



Total Product Design – PK2

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1 Abstract

Parking barriers are often considered to be unattractive and slow to assemble. Parking Facilities Limited (PFL), the largest manufacturer of parking barriers in the UK, has faced these problems with its articulating barrier. Poor customer response to this barrier has created concern about its position in the UK market as international competitor companies enter the scene. This report is a continuation of the preliminary report. It discusses challenges faced in the development of an innovative barrier that utilises an internal mechanism to create a sleek design, whilst maintaining PFL's current short lead times. Through detailed calculations, computer simulations, and prototyping, a new design has been successfully justified. The findings from this report will provide a foundation for PFL to continue development as they update their articulating barrier design.

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5 Introduction

Parking Facilities Limited (PFL) is one of the UK's leading companies for supplying and installing access management systems. They have products covering a variety of sectors, from barriers and turnstiles for public premises to robust designs for industrial sites. While offering a high standard of security, ease of use and adaptability, the company has one product that doesn't achieve their standards: the articulating arm.

The aim of this project is to produce and validate a design for an articulating arm barrier that improves customers perception, while not sacrificing other qualities that the company values, such as good lead times and being easy to install for clients. The current design has a multitude of problems that make it unmarketable in comparison to competitor designs. The usage of an entirely external linkage arm as part of a four-bar linkage design adds extra bulk to the barrier. Furthermore, the wiring for the safety edge and LEDs often break during assembly, adding to the already poor assembly time. The new barrier concept aims to improve on the aesthetics, and assembly of the original. This is achieved by internalising the mechanism and simplifying the assembly method. Significant work has been done to ensure the proposed solution meets all safety requirements identified in the preliminary report [1].

This report details the initial research, concept generation, design development and prototyping that led to the creation of the final concept. Progress was validated throughout the project utilising calculations, FEA, and engineering design methods. Testing was then done to evaluate the performance in comparison to the current PFL barrier. A final design will be proposed to PFL along with the recommended strategy for taking the concept further.

6 Preliminary Report Summary

6.1 The Current Articulated Arm Analysis

PFL's current design for the articulated arm is less competitive than the rest of their product line and several drawbacks have been identified including its aesthetics and unreliability. The current design uses a 4-bar linkage, which includes a fixed link, an input link, an output link and an intermediate link. [1]

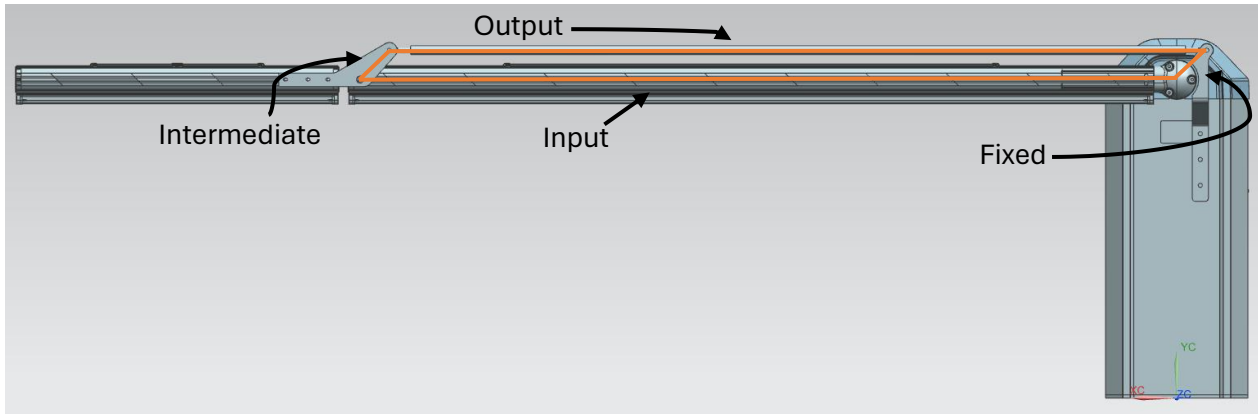


Figure 1 – An image of the 4-bar linkage articulated arm with the 4 bars labelled and highlighted.

6.1.1 Assembly time

The Assembly of the current articulating design takes 6-8 hours per barrier with one-off manufacturing. The current method has problems pertaining to the electrical wires for the LEDs and safety edge being too tedious to thread through the barrier extrudes. This results in a high frequency of breakages, causing large fluctuations in the assembly time. Reducing the assembly time can therefore be achieved by reducing the overall number of parts and making difficult assembly steps easier to perform [1].

6.1.2 Barrier Aesthetics

PFL have determined their barrier has unappealing aesthetics, mainly due to a large linkage pole on top of the beam, which is required for a 4-bar mechanism. Therefore, an ideal solution would be able to hide the external bar or would be able to eliminate it completely [1].

6.2 Competitor analysis

Evaluating the current competitors in parking equipment, and more specifically parking barriers, can provide a better understanding of how PFL fits into the market. This develops a deeper understanding of the requirements of the target product in terms of quality, pricing, and functionality, ensuring the final product is competitive and therefore profitable[1].

6.2.1 General Market Analysis

An analysis of competitor companies was carried out with two main variables considered for each company: variety of products and product innovation (the number of products or features that are not sold or provided by other companies). These variables were chosen as both variables are desirable but often oppose each other, as producing large amounts of different products requires more resources and therefore can reduce the innovation in each product. However, it was found this is not the case for the parking barrier market.

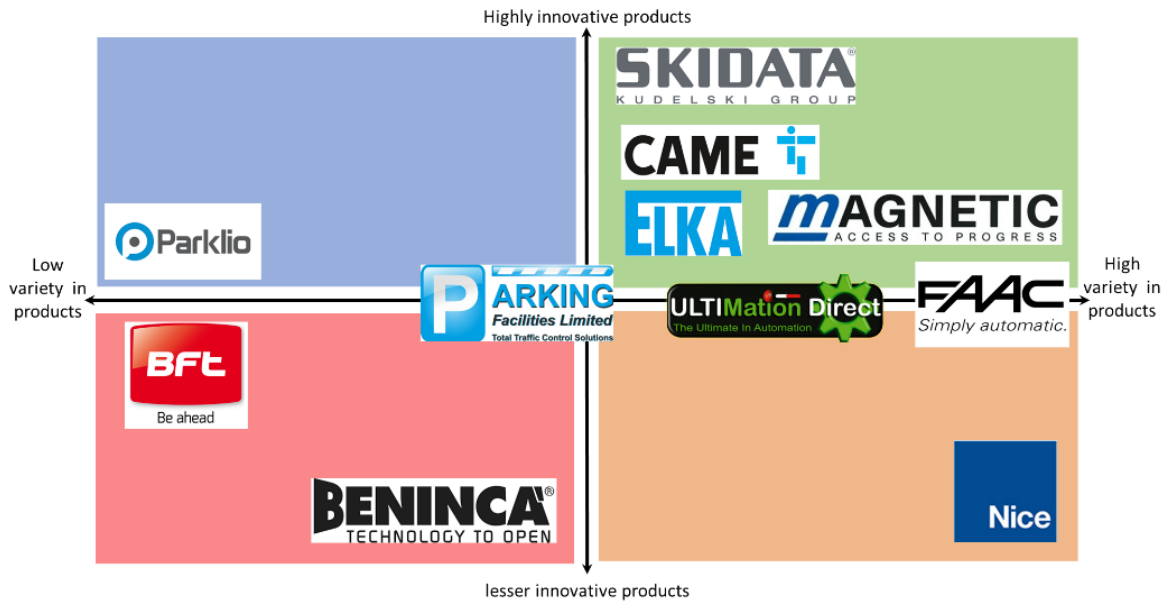


Figure 2 - A diagram showing companies compared in innovative products and variety of products [1].

Figure 2 shows a growing trend of highly innovative products and a wide variety of products, shown by a large number of companies in the top right sector of the graph. These companies often offer complete solutions to parking, rather than the individual boom bar. This diagram also shows that PFL is average in both variety and innovation[1].

6.2.2 Direct Competitor Comparison

A direct competitor analysis against other companies with boom barrier solutions was completed to evaluate the specialities and strengths of each company and how PFL can absorb these strengths into the articulated arm solution. During research, the following companies were highlighted as companies of high interest to us, and the following points were observed.

Skidata focuses on complete solutions with a high focus on customer satisfaction. Their barriers use fully internalised systems to maximise the aesthetics of the barrier. This means that they have a perception of premium quality attached to their brand and can charge prices that reflect that, primarily selling to high end commercial companies.

Magnetic's range of products stretch more into the industrial range, there create barriers up to 10m in length and they focus on security and robustness, as their barriers are more likely to be in contact with heavy load vehicles. Their designs have a more industrial aesthetic than PFL's products, though the markets for the two companies are closer than they are to Skidata.

Other companies were looked at such as **FAAC**, **Elka** and **Ultimation**, these companies were deemed to be PFL's closest competitors in terms of target market. In order for PFL to outperform them, lead times will need to be kept to the company standard. Which will in turn allow the price to be raised [1].

6.3 Customer Needs

Phase 1 and 2 customer needs tables helped in the creation of the PDS, the phase 1 customer was determined to be PFL while the phase 2 customer was a construction company that would buy the proposed barrier. The needs of both phases of customers were considered when moving forward to the QFD and PDS[1].

6.4 Quality Function Deployment (QFD) Chart

The Phase 2 customer requirements became the basis for a QFD chart which could be used to create objectives for the requirements tree and PDS. The QFD chart compared the customer requirements to functional requirements of the barrier system that can be measured. It can be seen in the preliminary report [1].

6.5 Requirements Tree

A requirements tree was created to better display the hierarchy of customer needs. The tree is divided into two halves, one for constraints and one for objectives. The constraints being points that need to be met, and the objectives having a weighting to indicate their importance. This tree is shown in the preliminary report and was used as a tool to help with the creation of the Product Design Specification [1].

6.6 Product Design Specification

From the Requirements tree The PDS for this project was made, this formed the basis for the project moving forward, later on the PDS would be refined as the project evolves. The initial PDS can be found in the preliminary report [1]. The PDS will also be used to help evaluate the success of the design and how well it meets PFL's requirements.

7 Synthesis of concepts

7.1 Initial Concept Selection

During the ideation process, over 120 sketches were drawn up. This process allowed the team to explore all concepts they could think up to identify a new way to achieve the aim. This process was supplemented by the research carried out in the initial stages of the project and resulted in a wide variety of ideas.

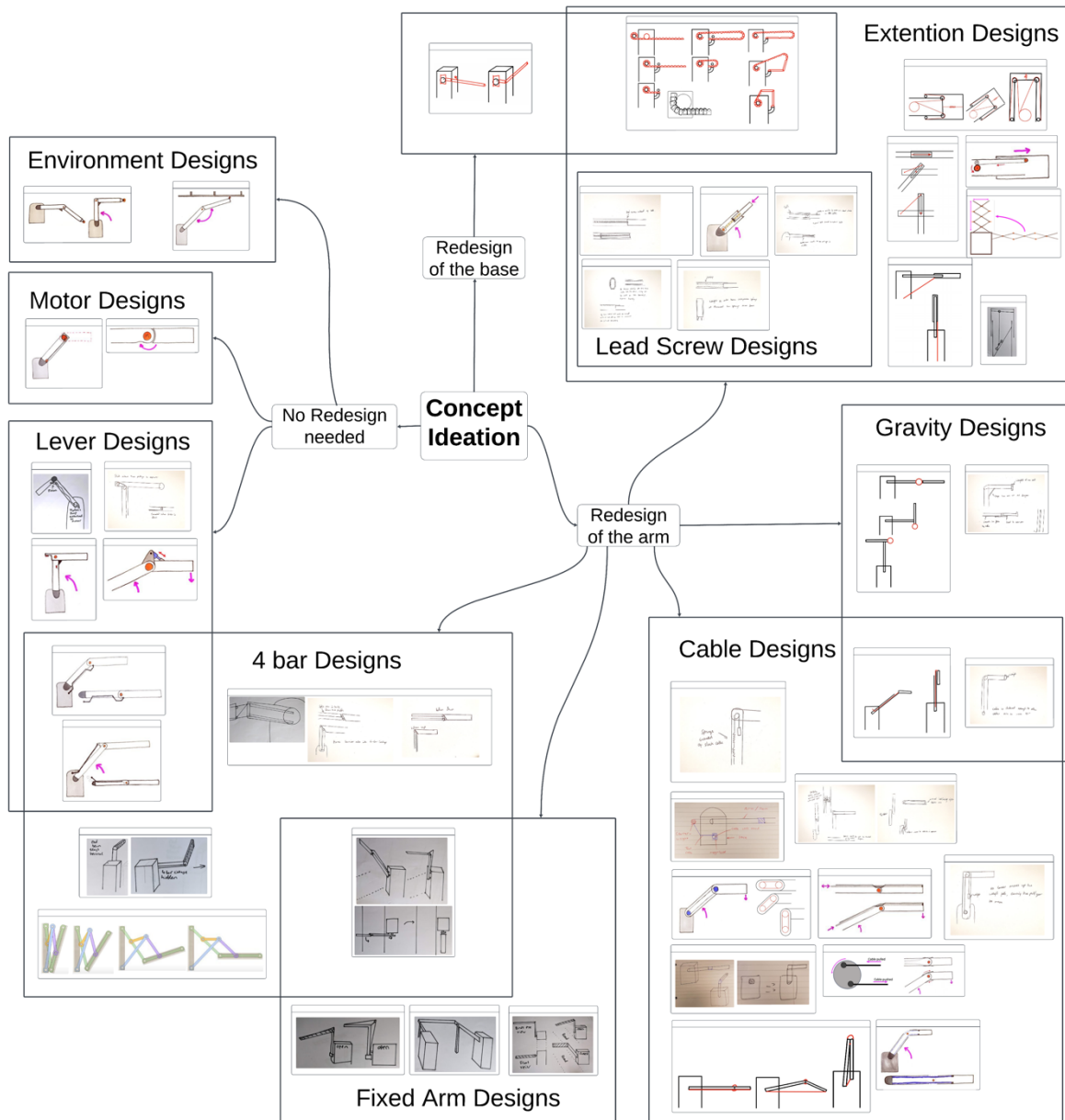


Figure 3 - Initial Concepts Map

The 'initial ideas' are put into a map design (Figure 3 - Initial Concepts Map) to help further visualise the direction and breadth of imagination. It was also used to help recognise any unidentified links between the sketches that could be used later to assist in the development process. This process was also used to split the ideas into three categories, 'no redesign needed' contained ideas that wouldn't require any redesigning to parts that PFL have deemed outside of scope. This is the most

desirable outcome due to PFL's requested scope being limited to only the arm of the barrier. 'Redesign of the arm' indicates designs where parts of the arm would have to be redesigned for the concept to work; for example, one design had an internal belt running through the arm. However, this would require a stationary pulley to be placed within the arm to utilise the barrier motion to articulate the arm. The final category is the redesign of the base; this included all the designs that would require a redesign of the housing that was outside the project's scope and, therefore, very undesirable. Although PFL had set the project's scope, they had also stated they were still open to blue-sky thinking ideas should they be justifiably better than the existing barrier. Therefore, these ideas will still be considered.

The team then identified all the advantages and disadvantages of each drawing before assigning it a score out of 5. This score was based on the team's assessment of the idea rather than any other metric system as, at this stage in the selection process, the competency of each design was questionable and, therefore, would require filtering before any customer-facing selection processes could be applied.

Examining and ranking each idea allowed the team to gain a greater understanding. The main drawback of this selection method is the lengthy time required to examine each idea. Nevertheless, it was considered an effective process as some of the advantages from concepts not selected were chosen to progress to a later development stage.

7.2 Hand Calculation Verification

The concept ideation phase is a great way to let the team 'think outside the box' and explore new ideas that they thought might be useful without the bounds of physics or the requirement to have it work. This encourages innovation, fosters divergent thinking, and avoids premature judgment that would otherwise destroy ideas before they had been fully realised.

However, this can often lead to ideas that are difficult to implement or lack feasibility. Therefore, at this stage in the project, filtering out any 'impossible' ideas becomes crucial. The team analysed each idea, looking for potential floors and devising some hand calculations that could be used to justify the feasibility of the design.

7.2.1 Barrier Functionality

Design 4 used a near-fully internal cable, instead of an external pole, it was necessary to verify its feasibility with basic hand calculations. The design uses a cable-pivot system to achieve articulation, with the cable providing sufficient force in tension to maintain the second boom horizontal while the barrier is in the closed position. During motion, the second boom is free to rotate about the pivot through an angle slightly less than 180 degrees. The exact angle would require further calculations to be determined. In the open position, the first boom is vertical, while the second boom is roughly facing downwards towards the ground and is structurally supported by both the pivot and tensioning cable. There is scope in the design to maintain the second boom at the horizontal position throughout the whole range of motion. Figure 4 shows sketches of the proposed design. (A) shows the barrier in the closed position, with the red line representing the support cable, which is fastened at the base housing and enters the first arm at a location near the shoulder. (B) shows the barrier in the open position, with both arms are now near-vertical, (C) shows a cross-section of the boom, with an assumed-elliptical profile (this was used for the basic calculations).

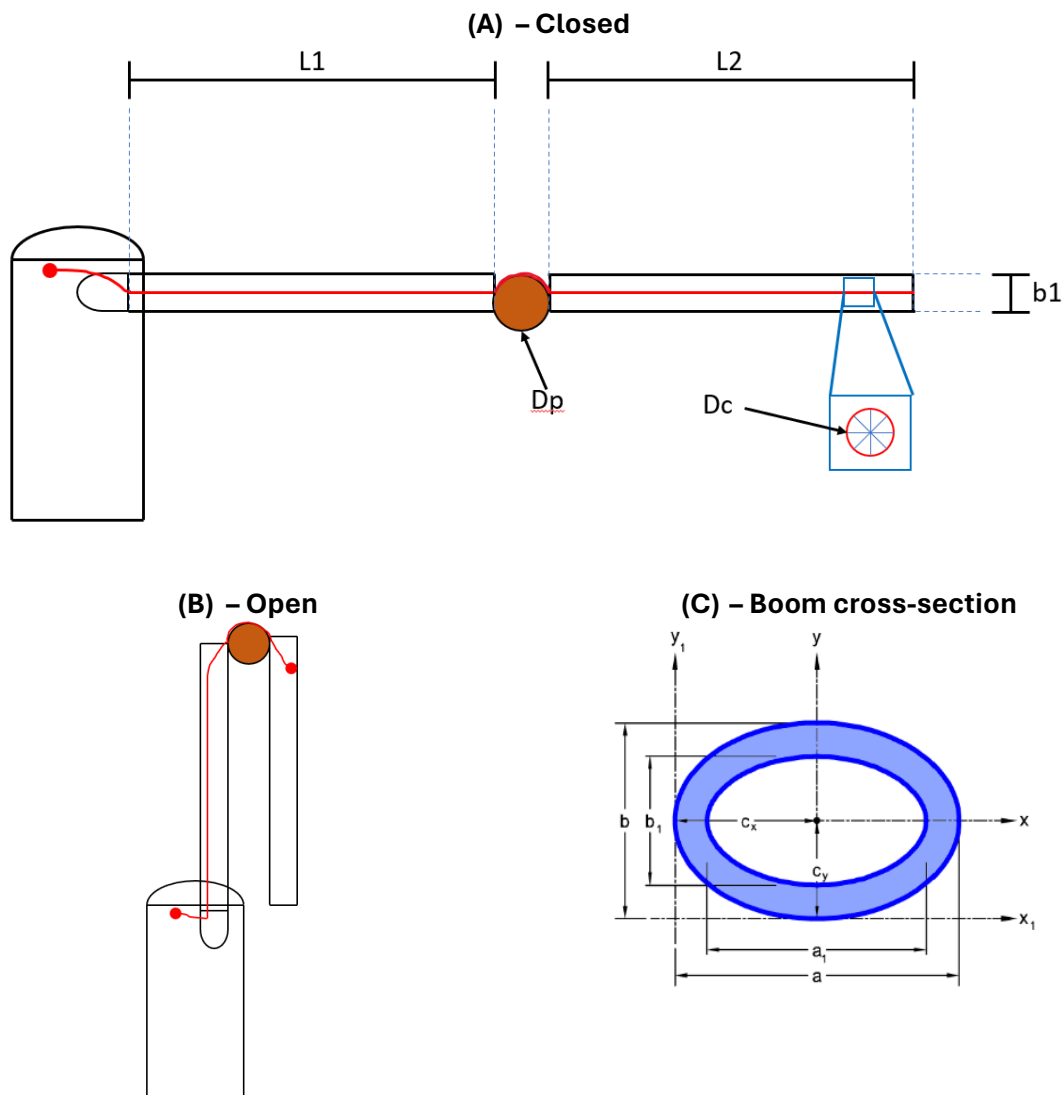


Figure 4 – (A): The barrier is shown in the closed position, with both arms horizontal. (B): The barrier is now shown in the open position. (C): An assumed-elliptical cross-section of the beam is shown.

In reality, the tensioning cable will not attach at the centreline of the boom sections, but will be offset in order to leverage additional mechanical advantage to provide a sufficient counter-moment to hold the second boom in place when horizontal, as shown in Figure 5.

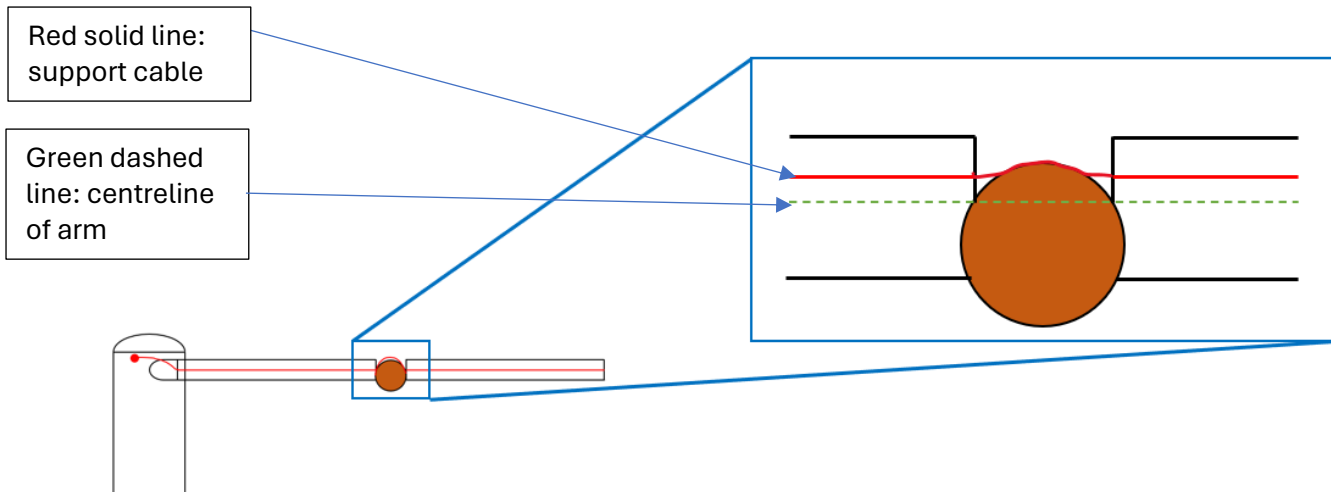


Figure 5 – Expanded view of a cable-pivot design.

Further calculations would be required to optimise the design of the mechanism. The main considerations would be:

- The maximum loads in bending and shearing that the mechanism could accommodate.
- The fatigue and wear imparted on the mechanism by expected cyclic loads that would be experienced during operation.
- The weight of the mechanism.
- Electrical power requirements of the mechanism compared with the existing 4-bar linkage.
- Effect of the mechanism on the use of the existing electrical cable system.

4.2 Initial Hand Calculations

To validate the design at this stage, a series of simple hand calculations were performed, determining loading conditions and absolute failure criteria for the design. Table 1 summarises the known values relating to the design, including component dimensions and relevant material. The mass per unit length of the boom was measured by the team using a sample 1 metre arm, and the boom dimensions approximated the actual cross-section of a simple oval.

Description	Symbol	Units	Value
Length of first boom	L1	m	3
Length of second boom	L2	m	3
Boom inner height	b1	mm	80
Boom outer height	b2	mm	85
Boom inner width	a1	mm	100
Boom outer width	a2	mm	105
Boom wall thickness	wt	mm	2.5
Mass per unit length of current boom	Mu	Kg/m	2.312
Density of steel	ρ_{st}	Kg/m ³	7750 [2]
Diameter of support cable	Dc	mm	15
Distance of cable from boom central axis	yc	mm	20
Pivot diameter	Dp	mm	80
Pivot width	Wp	mm	105

Table 1 – Initial values used for the hand calculations.

First, geometrical constants were calculated, beginning with the moment of inertia in the x and y planes for the boom (1) and pivot (2) respectively. The cross-sectional area of the tensioning cable was then calculated (3), as was the weight of the barrier arm, assuming a barrier with a 3m x 3m profile (4). For these calculations, the weight of the cable was assumed to be negligible.

$$I_{boom} = \frac{1}{12} * bh^3 \quad (1)$$

$$I_{pivot} = \frac{2}{5} * MR_p^2 \quad (2)$$

$$Ac = \frac{\pi D_c^2}{4} \quad (3)$$

$$Wb = M_u * L_1 * g \quad (4)$$

Description	Symbol	Units	Value
Cable cross-sectional area	Ac	m ²	1.77e-4
Boom weight	Wb	kg	6.936
Moment of inertia of boom in x	l _{bx}	m ⁴	6.52034E-07
Moment of inertia of boom in y	l _{by}	m ⁴	9.03116E-07
Moment of inertia of pivot in x	l _{px}	m ⁴	5.62659E-05
Moment of inertia of pivot in y	l _{py}	m ⁴	5.62659E-05

Table 2 – First set of calculated values (cross-sectional area, weight, moment of inertia).

From this, it was possible to calculate the loads in the system. The main loads are the shear forces resulting from the weights of the two boom sections (5), as well as the pivot joint and tensioning cable. The latter two components were assumed to be small relative to the arms and were assumed to be massless in the initial calculations. A large moment results from the weight of the barrier, which is supported by the tension in the cable (6).

$$V_{max} = 2W_b \quad (5)$$

$$M_{max} = 2W_b * L_1 \quad (6)$$

The main points of failure are assumed to be the cast shoulder, the support cable and the pivot (although failure at the latter 2 depends on design characteristics, including dimensions and materials). Although failure is usually the result of fatigue due to cyclic loading conditions, the calculations focus on failure due to bending stress, shear stress and tensile failure. This is to achieve basic validation that the rough design is mechanically feasible, with the expectation that any designs taken forward to the next phase of concept generation would be modified based on a more thorough

set of calculations. These would include design factors such as fastening methods, stress raisers, fatigue under cyclic loading, wear, corrosion, brittle fracture of the adapter, lubrication, etc.

Failure is first considered at the adapter, then at the cable, and finally at the pivot. The maximum shear stress was calculated for each component, being the maximum expected shear stress multiplied by a design safety factor of 1.5 (7). The procedure for failure in bending assumes the two boom sections as a single pole, with a point load equal to the combined mass acting downwards at half the combined length from the adapter (8). The maximum tensile stress is calculated for the cable using the maximum bending load divided by the cross-sectional area of the cable (9).

$$\tau_{max, shear} = \frac{QV_{max}}{I_y b} * SF \quad (7)$$

$$\sigma_{max, bending} = \frac{My}{I_y b} * SF, \quad y_{adapter} = \frac{1}{2} a_1 \quad (8)$$

Failure in the cable is calculated using the simple uniaxial stress formula (9), with the load equal to the weight of one boom section.

$$\sigma_{max, tensile} = \frac{P}{A_c} * SF \quad (9)$$

Failure at the pivot is resolved using the same procedure as for the adapter, except that the moments at the pivot are equal and opposite, resulting in no net moment. The failure criteria for the design are set by steel's yield strength (factor of safety already included in the maximum stress calculation). If the stress in the design exceeds the yield strength, it cannot be taken forward.

Failure at the Adapter			
Mechanism	Stress (KPa)	Max Allowable Stress (Yield Stress) (KPa)	Suitable (Y/N)
Bending	35,598	250,000 [3]	Y
Shear	218	250,000	Y
Failure in the Tensioning Cable			
Mechanism	Stress (KPa)	Max Allowable Stress (KPa)	Suitable (Y/N)
Tensile stress	13.54	250,000	Y
Failure at the Pivot			
Mechanism	Stress (KPa)	Max Allowable Stress (KPa)	Suitable (Y/N)
Shear	6.696265641	250,000	Y

Table 3 – Tabulated data from simplified hand calculations.

Based on the results summarised in Table 3, it is concluded that design 4 can be considered mechanically feasible at this stage, as it does not exceed the maximum allowable stress for any of the three failure modes.

7.3 Pugh Matrix

At this stage, the 120 sketches had been condensed into ten feasible concepts within the project’s scope and could probably be carried out by the team. A Pugh Matrix was selected as a decision-making tool that could be used to compare and evaluate each alternative to the existing PFL design. It was chosen for the following principal reasons:

- **Systematic Evaluation:** Providing structure to evaluate each concept idea systematically helps organise the decision-making process and ensure that all relevant factors can be considered.
- **Objective Comparison:** Assigning numerical values to customer needs and using a standardised method lowers the chance of biased or subjective opinions.
- **Quantitative Analysis:** Assigning Weightings to each objective facilitated a more effortless and faster numeric comparison to be drawn.

This process allowed the team to make a more informed and transparent decision while ensuring the idea aligned with the project’s aims and requirements. It quickly eliminated ideas that were non-viable and used objectives that were chosen from the customer’s needs. Each weighing was based on the primary research conducted on PFL to ensure that the customer needs they thought were important would also be reflected in the design selection. For example, as PFL values its lead time as a key differentiation from its competitors, the team selected ‘easy to manufacture’ as an objective and weighted it 5 to show its importance. The scoring was decided against the current design to provide only ideas that were better than the current PFL would be considered.

Criteria:	Weighting:	Current Solution	Idea 3		Idea 4		Idea 9.2	
		Baseline	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Easy to Manufacture	5	0	2	10	-1	-5	0	0
Low maintenance requirements	2	0	1	2	-1	-2	0	0
Barrier must look good	4	0	1	4	2	8	1	4
Barrier must transport easily	1	0	-1	-1	0	0	0	0
Weather resistance	1	0	1	1	-1	-1	0	0
Speed of operation	2	0	-2	-4	0	0	0	0
Barrier is safe	3	0	0	0	1	3	0	0
Easy to adapt for a range of lengths	2	0	0	0	0	0	0	0
Competitively priced	1	0	1	1	0	0	0	0
Innovation/creativity/uniqueeness	2	0	0	0	2	4	2	4
Engineering science (achievable?)	2	0	-1	-2	0	0	0	0
Net Score:			2	11	2	7	3	8
Ranking:			1st		3rd		2nd	

Figure 6 - Pugh Matrix on Final Ideas

The scores ranged from -9 to 11, with the top three ideas (Ideas 3, 4, 9.2) being carried forward to a second Pugh matrix as it was identified that the top three ideas had advantages in specific objectives and, therefore, could be combined to utilise the benefits of each design. Idea 3 excelled in this ‘easy to manufacture’ section. Idea 4 excelled in the ‘barrier must look good’ (aesthetics was another important feature to PFL). Idea 9.2 excelled in ‘innovation/creativity/uniqueeness’. These three ideas are showcased in Figure 6, with the full Pugh Matrix in 22.3.

A second Pugh matrix would allow the team to experiment with lessons learnt in the first round. Therefore, the team went away to develop these ideas, using some of the benefits newly identified from non-viable ideas to create 11 more ideas. Again, each idea was compared against its original idea. It was found that all three of the ideas were still the highest-scoring ideas. This indicated the concept ideation phase had been fully completed, with new ideas not ranking as highly against the most established ideas. The three other Pugh Matrices can be seen in 22.4.

7.4 Meeting with Joe from PFL

The group gained invaluable insight from previous interviews with Joe from PFL. It was decided to obtain his opinion on the current design before the team made their final selection. During a meeting on Tuesday, 12 December 2023, at 4 pm, the team presented the top three ideas to him, intending to use his advice to help select just one idea to progress with. He mentioned two critical facts the team had overlooked that resulted in the 'cable idea' (idea 4) being selected.

1. The safety edge would need to be facing the direction of travel consistently. This highlighted to the group that the swinging arm design was no longer an option, for as the barrier changed from the closed position to the open position, the safety edge would translate into the side of the arm, and thus would not be facing the direction of travel, therefore meaning two safety edges would be required for this design.
2. Any twisting out of the plane could be incompatible with some customers' car parks due to restrictions in 3d space.

He also reemphasised the importance of creating a barrier that is easier to assemble and does not affect PFL's competitive advantage of lead time.

7.5 Moving forward

The group explored a wide range of ideas and performed hand calculations to validate each idea. Following the results of the Pugh matrix, and with the approval of Parking Facilities Limited, the team selected idea 4: 'the cable idea'. This idea was to be progressed to the next stage, 'development'.

However, the team also kept the other remaining ideas in mind as backup ideas in case unforeseen problems were to arise in the future.

8 Design Development

8.1 Initial concept development

The selected concept was then development in CAD. This helped to visualise how it might come together. The first iteration of this development is shown in Figure 7. The hinge featured an L shaped design, which allowed the hinge pin to be moved further away from where the cable attaches. This led to an increase in the moment effect that the cable would have. The idea of using a cover for where the cable enters the arm was also introduced to enhance both safety and aesthetics.

