregarded here.

$$s = ut + \frac{1}{2}at^2$$
$$t = \frac{-u \pm \sqrt{u^2 - 2a^2 s}}{a} \qquad 5$$
$$t = \frac{-0 + \sqrt{0^2 - 2(10)^2 \times \left(-\frac{2}{1000}\right)}}{10} = 0.06\ s$$

This time is the time taken for half a cycle of the pump, thus the total pump cycle is 0.12 s. From this, the minimum angular velocity can be found by converting this into angular velocity (equation 6).

$$\omega = 2\pi f = \frac{2\pi}{T} \qquad 6$$

$$\omega \geq \frac{2\pi}{0.12} = 52\frac{rad}{s} = 5.4\ rpm$$

10 APPENDIX D

Table A 1 provides a table of the functional specifications for the pump.

Table A 1 – Table of metrics for pump prototype parts

<table>
<tr><th rowspan="2">Part</th><th colspan="4">Metric</th></tr>
<tr><th>Functional Requirements</th><th>Constraints</th><th>Objectives</th><th>Free Variables</th></tr>
<tr><td>General (relating to all parts)</td><td>• Vertically reciprocating, simplex, positive displacement pump</td><td>• Max life (>65 million revolutions)
• Create 24,000 units
• Operate in a dry and stable environment at normal room temperature and pressure (298.15 K / 101.325 kPa)
• No adhesives
• Safety factor > 2
• Material modulus of elasticity greater than 50 MPa</td><td rowspan="3">• Cheapest Net Cost for 24,000 units
• Shortest production time/greatest yield
• Suit HV manufacturing methods as close as possible
• Possibility to be scaled further
• Greatest safety factor between stresses applied and yield stress of material
• Minimum manufacturing tolerance
• Minimise wear</td><td>• Material
• Combination of components
• Altering edge conditions for more favourable stress concentrations and aesthetics
• Weight</td></tr>
<tr><td>Base</td><td>• Provide a means of attaching the pump to the jig
• Support and allow for the attachment of pump housing</td><td>• Maximum face dimensions of 100 mm x 70 mm
• Maximum thickness of 10 mm
• Be connected to other pump components without adhesives (using nuts and bolts)
• Contain a 10 mm hole at the centre to accommodate the piston connecting rod having a good fit with a tolerance of +0.1 mm
• Contains two parallel slots on either side of the with a distance of 75 mm between their centres and allow for use with M5 bolts
• Withstand forces of an electric motor drive (with the piston connecting rod moving through the base)</td><td>• Dimensions</td></tr>
<tr><td>Housing</td><td>• Interface with base, cover, and piston to provide airtight seal.
• Fits to the base</td><td>• Withstand pressure created by the movement of the piston (10666 N/m^2)
• Withstand the heat due to friction
• Interfaces with piston to provide 20-22.5cm^3 air volume displacement
• Max dimension 50x50 mm</td><td>• Shape</td></tr>
</table>

Piston	• Transducer to convert motion of jig to displacement of air	• Pass through hole in the base • Stroke length of 20, 25, 30, 35 mm • Total air displacement of 20-22.5 cm^3 • Withstand net internal pressure of 10666 Pa (see Appendix section 11.1) • No adhesives • Max life (>65 million revolutions) • Withstand axial forces created by linear motion from jig • 10mm shaft diameter • 6mm hole in shaft		• Dimensions
Cover	• Enclose and seal the top of the housing • Interface between main pump assembly and input/output valves	• Withstand net internal pressure of 10666 Pa (see Appendix section 11.1)		• Geometry
Input/Output Valve	• Allow single directional flow of air • Interface with pump • Interface with balloon	• Total air displacement of 20-22.5 cm^3 • Withstand net internal pressure of 10666 Pa (see Appendix section 11.1) • Mouth of balloon stretches to max of 20mm; • Balloon remains on output valves • Dimensions of valve relative to pump		• Valve mechanism

11 APPENDIX E

11.1 Calculation of maximum expected stress for housing and valves

The internal pressure of the housing chamber is at a maximum during piston upstroke immediately prior to the balloon popping (Figure 11.1). The pressure required to pop a balloon is $111\ 991\ Pa$ [36]. Thus, in order for air to move from the internal chamber to the balloon at the point immediately prior popping, the pressure inside the chamber is required to be greater than the pressure inside the balloon. It is assumed that this difference is small due to small air volume displacements during each upstroke. Thus, the assumption is made that the internal pressure inside the chamber is $111\ 991\ Pa$ (equal to that in the balloon) immediately before the balloon pops.

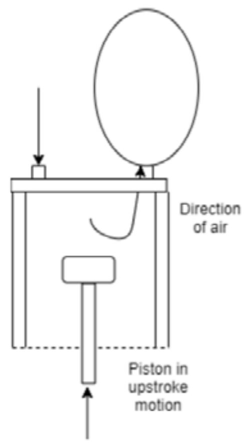


Figure 11.1 – Diagram illustrating the dynamics of the pump immediately prior the balloon popping

11.2 Minimum Young's Modulus for Cover

Combining this internal chamber pressure with the pumps operating condition at normal atmospheric pressure (101 325 Pa) [1], the maximum net force acting on the cover can be calculated.

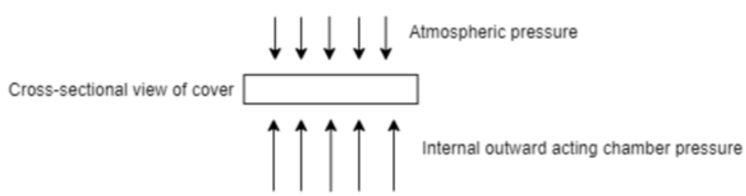


Figure 11.2 – Pressure within the pump cover

$$Net\ pressure\ =\ internal\ outward\ acting\ chamber\ pressure - \ atmospheric\ pressure \qquad 7$$

$Net\ pressure = 111\ 991 - 101\ 325 = 10\ 666\ Pa.$

Assuming a cover area (area experiencing the pressure) is a circle of diameter 31 mm, this gives the following pressure found with

$$Area\ of\ circle\ =\ \pi r^2\ =\ \pi(0.0155)^2\ =\ 0\ .000755\ m^2$$

$$Air\ pressure = \frac{force}{area} = \frac{F}{A} \tag{8}$$

$$F = (10\,666)(0.00075476763) = 8.050351595\ N$$

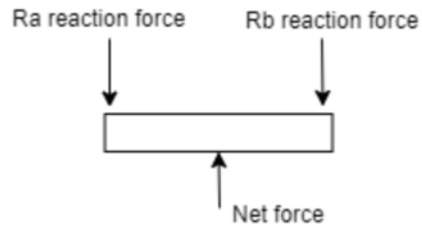


Figure 11.3 – Model of the cover as a beam loaded in bending

The cover can be modelled as a disk of radius 15 mm and thickness of 1.5 mm. This disk is approximated as simply supported with the load concentrated at its centre (see Figure 11.3).

The maximum deflection for a simply supported disk with load concentrated at centre is found using equation 9.

$$Maximum\ deflection = \frac{0.217(net\ force)r^2}{E(thickness)^3} \tag{9}$$

For the maximum desired deflection of the cover of < 0.001 m, equation 9 is used as below to provide the required Young's modulus.

$$E = \frac{0.217(net\ force)r^2}{(maximum\ deflection)(thickness)^3} = \frac{0.217(8.050351595)(0.015)^2}{(0.001)(\ 0.0015)^3} = 116456666.7\ Pa$$