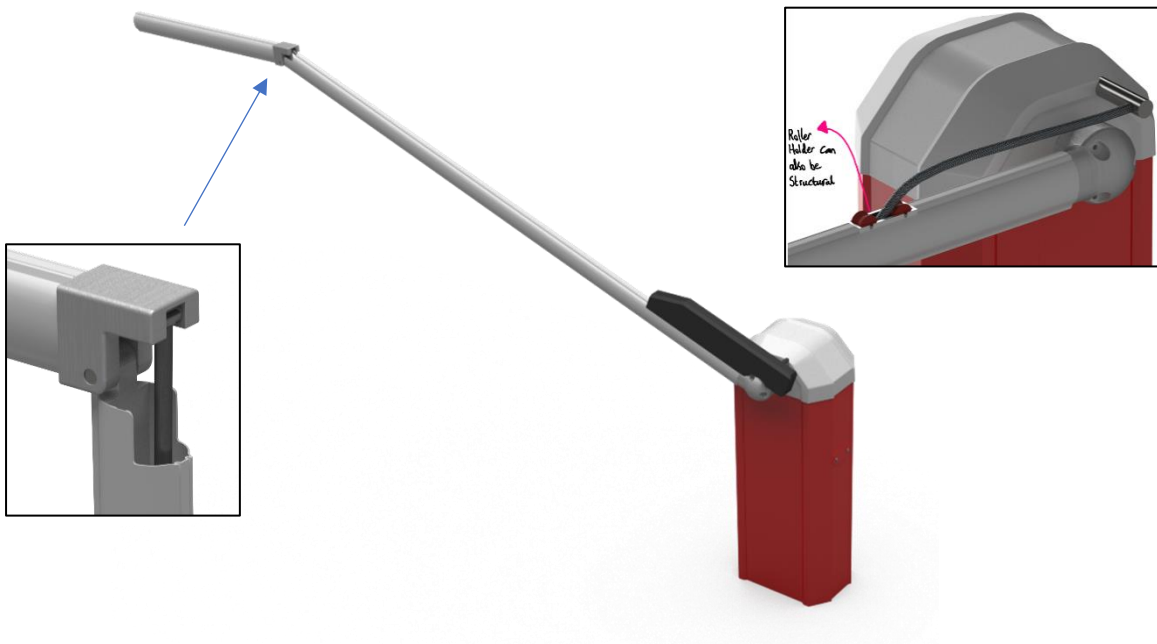


Figure 7 – Initial Design Development

The main concerns with this design included:

- The tension in the cable being too high and breaking.
- Calculating the cable movement needed to keep the second beam level, and the subsequent positioning of the cable anchor to the base.
- The cover being too large.

8.2 Hinge Development

The hinge was redesigned to reduce tension in the cable as shown in Figure 8, Figure 9 and Equation (10). By increasing the distance X , the tension in the cable is reduced.

$$\text{Moment} = \text{Force (Tension in cable)} * \text{Distance (X)}$$

(10)

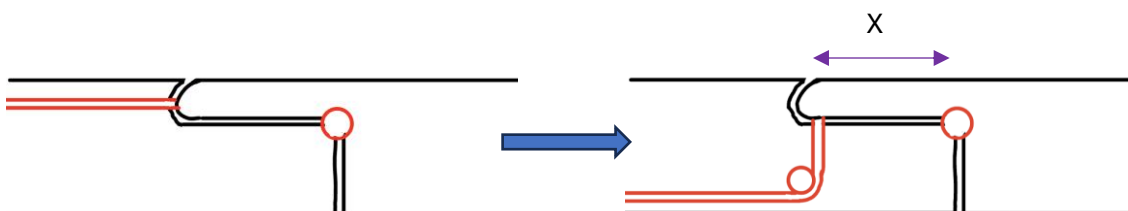


Figure 8 – Hinge redesign to reduce tension.

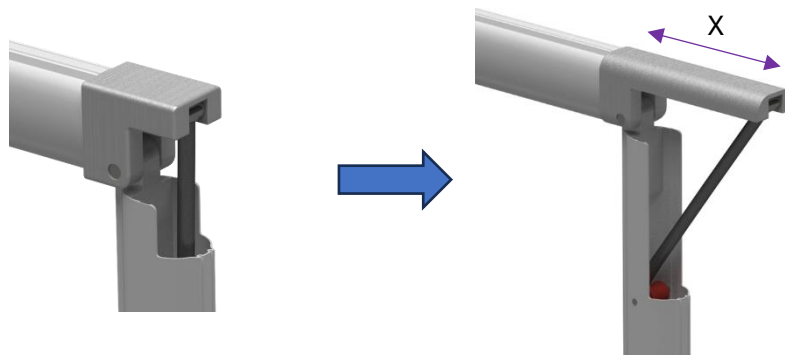


Figure 9 – Hinge Redesign

Although this design reduces tension it requires more cable movement and subsequently a larger cover at the entry point as shown in Figure 10. Calculations would be needed to work out the optimal value for the overhang value 'X'. Work on developing the design of the hinge continued whilst these calculations were being carried out, as dimensional changes would be easy to implement later.

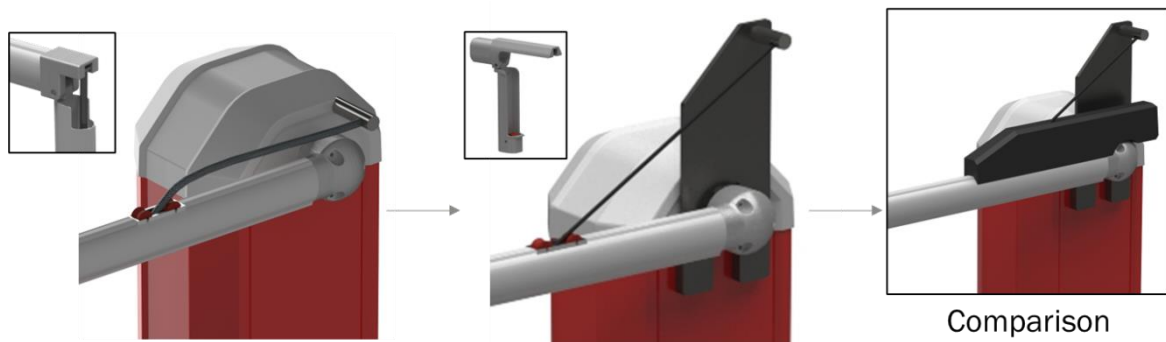


Figure 10 – Larger overhang 'X' requires a larger cover.

With a key factor of this project being to reduce assembly time, the decision to make the hinge one pre-assembled component was made. This allows for the hinge to be easily inserted into the beam, then the required holes can be drilled for a securing bolt into the two halves. By adding a rim to the hinge, it will stop where required when inserting. This avoids the need for time consuming measuring and marking. Currently PFL's cast shoulder is a standardised bought in component. We have the same vision for the hinge. The two halves of the hinge would be cast and delivered to PFL, where only the hinge pin will need to be added. This concept is shown in Figure 11.

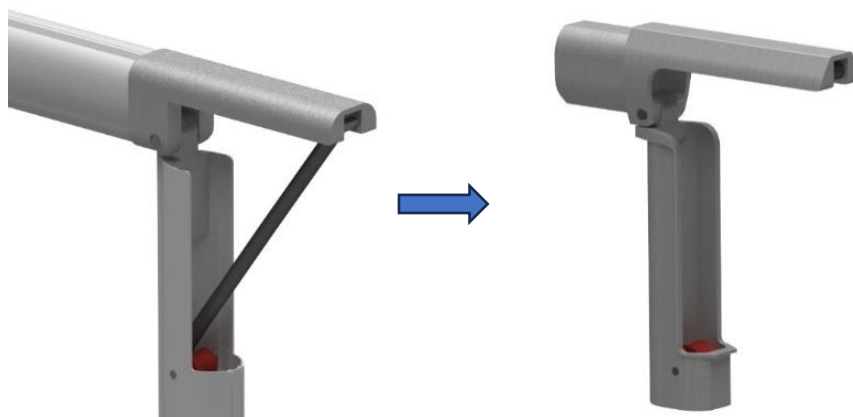


Figure 11 – Design for Assembly.

To further simplify the design, more inspiration was taken from the current PFL shoulder which uses a simple oval shape. The need for a cut-out from the beam was also eliminated. This simplifies the assembly process as once the beams are cut to length no more work is needed before inserting the hinge. Using ridges in the casting around the holes to add strength was also explored, as this was something the existing shoulder casting had. These changes are shown in Figure 12.



Figure 12 – Design simplification.

Up until this point the CAD models were designed around the CAD beams that PFL initially supplied. However, these models actually used a smaller beam profile than the company produces. The beams were remodelled in CAD by taking measurements of the larger beam section and shoulder that the team were supplied with by the company. Since these dimensions will be critical, a test piece was 3D printed to check that the hinge would fit in the barrier before committing to manufacturing it in metal. This test is shown in Figure 13. The test was a success, and indicated that a couple measurements needed adjustment, but none more than 1mm, and even without further adjustment it would be an acceptable tolerance as is.

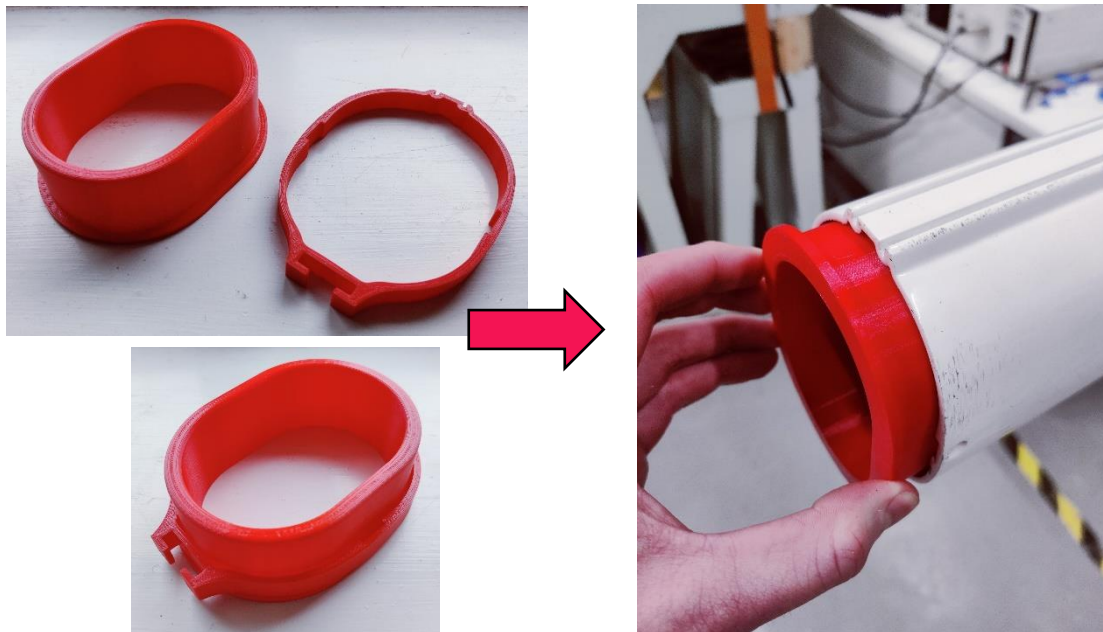


Figure 13 – Rapid prototyping to validate design.

The next step of the hinge development process required completion of calculations and FEA to decide upon critical dimensions.

8.3 Cable and Chain Calculations

The proposed design includes an internal cable (also known as a wire rope) to keep the 2nd beam of the barrier parallel to the ground at all angles during the opening and closing cycle. There are many factors to consider when choosing which cable composition should be purchased, such as cost, maximum allowable tension, cable stretch, fatigue, weather and rust resistance, and minimum pulley diameters.

Initial research on cables was conducted to understand the challenges. It was found that there are different compositions of cables, known as the strand design. The strand design determines how many wires are twisted into strands and how many strands are twisted into the cable. Figure 14 and Figure 15 below show diagrams of cable compositions and different cable strands.

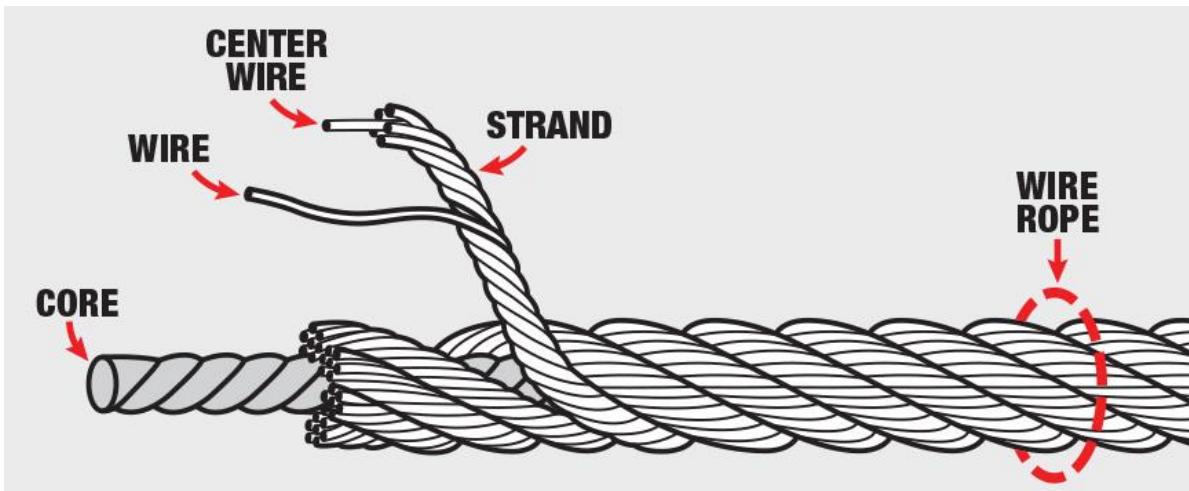


Figure 14 – A diagram showing how wires are wound into strands and how strands are wound into cables [4]



Figure 15 – A diagram showing the different strand designs of cables [5]

A strand with fewer wound wires, such as the 1x19 configuration, can withstand much higher tensions but is much less flexible, while a cable such as 7 x 19 can bend much more easily but will stretch more and snap under less tension.

The material of the cable largely affects its rusting and weather resistance properties. Common materials used for cables are stainless steel type 304 and 316. Type 304 is cheaper than type 316 and is corrosion-resistant for most outdoor applications; type 316 is also resistant to chlorine and saltwater applications, making it the better choice for barriers in coastal locations. Furthermore, type 302 stainless steel, commonly used for military aircraft, is stronger but much more expensive and less corrosion resistant.

8.3.1 Chain Tension Calculations

A free-body diagram of the barrier’s closed and open state was drawn. Using known values, such as the weight of the beam and some distances determined by the design, the required tension of the cable could be calculated for a range of ‘x’ and ‘L’ values. See Figure 16 below for the free-body diagrams of the open and closed state of the barrier.

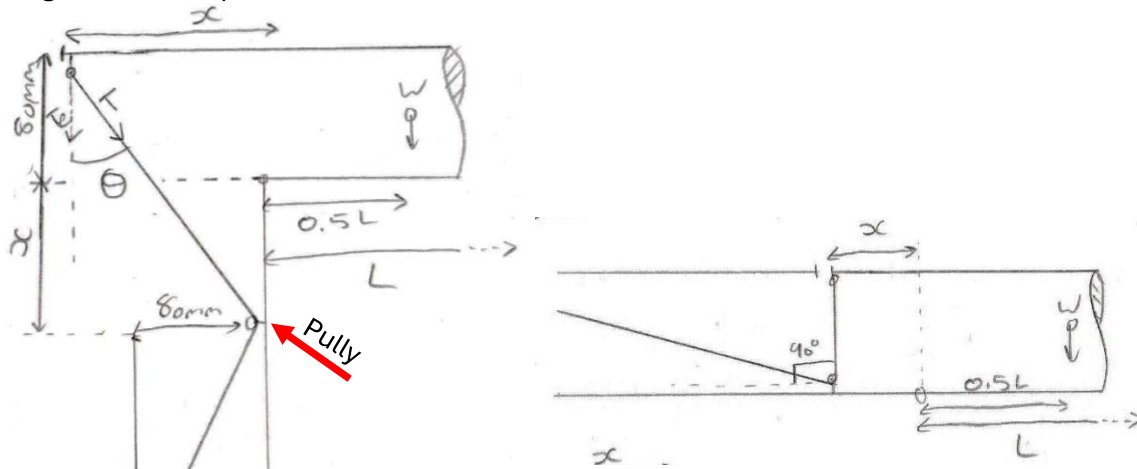


Figure 16 – A free-body Diagram of the open barrier (Left) and closed barrier (Right). This free body diagram included an unknown distance variable ‘x’, an unknown distance variable ‘L’ and Tension ‘T’.

A table of Tensions against L and X was generated. This allowed the team to understand the required tensions given all possible barrier compositions (see Table 4 below). Therefore, this allowed for an understanding of what cable will be required.

Table of Tension T										
x\L	0.5	1	1.5	2	2.5	3	3.5	4	4.5	
0.1	63.38241	253.5297	570.4417	1014.119	1584.56036	2281.767	3105.738	4056.475	5133.976	
0.15	31.69121	126.7648	285.2209	507.0593	792.280179	1140.883	1552.869	2028.237	2566.988	
0.2	25.55027	102.2011	229.9524	408.8043	638.756701	919.8096	1251.963	1635.217	2069.572	
0.3	15.74749	62.98995	141.7274	251.9598	393.687186	566.9095	771.6269	1007.839	1275.546	
0.4	11.34373	45.3749	102.0935	181.4996	283.593146	408.3741	555.8426	725.9985	918.8418	
0.5	8.85541	35.42164	79.69869	141.6866	221.385256	318.7948	433.9151	566.7463	717.2882	
0.6	7.259233	29.03693	65.3331	116.1477	181.480826	261.3324	355.7024	464.5909	587.9979	
0.7	6.149318	24.59727	55.34386	98.38908	153.732938	221.3754	301.3166	393.5563	498.0947	
0.8	5.333199	21.3328	47.99879	85.33119	133.329979	191.9952	261.3268	341.3247	431.9891	

Table 4 – A table showing x distance [m] and L distance values [m] on the x and y axis, respectively, and required tension [N].

From geometry limitations (see section Hinge Development), the x value is expected to be between 0.1 and 0.2 m, and according to project requirements, the maximum L is expected to be no more than 4.5m but more likely 3.5m. This gives expected maximum and minimum tensions of 3.1kN and 1.2kN, respectively.

As part of this design the pulley (labelled ‘pulley’ in Figure 16) is inside the beam, and therefore, limits the pulley size. It was discovered that the maximum pulley diameter could be around 60mm. A general guide for the pulley diameter of a 7 x 19 (most flexible) cable is 25 times the cable diameter [6]. Limited at 60mm, this would give us a maximum cable diameter of 2.4mm. Looking at cable specifications online, a 3mm diameter 7 x 19 cable gives a maximum safe working load of 80 kg (0.78 kN) [7]. Comparing this to Table 4 above, with the upper limit of 0.2m ‘x’ value, this would limit the 2nd arm to 2.5m length. This does not achieve the requirements in the PDS. Further research in cables with small enough pulley diameters and high enough safe working loads was unsuccessful. It

was concluded that finding a cable with a low enough ‘maximum pully diameter’ and a sufficient safe working load is unlikely.

Therefore, research into alternative solutions, such as belts and chains, was conducted. Commonly used for forklifts, leaf chains are designed for extremely high tensions and only require pully diameters of 5 times the chain’s pitch [8]. Furthermore, leaf chains come in standardised sizes with standard parts. This means parts can be bought on a larger scale and for cheaper, compared to designing specialised parts. Additionally, leaf chains can cost as little as £14.89 per meter [9]. Leaf chains do not have teeth or spikey profiles, unlike inverted tooth chains, and use pullies rather than sprockets, which look less aggressive and safer to customers. Therefore, leaf chains were considered an ideal solution for the barrier.

A leaf chain specialist was contacted to discuss this use of the chain. The idea was deemed plausible; however, some considerations were addressed, such as chain lubrication, chain wear, safety factors and tensioning. Although parking barriers are less safety-critical than forklifts, PFL places high importance on the safety of their barrier. Therefore, it was decided to treat the chain to the standards expected in a forklift. This includes a 5:1 safety factor, chain replacement at 3% extension and regular lubrication. Given the outdoor conditions, it was also recommended that a zinc-coated chain should be used to provide an extra level of rust protection. Furthermore, using a chain anchor and a bolt was recommended to tension the chain, also replacing the need for a separate tensioner. This could easily be implemented into the design using the standard leaf chain anchors, as the connection point between cable and support had not yet been fully developed (see section Cable attachments).

8.4 Hinge Calculations

8.4.1 Horizontal Beam Calculations

To ensure the 2nd arm is horizontal when the barrier is in the fully open position, calculations were completed to determine the relationship between the chain mounting position and the geometry of the hinge. 2D sketches of the barrier were drawn in both the shoulder and elbow’s open and closed positions. See Figure 17 below.

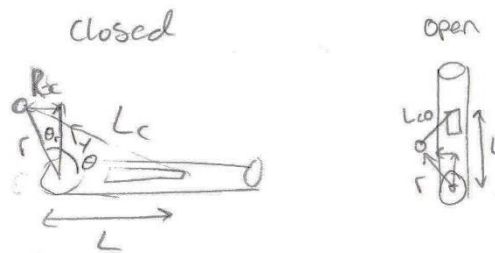


Figure 17 – Calculations for the ‘Cable pull in’ at the shoulder.

As the 1st beam is lifted, the cable is released into the arm. This length of cable was calculated using the cosine rule in the open and closed state and then calculating the difference. This was named the ‘cable pull in’ and denoted ‘ ΔLc ’. The relationship between distances r , L and the cable pull-in was determined to be;

$$\Delta Lc = \sqrt{r^2 + L^2 - 2RL \cos \theta} - \sqrt{r_x^2 + (L - r_y)^2}$$

(11)

Where ΔL_c is cable pull-in, r and L are geometric distances shown in Figure 17, and θ is the angle of the beam to vertical. R_y and R_x are the vertical and horizontal components of the distance R .

To maximise cable, pull in (and therefore increase the hinge overhang 'x' distance and decrease tensions (see Chain Tension Calculations), L should be equal to R_y . However, the distance L was limited to a minimum of 0.66m, due to an internal component that PFL cannot change. As the distance R_y is much smaller than L , the team decided to keep L to the minimum distance of 0.66m. Therefore, L can be treated as a constant within the equations above.

8.4.2 Cable out and hinge overhang 'x' relationship

As the cable has a constant length, the cable pull in at the shoulder is the same length as the 'cable out' at the elbow of the barrier.

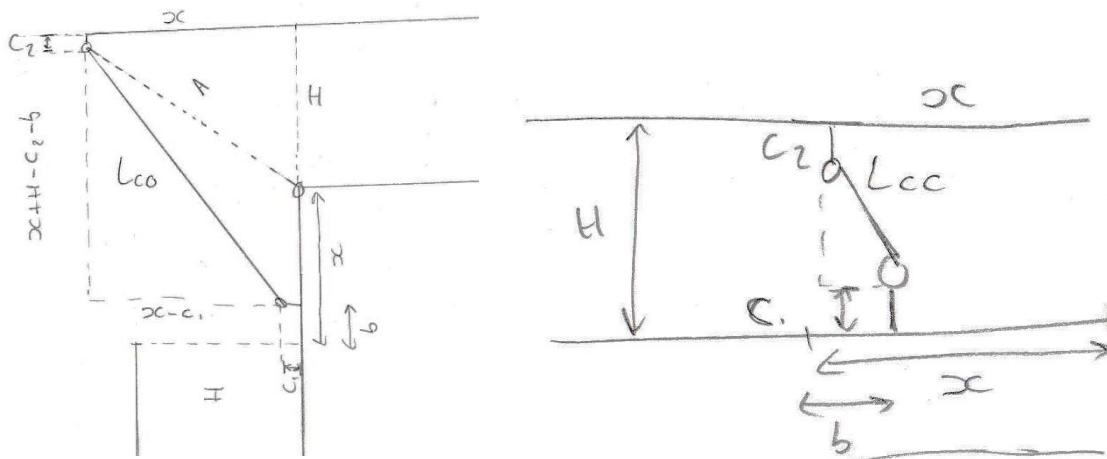


Figure 18 - Sketches of the 'elbow' hinge in the open (left) and closed (Right) position used to find the relationship between cable pull in and the variable x .

The elbow joint was sketched in the fully open position, as seen in Figure 18. using the Pythagoras theorem and given the constants H , b , $C1$ and $C2$, the relationship between x and ΔL_c was determined to be;

$$\Delta L_c = \sqrt{(x - C1)^2 + (x + H - C2 - b)^2} - L_{cc} \tag{12}$$

Where L_{cc} is length of cable when barrier is closed, ΔL_c is the cable pull in, H , b , $c1$, $c2$ are geometric constants and x is the unknown variable.

Which can be rearranged and solved using the quadratic formula to give x .

Therefore, using the Cable pull in calculations (see section Cable pull in calculations) for any given R_x and R_y , it is possible to calculate the cable pull in, and using 'Cable out and hinge overhang relationship' calculations above, it is possible to calculate an x which will keep the 2nd arm horizontal when the barrier is fully open.

8.4.3 Droop Calculations

PFL have put high importance on the customer perception of the barrier. It was concluded that a barrier with high droopage implies poor quality, and therefore, the team also completed calculations to predict the angle of the 2nd beam for angles between 0 and 90°.

As previously mentioned, using Figure 17 and equation ((12), the cable pull in can be calculated for any angle between 0 and 90 degrees. A new sketch was drawn for the barrier elbow hinge at any given angle, θ , and with given droopage α .

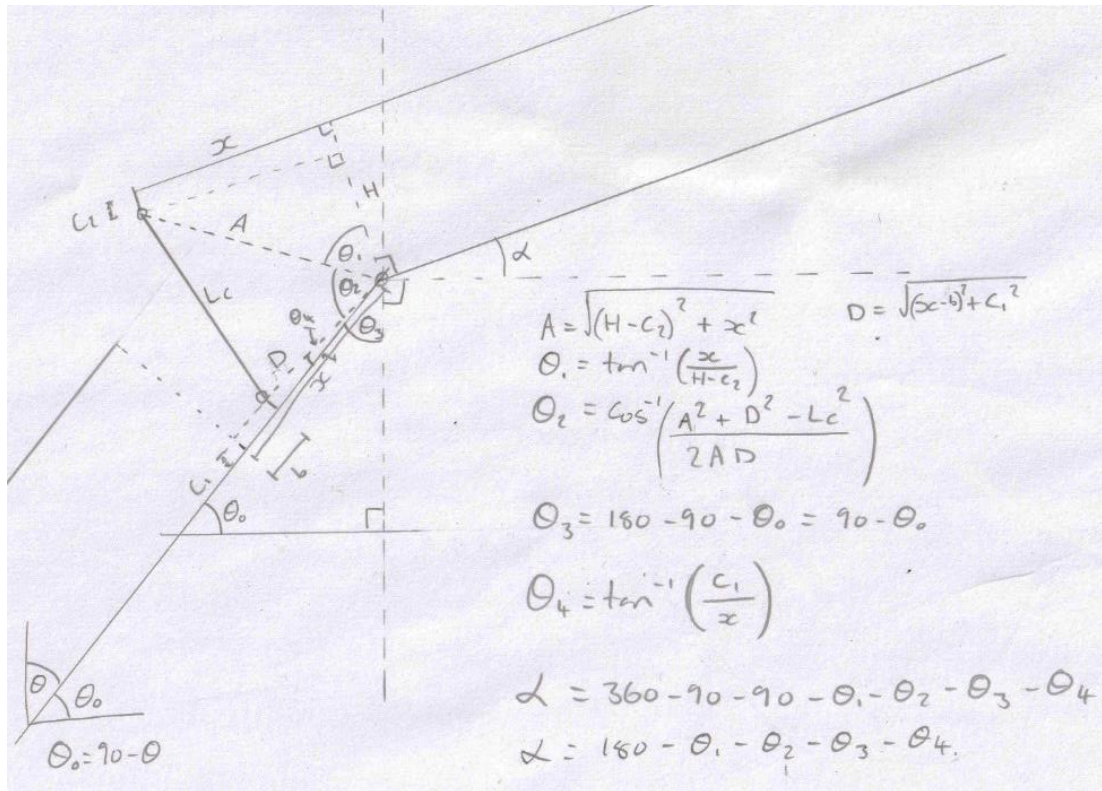


Figure 19 - A 2D representation of the barrier at a given angle ' θ ' (seen at the bottom left), and known geometry x, H, b, C_1, C_2, L_c .

Given the angle of the first beam (denoted θ in both Figure 17 and Figure 19), the geometric distances X, H, C_1, C_2 and b (determined by the geometry of the hinge design) and the 'cable pull in' (Calculated from Equation (15)), it is possible to calculate the angle of the 2nd beam, denoted α in Figure 19.

Using Microsoft Excel to calculate the angle α for all angles 0-90°, using the variables shown and plotting the results gives;

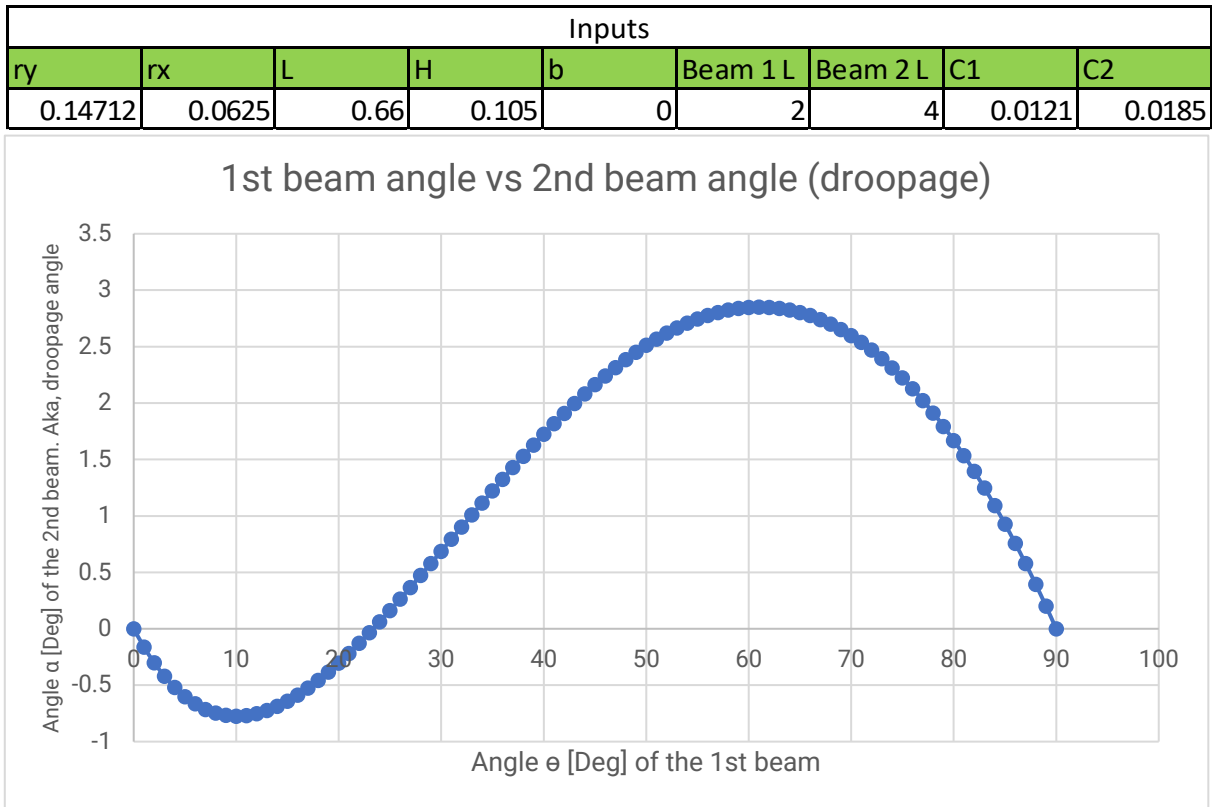


Figure 20 - A table showing the numerical values used for the design and a graph showing the resultant droopage angle of the 2nd arm through all angles during the opening of the barrier.

Note the variable X is not an input, as it is calculated from r_x , r_y and L (see section 8.4.2). This is seen in the results graph as the barrier starts and ends with no droopage (and therefore a perfectly horizontal 2nd beam when closed and fully open).

This calculation allows for the optimisation of hinge geometry to minimise the drooping as the barrier opens and closes.

8.4.4 Hinge Pin Radius Calculations

An analysis of the supposed hinge was done to find the maximum shear stress and bending moment that it will experience, Figure 21 below shows the rough dimensions relevant to the problem, L1 is 40mm and L2 is 22.5mm

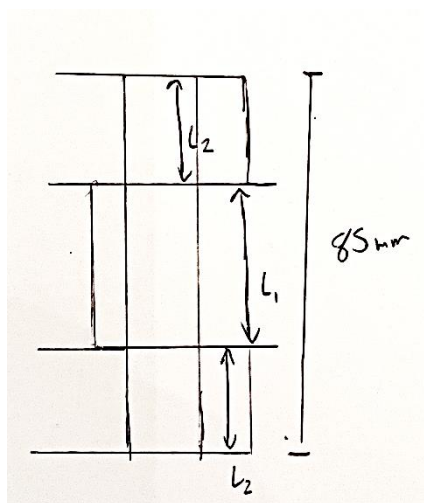


Figure 21 - Diagram of hinge pin and knuckles.

The assumption that the barrier will be at its maximum length at 6m and the calculated cross-section dimensions and material properties of aluminium were used to find the force applied at the hinge due to the beams weight. For the hinge pin it was assumed to be stainless steel for the first set of calculations. When evaluating the stresses acting on the pin of the hinge joining the two halves of the barrier extrudes, the length of the pin will be assumed to be the same as the width of the barrier at its widest point being 85mm, the diameter will be assumed to be 10mm, using the assumed barrier dimensions and having 4m length of outer extrude the weight will be 90.704N.

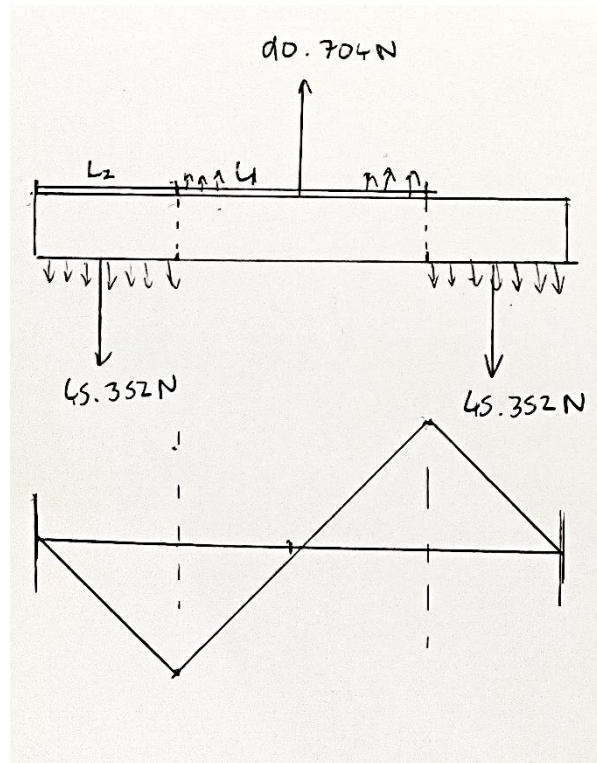


Figure 22 - Free body diagram of the hinge pin (top) and the graph of stress experienced (bottom).

From the shear stress diagram in figure 22, the maximum stress will be where the separate parts of the hinge meet and the force acting on the pin is reversed, the maximum force at this point being 45.352N, the maximum shear stress can be calculated using the formula:

$$\tau_{max} = \frac{VQ}{Ib} \quad (13)$$

Where τ_{max} is the maximum shear stress, V is the shear force, Q is the area above where the shear stress is being calculated, I is the moment of inertia and b is the width of the cross section. For a circular cross-section the maximum shear can also be calculated from:

$$\frac{VQ}{Ib} = \frac{4V}{3A} \quad (14)$$

Where A is the cross-sectional area found from πr^2 . From this formula the maximum shear stress was found to be 2664.4Pa for the case of a 4.5m outer arm (the longest length decided to be feasible for a 6m barrier). When using stainless steel as a material for the hinge pin the minimum

radius was found to be 2.127mm. with a safety factor of 2 the minimum hinge radius must be 4.254mm.

8.4.5 Fatigue Calculations

The service life of the barrier is critical to the success of the design. A warranty of 3 years is implemented for the existing barrier used by PFL, and this is considered to be the absolute minimum for an acceptable life for the proposed design. Accounting for safety factors, 5 years was selected as a desired target for design life. Achieving this target product life is critical to maintaining the current customer perception of PFL as a company that delivers robust and reliable products.

As the proposed design bears much similarity to the existing PFL barrier, the fatigue analysis focused on the most significant changes to the design: the entry point of the cable into the arm (and associated pulleys) and the articulating hinge. The base unit, cast shoulder and the second arm are unchanged from the current PFL barrier. The location and dimensions for the entry point were also not yet calculated. The proposed chain in section 8.3.1 was rated for significantly larger loads than were expected in the barrier and it was considered to have a sufficient lifespan for the proposed design. Additionally, the dimensions of the hinge bearing and the exact details on how it would fasten the chain had not yet been finalized. Therefore, it was decided to not investigate these components at this stage and instead focus solely on the hinge, as is shown below in Figure 23.

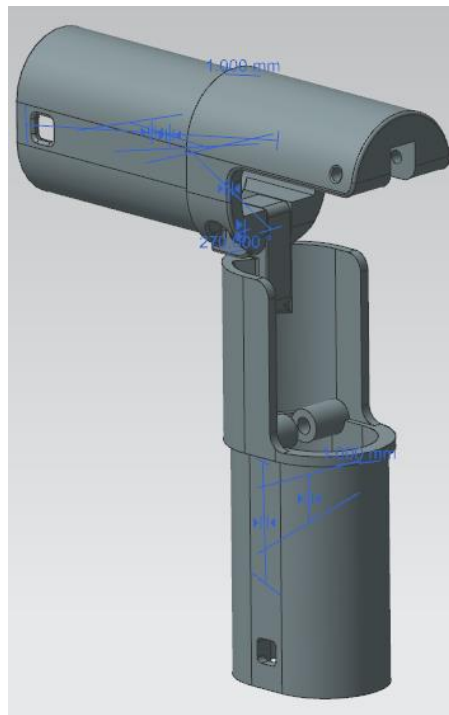


Figure 23 - The two hinge components are shown for when the barrier is in the vertical (open) configuration.

The initial fatigue calculations assumed that both hinges were identical in form and that both would experience a maximum load of 2280N. Up to this point, calculations have only accounted for maximum static loads. However, the maximum loads on the barrier will occur when the acceleration is the largest. For fatigue calculations, the critical factor is the average stress on the system experienced in a given cycle. Therefore, it was necessary to approximate the acceleration experienced by the barrier.

The current barrier is rated for 10 seconds opening / closing time, however, following discussion with PF, it was understood that the end user often modified the motor torque to achieve much faster times than this. Based on this discussion, it was decided to perform the calculations for a 3 second opening time, as this was considered the absolute lower limit for opening / closing times. Although such a fast speed was not considered realistic for larger barrier sizes, it was chosen in order to provide a large factor of safety for the hinge design.

In order to derive the linear acceleration and velocities, it was first needed to calculate the respective angular values and then work backwards. This was done knowing the arc length (the length of arm 1) and that the angle between the open and closed positions was 90 degrees. With the linear acceleration calculated, the inertial loads were found using $F = Ma$. The total load was simply the sum of the static and inertial loads.

The speed was assumed to increase rapidly from 0 to maximum within 0.6 seconds and decrease to 0 within the same time at the end of the 3 second cycle. Having calculated the distance covered by the arm (moving 90 degrees in 3 seconds) and establishing the periods of acceleration, the maximum speed was reverse engineered. With this, the acceleration profile could be derived, giving the maximum acceleration of 4.2 m/s^2 . As the calculations were very rough, assumptions were made to err on the side of caution. Figure 24 shows a graph which plots the estimated speed and acceleration of the barrier during a 3 load cycle.

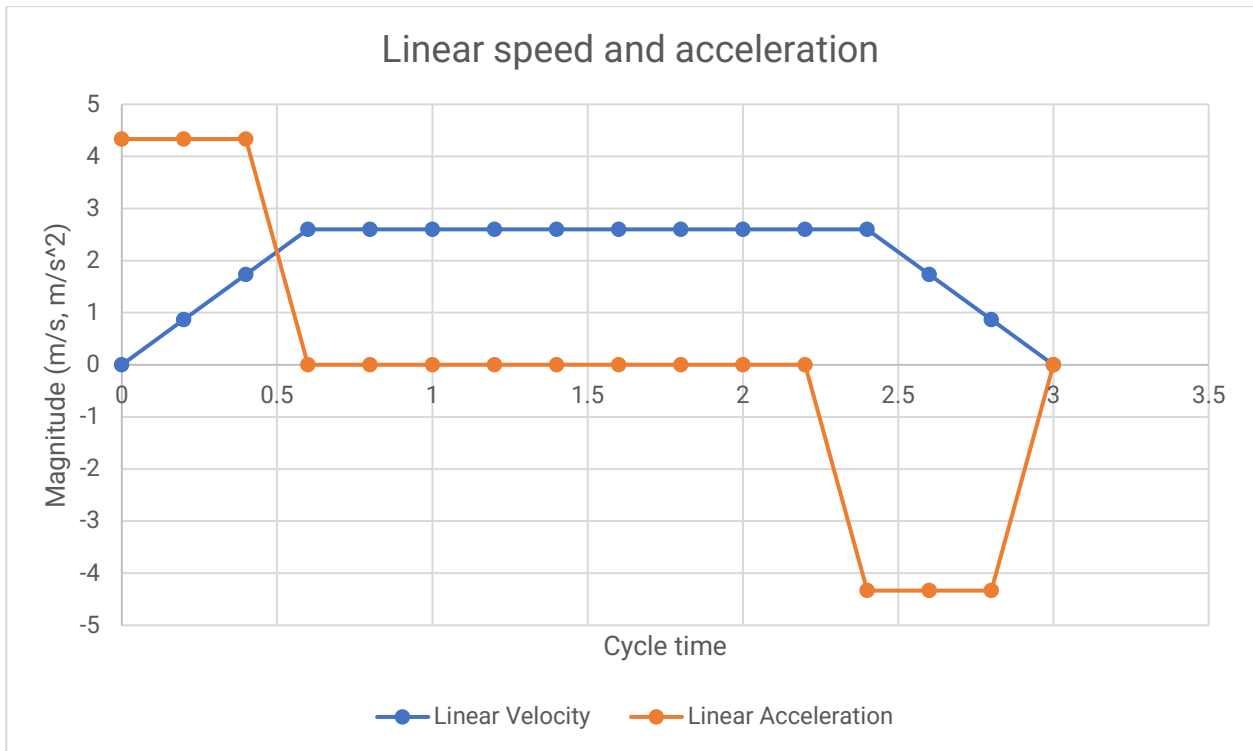


Figure 24 - Graph of estimated acceleration and velocity over time.

Having produced an acceleration-time graph, the basic formula of force = mass * acceleration was used to calculate the respective inertial loads at each time step. From this, the stress due to inertia was calculated at each time step, assuming that the stress was due to increased bending. The stress-time graph was then used to determine the average cycle stress, which was the critical value for estimating fatigue life.

$$\sigma_{Total} = \sigma_{Static} + \sigma_{Inertial}$$

(15)

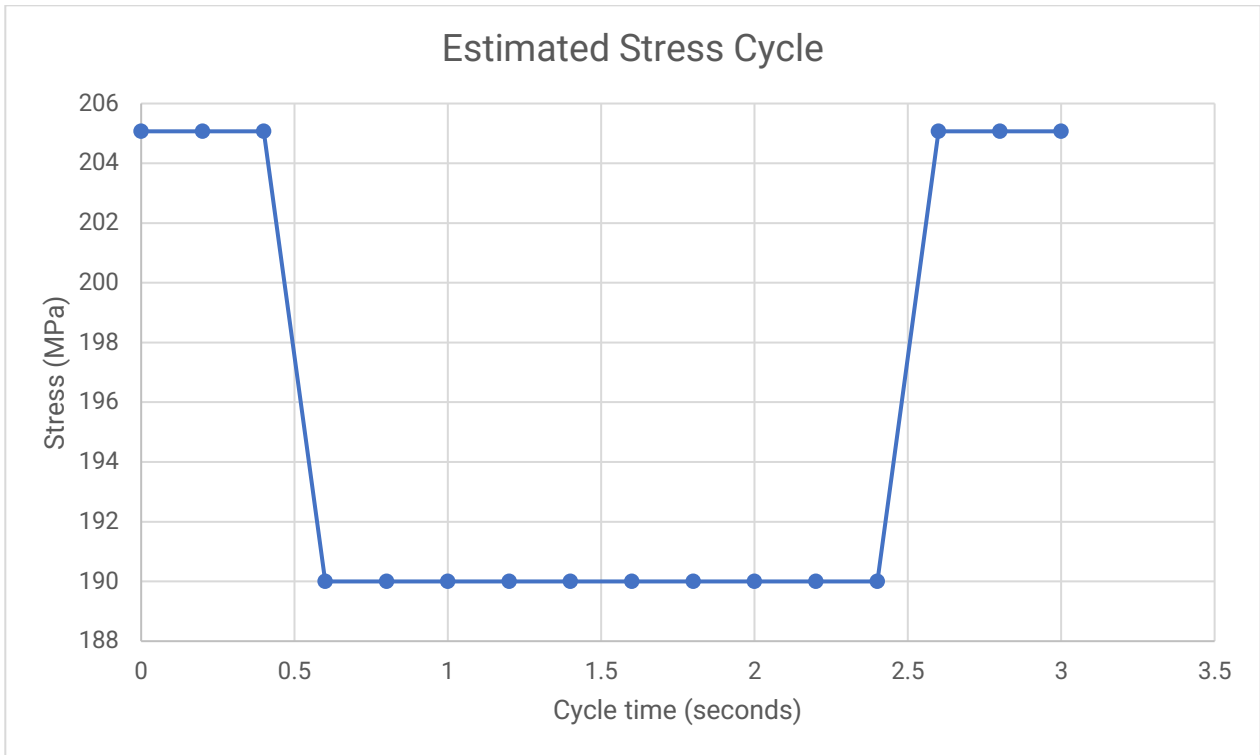


Figure 25 - Graph of stress in the barrier over time.

In addition, to the average cycle stress, the other critical variable was the expected upper limit for daily cycles. This could be combined with the stress to estimate the number of days (and thus years) that the barrier design would last. This data (Figure 26) was taken from Ahmed et al. [10] and shows the recorded frequency of barrier usage on Loughborough University campus for a 24-hour period. This was used to estimate the number of daily cycles – taken to be approximately 400 – for a parking barrier.

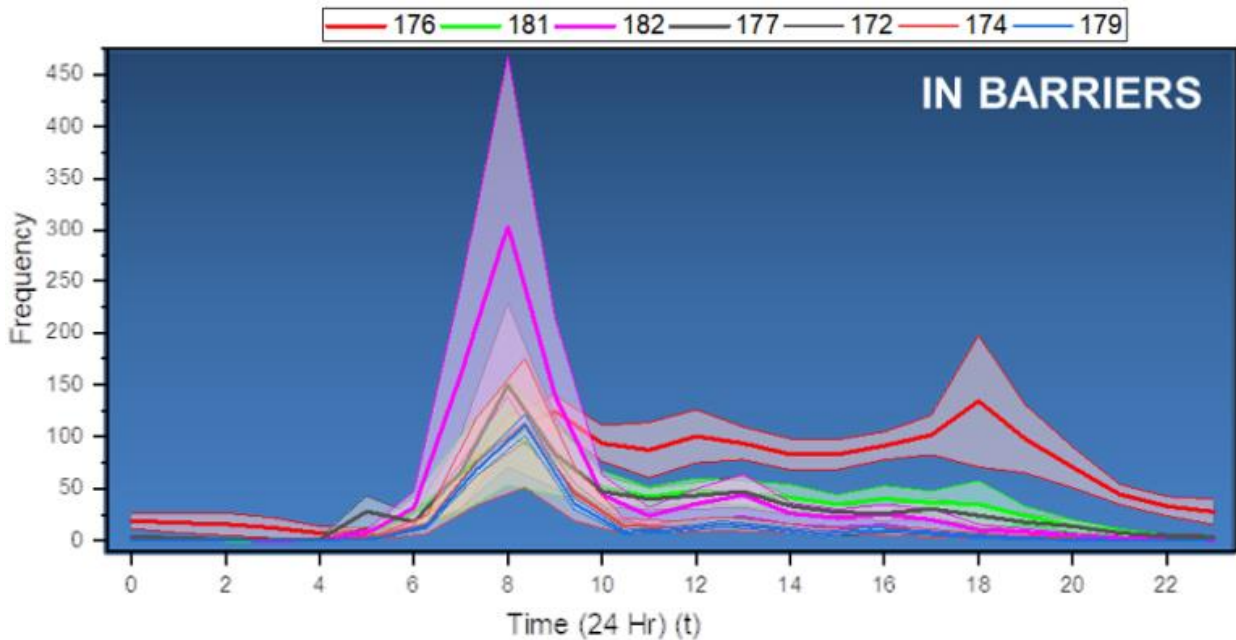


Figure 26 - Plot of frequency at which parking barriers were used on Loughborough University campus, for a 24 hour period. [10]

With all the necessary data, the fatigue life could be estimated using an S-N curve for standard aluminium (and steel) – see Figure 27 [11][12]. The expected life (in number of cycles) is plotted on the x-axis. The average cyclic stress is plotted on the y-axis. The green lines show the expected life for the calculated cyclic load.

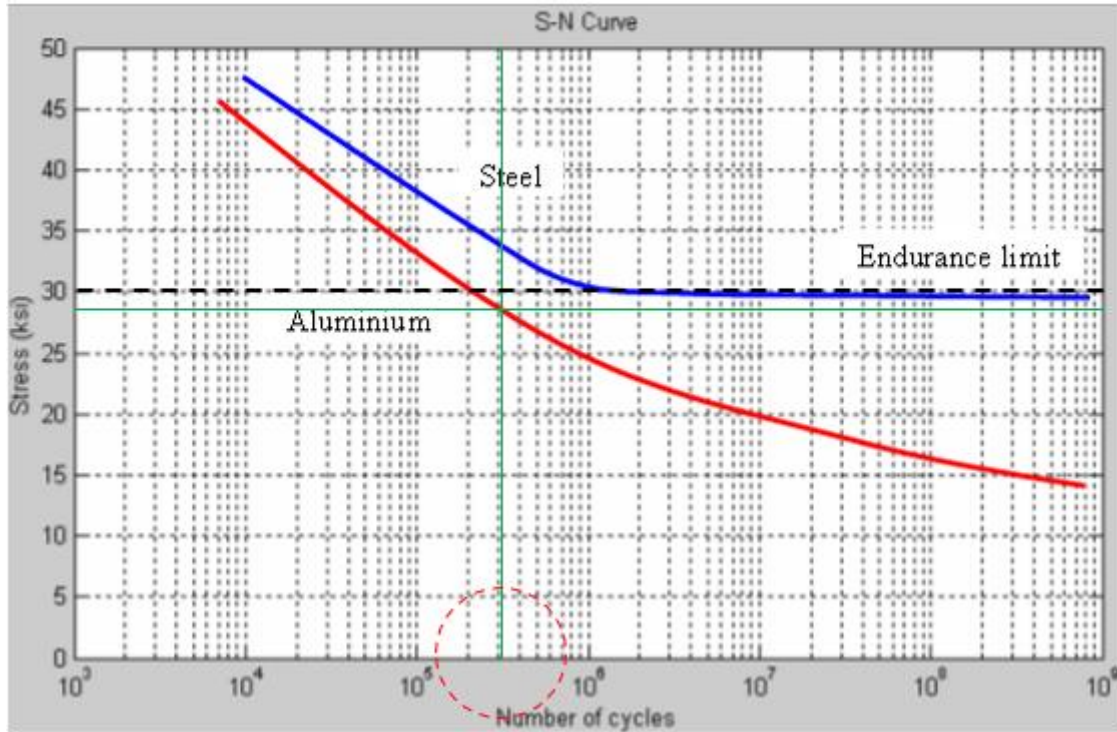


Figure 27 - S-N curve for aluminium and steel [11].

The fatigue life was calculated as 120,000 cycles, or 0.41 years. This was far below the 5 year target. Therefore, new calculations were performed to determine the acceptable average cycle stress for 3, 4 and 5 years respectively. From this, the required wall thickness of the hinge was reverse engineered.

Average Load per Cycle Required (MPa)	Average Load (ksi)	Total number of cycles - aluminium	Assumed cycles per day	Number of open and close cycles per day	Est. max fatigue life - aluminium (days)	Est. max fatigue life - aluminium (years)	Required wall thickness (mm)
172.4	25	876000	400	800	1095	3	6.15
168.9	24.5	1168000	“”	“”	1460	4	6.3
165.5	24	1460000	“”	“”	1825	5	6.5

Table 5 - The calculated wall thickness, required for the hinge in order to provide an acceptable minimum service life.

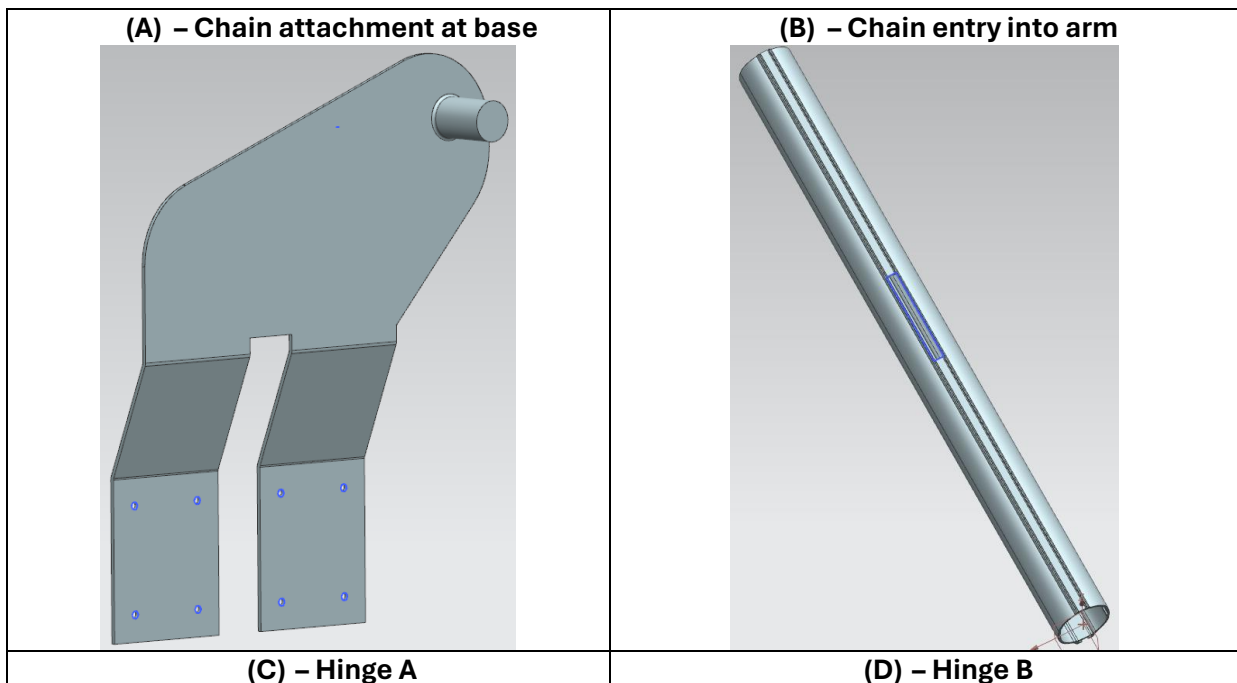
The basic fatigue study identified a suitable wall thickness for the hinge, which informed the design of the hinge components. The fatigue calculations assumed the half-section for the hinge maintained the same profile as the arm. The hinge design concepts thus used an increased average thickness,

with sections significantly thicker than the recommended 6.5mm minimum. The selected design for the hinge was then analysed in further detail in FEA.

8.5 FEA

Following on from the basic hand calculations, finite element simulations were performed on the prospective barrier design. This was done to attain more accurate data on the loading conditions experienced by the barrier and the distribution of stress and displacement throughout the various components. For computational simplicity, key components were analysed individually, with boundary conditions applied to reflect those experienced during operation. These were used to verify that the proposed design would not fail during operation. Due to manufacturing limitations (see Development for Prototyping 9), the prototype barrier required significant modification. The prototype was deliberately overengineered (and was very different final product design). Therefore, finite element simulations were deemed unnecessary.

The main differences between the proposed design and the existing PFL barrier are the hinge, the chain, the entry point in the first arm and the fastening of the chain at the base plate (and hinge). The other aspects of the design remain the same and are already verified to operate to a level that is acceptable to PFL. The proposed chain identified in section 8.3.1 was already understood to be more than strong enough to handle the peak loads and was not investigated. Shown below are views of the relevant CAD parts from Siemens NX 12.0. Edge blends of small radii were applied to hard edges to prevent computational singularities.



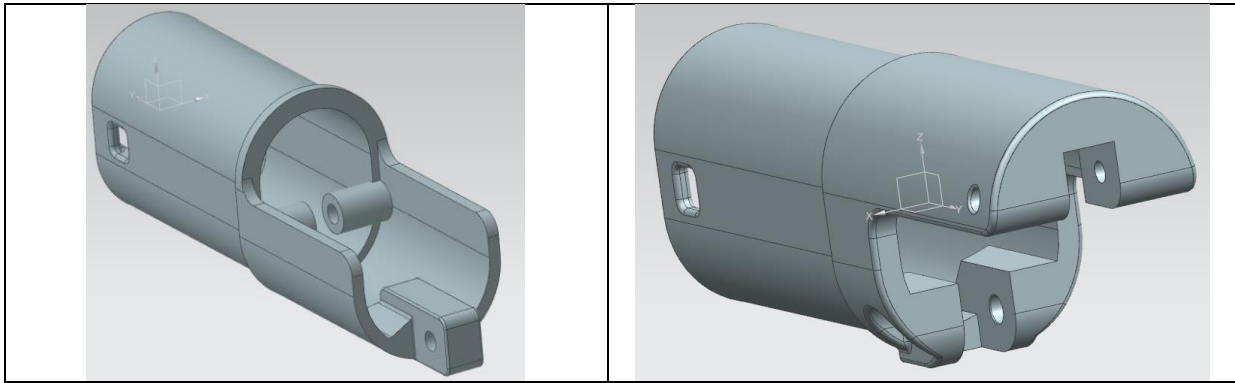


Figure 28 - CAD images of the components for which FEA was performed. (A) – The sheet plate where the chain fastens to the base housing. (B) – The entry point in arm 1. (C) – Hinge A. (D) – Hinge B.

8.5.1 Finite Element Modelling Setup

The finite element simulations were performed using Dassault Systèmes Abaqus 2023. The part geometries were first exported as STEP files from NX 12.0 and then imported into Abaqus. Abaqus does not maintain a database of materials and their respective properties. The required materials were thus created within the software and the respective properties added [2] as shown in Table 6. All of the components were initially modelled as Aluminium, and steel was created in the event it would be needed for comparison.

Alloy	Modulus of Elasticity (MPa)	Poisson's Ratio	Density (tonne/mm ³)
Steel	210,000	0.3	7.85
Aluminium	70,000	0.33	2.8

Table 6 - Table of material properties used in Abaqus.

The next step was to identify the loads and boundary conditions with which the components could be approximated.

A uniform gravitational load is applied in every simulation. The force is 9810 N acting in the negative y direction – although some simulations use different axis orientations. As outlined above, the materials are provided with density values, which link to the created gravitational load. This helps to provide a realistic simulation and account for loads within the simulation that directly relate to the weights (and weight distribution) of the components, rather than direct forces such as the chain tension.

In addition to the weight of the barrier, the motor must overcome the inertia required to accelerate the system, resulting in increased stresses in the system compared with the static loads. Inertia depends on the maximum acceleration experienced by the barrier, which depends on the speeds set by the user – and can thus be in excess of the speeds recommended by PFL. Additionally, the maximum inertia depends on the total weight of the barrier. This was assumed to be the weight of the two arms, the hinge, and an approximated weight for the chain.

Characterising the inertial loads accurately is difficult and as such, several assumptions were made: First, the barrier is assumed to accelerate from rest to peak velocity in 0.6 seconds (for a 6m barrier). This reflects a small period of high acceleration, and as a result, a sizable inertial load. This assumption provides a built-in safety factor to the calculations. Secondly, the maximum tension in the chain would be larger than the 2280 N value to account for the inertial loads.

To account for this in Abaqus, the maximum expected acceleration was derived and then added to the existing uniform gravity load. Based on the estimations made in section 8.4.5, the maximum acceleration was calculated to be 4.2 m/s², which was initially rounded up to 5 m/s² (5,000 mm/s² in

Abaqus) for the finite element simulations. However, since the initial fatigue calculations were made, it was decided that this value would be very large for a 6m barrier, as an unrealistically small opening/closing time of 3 seconds was assumed. Therefore, a new value was calculated for an 8 second opening time – slightly less than the specified 10 second time to give a factor of safety. Furthermore, the new calculations assumed a length of 1.5 metres for arm 1. The new maximum acceleration was calculated as 1 m/s^2 . The gravity load was thus increased from -9810 mm/s^2 to $-10,810 \text{ mm/s}^2$. Furthermore, for specific loads – such as where the weights of components are the main force on a component – the weights were recalculated using a gravity force of 10.81 instead of 9.81, thus reflecting the inertial load. For the chain tension, a basic scaling was applied, given that 10.81 m/s^2 is approximately 10% larger than 9.81, with the maximum operational tension assumed to be 2500 N (compared with the 2280 N static tension).

Several dimensions had not been finalised at this stage, including the cable/chain angles and the exact overhang values. As such, suitable approximations were made (and outlined) when needed.

A mesh convergence study was performed to identify a suitable mesh size for each series of simulations. As hinge A and hinge B have similar part volumes (387.44 cm^3 and 472.17 cm^3 respectively) and geometry, it was decided to only perform the convergence study for hinge A and then use a slightly larger base size for hinge B. The procedure for measuring convergence was as follows:

1. Select mesh base size.
2. Generate mesh.
3. Record element and node counts.
4. Run simulation.
5. Measure and record stress (von Mises and max principal) and displacement values at control points.
6. Add data to graph plot.
7. Continue steps 1-6, reducing the base size until convergence is observed.

The selected base size is outlined for each component. It is noted that the convergence studies used old boundary conditions and did not include the effect of inertia on the loads present in the system.

8.5.2 Chain attachment at base

Where the chain attaches to the base unit, the plate is fastened using 8 bolts. An encastre boundary condition is applied to each of the 8 holes where the plate is bolted to the barrier base. This completely constrains all 6 degrees of freedom of the surfaces of the holes and reflects the effect of the bolts fastening the plate to the base. The chain attaches to a fastener at the cylinder, placing a transverse load on the base plate. The load acts at an angle of approximately 15 degrees to the x-axis. With the maximum expected load of 2500 N, the load was created in Abaqus with a magnitude of -2400 N in the x-axis, and -650 N in the y-axis.

The chosen element count was 72,404, which was generated using a base size of 4. As later simulations resulted in significant increases in part volume, the base size was increased on a discretionary basis.

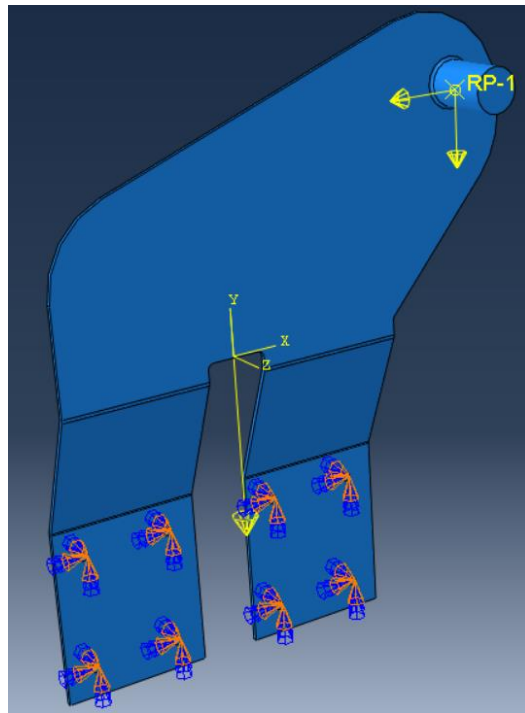


Figure 29 - View in Abaqus showing loads and boundary conditions when the barrier is closed.

When the barrier is upright, the load is assumed to be fully vertical. Additionally, there is no inertial load as the barrier is now at rest. As such, the tension in the chain is modelled as the 2280 N maximum static load.

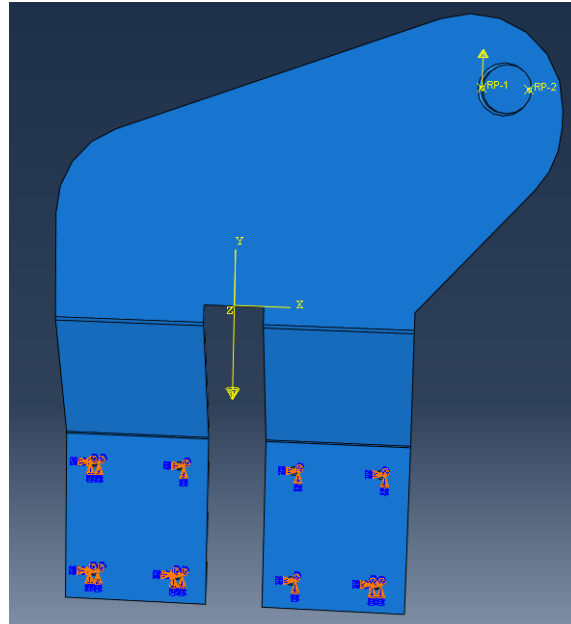


Figure 30 - View in Abaqus showing loads and boundary conditions when the barrier is open.

8.5.3 Chain entry point into arm

For the entry point into the arm, the loads are the same as in the current PFL barrier. The arm is supported at one end by the cast shoulder, and it directly supports the combined weight of the hinge and the second arm. The loads on the first barrier arm are unchanged from the current PFL barrier, with the major difference of the entry point for the chain weakening the barrier. In order to reduce the part size (and therefore allow for a finer mesh) a point load of 145 N is applied at the hinge-end of the arm, equal to the combined weight – which includes the effect of inertia – of the hinges A and B (1.08 kg and 1.32 kg respectively) and the second barrier arm (11.04 kg). The maximum inertia was expected to occur close to when the barrier was horizontal, and the simulation thus assumes the barrier to be horizontal. The load of the cable/chain on the entry point itself was ignored in these simulations as a pulley system was in consideration, but not yet finalised.

A base size of 6 was used for the final simulations on the entry point (a smaller base size was used for initial simulations).

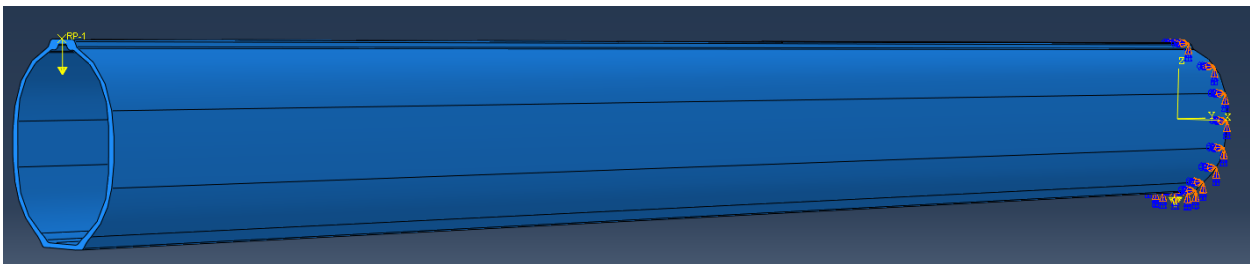


Figure 31 - View in Abaqus showing loads and boundary conditions for the entry point (arm 1).

8.5.4 Hinge A

A base size of 4.0 was used in the convergence study, generating a mesh with 70877 elements. Hinge B was considered similar to hinge A in geometry; therefore, it used similar base size, slightly increased in scale to match the larger part volume of B.

Closed – horizontal:

Hinge A attaches to the first barrier arm and has an internal fastening for the chain / cable. Along with the chain / cable, it supports the weights of the second arm – assumed as 4 meters – and hinge B: 11.04 kg and 1.32 kg respectively; 12.36 kg in total. A load of 132 N (includes inertia) is applied to a reference point coupled to the interior of the pin hole. It is fastened to the barrier arm via bolts and an encastre condition is applied to the end of the hinge to approximate this. The chain is fastened to the hinge (and ensures hinge B and arm 2 stay horizontal). The chain tension is assumed to act at an angle of 60 degrees to the horizontal, with a magnitude of 2500 N. This was created as a load with the magnitude of 2150 N in the positive z and 1250 N in the negative y. As with the entry point, the maximum inertia was assumed to act when the hinge is close to horizontal.