11.3 Calculation of maximum ultimate tensile strength

This section provides a calculation of the ultimate strength for the pump, occurring at the top surface and centre of cover. This is carried out using equation 10. $\sigma = \frac{P}{t^2}\left(0.631 \ln\left(\frac{r}{t}\right) + 0.676\right)$ 10

$$\sigma = \frac{8.050351595}{0.0015^2}\left(0.631 \ln\left(\frac{0.015}{0.0015}\right) + 0.676\right) = 7.62 \times 10^6\ \mathrm{Pa}$$

11.4 Calculation of maximum stress experienced by housing

The housing is approximated as an open cylinder with an outer radius of 16.5 mm and inner radius of 14.6 mm. These dimensions allow for the analysis of the housing using a thin-walled pressure vessel model [37]. The maximum stress experienced by the housing is hoop stress is found as in equation 11 (where P is internal pressure, and r_m is the mean radius and t is wall thickness.

$$Hoop\ Stress = \sigma_h = \frac{Pr_m}{t} \quad 11$$

$$\sigma_h = \frac{(10666)(0.0155395)}{0.001921} = 86\ 280.2 \text{ Pa}$$

11.5 Calculations of fracture stress in the housing

In order to analyse fracture toughness of the housing, Griffith's equation has been utilised (equation 12), where σ is the maximum stress before fracture failure occurs, γ is the surface free energy per area, E is the Young's modulus of the material and a is the fracture length.

$$\sigma = \sqrt{\frac{2\gamma E}{\pi A}} \quad 12$$

In order to calculate γ, the assumption is made whereby the housing is modelled as a rod of radius 17.39 mm and length of 50 mm, permitting the use of the equation 13, where P is force applied to sample, l is length and r is radius of sample [38].

$$\gamma = \frac{Pl}{\Pi \mathrm{r}(1 - 2\mathrm{r})} \quad 13$$

$$\gamma = \frac{8(50 \times 10^{-3})}{\pi(17 \cdot 39 \times 10^{-3})\left((50x10^{-3}) - \left(2(17.39x10^{-3})\right)\right)} = 481.06\, J/m^2$$

Knowing that the minimum Young's modulus of ABS plastic is 1.19 GPa [39], and assuming an initial crack size of 2mm, the stress (found using equation 12) is as below.

$$\sigma = \sqrt{\frac{2(481.0562752)(1190000000)}{\pi(2x10^{-3})}} = 13\ 498\ 841.14 \text{ Pa}$$

11.6 Calculation of max shear stress experienced by valve

The maximum pressure the valves (Figure 11.4) experience is $10\ 666\ Pa$, the same as that determined in Appendix section 11.1.

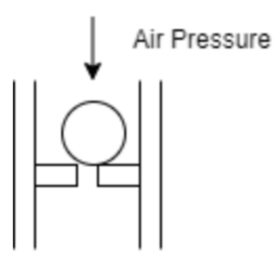


Figure 11.4 – Diagram of pump valves

The air pressure (P) can be approximated as a force (F) which acts over the ball bearing and valve lip area (A) as in equation 14.

$$F = P \times A \qquad (14)$$

$$F = (10\,666)(\pi(0.0035)2) = 0.410\ N$$

Thus, this downward net force needs to be counteracted by the shear stress between the lip and valve.

$$Shear\ stress = \tau = \frac{0.4104757837}{(2\pi(0.0035)(0.0015))} = 12443.66\ Pa$$

11.7 Calculation of maximum stress exerted on base

This calculation of the maximum stress on the base is required to find the minimum Young's modulus (ensuring a maximum deflection no larger than 1mm).

As determined earlier, the housing experiences a force of approximately 8.05 N upwards due to the pressure required to pop the balloon. Thus, an 8.05 N downwards force must be provided by the base to ensure equilibrium.