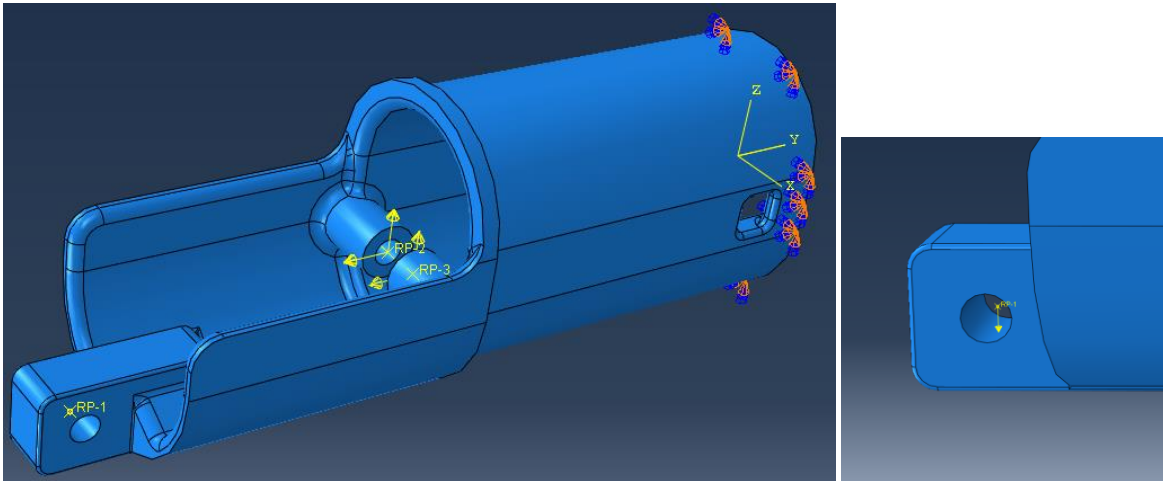


Figure 32 - View in Abaqus showing loads and boundary conditions for hinge A when the barrier is closed.

Open – vertical:

When at rest in the open position, the entire weight of the second arm acts through the hinge, with the chain tension at a static maximum, counteracting the moment resulting from arm 2 (and hinge B) wanting to pivot away from the base unit. The actual orientation of the hinge (the negative y-axis represents the upwards vertical plane) is shown to the right of the main image (which is shown horizontal for easier visualization of the boundary conditions). To reflect this, a pressure load is applied along the surfaces of the hinge which come into contact with hinge B. The chain is assumed to act at an angle of 30 degrees to the y axis, with a tension of 2280 N – there are no inertial loads as the barrier is at rest. A force, equal to the weight of hinge B and the second arm is applied at the hinge pin, with magnitude of 1140 N in z and 1970 N in negative y. The weight of arm 2 and hinge B is a 120 N point load in the positive y (there is no inertia as the barrier is at rest).

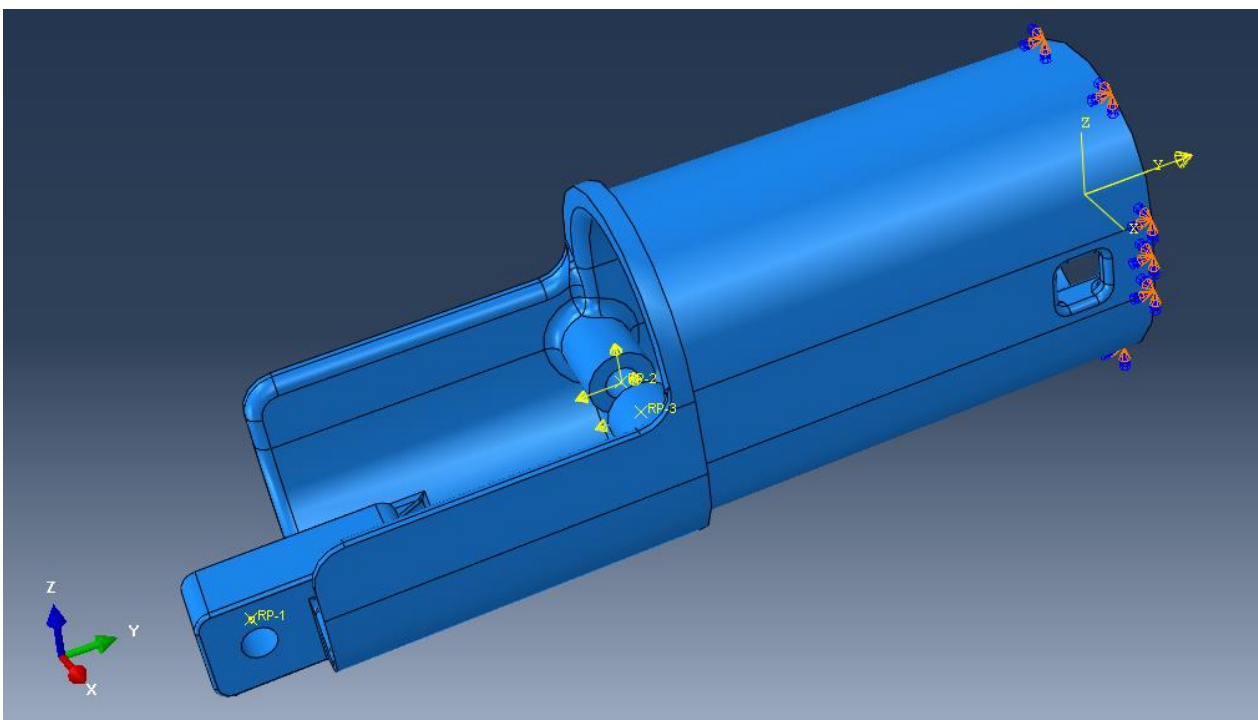


Figure 33 - View in Abaqus showing loads and boundary conditions when the barrier is open.

8.5.5 Hinge B

Hinge B attaches to the second barrier arm and hinge A. It supports the weight of the second arm and the load from the chain/cable. The tension in the chain is the inertial maximum of 2500 N and is assumed to act at an angle of 30 degrees to the positive y axis, created as 2160 N force in y and 1250 N in negative z. The hinge also supports the weight of arm 2; again, taken to be 4m – weighing 120 N in the negative z (including inertia). Hinge B remains roughly horizontal throughout operation, although the angle of the chain changes throughout. Therefore, a second simulation is performed for the top position, with the chain now at an angle of 60 degrees left of the negative z.

As hinge B was slightly larger than hinge A in part volume, a base size of 3.5 was used for B.

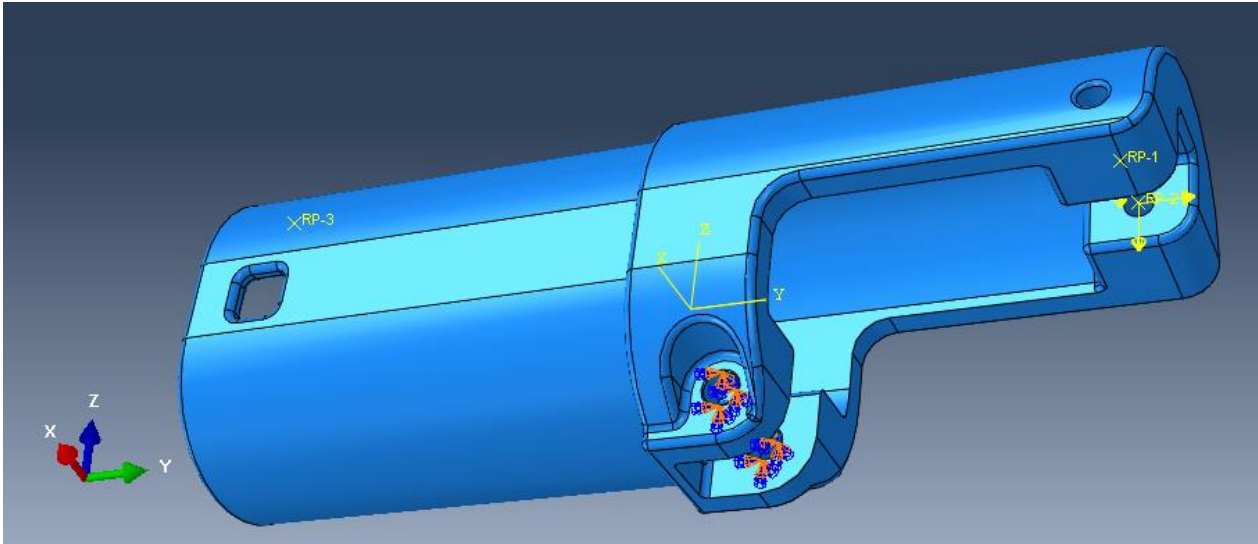


Figure 34 - View in Abaqus showing loads and boundary conditions for hinge B when the barrier is closed.

8.6 Final Results

Following the performance of the mesh convergence studies, the selected base sizes were used to produce stress and strain data for each part. The results of the finite element simulations are shown below. The stress results are shown in megapascals and the displacement values are in millimetres. The results were then used to determine if the component was acceptable for use, or if modifications were needed to achieve stress reduction. Given restrictions in part sizes (and general space limitations), different materials were also considered – primarily higher strength aluminium alloys.

As all the analysed components are made from aluminium – a ductile metal – the Von Mises failure criterion was used to evaluate their performance in the simulations. The criterion determines failure as occurring at locations where the Von Mises stress exceeds the yield strength of the material (40 MPa) [3]. This is the absolute maximum allowable stress in the barrier. However, the design requires a minimum factor of safety of 1.5 and the analysed components are held to this requirement.

Chain Attachment at Base

The chain attachment plate showed massive stress values, which was anticipated given its very small thickness of 3mm compared with the 12mm thickness of the existing P.F. plate. Therefore, it was necessary to investigate options for stress relief for the prototype, especially given the limitation of bending thickness being restricted to 3mm. A series of stress relief permutations were investigated for adding reinforcing structures around locations of peak stress. However, it was quickly clear that there was no option other than to increase the thickness of the sheet. The thickness was thus increased in increments of 3mm, from the initial 3mm to a final thickness of 12mm. The 12mm sheet

(the same thickness as the existing P.F. sheet) was the first thickness that could fully support the maximum loads without any areas of stress above the yield limit of 40 MPa. Although stress concentrations slightly higher than the yield strength were identified at the supporting rib.

For the prototype, the limitation of 3mm sheet thickness could be circumvented by manufacturing multiple sheets and then fastening them together with bolts or spot welds. However, given the time and material required for this, an entirely different design was devised for the prototype, making use of box frames welded together: see section 10.2.4 for further detail.

Barrier in the closed position – True to scale deformation:

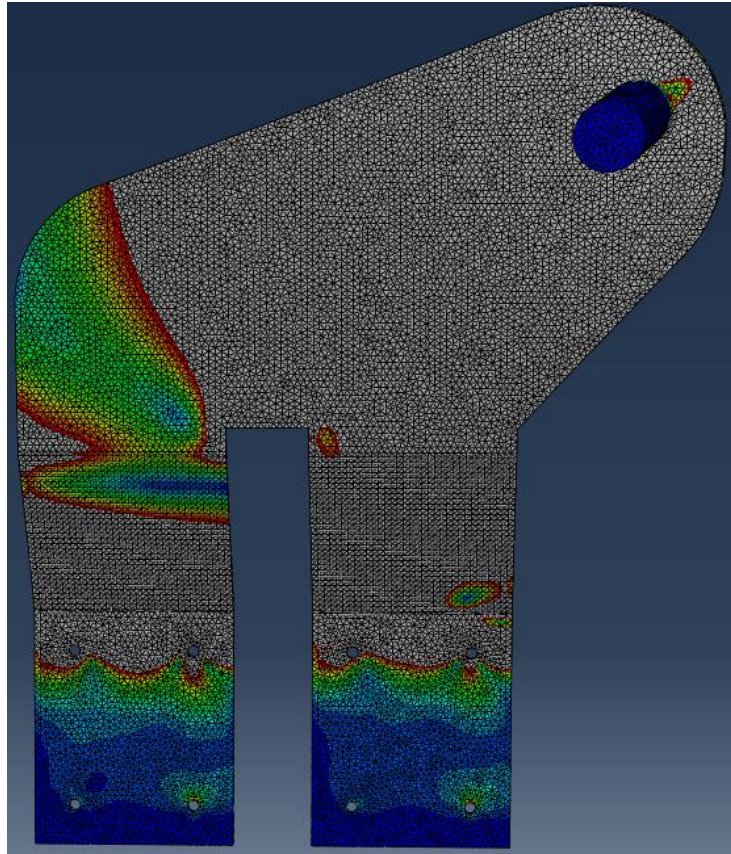


Figure 35 - Von Mises stress plot of the sheet, when the barrier is in the closed configuration. The grey elements represent areas where stress exceeds 40 MPa.

Barrier in the open position:

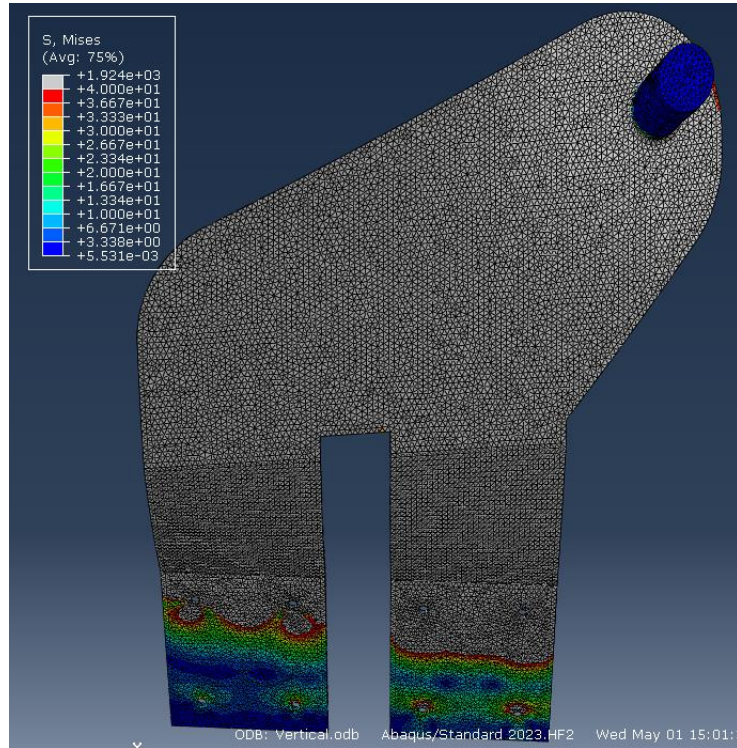


Figure 36 - Von Mises stress plot of the sheet, when the barrier is in the open configuration. The grey elements represent areas where stress exceeds 40 MPa.

Chain Entry Point into Barrier Arm

The chain entry point was considered acceptable and did not need any modifications to relieve stress. Creating a suitable mesh was very difficult and the process of simplifying the geometry increased the material volume and thus its mechanical strength. However, the fact that the maximum stresses were approximately 60% of the yield strength gave the part a significant factor of safety and it was decided that the part was acceptable in its performance. Areas of singularity were observed in the mesh due to poor element formation, but these were very difficult to remove and were thus simply ignored.

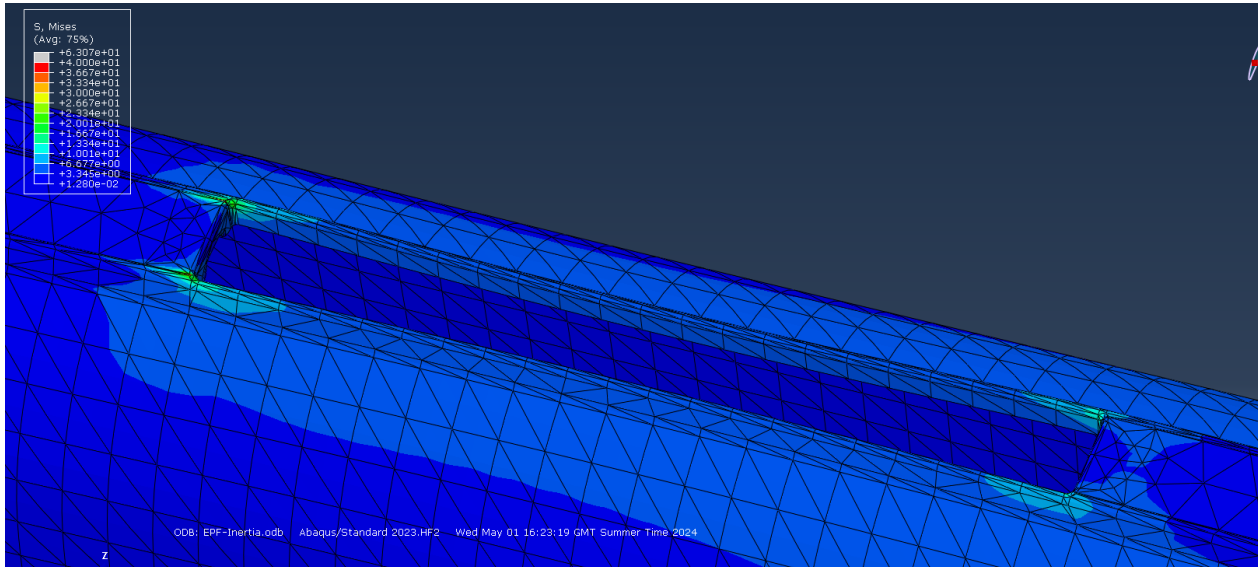
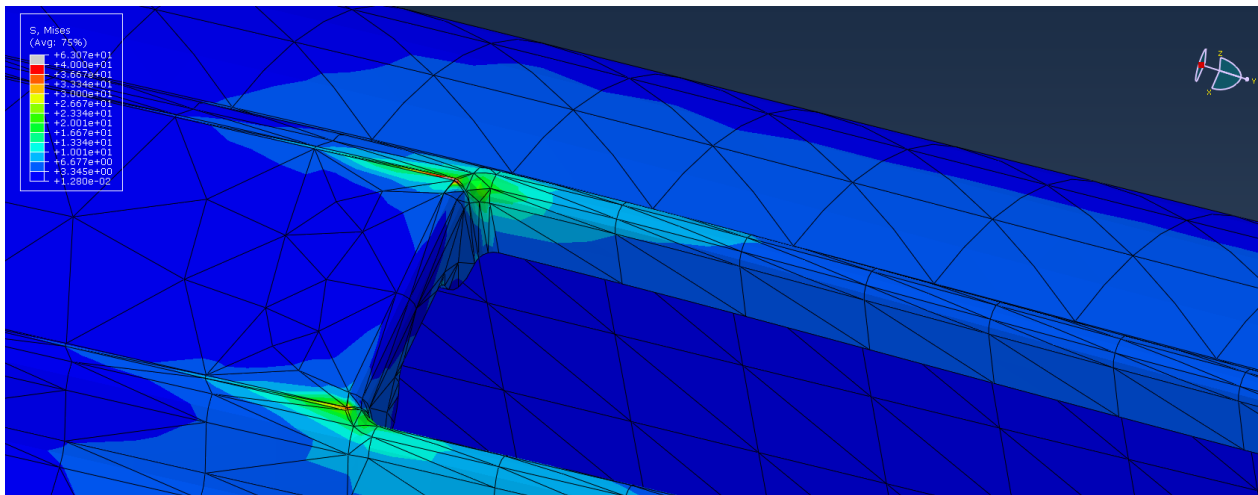
(A) – View of whole entry point**(B) – zoomed in view of stress concentration areas – note the singularities (in red) due to poor element formulation**

Figure 37 - Von Mises Von Mises stress plot of the entry point when the inertial loads are at a maximum. (A) – a zoomed out view of the whole entry point. (B) – a zoomed in view, showing 2 computational singularities (which are ignored in the results) due to poor element formulation.

Hinge A

Hinge A was simulated for both the open and closed positions. All the final simulations used a base size of 4.0 selected from the convergence study.

In both open and closed, the areas of peak stress in excess of the yield strength were located around the fastening points (70 MPa for closed and 60 MPa for open). However, as stated earlier these points are not intended to be realistic at this stage. The stress concentrations were noted and informed the final design. As the rest of the hinge showed acceptable stress levels, the design was carried forward as acceptable.

Closed – max inertia assumed:

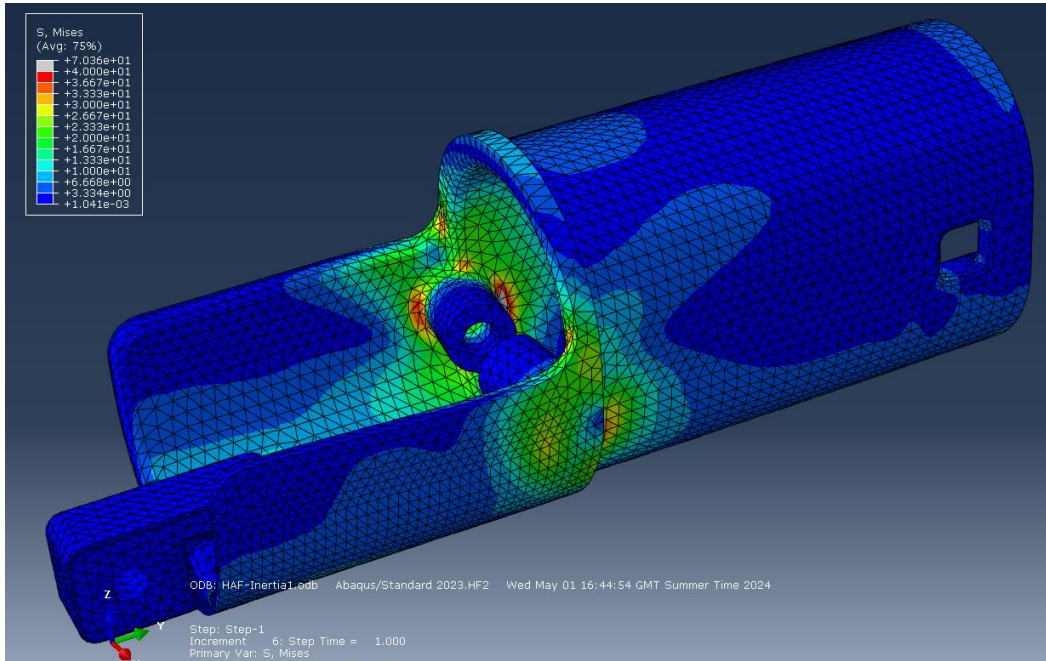


Figure 38 - Von Mises stress plot of Hinge A when the inertial loads are at a maximum.

Open – assumed no inertial load:

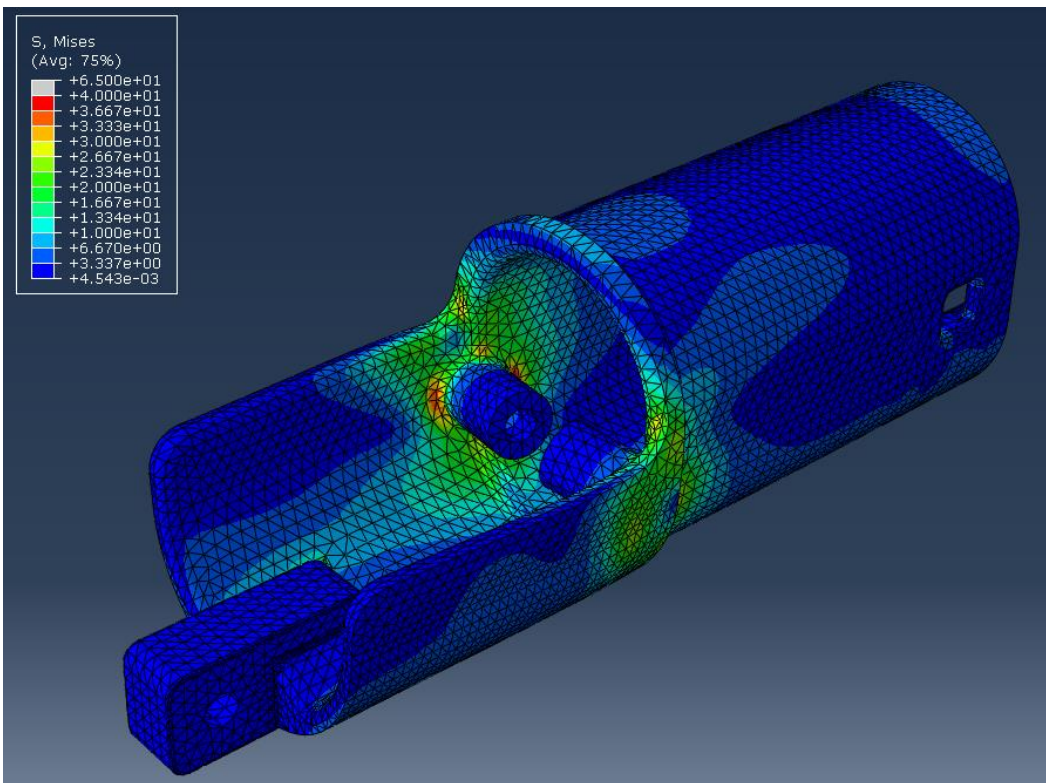


Figure 39 - Von Mises stress plot of Hinge A when the barrier is open. Note the view shows the hinge as horizontal, but this is merely the orientation from which the image was taken.

Hinge B

For hinge, B areas around the hinge pin showed massive stress concentrations, with a peak value of 260 MPa – far in excess of the yield strength. Therefore, the team modified the design and performed further simulations.

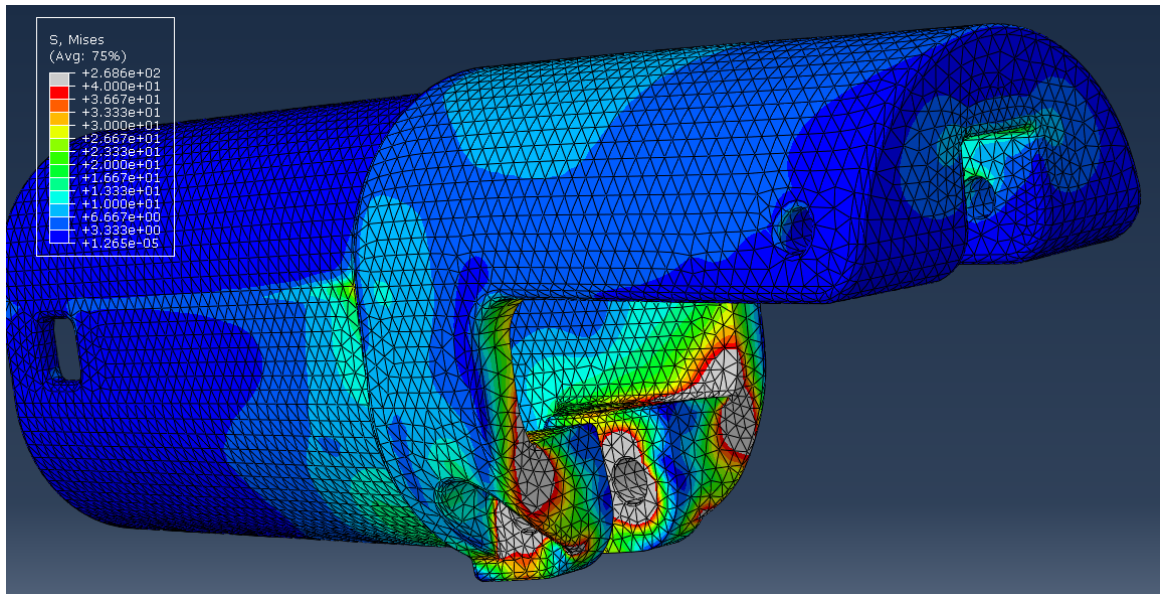


Figure 40 - Von Mises stress plot of hinge B when the inertial loads are at a maximum.

The results of the finite element simulations are summarised below:

Component	Maximum von Mises stress (MPa)	Factor of Safety	Acceptable
1. Chain attachment at base	Final design not simulated	n/a	Design rejected for prototype
			Final design: yes
2. Chain entry point in arm 1	~ 25MPa	1.6	Yes
3. Hinge A	~ 17.75MPa (final)	2.25	Intermediate design: No
			Final design: Yes
4. Hinge B	~ 100 MPa +	Dependent on further work	Intermediate design: No
			Final design: Yes (with further modifications and use of suitable alloy)

Table 6 - Summary of the results from the finite element simulations.

Refer to section 9.11 Further Hinge Development for details on final hinge simulations.

8.7 Entry point development

The chain will need to enter the barrier and travel along the arm to the hinge. In order for this to happen, a section would need to be cut out the top of the barrier to pass in the cable. Removing this section would create weaknesses within the arm; therefore, reducing stresses at this section of the barrier was very important.

Another important thing to think about was the manufacturing and assembly process. Due to the difficulties of manoeuvring the beam about the workshop and the limitations in tooling PFL have.

Due to the forces of friction on the hinge, entry point and other components, it's been established that the chain will exert the largest force on the arm during the closing action as can be seen in Figure 41 - Entry Point Forces. Specifically at the end of the closing cycle when the arm is in the down position. Due to the fact that the cable will always be in tension, we can deduce that the majority of the force will act of the furthest part of the cross-section.

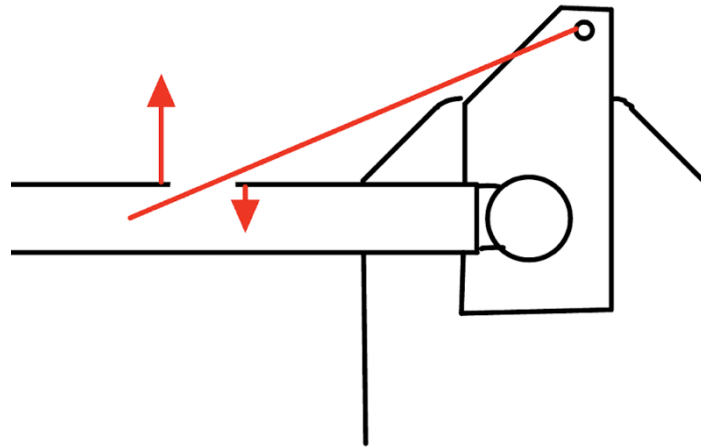


Figure 41 - Entry Point Forces

A number of designs were thought up as to how the chain can passed into the arm. One idea was to use bearings however after further evaluation, it was identified that this would result in more force applying through the entry point.

Therefore, a second idea of a raceway was chosen for a number of reasons:

- Reduction in friction. This, in turn, will also improve the efficiency of the system as well as reduce wear on the components. Therefore, also reducing maintenance.
- Enhanced performance. With the forces being applied over a larger area, this allows less material to be used and therefore making the component lighter.
- A pulley can only divert the direction of the chain around a single radius. But the raceway can be designed to optimise this. This can lead to better force distribution, which can then also reduce noise.

However, the main restriction that meant this design was superior over the pulley design was the restriction in space within the beam. Having the pulleys held within the beam would mean that the design would require a larger opening hole in order to allowing the chain to reach the desired depth without interacting with the close edge. This larger hole would also reduce the beams strength. This is due to the minimum sizes of the pulley that would be required, would pull the chain deeper into the am over a raceway, as can be seen in Figure 42 - Entry point Pully (above), Raceway (below). Therefore, this raceway design would allow for a smaller hole as well as it's other benefits.

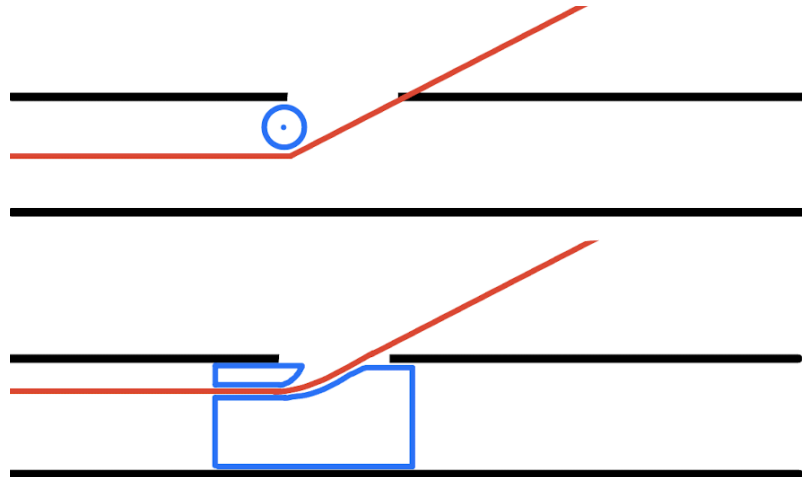


Figure 42 - Entry point Pully (above), Raceway (below)

Nylon was chosen as the material for the raceway due to its low friction which can reduce the wear on the chain as well as decrease any energy used by the system. However, it's potential drawbacks are its own wear resistance and strength. To combat this, a glass fibre-infused nylon was the final decision, as the glass fibres would enhance the wear resistance and make the nylon more durable and able to withstand the abrasion caused by the moving chain [11].

The next challenge was determining its construction to allow it to be easy to manufacture and assemble, as this is a key aim from PFL. Whilst injection moulding or compression moulding might be good manufacturing processes, they would not be suitable for the production volume of 30 due to the high initial costs. Therefore, a more reasonable process would be additive manufacturing. Both select laser sintering (SLS) and fused deposition modelling (FDM) can be used to create this part, but SLS will produce a more accurate and strong part and therefore would be selected as the recommended manufacturing method. However, if PFL where tight on budget, then FDM could be used as a more cost-effective solution.

Additive manufacturing allows for complex structures, allowing the raceway to have sides. It was selected as these methods of manufacturing is not labour intensive and therefore a very cost effective method. The CAD model with the front panel made transparent can be seen in Figure 43 - Entry Point Raceway CAD.



Figure 43 - Entry Point Raceway CAD

8.8 Further hinge development

A Summary of the key changes made to the hinge design is shown below in Figure 44.

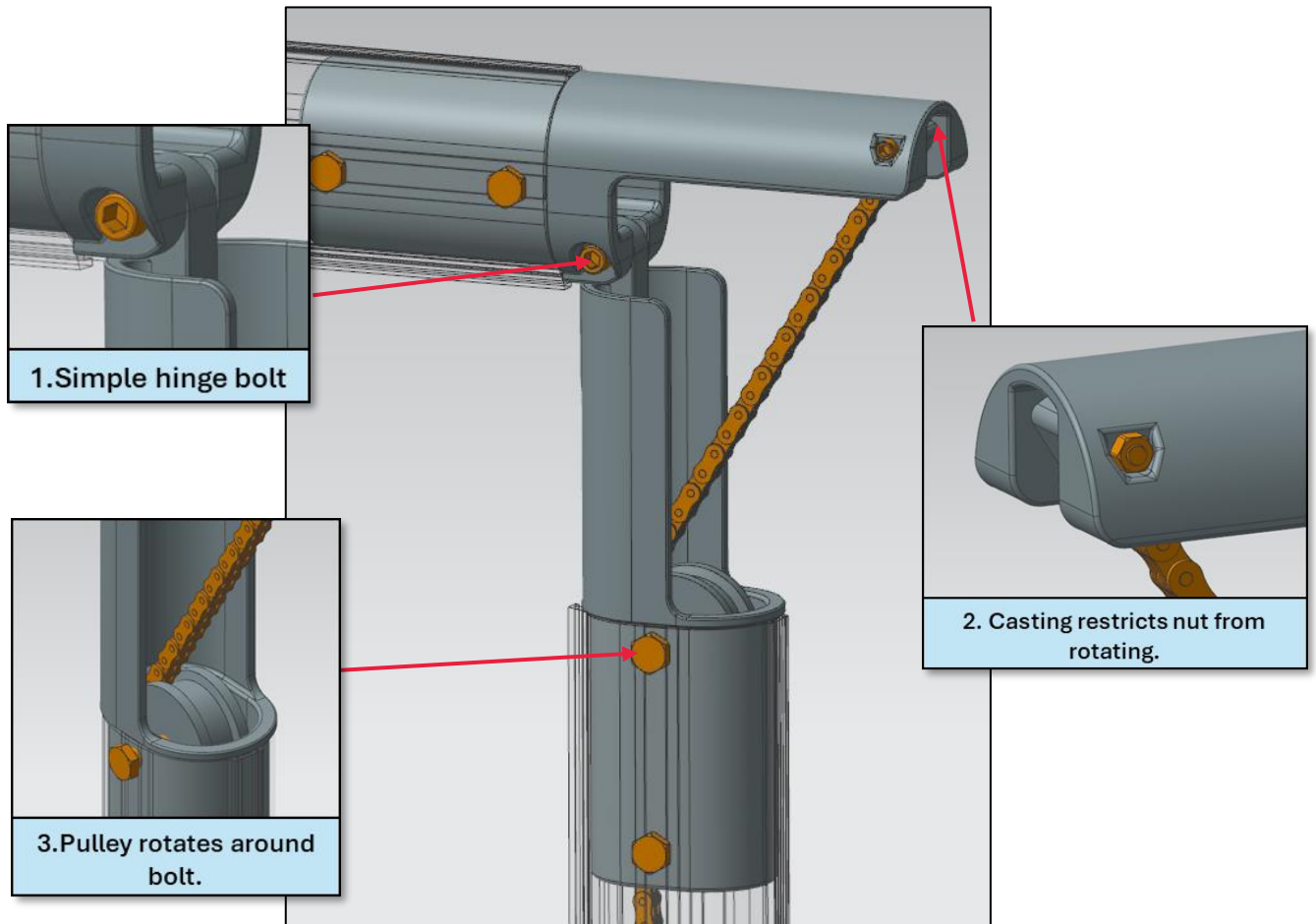


Figure 44 - Overview of further hinge development following calculations and engineering theory.

Key developments include:

1. A simple hinge bolt, where the two halves can easily be assembled and taken apart if needed for maintenance.
2. Modifying the casting to hold the nuts for the hinge and chain bolts in place, allowing for easier manufacture.
3. Having the pulley rotate around the same bolt used to fix the hinge to the beam simplifies the design. The pulley can now simply be added whilst the securing bolts are pushed through.

8.8.1 Final Hinge FEA

With the hinge undergoing redesign following the initial finite element models, a new set of simulations were performed using the same model setup.

Hinge A – Finalised Design FEA

Following from the first simulations on hinge A, a final design was created with a new fastening method. A new analysis was performed with the same setup as the previous simulations. The peak stresses were again located at the fastening points, with a maximum of 18 MPa, but were sufficiently below the yield strength. As the stress were higher for the closed hinge, the open position was not revisited for the final design. The final design for hinge A was therefore accepted.

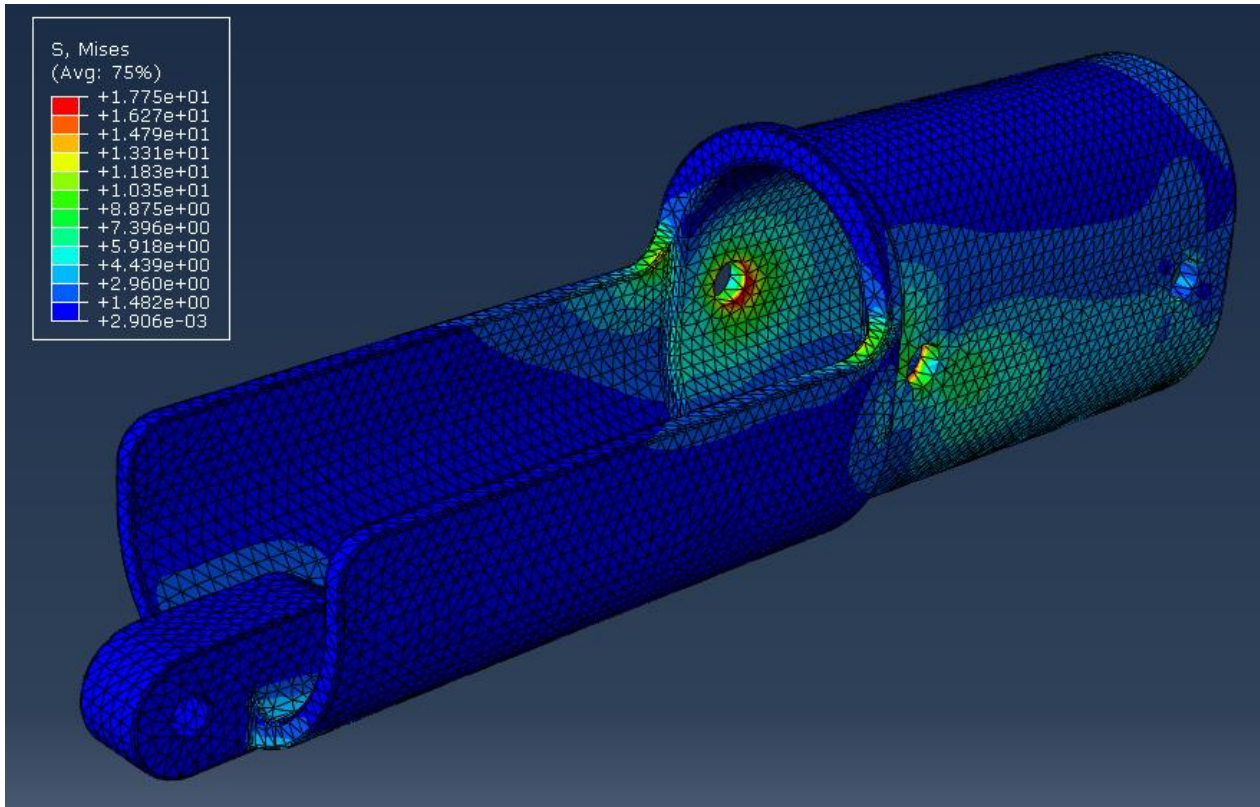


Figure 45 - Von Mises stress plot of hinge A.

Hinge B – Finalized Design FEA

Similar to the original simulation, the peak stresses were again distributed at the pin holes, the location of the 90-degree bends (where the component becomes halved in height) and where the end of arm 2 meets the hinge.

To counter this, material was added around the pin holes. Large edge blends were added on the interior of the hinge, as well as the 90-degree bends. Finally, the diameter of the hinge pin was reduced from M12 to M8. Significant stress reduction was observed upon implementing these modifications.

Finally, it was decided to investigate the impact of increasing the amount of material lengthways (Abaqus y-axis). This would require hinge A to be slightly increased in length, but as hinge A is already validated with significant factor of safety, this is assumed to not impact its suitability. This allows an

increase in material without altering the critical dimensions. The visible length of the hinge would increase, but this is a necessary compromise and of limited visual impact.

However, peak stress values still exceeded the yield limit, with the pin hole remaining an area with a maximum stress of 160 MPa. Adding any further material to the hinge would severely damage the aesthetics. Although it can be seen from the stress profile that there is potential for removing material from several areas of the hinge. Therefore, it is recommended that further analysis be performed on the hinge, to investigate potential stress reduction to acceptable levels. Manufactured the hinge using an aluminium alloy is also a path that could be explored in combination with further analysis.

(A) – Initial Design

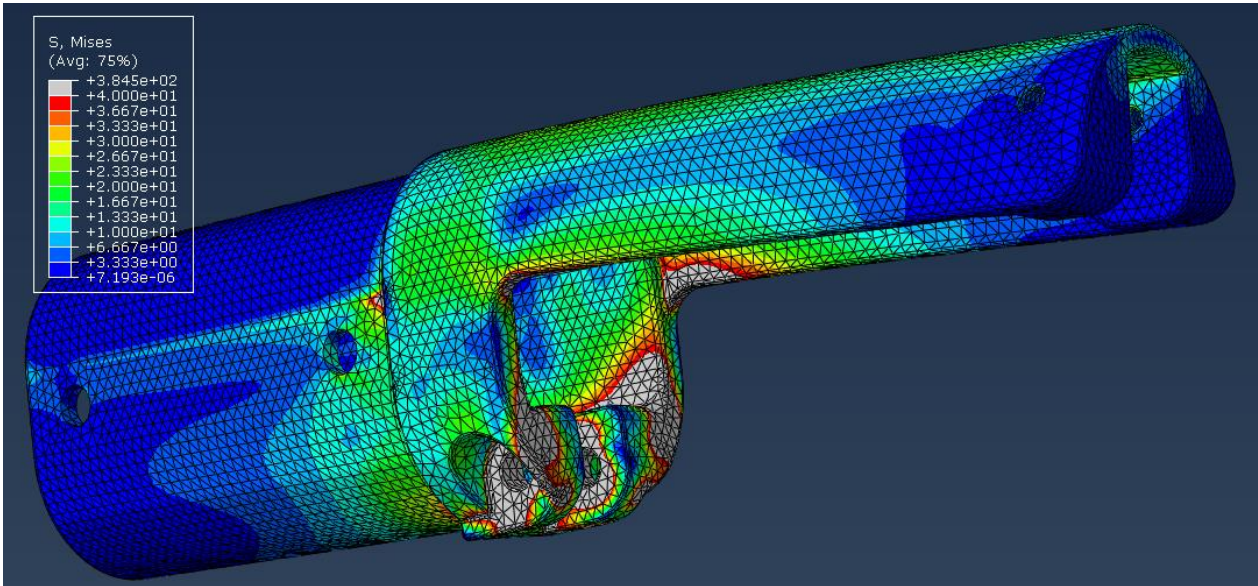


Figure 46 - Von Mises stress plot of hinge B.

(B) – Design with Stress Relief Modifications

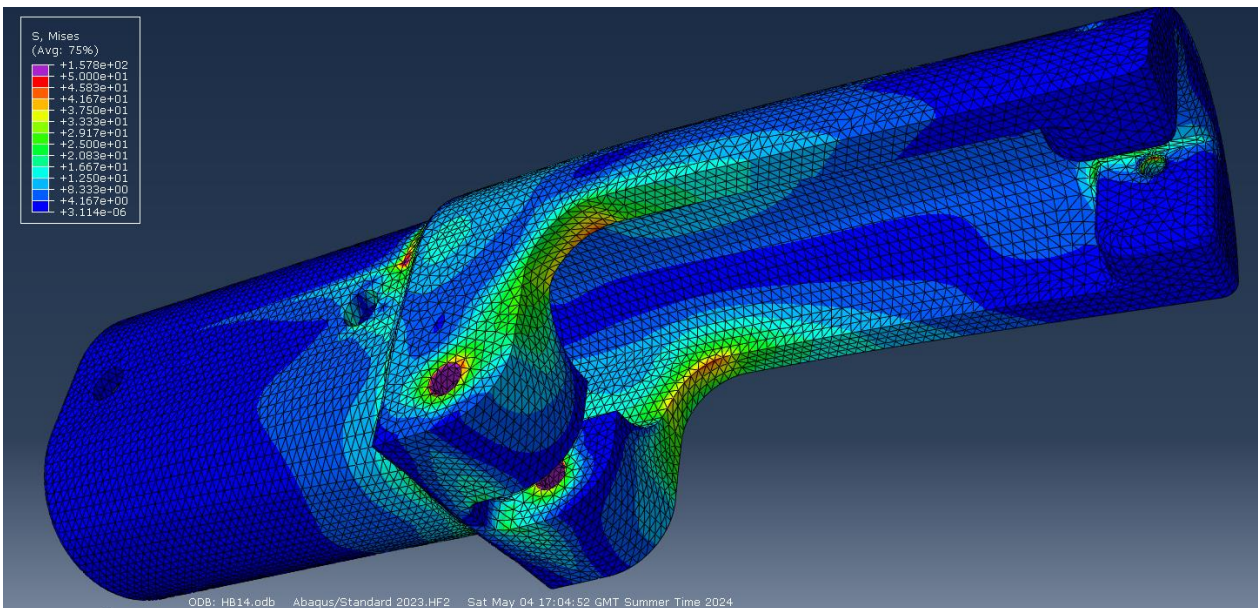


Figure 47 - Von Mises stress plot of hinge, with stress relief modifications.

(C) – Left: initial. Right – stress relief.

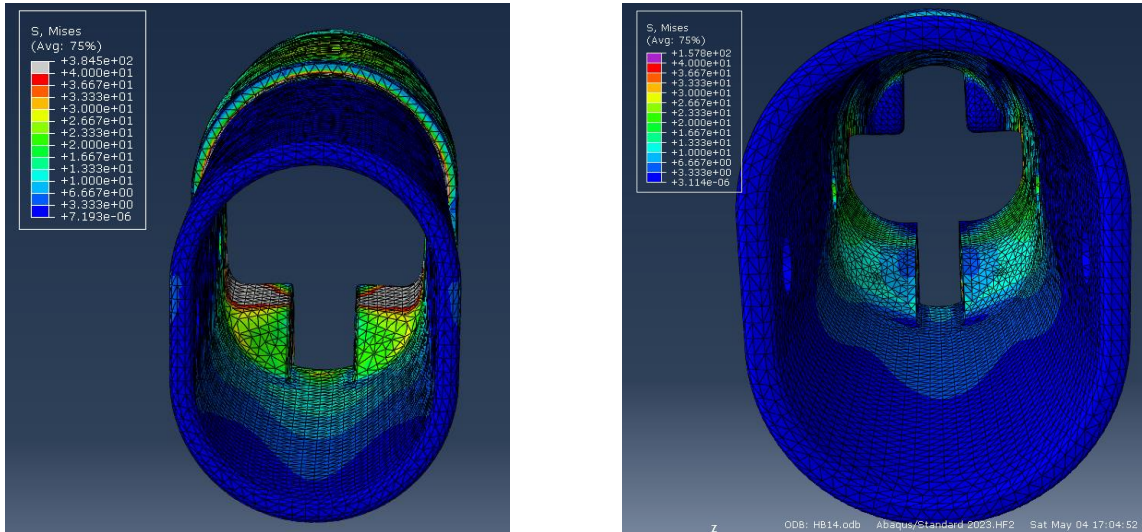


Figure 48 - Von Mises stress plot, comparing the unmodified hinge A (left) to the stress relief design (right).

8.9 Cover

During the interim presentation, Joe was asked about the exact requirement for a cage surrounding the chain to prevent people from sticking their hands in the device. Joe clarified that safety precautions would not be needed when the barrier is in motion but only for the transition between stationary and motion. i.e., as the hinge was designed to be fully closed when stationary, it would be impossible for someone to injure themselves once the barrier started to move. On the other hand, the entry point has a hole where the chain enters the arm. This was a potential hazard as a person could stick their finger in the hole, which could cause it to be pulled in further once the barrier started to move and the chain was pulled into the hole.

A few designs for a cover were thought up and discussed with the group. The idea that had the fastest assembly time was the sleeve idea seen in Figure 49 - Simple Cover Design. This idea was to connect the hole in the arm and the base connection point with an expandable braided nylon mesh. This could cover the chain and prevent a person from sticking their finger in the hole. It was also easy to assemble as the mesh could be bought and cut to length. It can also be fastened to the entry point using adhesives such as a contact cement.

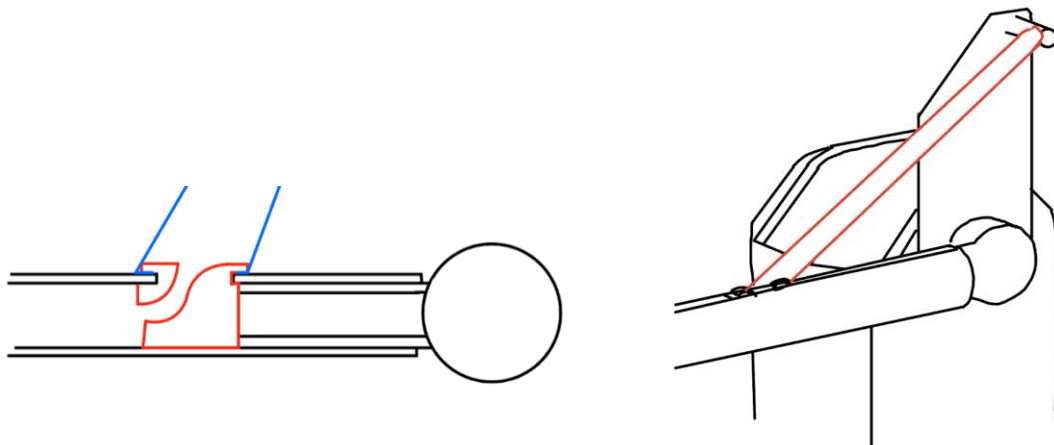


Figure 49 - Simple Cover Design

8.10 Cost-Function Analysis

During the design development stage, a cost function analysis chart was made to determine how to best optimise the design; this entailed listing the different functions of the barrier and how much each part contributed to those functions. This allowed the team to see which functions cost the most to achieve. The analysis focused on the inner chain system of the barrier, as this was the design that would be added to the unchanged motor and electrics.

Components	Primary Function	Opening barrier in a height restricted area	Secondary Function	Stop at 90 degrees	Prevent exposed parts	Maintain flat outer arm during opening	Work with hand crank input	Prevent water getting in	Reduce drooping in closed position	Cost of component (£)
1 Leaf chain		9.93		4.96		2.48	2.48		4.96	24.82
2 Shoulder		8.28		1.77			1.77			11.83
3 extrude A		3.45			1.73			1.73		6.9
4 extrude B		5.79			2.89			2.89		11.57
5 Pulley		0.65		0.28						0.93
6 Hinge A		1.00		0.60	0.20			0.20		1.99
7 Hinge B		1.11			0.56			0.56		2.22
8 chain block x3		0.05							0.11	0.15
9 Base plate		1.40				1.40				2.8
10 Bolts x14				0.75		0.75		0.75	0.75	2.98
11 Chain anchor				0.03					0.07	0.09
12 Bearing x4		18.34				4.58				22.92
13 Entrance pulley x2		0.05				0.04				0.09
14 Entrance bracket x2					0.10					0.1
15 nylon cover					12.00					12
16 Cable		0.60		0.30		0.15	0.15		0.30	1.51
17 Cable eye bolt		0.22		0.11		0.06	0.06		0.11	0.55
18 Cable clamp		2.95		1.48		0.74	0.74		1.48	7.38
Cost of function (£)		53.81		10.28	17.47	10.20	5.20	6.12	7.78	
% of cost		48.54		9.28	15.76	9.20	4.69	5.52	7.02	

Table 7 - Cost-Function Analysis [26] [27] [28] [29] [30] [31] [32] [33].

The analysis shown in Table 7 did not reveal that any design components were overly expensive for the prototype other than potentially covering the chain, making up 17% of the overall cost. However, the problem of covering the chain is complicated due to its requirement for freedom of motion when opening and closing, and ensuring that the barrier is safe to operate with any uncovered openings was of top importance during development, so contributing considerably to the cost of the assembly could be justified, the analysis was done with a chain/cable combination to theoretically cut down on the cost overall, though it was found that the addition of fastening multiple elements would not reduce the cost enough to justify adding multiple more steps to the assembly for each barrier.

9 Development for Prototyping

9.1 Hinge Prototype design.

Up until this point the hinge design relied on casting for its manufacture. However, due to a lack of casting facilities, the manufacturing plan for the prototype had to be rethought. The first step was to split each half of the hinge into two halves, resulting in four components which could be manufactured on a CNC mill. The halves would be joined together by the bolts securing the hinge to the barrier arms. With this redesign, it was also envisioned that the pulley could rotate around the same bolt that would be used to attach the hinge. This helped to reduce complexity and the number of components required. These changes are shown in Figure 50.

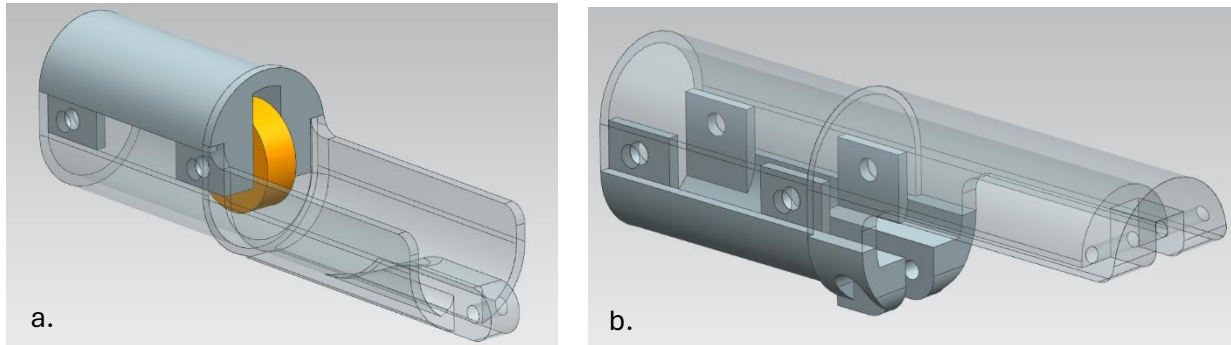


Figure 50 a/b - Hinge halves.

Following a meeting with several workshop technicians it was discovered that the lead time for using the CNC mill would be at least three weeks. To ensure that the prototype could be manufactured faster, the design was drastically simplified, enabling it to be manufactured using manual workshop processes. This led to the redesign shown in Figure 51.

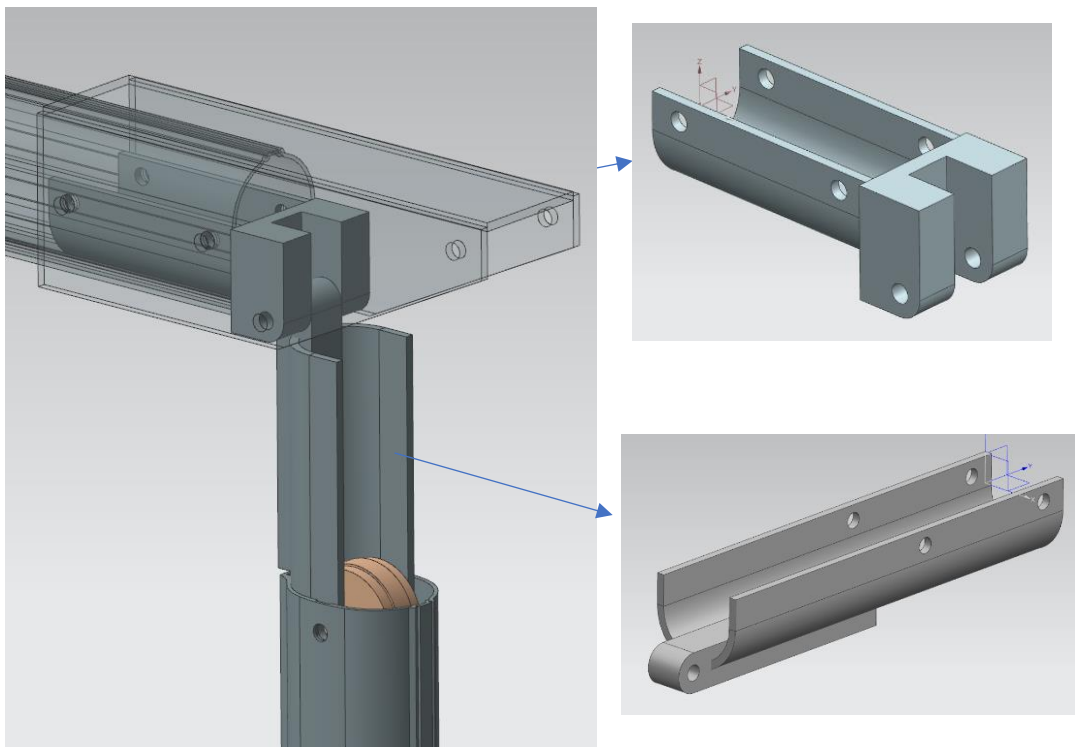


Figure 51 - Hinge design for simple manufacture.

This new design was made up of simplified stock shapes which are readily available. These stock shapes included 25x6mm flat, 74x6mm tube, 30x30mm square bar, and 85x70mm block. The overhang would now be made from sheet metal and would be a separate component from the hinge.

In the workshops the team found the following materials: 30x30 square bar, aluminium block, 70x3mm tube section and some 10mm plate that could be substituted for the 25x6mm flat. The team decided that modifying the design to make these materials work was better than waiting for a material order. The 6mm parts being replaced by 10mm parts would also help to account for the strength lost by using 3mm wall thickness tube over 6mm. Extra supports could also be added later on in between the 30x30 bar and the side plates if further strengthening was required. These material constraints caused the design to evolve into the one shown in Figure 52. This is the design from which engineering drawings needed to manufacture the parts in the workshop were generated.

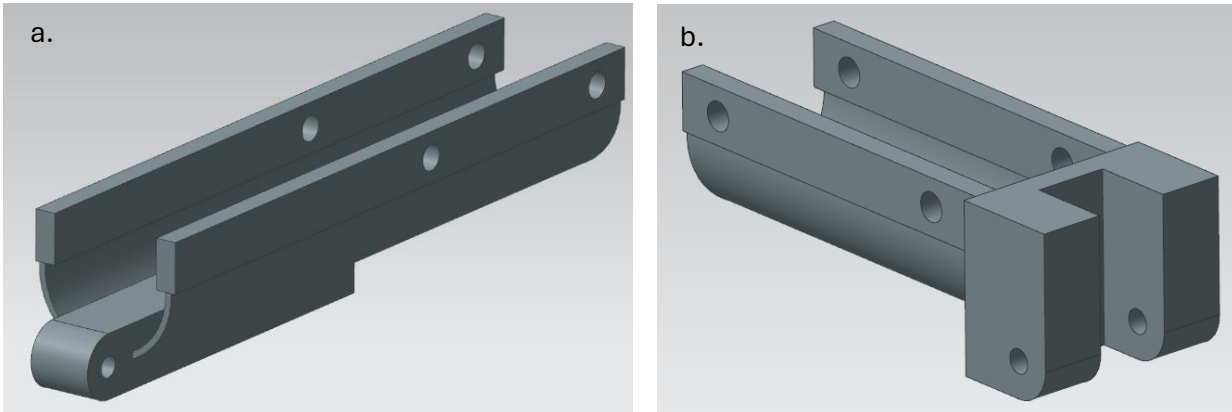


Figure 52 a/b - Prototype hinge design.

For the overhang section sheet metal would now be used. The maximum sheet thickness that could be bent in the workshop was 3mm, which was unlikely to be thick enough, therefore the decision to use three separate sheets and then weld them together was made. This is shown in Figure 53.

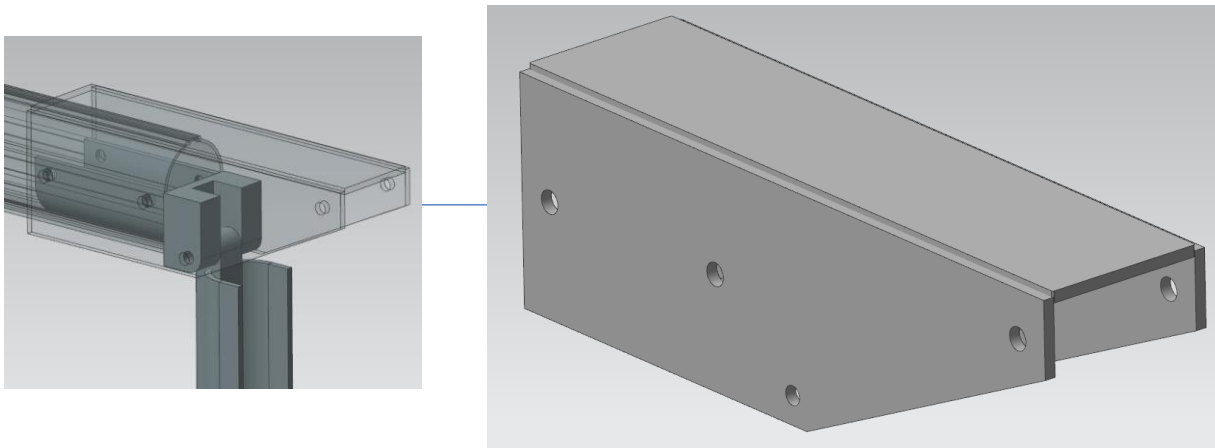


Figure 53 - Overhang prototype design.

9.2 Entry point prototype design

The original plan was to SLS print the entry point from glass infused nylon. However, this capability is not available at the university and so FDM is used instead. FDM printing with a nylon composite has the problem that the material extruded is very viscous, which can result in instability when printing; therefore, the design would need to be simplified. This meant removing any over hangs or other supports which could cause the print to fail. Also, the start point of each layer would be randomised to prevent the formation of a seam along the side of the holes. This should result in a cleaner surface finish on the sides of the print.

As a result, the prototype's design changes to resemble more of a block of material. The edges of the race way responsible for preventing the chain from making contact with the arm would be replaced with laser cut steel panels that would be bolted to the printed structure. These can be seen in Figure 43 - Entry Point Raceway CAD.

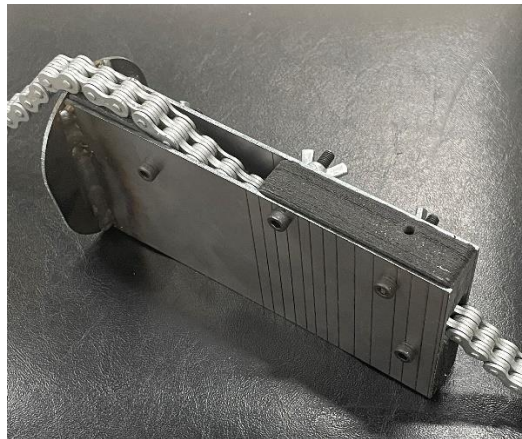


Figure 54 - Entry Raceway

9.3 Cable attachments

There are three main standard attachment methods for leaf chains. Figure 55 below shows the chain block and chain anchor. The simplest method is to pin directly through the chain and into the attachment point.



Figure 55 - An image of a leaf chain with an attached leaf chain anchor (top) and leaf chain block (bottom)

These parts are standard attachments for a leaf chain and, therefore, are likely to be the cheaper and easier than a bespoke solution, if implemented correctly in the design.

The chain anchor (see Figure 55) also removed the need for a tensioner, as the bolt can be tightened until the chain is tight. Furthermore, if the bolt reaches the head of the anchor, the use of a chain allows excess links to be removed. The anchor can be directly attached to the base anchor point (see section Figure 57).

Due to manufacturing limitations in the university workshop, the point at which the chain block connects to the hinge would be dissimilar to the final design. Where the final design is suited to use a standard block and a pin, the prototype had a pin spanning the whole width of the barrier. Due to the long pin, the team was worried about the pin bending. However, since the barrier was reduced to 1m, this was no longer an issue and a standard part was used and held in place by 4 nuts, as shown in the image below.



Figure 56 – An image of the chain block with the bolt spanning the whole width of the hinge.

The chain anchor simply passes through a hole and is secured in place with two nuts. This can be adjusted to increase the tension of the chain. However, this has a slight effect on the R_x value seen in the hand calculations (see section 8.4.1). The base anchor was designed to secure the chain in the correct position when the chain anchor is secured in the middle position, allowing for the most adjustment in both directions.



Figure 57 – An image of the chain anchor connected to the base anchor with two bolts. The chain can be tensioned by adjusting the position of the two bolts.

10 Prototyping:

10.1 1/4 scale prototype

Section 8.4.1 of this report showed how the motion of the barrier was modelled in Microsoft Excel. However, the decision to validate this practically was made to validate the model before committing to the design. This led to the development of a scale prototype. Initially it was thought that the existing CAD models could be scaled down and 3d printed, without much editing required. However, some of the wall thicknesses in the CAD were already only 1-2mm and making these 4 times smaller would make parts not strong enough. Therefore, every component of the barrier had to be redesigned for the scale model. But the critical dimensions, such as the positioning of the hinge, and the overhang, were kept to scale to ensure that the motion of the arm would be an accurate representation of the larger design. For the prototype PVC pipes were used for the arms and laser cut panels for the base, as this was quicker and cheaper than relying on 3D printers for every component. The prototype was designed to work with 608 ball bearings which are commonly used in skateboards. Although the prototype likely didn't require bearings, they were accessible and improved the operating experience. The scale prototype designs are shown in Figure.