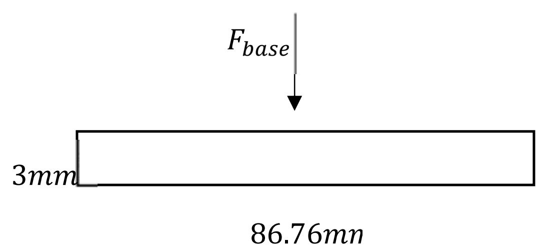


Figure 11.5 – Forces on the base plate

This force will be experienced in the base only where it makes contact with the housing. Therefore, the normal stress (σ) in the base can be calculated using equation 15.

$$\sigma = \frac{F}{A} \qquad (15)$$

$$\sigma = \frac{8.05}{\pi(0.01739^2 - 0.01589^2)} = 51.33\ KPa$$

Setting the maximum deflection of the base to be 1mm, equation 16 describing the maximum deflection of a beam can be implemented.

$$\delta_{max} = \frac{FL^3}{48EI} \qquad (16)$$

$$0.001 = \frac{8.05(0.08676)^3}{48E(\frac{0.055 * 0.003^3}{12})}$$

$$E = 0.885\ GPa$$

11.8 Calculation of minimum Young's Modulus for base

It was provided that the jig motor could be expected to operate at a constant speed of approximately 70RPM. From this, the forces experienced by the piston connecting rod could be determined.

$$\omega = 2\pi f = 2\pi * \frac{70}{60} = \frac{7\pi}{3}\ rad/s$$

When the piston is at the top of its stroke, it will experience its maximum stress due to the compressed air and the force generated by the motor, as shown in the FBD in Figure 11.6.

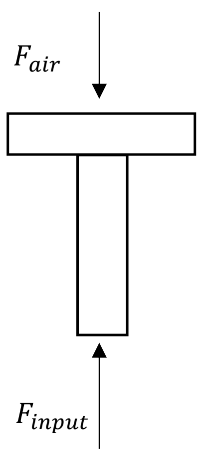


Figure 11.6 – FBD of piston

The piston undergoes simple harmonic motion, so its displacement can be modelled with the following equation:

$$y(t) = A\sin(\omega t)$$

Where A is the amplitude of motion which is equal to the stroke length, and ω is the frequency of the motor. Differentiating this equation twice, the pistons acceleration equation can be determined:

$$a(t) = -\omega^2 A\sin(\omega t)$$

Thus, the maximum force experienced by the piston is as in equation 17

$$F_{input,max} = ma_{max} = A\omega^2 m \qquad 17$$

Using the maximum stroke length of 35mm, and the maximum mass of the piston to be 250g, the maximum force experienced by the piston will be approximately:

$$F_{input,max} = 0.035 * \left(\frac{7\pi}{3}\right)^2 * 0.25 = 0.47\ N$$

The compressed air acts as a gas spring, and provides a force as in equation 18.

$$F_{air} = A(P_{internal} - P_{external}) \tag{18}$$

Where A is the area of the piston and P is the pressure. Using values calculated earlier, the maximum value F_{air} will take is approximately 8.05 N. Assuming this force will be experienced by the entire piston, and adding this to $F_{input,max}$, the maximum normal stress experienced in the connecting rod can be calculated by using the smallest cross sectional area of the connecting rod with equation 15.

$$F = 8.05 + 0.47 = 8.52\ N$$

$$\sigma_{max} = \frac{F}{A} = \frac{8.52}{\pi(0.00408^2 - 0.003^2)} = 0.355\ MPa\ (Compression)$$

Setting the maximum allowable decrease in length of piston to be 1mm, the strain can be calculated as in equation 19.

$$\varepsilon = \frac{\Delta L}{L} \tag{19}$$

$$\varepsilon = \frac{1}{63} = 0.01587$$

Thus, Young's Modulus for the piston can be determined (using equation 20).

$$E = \frac{\sigma}{\varepsilon} \tag{20}$$

$$E = 0.0224\ GPa$$

12 APPENDIX F

This appendix contains the routing chart for the pump production on the following page. This has the production of the individual parts and their assembly into a complete part.

HVM Assembly Routing Chart