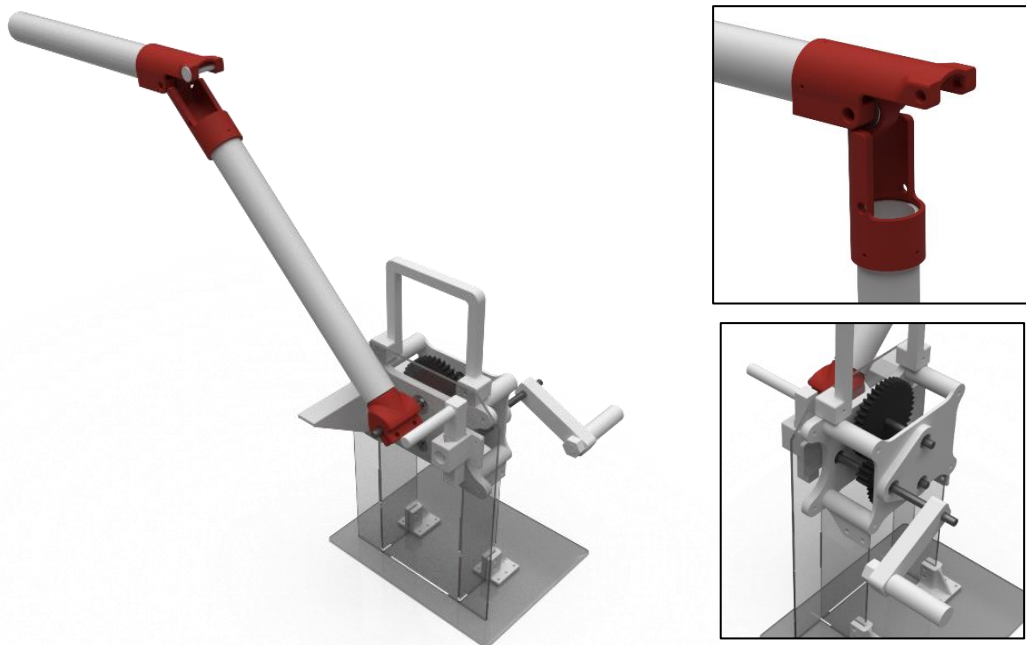


Figure 58 - Scale prototype CAD.

The additions of the gearbox and the crank handle to the scale prototype made it easier to operate the arm and experiment with the motion profile. The gearbox utilised a 16:1 ratio, made up of a multiplication of two 4:1 gears, meaning that it would take 4 crank rotations to raise the barrier.

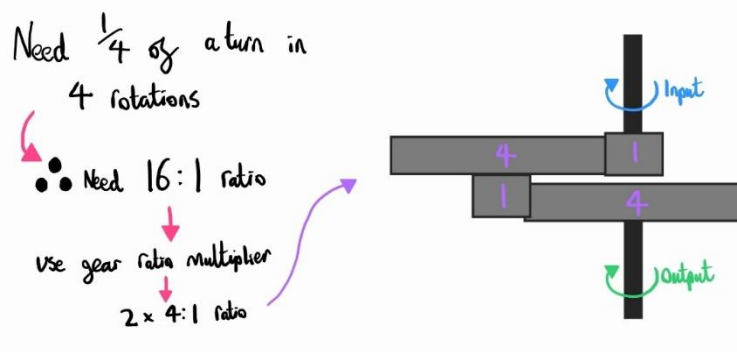


Figure 59 - Gearbox Calculations

8mm threaded bar was used for the axles within the gearbox, as this allowed the gears to be clamped with nuts, which was a simple solution for attaching them to the axles. A carry handle was added for the easy transportation to group meeting and presentations. An overview of the prototype is shown in Figure 60.

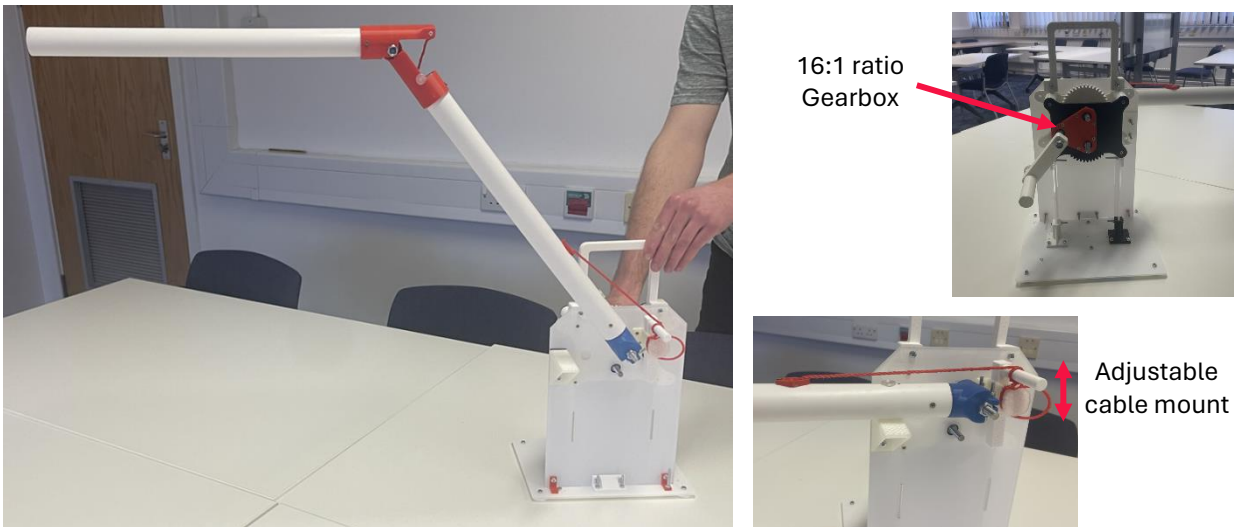


Figure 60 - Scale prototype.

The mounting point for the string at the base of the barrier was made to be telescopic, the 3D printed thread allowed for it to be clamped in the desired positions, which allowed for experimentation of where the best height is. Along with this experimentation we used data from the Excel document to validate it against the model. Figure 61 shows the prototype in action and the successful validation of the design.



Figure 61 - Operating the scale prototype.

10.2 Main Prototype

10.2.1 Prototype Hinge Manufacture

To manufacture the milled block used in Hinge part B, a manual milling machine was used. For the tube sections a band saw was used to cut the tube in half. Due to the lack of availability of stock 10mm flat sections they were cut from 10mm plate using a band saw. The cuts made on the band saw were not very accurate. However, using the PFL beam as a reference, adjustments could easily be made using a file to get the components correctly lined up before welding.

For the TIG welding, the components were first tack welded together. This allowed the fit of the hinge inside the barrier arm to be checked before committing to complete welds. The resultant hinge halves can be seen in Figure 62.



Figure 62 - Prototype Hinge

Figure 63a shows the validation of the hinge by ensuring a good fit with the barrier. Figure 63b shows that there is enough tolerance to allow for a smooth hinge motion.

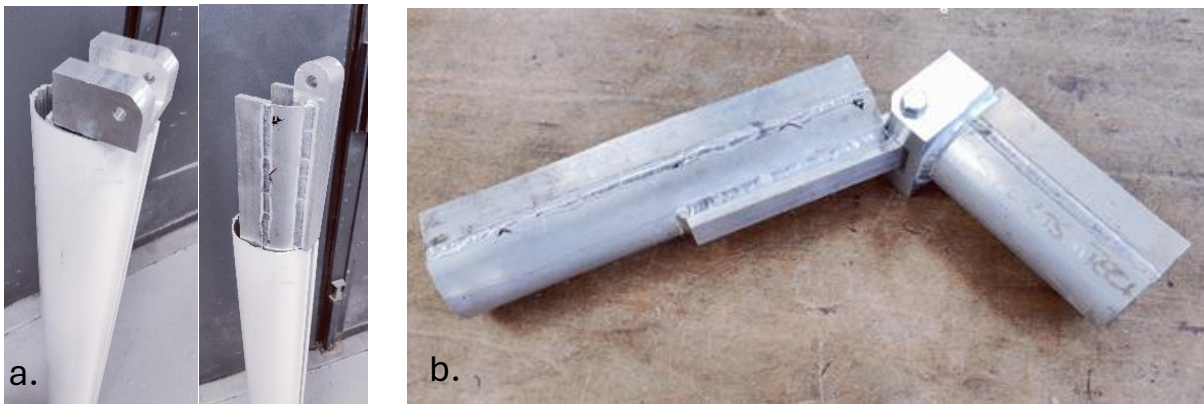


Figure 63a/b - Hinge prototype fit validation.

The next step was to Drill the holes for the bolts that will secure the hinge in place. The positioning of 3 out of the 4 holes was not critical. But since one of the bolts will also act as the axle for the pulley, it was crucial that this was positioned correctly. This could be done easily by referring to the engineering drawings. The internal perimeter of the beams gave a good reference to use as the centre which helped to ensure the holes in the different parts aligned. The secured hinge can be seen in Figure 64.

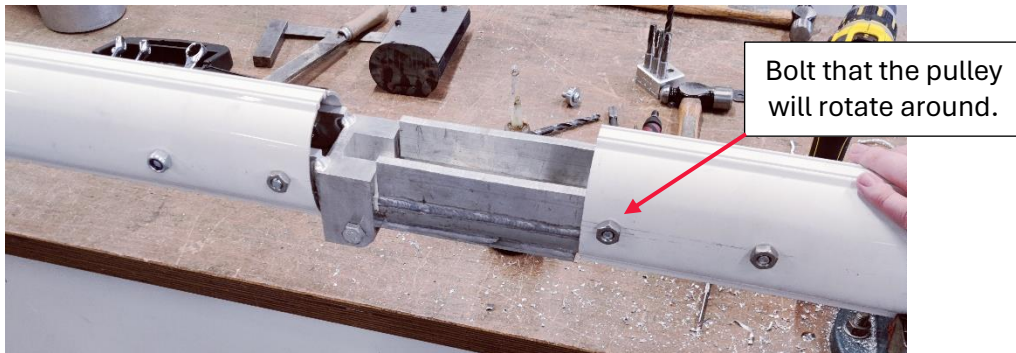


Figure 64 - Hinge secured to PFL beams.

The next step was to attach the side plates that the chain will anchor to. These plates were initially water jet cut with the holes the team thought would be needed. However, this was a mistake as lining the holes up with what had already been done was not possible, and the holes had to be welded up and new ones were drilled. Once this was completed, the plates were secured in place using the hinge bolts. A small amount of plate was added across the two plates to strengthen the hinge. Initially an entire top section made of 6mm plate was planned. However, there was not enough 6mm plate and thicker plate would have been significant overengineering, as only a small amount was needed to add the required strength to the prototype. This was sufficient for the prototype as it would only be used inside and would not be exposed to the elements, rendering the need for a full cover redundant. However, if this was to be used outside it is recommended to add a sheet across the entire top to reduce water ingress into the barrier. The part is shown in Figure 65.



Figure 65 - Side plates secured in place.

10.2.2 Prototype Entry Point manufacture

A 0.8mm nozzle was also required, due to the abrasiveness of the glass fibres within the material. This result is a more visible layer lines and a poorer surface finish.

As expected upon printing, the glass-infused nylon had large amounts of stringing caused by the filament's viscosity. This was then removed using standard 120-grit sandpaper. The stringing within the holes was removed using a drill bit. This also smoothed the surface quality of the print, removing layer lines.

The laser cut steel turned out very well with few defects and was quickly and easily welded together, as can be seen in Figure 66 - Welded Steel Raceway.



Figure 66 - Welded Steel Raceway

10.2.3 Cover Prototyping

The design boasts an expandable braided nylon mesh. However, purchasing this in smaller quantities proved challenging and so a polyester substitute was used in the prototype, to test the safety functionality as can be seen in.



Figure 67 - Polyester Cover

The polyester performed its role of protecting the cable from being touched very well, and thus removing the entrapment hazard when the barrier is stationary. It therefore, satisfies PDS 11 as well as the strong emphasis on safety from PFL.

10.2.4 Prototype Cable mounting

PFL's original articulated arm barrier uses a bent sheet metal plate to connect the linkage arm to the main body.

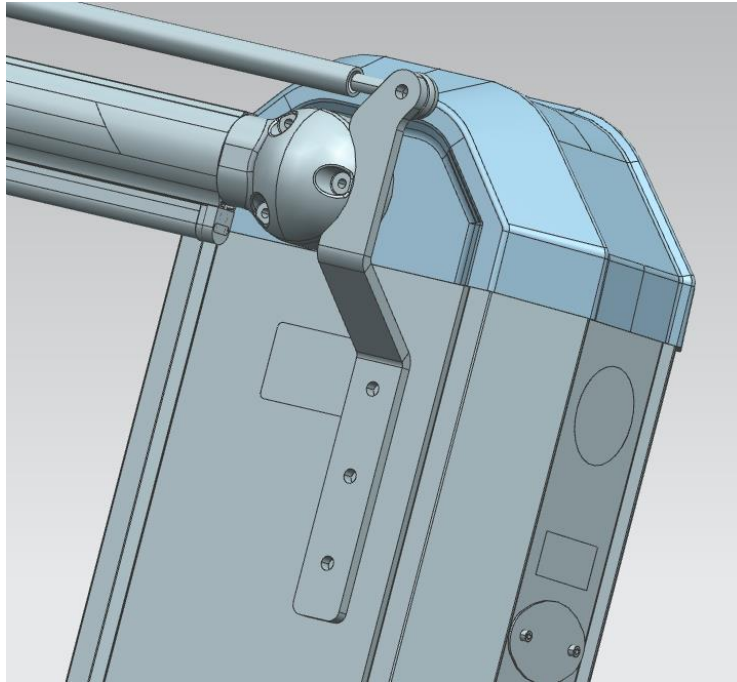


Figure 68 – An image of PFL's original solution to connecting the plate used to connect the linkage arm to the main body.

The team aimed to reuse or edit parts used in the original design where possible. This reduces costs as this reduces new manufacturing processes and reduces the required work. Additionally, the current part is already known to work in actual operation, increasing the team's confidence in the capabilities of the new part, which draws heavily on the current design.

The base anchor point of the chain copies the original design, only repositioning the connection point, with aim to reuse existing manufacturing capabilities in the PFL's facilities. The original part (see Figure 68) uses 12mm thick aluminium; however, the team could only create a 3mm aluminium sheet due to limitations in the university workshop. Therefore, the size of the prototype part was significantly increased in hopes of providing sufficient strength to support the maximum chain tension.

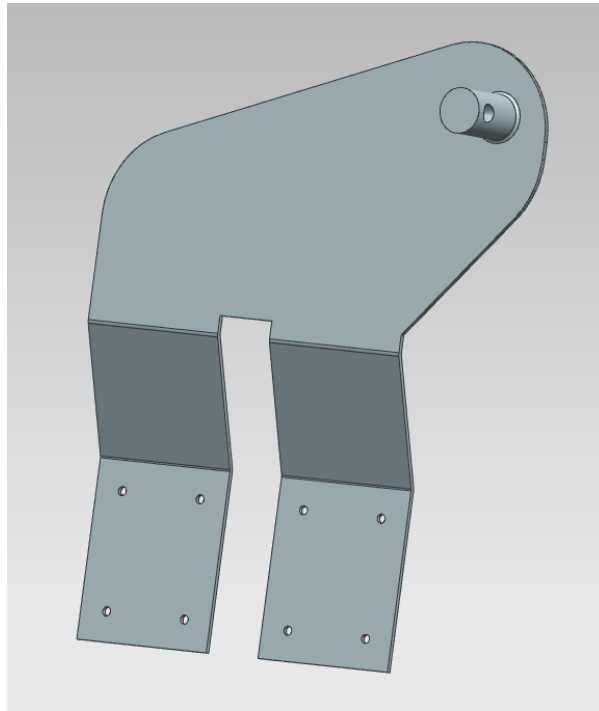


Figure 69 – An image of a CAD model of the base anchor point for the large prototype.

The Base anchor point was to be water jet cut from a 3mm aluminium sheet and bent into shape. Then, an aluminium cylinder was welded onto the front surface. The eight holes at the bottom allow for the plate to be bolted onto the main body of the barrier, and the hole in the cylinder at the top allows for the leaf chain anchor to be attached using a nut (see section Cable attachments). The positioning of the cylinder matches the Rx and Ry values (see section Horizontal Beam Calculations) with offsets for the length of the anchor.

However, after FEA analysis (see Chain attachment at base) it was found that a 3mm aluminium sheet is far too weak to hold the barrier. Therefore, an improvised solution was created by welding aluminium box cross sections. Although this solution does not resemble the part designed for the final solution, it allowed for the prototype to work.



Figure 70 – An image showing the improvised solution for the base anchor point.

11 Testing

11.1 Barrier Testing

11.1.1 Rain Testing

Intro

With the hinge design boasting a new uncovered hole, to meet the PDS point 18 a rain test would be needed to quantify if it could deal with the UK's weather. Therefore, a test to simulate rainwater was conducted to determine if the current design could withstand the rate of rain currently present in the UK, or if additional drainage holes would be needed to remove the water from the barrier.

According to the Met Office, the UK record for rainfall in a 30 minute period is 80mm of rain in 1953 (Dumfriesshire) [12]. The 30 minutes period time was chosen as it was felt would give the most accurate value for which to calculate it.

Assumptions

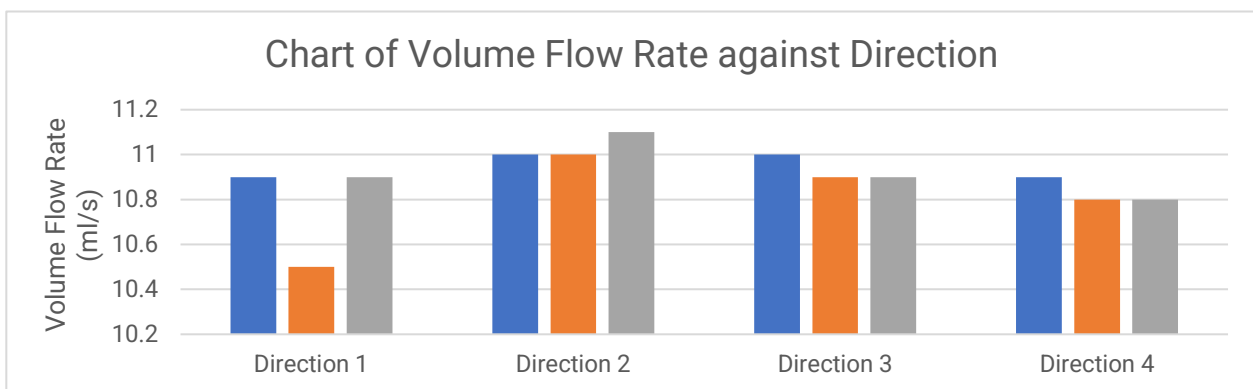
- Water would enter the barrier only from the hinge joint.
- All of the water would exit via the shoulder joint.

Test design

The hole in the hinge is only open when the barrier is in the open position, and the arm is up. Therefore, the test was designed with the barrier in the upright position. A shower head was used to vary the water entering the barrier as well as simulated rain dispersion. The water flow rate was turned on until the shoulder joint started to fill with water. Then, the water flow rate was reduced until the shoulder joint stopped filling.

The test was carried out three times, each time the direction of the water entry was changed. Direction 1= 0° (But straight down the arm), Direction2=0°, Direction3=90°, Direction 4=180°.

Results



These results show an average of 10.9 ml/s. The hole in the hinge has a cross-section of 4500mm². Therefore, the value of flow rate per unit area is 49.05 l/(s*mm²).

The UK over a 30 minute period has recorded a maximum value of 0.0444 l/(s*m²). As this is approximately 1000 times bigger, it is clear that drainage holes will need to be incorporated into the design.

Assuming the barrier is continuously used over a 30-minute period, it is only in the open position for 38% of the time. Therefore, to ensure the water is drained, a hole with a radius of 23mm would need to be drilled; alternatively, 4 holes of 11.7mm could also be drilled.

These holes should not affect the structural integrity of the barrier arm due to their small size. However, it should be recommended that the number of holes drilled in the barrier should reflect its location, i.e. if it's inside, then 0 holes will be needed, or if it's in a position which encounters less than the average rainfall, then 2 holes should be plenty, 4 holes was only considered for the maximum rain the barrier could ever face.

11.2 Main Prototype Testing

Tests were completed to measure the droopage of the barrier and compare the prototype performance against the current PFL articulated arm. Both barriers were cut to the same length for the 2nd beam, but due to the length of the linkage arm, PFL provided, the first beams of the designs were different lengths. However, since this is before the hinge, it will have no effect on droopage.

Firstly, both barriers were filmed to compare their motion and understand the customer perception of the barrier. Figure 71 below shows an image representing the motion of each barrier.

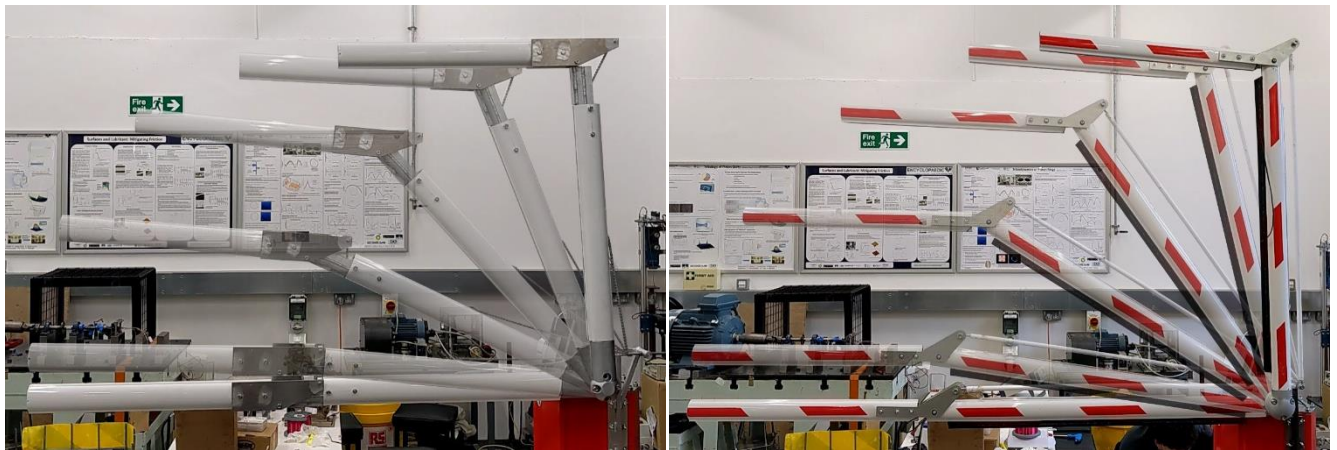


Figure 71 – An image comparing the motion of the proposed solution (left), against PFL’s solution (Right) as it opens.

Visually comparing Figure 71 shows there is a close resemblance between the prototype and the original solution. The proposed design tilts upwards halfway to the open position but returns to a horizontal position when fully open. PFL’s solution also droops upwards but has a maximum droopage angle while in the open position. However, the team concluded that neither design has severe droopage, which could cause the customer to question the safety and security of the barrier. However, this is subject to individual opinion.

To accurately measure droopage of each design, a digital spirit level was attached to the tip of the 2nd beam of each design and the barrier was adjusted until the digital spirit meter was at 0°. The barrier was then opened and closed and the droopage angle of the open barrier, and the maximum droopage angle were recorded.

	Our Design	PFL Design
Droopage angle when closed (adjusted to be close to 0°) [Deg]	0.3	0.1
Maximum recorded Droopage angle [Deg]	6.3	4.0

Droopage angle when open [Deg]	0.2	4.0
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Table 8 – A table of results from the droopage test, comparing the proposed solution to PFL’s solution.

The maximum droopage angle of our design is larger than the maximum droopage angle of PFL’s design. However, our design has less droopage in the open position, while PFL’s design has maximum droopage angle in the open position. The open position is when the barrier stops and stays, and therefore, the droopage in this position has a large effect on customer perception. Our design reaches a higher maximum temporarily while moving and returns to a horizontal position in the open position. Therefore, this test concluded that the droopage performance of our barrier is an improvement over PFL’s solution.

During the hinge development process hand calculations were completed to determine the droopage depending on hinge geometry (see section 8.4.3). Inputting the prototypes final dimensions into the same calculations, the team plotted a graph of the expected droopage to compare against the measured droopage.

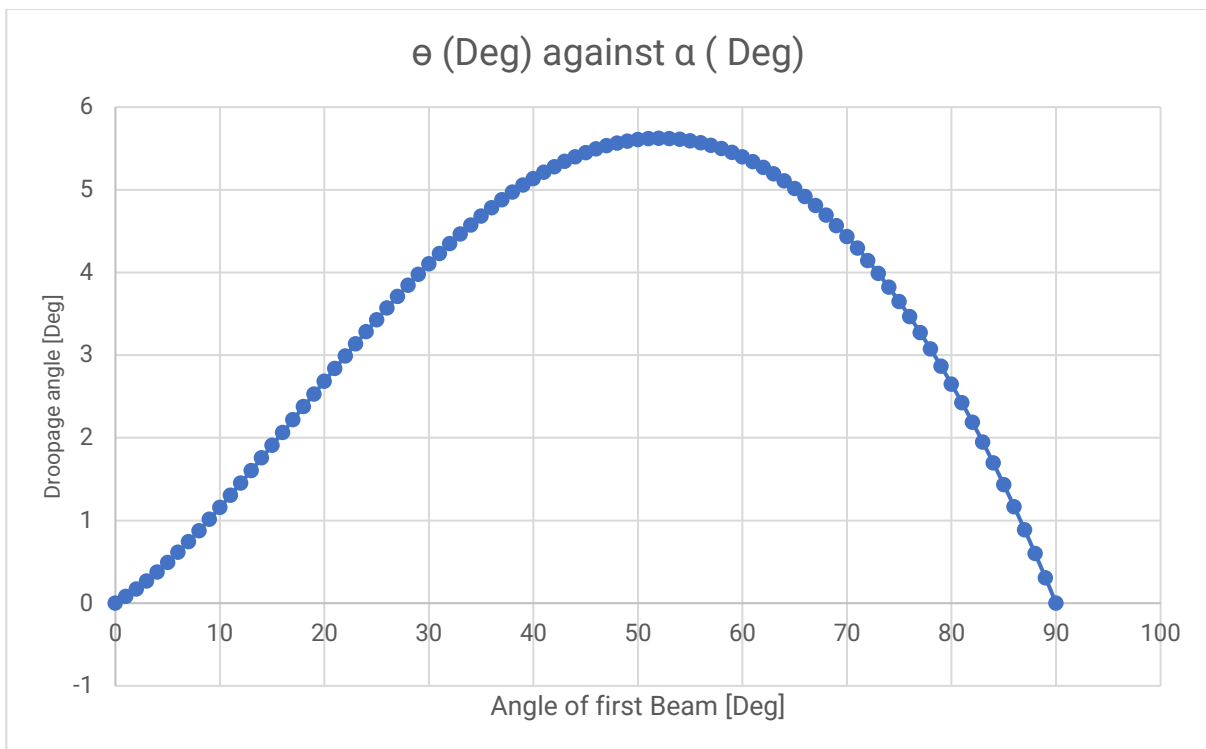


Figure 72 - A graph showing the predicted droopage angle of the 2nd for each angle of the 1st beam.

Figure 72 shows the maximum predicted droopage angle of the beam being 5.6 degrees, when the first beam is at 53 degrees. Comparing this to the maximum droopage angle measured of 6.3° (see Figure 72) this is sufficiently close to validate the calculations. With more design freedom and accuracy, according to the calculations, this droopage can be reduced to a maximum of 3°. This further proves the plausibility of the design, allowing for high precision design optimisation.

Furthermore, tests were completed to compare the noise of the proposed solution against PFL’s solution. To measure the noise made by each barrier, a digital decibel meter was placed 2m from the barrier during an operating cycle. Due to practical limitations, the noise test was completed without the side cover of the barrier’s base. This meant the noise from the motor is much louder than it would be installed fully with covers on, however, since the design change had no change to the motor, and each test was completed without the covers it was deemed to be a fair test. The maximum noise recorded while running our design was 48 dB and the maximum noise recorded running PFL’s Design was 50 dB. While testing the team noticed the motor sounded louder than the

arm, and the test results reflect this since both designs have very similar peak noise, implying the change in barrier arm had no effect. Regardless, 50db is the same volume as ‘moderate rainfall’ [13] and negligible compared to other outside noise levels. The team concluded the noise of our barrier design will not affect the user experience.

11.2.1 Fatigue Testing

The barrier was programmed to operate on the following cycle: move from horizontal to vertical in approximately 15 seconds, wait at the vertical for 5 seconds, return to horizontal in 15 seconds and then wait 5 seconds at the bottom. The barrier was then run continuously for 120 cycles, which provided useful data on the suitability of the prototype for operational use, informing the final design of the barrier.

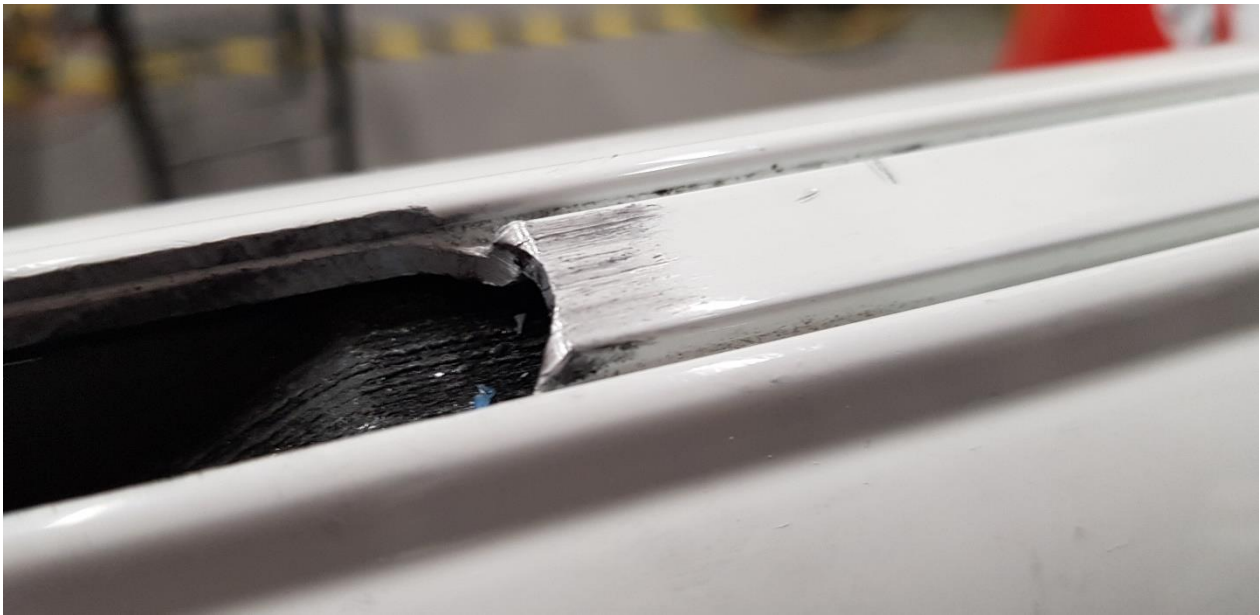


Figure 73 - Image of the entry point following fatigue testing. Scratching of the metal is visible.

As seen in Figure 73, the rubbing of the chain on the area around the entry into the arm had the effect of wearing on the material, with significant scratching observed. In the long term, this would potentially compromise the structural integrity of the entry point and would result in wear on the chain itself, posing questions about its ability to continue safe operation. As a result, the entry point was developed further in section 13.1. There was no visible damage to any of the other components upon completion of the fatigue testing.

11.2.2 Safety Testing

One point raised by a PFL representative in a previous meeting, was that he wanted to ensure that should the chain break, the extension would not fold 180 degrees back on itself. As this would trigger the barrier to have to rise again. BSI EN 12453:2017 Annex E specifies that when safeguarding against dropping, the following is an acceptable solution: “The failed component is clearly visible, or further use of the door is automatically prohibited, at the latest when the door has reached its lower terminal position” [14]. This, in combination with point 5.5.4 of the same specification states that upon failure resulting in falling or ejected parts, or uncontrolled movement, so long as it’s clearly visible that the component has failed, it can be deemed safe. Therefore, we should test to see that should the chain break, the extension cannot trigger the safety edge causing it to rise.



Figure 74 - Prototype with Chain Detached

We tested what would happen should the chain detach mid lift, as a result the chain arm to a stop at an angle just over 90 degrees as can be seen in Figure 74 - Prototype with Chain Detached. This is due to the tolerance in the prototype leaving a small gap allowing the prototype to rest just past the desired angle. Despite this, the test was successful as the barrier was unable to fold 180 degrees and trigger the safety edge. It is therefore deemed safe via the BSI standard 12453:2017.

12 Materials and Manufacturing Processes

12.1 Manufacturing Processes

The aim of this project was to design a barrier for PFL. Therefore, it has always been essential that any material or manufacturing process chosen should minimise the changes that PFL need to make, or to provide enough justification as to why PFL should invest in it. PDS specification 3a states that the barrier should utilise existing company parts and processes where possible.

In February, a trip to PFL's factory was made not just to obtain a list of all the machinery that was there but also to look at the current structure of the factory, where all the machines are placed, and the limitations of these machines.

12.1.1 Sand Casting

There are a number of different manufacturing methods that could be used to make the hinge joint. Sand Casting, Investment Casting and Aluminium Die Casting. After consideration, sand casting was chosen as the process for a number of reasons [15].

1. From a process side, it doesn't require as high of an initial cost, unlike the other two processes. Due to PFL's estimated sales at 30/month. A high initial cost by purchasing any new machines would be undesirable for PFL on a product as it is likely that it would take a long time to pay off the initial investment. Also, the machine would not be in constant use and would therefore take up space in the workshop. Therefore, sand casting the part makes the most sense.
2. Currently, PFL outsources their shoulder joint with sand casting. Therefore, using the same source will allow for fewer logistical changes to be made.
3. From a process side, sand casting provides a low cost per part, unlike investment casting. This would, make the part cheaper to manufacture.
4. With another part being manufactured by sand casting, this could open up PFL to consider investing in the required equipment. Which they may not have thought of doing as the shoulder joints was not enough to justify the purchase.

One reason to choose one of the other casting methods is its tolerance requirements. Having a higher tolerance will make the part look objectively better. However, the hinge's design doesn't require this, and therefore, sand casting is an acceptable option.

To check if the design was capable of being sand cast, the design was taken to Christopher Ludlow, a technician at Loughborough University who has spent many years in the school of Design and Creative Arts sandcasting many objects. After a meeting with him, he agreed the design was a difficult sandcast design due to its hollow nature, however it was still feasible given the proper setup.

12.1.2 Electrostatic spray deposition

One of the downsides of sand casting is the surface finish. The rough surfaces could be machined down to provide a better surface finish. However, due to the cross-section of the beam having a white paint coating, a better solution to manufacturing a more consistent hinge would be to use an electrostatic spray deposition (ESD). This therefore adds the following advantages [16]:

1. The finish will smooth over any rough surfaces left behind by the casting process. Making it look more aesthetic.
2. This will provide better corrosion resistance to the aluminium hinge. Thus, increasing its durability, which is good if going to be placed outside in harsh UK environments.
3. This finishing process is already performed at PFL. Therefore, this process will not increase the number of new processes the company would need to invest in.
4. The white coating will give the barrier a more uniform appearance, as the cross sections are already coated like this. This will give the barrier a more streamlined image when in the closed position.

This, however, could also be removed from the manufacturing line if PFL wanted to reduce lead times further, as this process is only added to protect the aluminium further from corrosion and to make the barrier more uniform and therefore more aesthetic.

12.2 Materials

The requirements of the material are to be:

1. Lightweight, to reduce the inertia on the barrier.
2. Good castability to improve the performance of the material during the manufacturing process.
3. Good corrosion resistance, so it can handle the harsh UK weather.
4. Dimensionally stable so any holes or crucial dimensions remain consistent after the process.

One material that fits these requirements is Aluminium alloy 535 (Almag 35) [17]. It's a lightweight, high-strength aluminium and magnesium alloy. Its advantages are it doesn't require heat treatment thus reducing any additional processes on the part and therefore cost as well, has excellent corrosion resistance, is dimensionally stable, and is good for sand casting.

This material also has a Young's Modulus of 71GPa [18]. This is conclusive with the design as the FEA calculations have been carried out using the assumption of a generic aluminium at 70GPa, and thus this material would also be considered acceptable.

13 Development following prototyping and testing.

13.1 Entry point Development

During fatigue testing, it was observed that the chain would rub on the aluminium beam, (see Figure 73/ Figure 75a). Initially it was thought that the entry point would be significantly closer to the shoulder, and as such, it was not considered an issue in previous design iterations. To address this issue, two simple solutions were devised. The first involved modifying the existing nylon raceway part by adding a guide for the chain to the entry point. The second was to re-evaluate the use of rollers. These two options are shown in Figure 75b.

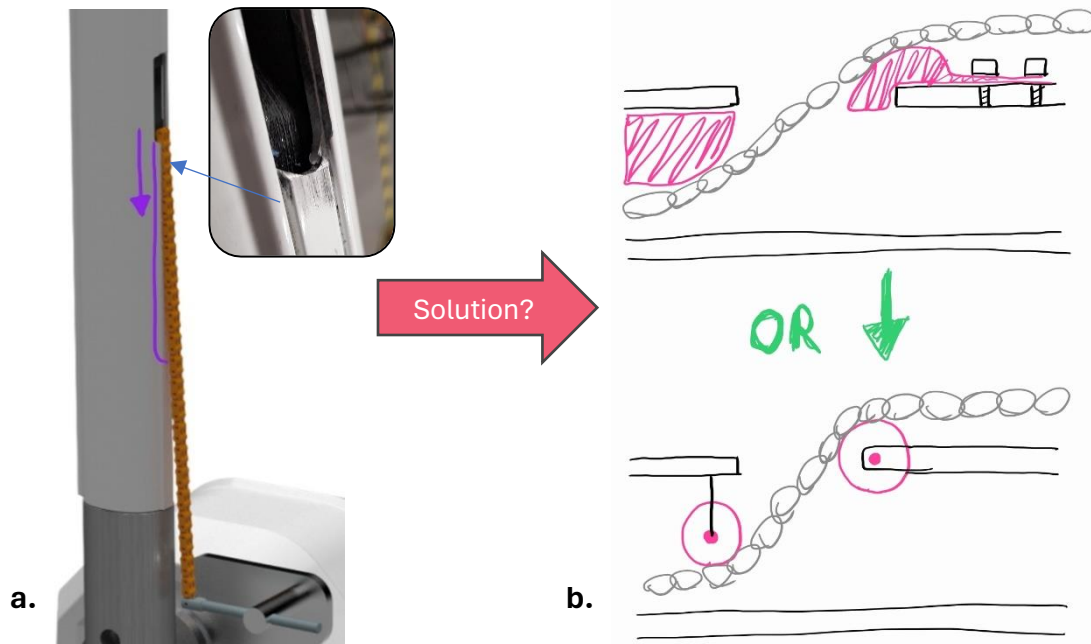


Figure 75 a/b - Coming up with a solution for the entry point.

Rollers were chosen for the final concept. This is shown in Figure 76. This design uses a simple laser cut sheet metal bracket to hold the roller. The bracket requires 2 bends to create the required shape and would attach using either bolts or rivets. The pulley could either be manufactured in house or swapped for a bought in component.

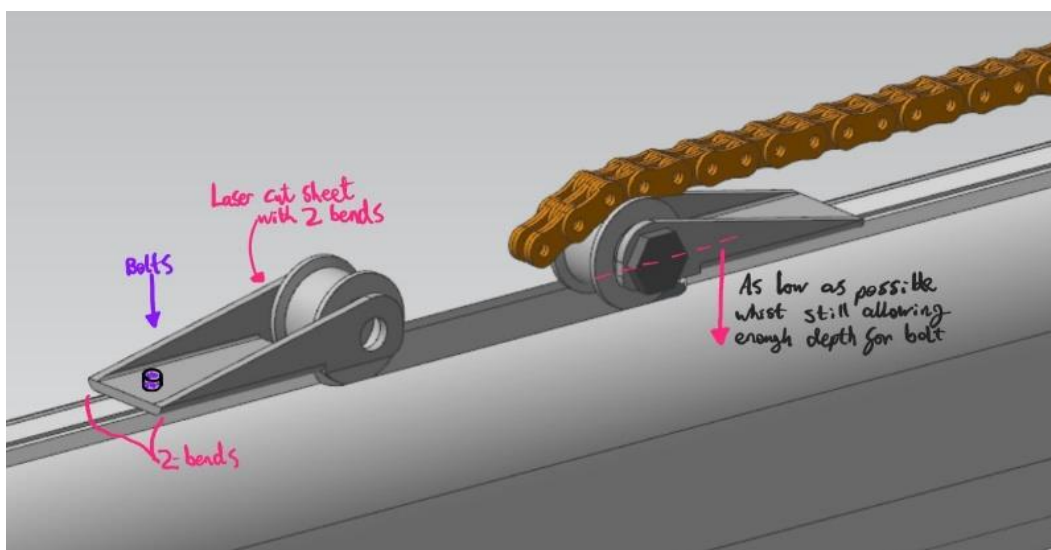


Figure 76 - Entry point design.

To select a bearing that would be suitable for the rollers, some simple calculations were carried out. Assumptions included: 2 pulleys, and the X and Y measurements for the chain attachments being equal. This resulted in selecting a 6800 bearing that can take a load of 208N (static). As two bearings would be used per pulley, taking the max load up to 416N which is greater than the 309N required. Stronger options are available, but this bearing also has a low profile which allows for the size of the rollers to be kept down. The calculations for this are shown below the diagram shown in Figure 77.

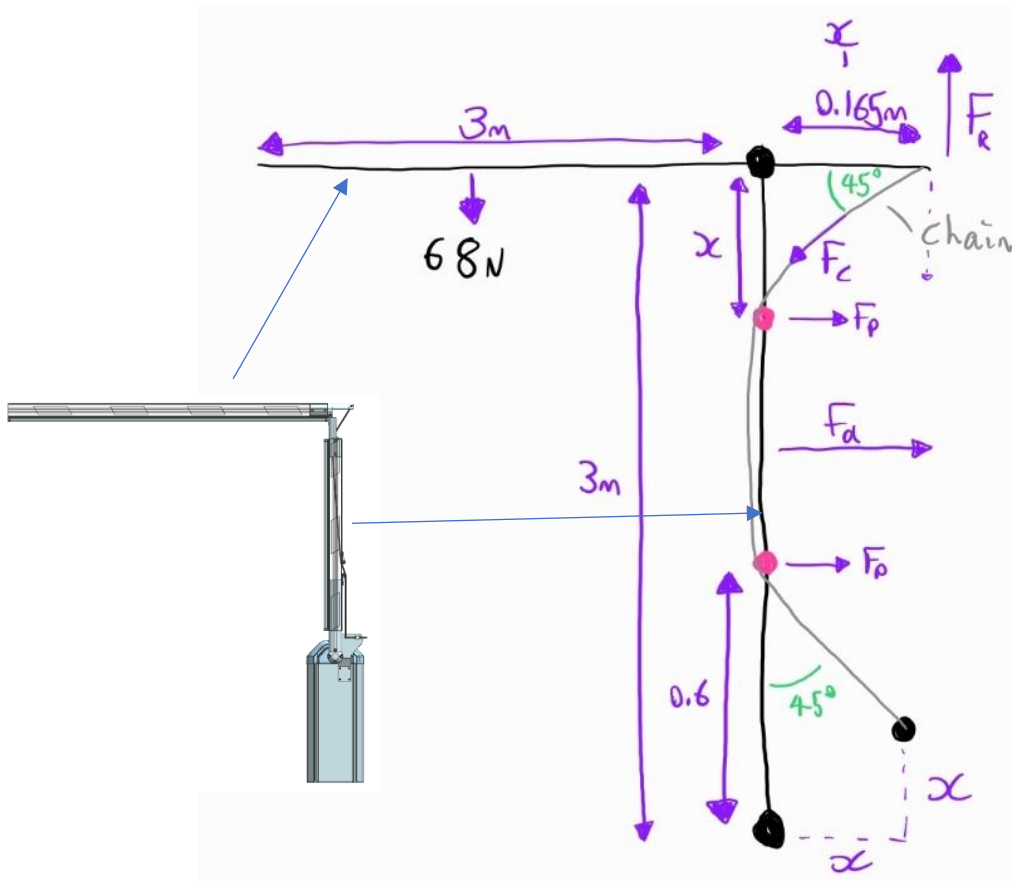


Figure 77 - Free body and calculations for entry point.

$$F_R = F_D = \frac{1.5 * 68}{0.165} = 618N, \quad \therefore F_p = \frac{618}{2} = 309N$$

(16)

13.2 Base anchor Development

The final proposed design for the base anchor point is a slight adaptation on PFL's current solution's part, only repositioning the chains anchor point to comply with the calculated R_x and R_y positions (see section Hinge Calculations). It is to be attached to the base in the same way as PFLs current solution and manufactured in the same process, as the thickness and most dimensions are similar. To connect the chain anchor to the base anchor, a standard eye bolt can be used. This allows for the chain anchor to adjust the chain tensions, using the same method as with the prototype.

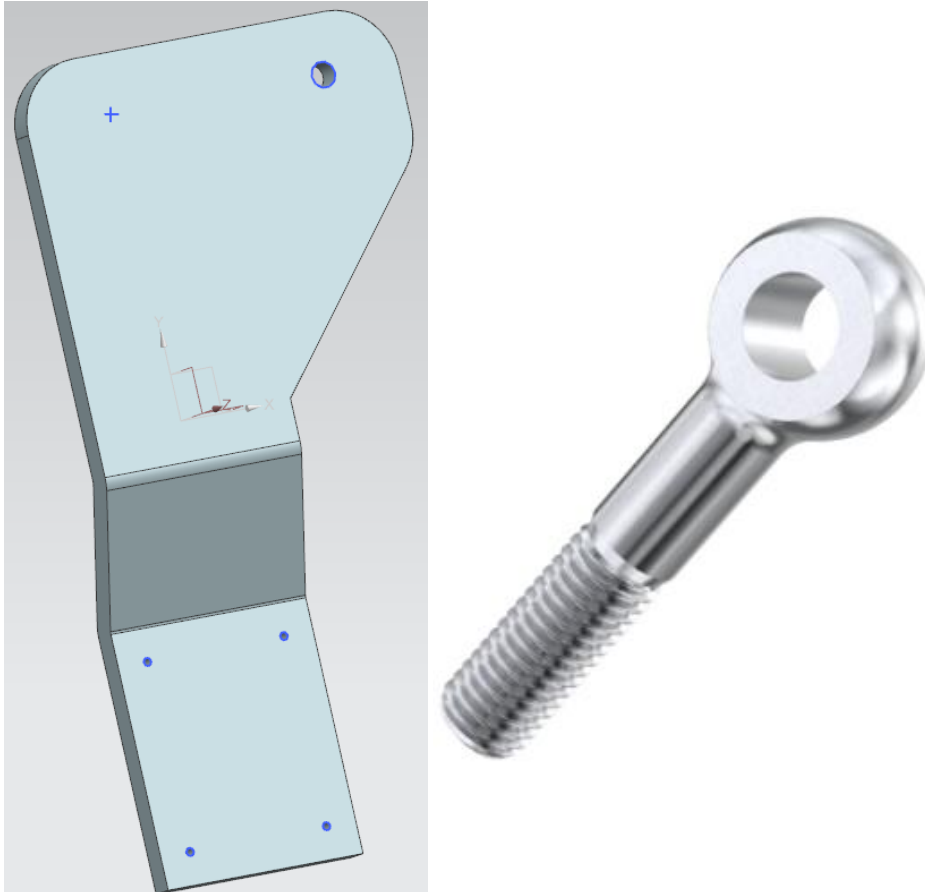


Figure 78 - An image showing the CAD of the final proposed design for the base anchor point and a standard eye bolt.

The forces in the linkage arm in PFL's solution are higher than the chain tension in the proposed solution. Due to the strong similarity to the current part, FEA simulations were not performed, and the strength of this part is considered sufficient.

13.3 Wiring Development

The main challenge with wiring the developed barrier is the lack of space to guide the wires in the hinge. This is due to the presence of the pulley and the chain. This presents the risk of the wires getting caught and sustaining damage. A simple solution to prevent this is to shield the wires. This can be achieved by passing them through a pipe. This concept is presented by the red tube in Figure 79.

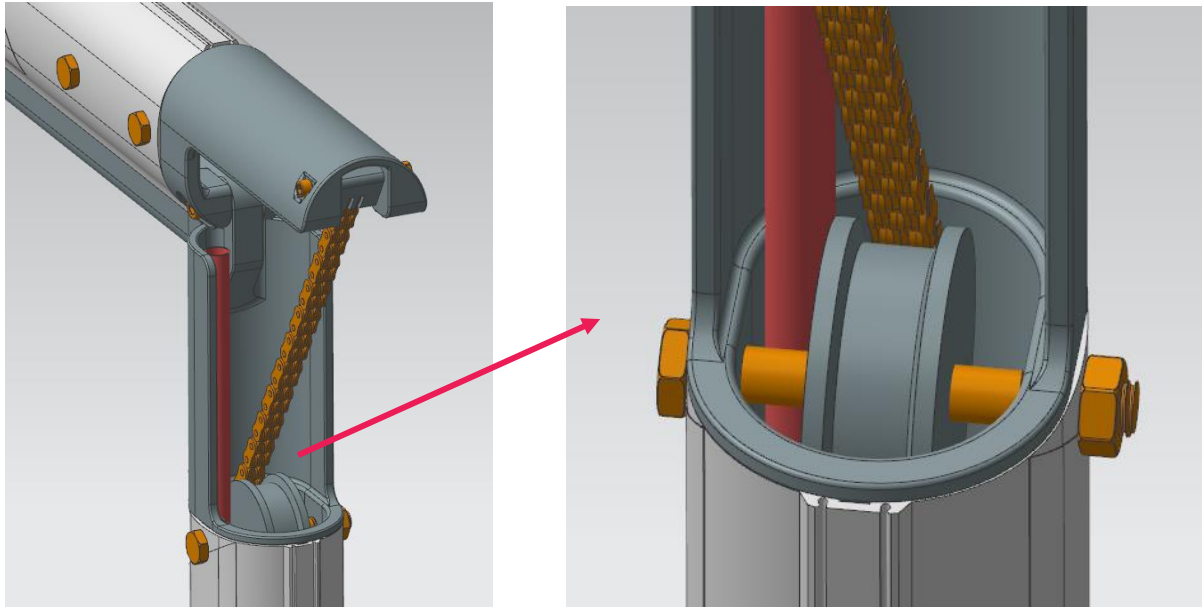


Figure 79 - Concept of pipe guide for wires.

One of the issues experienced with wiring by PFL, was that when they break it is difficult to replace. This is as the entire length of wire needs to be routed through both arms and the hinge of the barrier. By utilizing quick fit electrical connectors, the wiring can be split into modular sections. This would also help for when the barriers are transported to the customers, as instead of having a long and fragile barrier, it can be shipped in the two halves. This is possible as the proposed barrier only requires a simple hinge bolt and electrical connector to assemble the halves. The wire would be spiralled to help reduce fatigue caused by repetitive flexing. This concept is shown below in Figure 80.

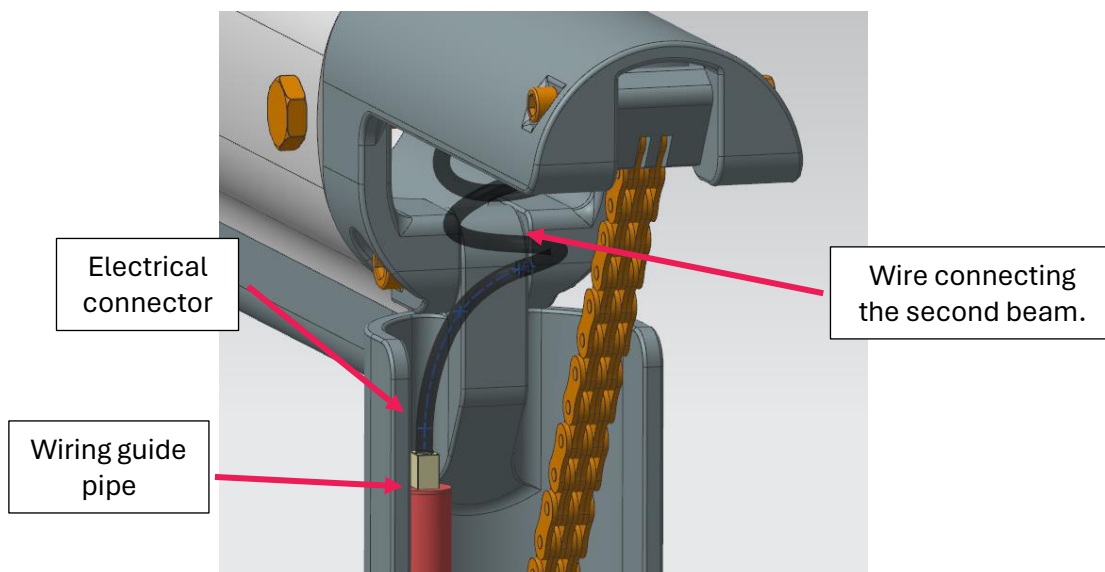


Figure 80 - Utilising electrical connectors for the wiring.

14 Detailed Concept Design

14.1 Mechanical Design Overview



Figure 81 – Design overview.



Figure 82 - Barrier closed.

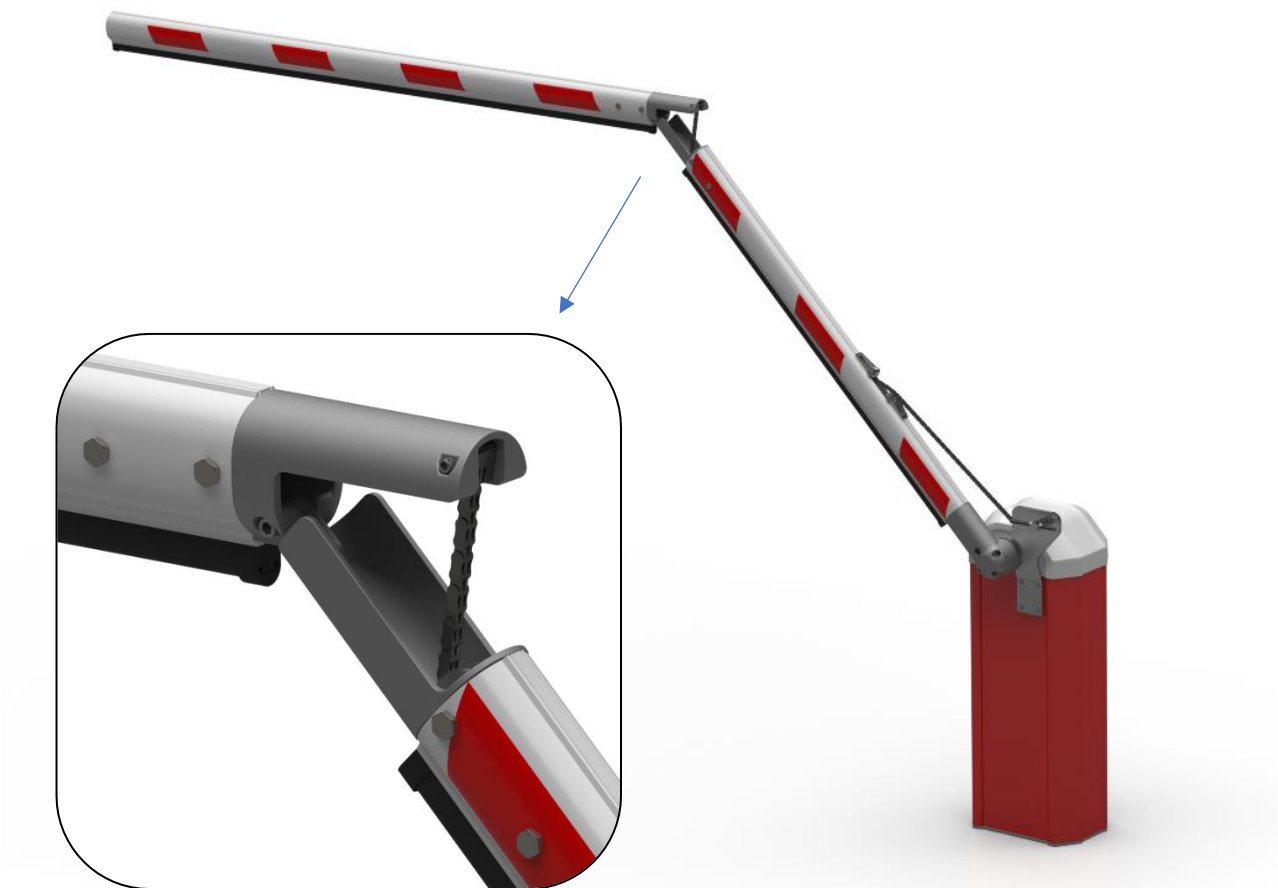


Figure 83 - Barrier half open.

14.2 Exploded View

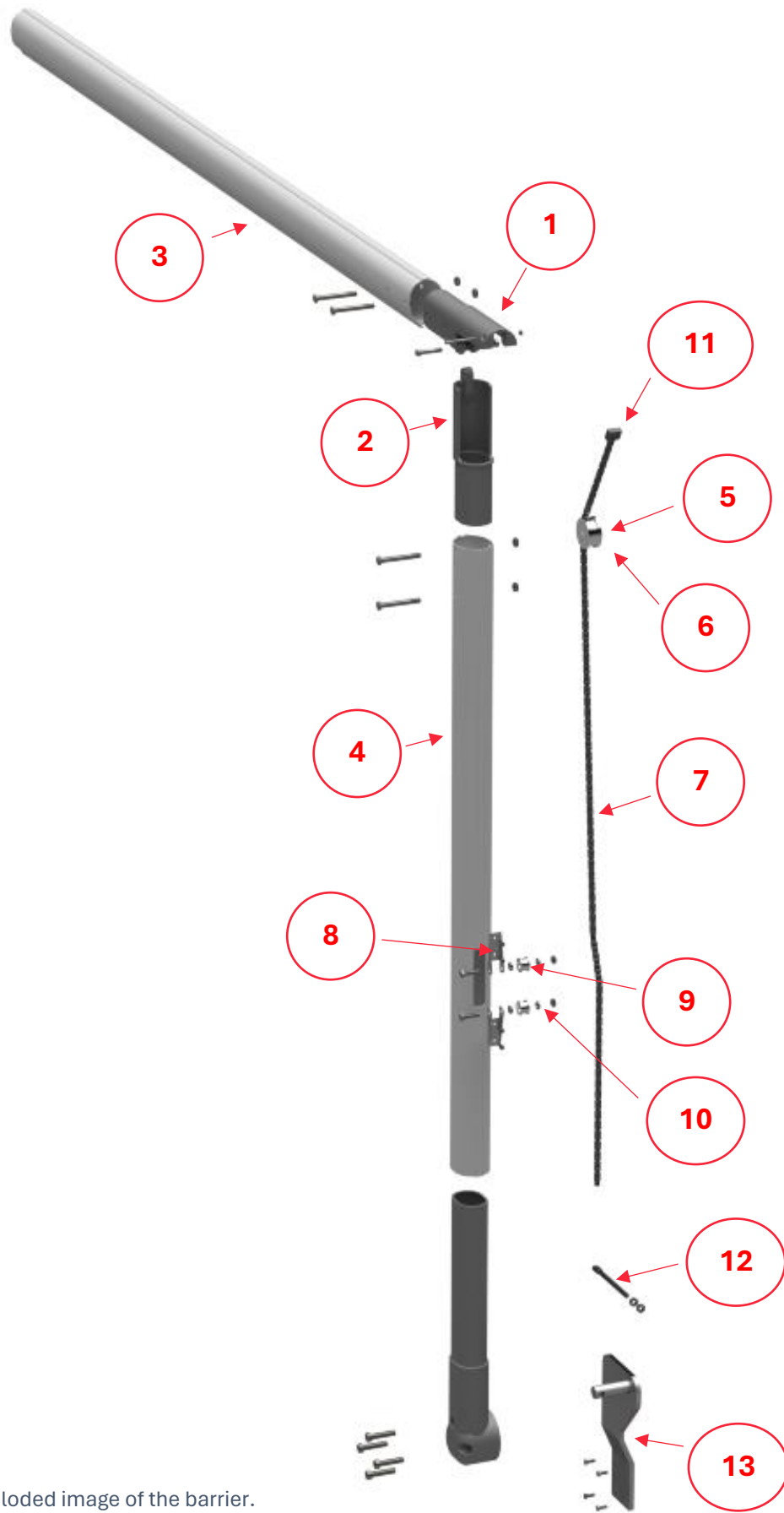


Figure 84 - Exploded image of the barrier.

14.2.1 Parts List

The part list shown in Table 9 includes all new or modified components. Current PFL parts have not been included.

Part Number	Quantity	Description	Material	Manufacture Method	Engineering Drawing
1	1	Hinge – 2 nd half	Aluminium	Cast	Appendix 22.6
2	1	Hinge – 1 st half	Aluminium	Cast	Appendix 22.5
3	1	First Beam	Aluminium	N/A	Appendix 22.8
4	1	Second beam	Aluminium	N/A	N/A
5	1	Pulley	Aluminium	Lathe/ bought-in component.	Appendix 22.10
6	2	6001 bearing	N/A	N/A	N/A
7	1	Chain	Steel	N/A	N/A
8	2	Entry point pulley bracket.	Stainless steel	Laser cut and folded.	Appendix 22.11
9	2	Entry point pulley	Aluminium	Lathe/ bought in component.	Appendix 22.9
10	4	6800 Bearing	N/A	N/A	N/A
11	1	Chain block	Steel	Mill/ bought in component.	N/A
12	1	Chain anchor	Steel	Mill/ bought in component.	Appendix 22.7
13	1	Base anchor	Aluminium	Laser/ water jet cut and welded	N/A
-	4	M12 x 100	N/A	N/A	N/A
-	1	M10 x 60	N/A	N/A	N/A
-	2	M8 x 60	N/A	N/A	N/A
-	4	M8 x 25	N/A	N/A	N/A
-	4	M6 x 15	N/A	N/A	N/A

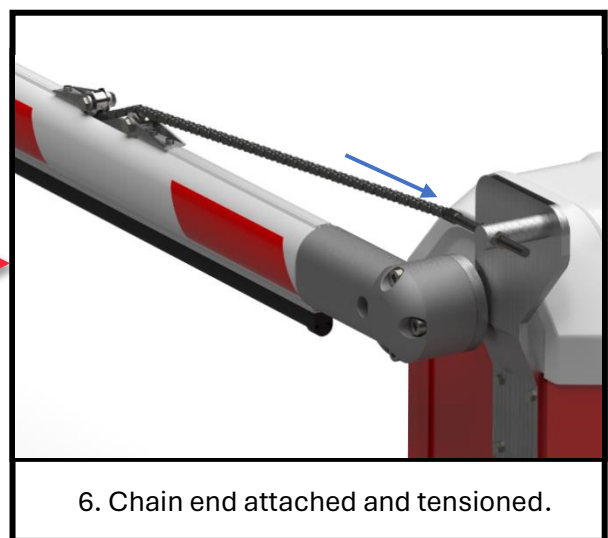
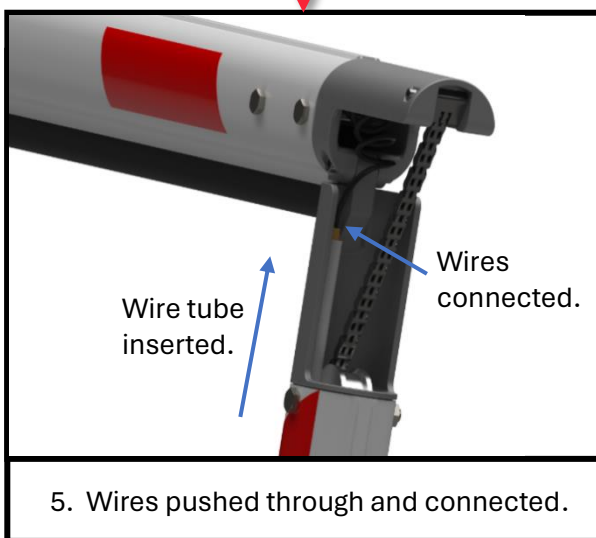
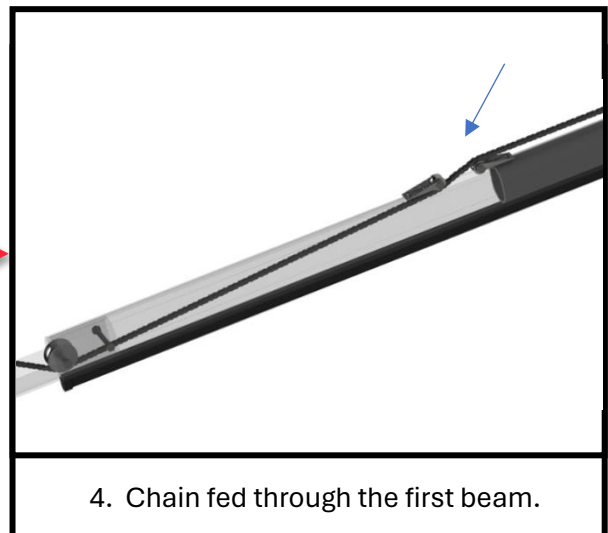
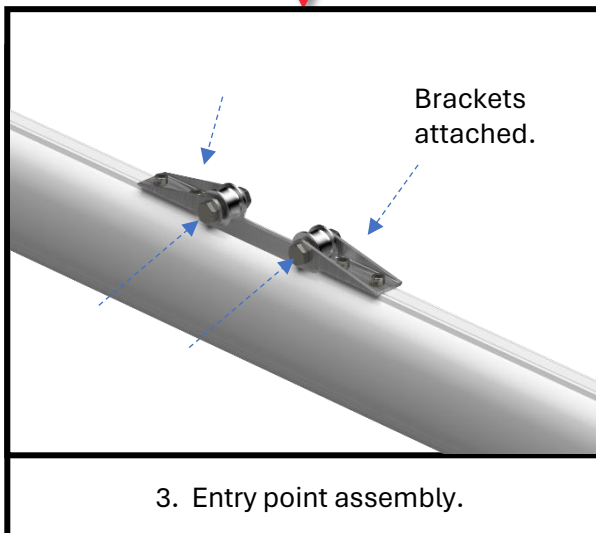
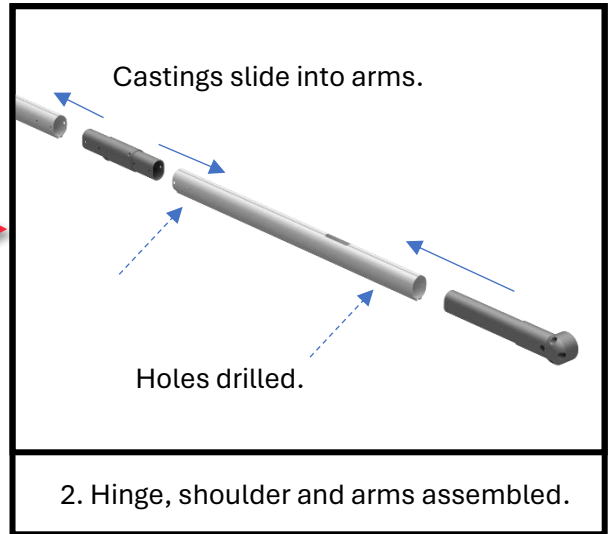
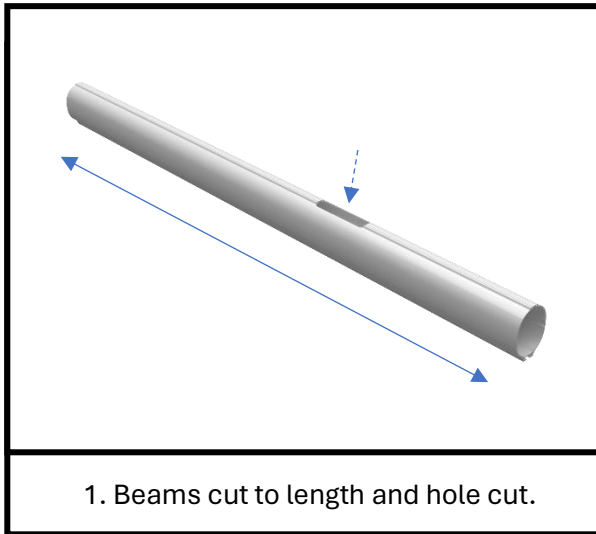
Table 9 - Parts List

14.3 Wiring solution



Figure 85 - A spiralled cable with a quick-fit electrical connector.

14.4 Story Board Showing Assembly Steps



14.5 Aesthetic Adjustments

Applying a white powder coat to the cast components improves the aesthetic of the barrier by giving it a more uniform look. Making the hinge less visible was one of our original goals, so this is recommended. Figure 86 and Figure 87 highlight this addition.

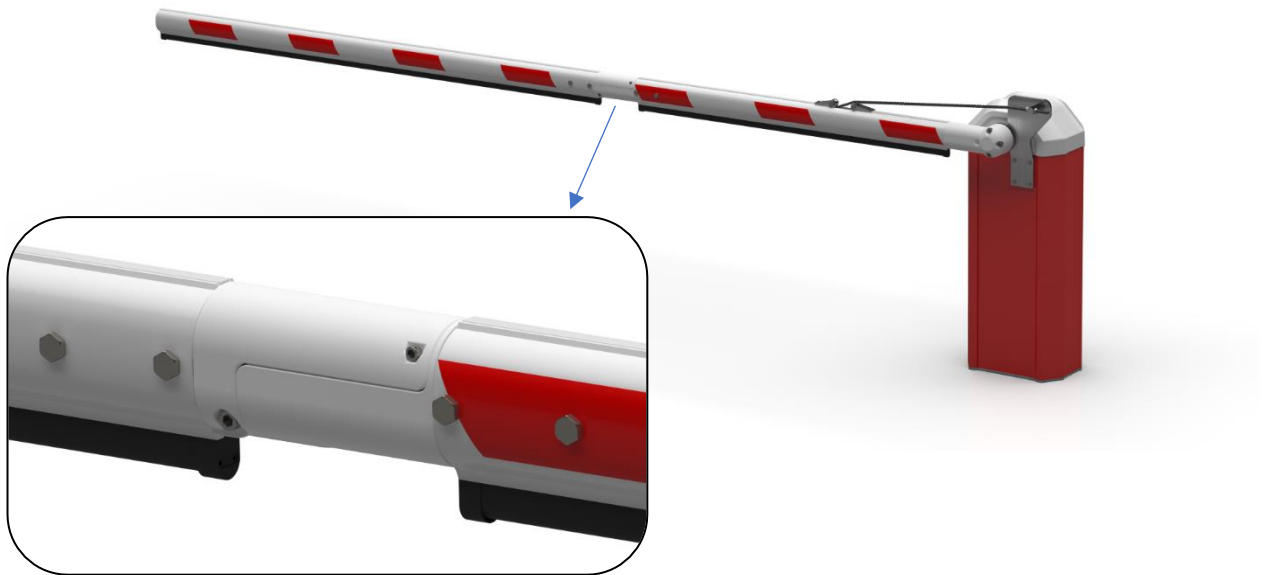


Figure 86 - Barrier with white powder-coated cast components.

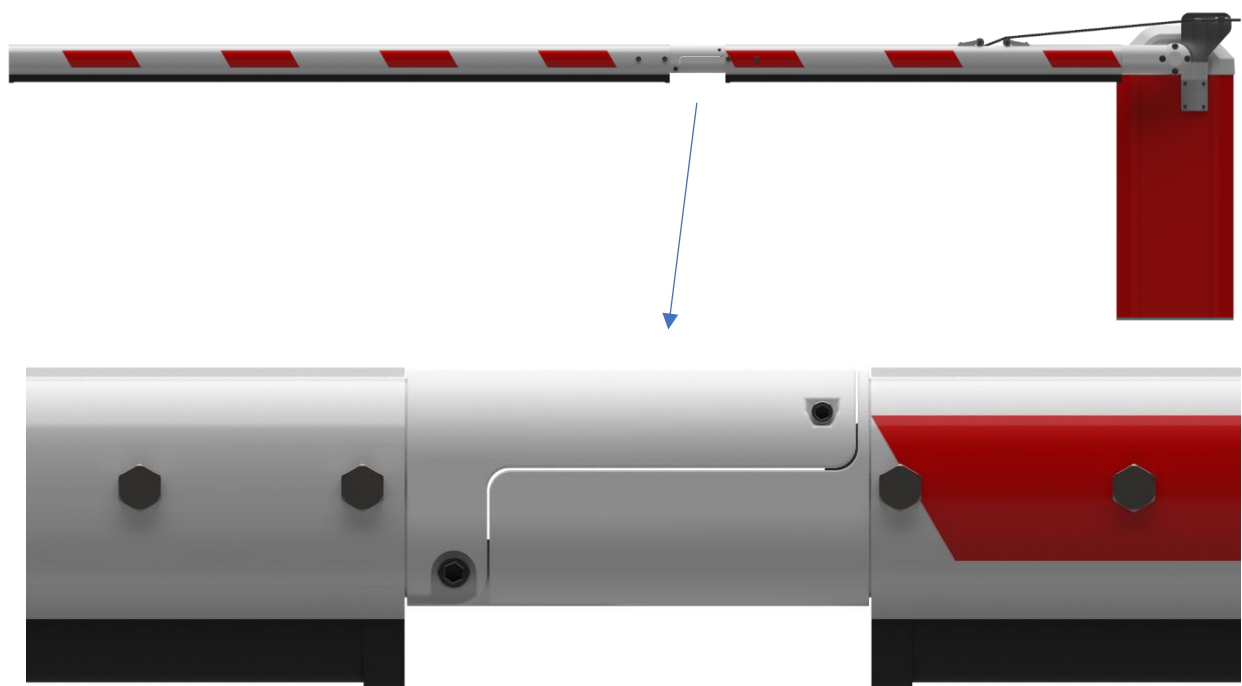


Figure 87 - Barrier with white powder-coated cast components.



Figure 88 - Final concept

14.6 Visualisation



Figure 89 - Barrier in context – closed.



Figure 90 - Barrier in context - open.

14.7 Bill of Materials

A bill of materials was created for the final concept. The costs for aluminium and steel were taken from index mundi and Focus Economics respectively and the volumes of all parts were found using the assembly file in NX 12.0.

Bill of Materials

Part	Quantity	Raw Material	Cost (£)
HInge - 2nd half	1	Aluminium	2.22
Hinge - 1st half	1	Aluminium	1.99
First beam	1	Aluminium	6.90
Second beam	1	Aluminium	11.57
Pulley	1	Aluminium	0.93
Chain	1	N/A	12.41
Entry point pulley bracket	2	Aluminium	0.10
Entry point pulley	2	Aluminium	0.09
6800 Bearing	4	N/A	2.29
Chain block	1	Steel	0.05
Chain anchor	1	Steel	0.09
Base plate	1	Steel	2.80
Base floor	1	Aluminium	4.41
Base structural rod	8	Steel	4.30
Base side panel	2	Aluminium	17.02
Base back panel	1	Aluminium	5.44
Base door panel	1	Aluminium	12.25
Base top plate	1	Aluminium	4.29
Base bearing plate	1	Aluminium	0.78
Pivot shaft	1	Aluminium	1.45
Shaft plate	1	Aluminium	0.71
Shoulder	1	Aluminium	11.83
Chain cover	1	Nylon	6.00
Motor	1	N/A	90.03
Gearbox	1	N/A	53.50
M12	4	N/A	0.77
M10	1	N/A	0.28
M8	5	N/A	0.40
M6	4	N/A	0.18
M12 nut	14	N/A	0.62
M10 nut	1	N/A	0.03
M8 nut	5	N/A	0.24
M6 nut	1	N/A	0.01

Overall Cost	255.98
After VAT	307.17

Table 10 - Bill of Materials Analysis [26] [27] [32] [9] [33] [28] [35] [36]

From the BOM analysis shown in Table 10, it was found that as an estimate, the barrier could be sold for £634.99 to achieve a profit margin of 30% for each individual barrier sold after VAT, this would mean that the barrier is similarly priced to the current design at 629.76, these prices being similar is satisfactory, though if the new barrier design is deemed more marketable, a price increase could be justified to increase profit margins further.

Raw Material Data

Material	cost per kg (£)	Density kg/m ³
Aluminium	1.73	2710
Steel	0.62	7850

Costings

Estimated Annual Sales	600
Weekly Sales	12
BOM cost (£)	307.17
Safety Factor	5%
BOM With Safety Factor (£)	322.53
Incoming Freight	8%
Duty Rate	2.5%
Engineer Weekly Salary (£)	576.92
Overhead £/week	1,000
Overall Cost of a Barrier (£)	488.45
Desired Profit Margin	30%
Price of Barrier Required (£)	634.99

15 Project and PDS Refinement

The PDS is intended as a guide for the product as well as a tool to determine how accurately the final product meets the needs of both phase 1 and phase 2 customers. However, as the project progresses, more knowledge is gained about the needs and preferences of PFL and the concept that has been selected. It becomes necessary to update the PDS to become more aligned with what needs to be achieved by the current design. Table 11 - PDS , outlines the changes to the initial PDS that have been made.

PDS	Specification	Ranking	Comments
Aesthetics			
1	The barrier should be more aesthetic than its predecessor.	Secondary → Primary	Through further talks with PFL, it has been identified that aesthetics is part of their key objectives for this project.
Company Constraints			
3b	The barrier should use the same company for outsourced parts where possible or provide justification as to the change.	Primary	More parts have been identified as outsourced than initially thought; therefore, PDS 3b was created to minimise logistical challenges; utilising the same companies for any new parts should be done unless a valid justification has been done.
Cost			
5	The barrier should be sold cost less than £500 to manufacture.	Primary	Due to fact that this design adds new features, simply selling it for the same price as the current barrier would not allow for value-adding features, therefore PDS 5 has been changed to ensure the cost of manufacturing remains similar, therefore not altering the cost to PFL.
Installation			
8	The barrier should complete all required tests after installation .	Secondary	Due to the understanding that PFL has no control over the engineers that install the barriers, it has been changed to pass all required tests that would be before the barrier leaves the factory.
Legal/Statutory/ Patents			
16	The barrier must not infringe on any existing patents. The barrier must not infringe on any existing barriers that have been identified through the competitor research.	Constraint	PDS 1.6 has been changed as it has been decided that it is almost impossible to find out if a patent has been infringed without the expertise of a patent lawyer, which has been deemed outside the budget of this project. However, ensuring the design of our barrier doesn't resemble any existing one is the closest we can come to achieving this PDS.

Life in Service/Maintenance			
17	The barrier must have a service life to match the standard current barrier (3 years).	Constraint	After a conversation with PFL, they have specified that the barrier must now last at least 3 years before reaching its end of life.
Manufacture			
21	The barrier must be manufactured and assembled by PFL faster than its predecessor after an order has been placed (10 seconds).	Primary	After testing, we have concluded the current barrier takes approximately x seconds to assemble. However, due to the identification of a number of outsourced parts in the original design as well as batch manufacturing to cut lead time, the specification has been focused on only including any manufacturing and assembly done by PFL after an order has been placed.
22	Fiddly assembly steps should be eliminated.	Secondary	
Quality and Reliability			
25	The barrier’s arm should be inaudible by the driver.	Tertiary	This specification has been changed to only include the notice sourcing from the articulating arm, as the barrier housing is outside the scope of the project.
26	The barrier beams mustn’t sag under normal use. (less than 10°)	Secondary	A drop of 5° has been deemed significant enough for a user to assume there is a manufacturing fault with the barrier.

Table 11 - PDS Refinement

Reflection: The following changes will ensure that the barrier can be more accurately assessed at the end of the project. This includes all the changes and new information that has been obtained through PFL since the initial PDS was created. This should allow for a better justification of the design during the evaluation state of the project.

16 Design Evaluation

16.1 PDS Evaluation

At the end of the project the PDS was used to ensure that the group had met all of the targets that had been set at the start of the project. Each individual specification was scrutinised to see if there have been any gaps in the design, and a table was made to show the outcome, with green meaning that the objective/constraint has been met, red meaning that it has not been met and yellow meaning that it is undetermined.

PDS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Ranking	P	T	P	S	P	S	S	S	C	C	C	C	C	C	C	C	C
Evaluation																	

PDS	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Ranking	C	T	T	P	S	P	S	T	S	S	C	C	C	T	C
Evaluation															

Table 12 - PDS Evaluation

An Evaluation of the Refined PDS was done to verify that the specifications have been met. From this, some of the specifications are noted as not being completely achieved and these cases thus required further evaluation. Almost all the points were met, with the small number in yellow being considered undeterminable at this stage.

As can be seen in Table 12, almost all targets have been achieved, with every constraint being met. Naturally, the aesthetics specifications are a highly subjective matter, especially with regards to which barrier looks better. Nevertheless, the proposed solution achieves objectives 1 and 2 through several features. By making the hinges fit within the arms, the size of the silhouette of the barrier are reduced through the introduction of continuity between the arms and hinges. For the company constraints section, the barrier was designed with consideration to the manufacturing facilities of the company. The barrier is designed to maximise the number of parts that can be made in-house or sourced from an existing PFL supplier. Only the supporting chain requires purchasing from a new supplier. Additionally, the assembly of the barrier does not require specialist tools (3)(4). The performance of the barrier prototype in testing was very successful, with it being able to open in less than ten seconds (23), while maintaining a very similar audio profile in operation to the original design (with most of the noise coming from the motor) (25). The outer arm of the barrier did not sag close to the 10° upper target (26).

Specification 19 states the barrier should be easy to clean, but the group was not able to say beyond doubt that this would be true, given the unplanned (but significant) differences between the proposed solution and the manufactured prototype rendering any attempt of testing this void. Though releasing the chain at the base to clean the inside would not be hard, without the evidence of testing this section was left as undetermined. To confirm that this specification is met a test would be recommended where the two barriers are cleaned whilst being timed using the same cleaning equipment and by the same tester, if the group’s barrier is cleaned in less time, then it can be said that this specification has been met.

Overall, the design met almost all objectives, with the one specification not met being due to time constraints or inability to prove that it had been achieved beyond doubt. Therefore we can consider the design a success and one that should meet all PFL’s requirements.

16.2 Competitor Evaluation

The previous section ‘Competitor analysis’ concluded that PFL focuses heavily on short lead times. Therefore, during the development of this solution, there was a strong focus on maintaining this competitive advantage. This could be achieved by using standardised parts, as well as developing parts that can be premanufactured and fit to a barrier of any length when ordered. Almost every part of the design has been made to fit any barrier length, with the only exception being the chain. However, if a large quantity of chain is bought and kept in stock, cutting a section of chain off to length is relatively easy. This allows for all parts to be kept in stock, and when there is an order with specific beam lengths, no additional manufacturing is required, therefore minimising lead times, and maintaining PFL’s competitive advantage over competitors (see section Competitor analysis).

The two most similar articulated arms on the market, are Magnetic’s and Elka’s articulated barrier. These barriers can act as a good benchmark for competitor solutions.



Figure 91 – An image of Magnetic’s articulated arm barrier [19].

It can be seen Magnetics solution has a linkage arm underneath the main beam. According to PFL, this is considered less aesthetically pleasing compared to our internal solution. Furthermore, with a max lane width of 3.5m [19], the proposed solution has a much longer lane width of 6m. This increases the target market to extreme case scenarios. However, while the team was unable to get the recommended maintenance for magnetic barrier, the lack of a chain (and therefore chain lubrication and replacement) implies magnetics solution has less maintenance and a longer life cycle.

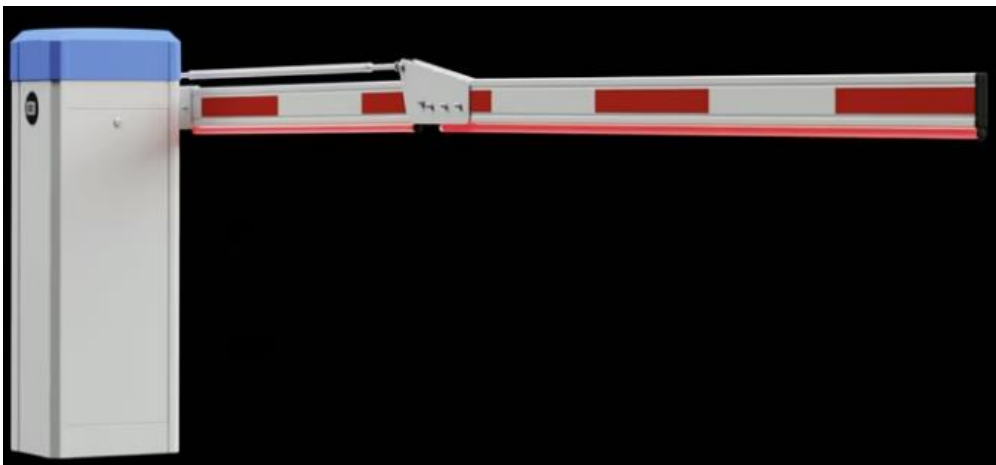


Figure 92 – Elka’s articulated arm barrier [20].

Elka's articulated arm barrier has an external linkage arm and a maximum length of 4m [20]. Compared to Magnetics solution (see Figure 92) the linkage arm is much closer to, and parallel to the main beam. This arguably gives it a more aesthetically pleasing look. However, the linkage arm is above the beam, and because of this, could be considered less aesthetically pleasing. However, compared to the proposed solution with no external linkage arm, the proposed solution is more aesthetically pleasing and with a wider lane width. However, this solution shared the same advantages of maintenance requirements and life cycle over the proposed solution.



Figure 93 – image of Skidata's articulated arm barrier [21].

Unlike the other primary competitors, Skidata's solution has no external parts. As previously mentioned, this is highly desirable as PFL determine it to be aesthetically pleasing, and therefore, Skidata's solution is more aesthetically pleasing than the proposed solution. However, Skidata's solution has a maximum lane width of 2.9m, which is significantly shorter than the proposed solution's 6m.

Although other solutions are more preferable in terms of ease of maintenance or aesthetics, there are no other companies supplying articulated arm barriers of 6m. Furthermore, no companies can provide a solution without an external linkage arm over 2.9m. This gives the proposed solution a unique selling point of a wide lane width while being more aesthetically pleasing. Considering Figure 2 in section 6.2, this unique solution moves PFL upwards, increasing the product innovation, with innovation in aesthetically pleasing and extra wide articulated arm barriers.

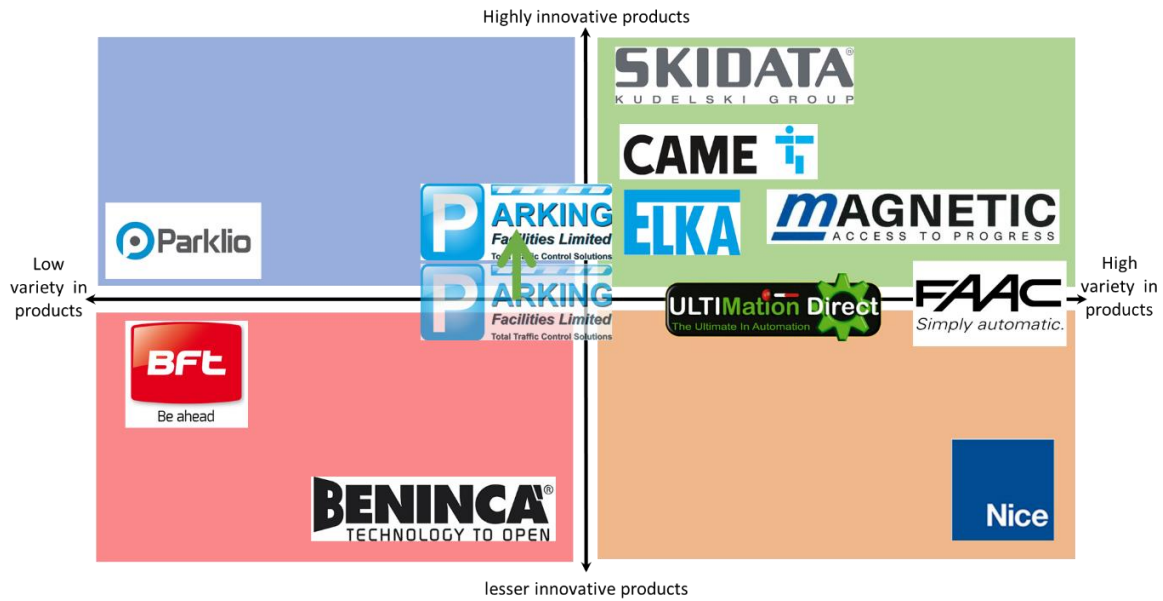


Figure 94 - Diagram showing how the new articulated arm solution changes PFL’s relative position to competitor companies, compared in innovative products and variety of products.

16.3 Safety Evaluation

The design has been checked against all the safety standards listed in the PDS and is deemed to have passed each. This is due to the fact that the main operations of the barrier have remained unchanged from the original PFL barrier, such as the safety edge, electronics used, drive forces exerted etc. From a safety standpoint, there are only two changes to the barrier that need to be recertified. The first is the open entryway, which presents a potential hazard to people who stick their finger in the hole. The second is the hinge itself and what happens to it when it fails and what force does it exert upon impact.

16.3.1 Trapping

BSI EN 12445:2000 point 4.4.2 Trapping, specifies that when it is not possible to decouple the drive from the door leaf or by actuation of the drive by an easily accessible means, the hazard of trapping is correctly specified in the installation and user manual [22]. Therefore, PFL will need to ensure they add specifications to their installation and user manual to alert the person installing the barrier of this hazard. Once the cover has been installed the trapping potential of the barrier is removed. Should this be done, then it will have been deemed safe by this standard.

16.3.2 Hinge Impact

BSI EN 12445:2000 point 5.2.5 Barriers specifies the point of measurement for an articulating barrier to test it’s maximum force output [22]. The standard states “The force shall be measured 200mm from the end of the arm, and at a maximum height of 2. Above the ground, and at an angel with the horizontal of maximum 45°, see Figure 95 - Diagram of Force Measurement Point on Articulating Barrier.

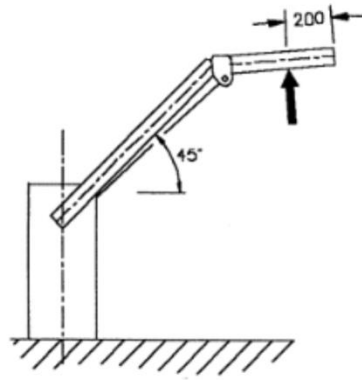


Figure 95 - Diagram of Force Measurement Point on Articulating Barrier

BSI EN 12453:2017 point A.2.1 specifies the maximum allowable impact force between closing edges and counter-closing edges is 400N [22]. Through experiments, we found assuming the maximum length beam of 4.5 meters (totalling a 6m barrier length), the maximum force reached at this point was 12.35 ± 0.3 N. therefore the barrier is not capable of exerting a force close to the maximum.

16.3.3 Hinge Failure

BSI EN 12453:2017 Annex E specifies that when safeguarding against dropping, the following is an acceptable solution: “The failed component is clearly visible, or further use of the door is automatically prohibited, at the latest when the door has reached its lower terminal position” [14] this in combination with point 5.5.4 of the same specification states that upon failure resulting in a falling or ejected parts or uncontrolled movement, so long as it’s clearly visible that the component has failed that it has been safe. Therefore, if our hinge was to failed resulting in the barrier falling, it would be deemed safe as it would be clearly visible due to the angle of the barrier.

16.4 PFL Barrier Evaluation and Comparison

16.4.1 Lead Time

It was critical for the design that its complexity would not jeopardise the current selling point of short lead times. The two designs have a lot of similarities in how they would be manufactured. The base housing and shoulder were unchanged and therefore there would be no change in lead time for those components. The arms were also kept the same except for the introduction of an additional process to cut the opening in the first arm to allow the chain to enter. This process should not take more than ten minutes to complete by the use of a router machine. Additionally, the shoulder extension that is used to connect the linkage arm in the current design was developed to form the base for the chain attachment and should not take any longer than the current attachment.

The components that would be added into the manufacturing process are the following with estimation of time to complete taken from ether our experience in the workshop manufacturing them or from primary research with:

- Both Hinge parts – These will both be sand cast in the same process as the cast shoulder; therefore, these will be manufactured off site.

- Chain pulley and entrance pulleys – These parts can be machined from aluminium using a CNC lathe and should take no longer than thirty minutes to complete. The bearing will be added afterwards, which would take a handful of minutes. These can be mass produced.
- Leaf chain – The chain is the most complex component and therefore will have to be sourced off site. For the prototype the chain was sourced from FB Chain Ltd, a company within the UK which will have a shorter delivery time than the extrudes which are currently sourced from overseas.
- Chain block and anchor – Both components are capable of being machined onsite with CNC machining, they can be batch manufactured and be stored in bulk to be available as an order is placed. Alternatively, they can be bought in bulk from the same company that may supply the chains.
- Entry Point brackets – These components can be made using laser or water jet cutting sheet stainless steel, bending to shape.

All the components that are needed to assemble the new barrier design are capable of being mass produced and stored thus not contributing to lead time at all. The main factor in lead time will be that once an order is placed with the requested dimensions, the arm extrudes, and the chain will need to be cut to the required shape. The process of figuring out the required length of the chain will not be complicated, simply needing to be put into a model to output the length to ensure that the barrier opens without drooping. Once the length is obtained, cutting the chain is a simple job that should not take more than 5 minutes for one technician to do. All other aspects that contribute to lead time are kept the same as the current setup, therefore the new design should not increase lead time at all.

16.4.2 Modular Wiring

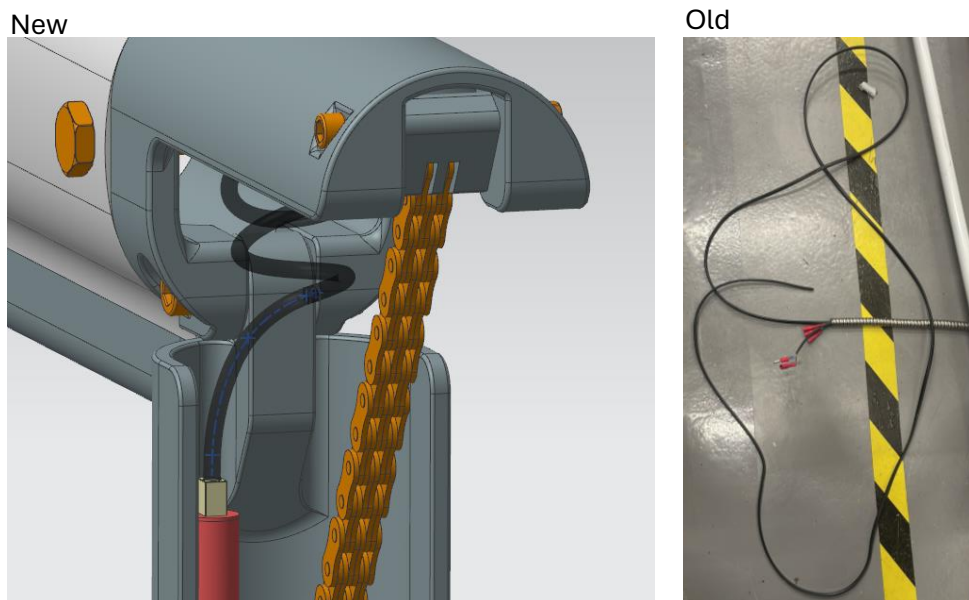


Figure 96 – A CAD model showing the new solution’s modular wiring (Left) and an image of the long wires that ran the entire length of the barrier in PFL’s solution (right)

PFL’s solution had long wires stretching the entire length of the beams. This made assembly tedious and the wires would often snap when being fed through the arms, meaning the entire cable

has to be pulled out and re-inserted. The proposed solution uses a modular wiring approach, meaning each beam can be wired separately in the factory, and once assembled on site the two beams are plugged into each other. This reduces cable lengths making assembly less fiddly, and if wires do snap, only that section has to be replaced.

16.4.3 Aesthetics



Figure 97 - A comparison of the beam aesthetics of PFL's current solution (top) and the proposed solution (Bottom)

It was determined (see section 'aesthetic research') that a beam with constant profile is more aesthetically pleasing. The hinge in the proposed solution was designed to match the beam profile, and therefore not disturb the profile. However, the chain entering the beam profile does disturb the profile to some degree. On PFL's solution the hinge reaches above the beam, disturbing the beam profile, and a linkage arm runs along the 1st beam, giving the impression one beam is larger than the other.

16.4.4 Assembly Time

As previously mentioned, the modular wiring design reduces assembly time through reducing probability of the wires snapping and allows for installation before the beam is taken to the installation site. Our design further reduces assembly time through minimising the number of tasks that must be done at the installation site. For example, the hinge is made from only 2 parts, held together by a single bolt and the hinge has a self-centring lip, meaning the hinge will land in the correct position when slid into the beam, eliminating added difficulty.

16.4.5 Noise, droopage and tensioning

PFL's design allowed for adjustment through rotating the linkage arm. This lengthens and shortens the arm, adjusting the droopage on the 2nd beam. Our design allows for tensioning in the chain through a bolt holding the leaf chain anchor. This allows for easy adjustments of up to 150mm without having to disassemble any of the barrier. For adjustment larger than 150mm the chain can be reduced in length and re-connected, also without having to disassemble the barrier.

17 Project Evaluation

17.1 Timeline Evaluation

A Gantt Chart was used to forecast the work scheduled over the planned time of the project. It allows good visualisation of the project allowing the owner the ability to schedule work based on the number of people available, and the length of the task. Archie as project manager was responsible for creating the Gantt Chart and keeping it updated as the project progressed.

A buffer zone is a period of time in the Gantt Chart where other non-essential tasks are scheduled. These tasks can always be completed at a later time in the project should the essential tasks before it run over. This was a great way for the team to stay on schedule when unexpected delays appear. The buffer zones can also be used to better optimise the team’s utilisation to ensure that everyone has a task to do. The second thing is a backup plan, this is essential when other when something goes wrong in the project that is results in the essential tasks to be delayed beyond the buffer zone. Over the course of the project, both tactics were implemented and required. Both a projected Gantt chart and the final Gantt chart (after the projects completion) can be seen in the appendix 22.13 and 22.12.

An example of where the buffer zones where used, was early in the concept development stage. In each section of the Gantt Chart, there is a Write Up task at the end, for example in Figure 98 - Gantt Chart Example 1. Should all the previous activities be completed on time, any member of the team not completing a task will be given the task of writing up the progress of the entire section. This is beneficial for a number of reasons, it can be used as a resource when later writing this report up, and it also allows for a more comprehensive resource as the activities are fresh in the person’s mind. During the concept development stage, the team decided that they were not completely happy entering the prototyping stage with the current design and elected to spend more time developing the concept. The concept development writeup stage was therefore postponed until later in the project allowing an extra two weeks to be allocated to further concept development. This resulted in a better design being carried forth into the prototyping as well as the team staying on time with deliverables having started prototyping at the intended time.

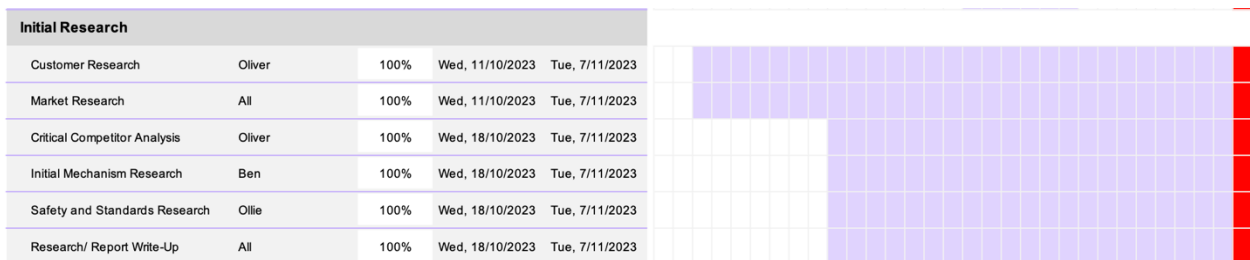


Figure 98 - Gantt Chart Example 1

An example of a backup plan is the prototyping section. In order to test our manufactured hinge, we needed two things, a working barrier housing and the existing PFL barrier arm for which to repurpose the cross-section into our design. From early February, at the planned start time, the team sent a request to PFL to start manufacturing on an articulating arm for the team to test. They also started enquiring to Paul King about the current state of the barrier housing. Both parties reassured the team that it would be done, however after it became clear to the team that both requirements would run over the buffer zone. Therefore, the backup plan was implemented as can be seen in Figure 99 - Gantt Chart Example 2. This contained two countermeasures, the first was to start the report writing earlier than expected, this would give the two parties an extra 3 weeks to deliver. This was doable as this task could be 80% completed without the need for testing of our barrier being completed. The second countermeasure was to utilise existing parts given to the team from PFL to construct their own barrier meaning they would no longer be reliant on PFL delivering their barrier. Both counter measures proved to be a success, minimising the delay in which the project took. Both parties ended up deliver 37 days later than intended, however the counter measures meant the delay was reduced town to approximately 10 days.

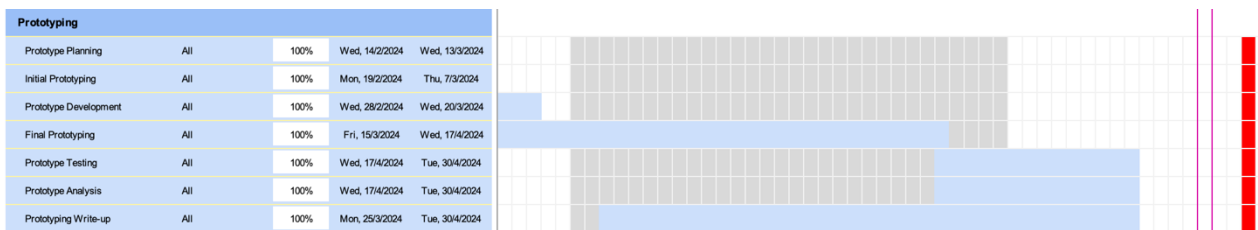


Figure 99 - Gantt Chart Example 2

Overall, the Gantt Chart was a success in helping the team remain on track. It means all deliverables were met on time to the intended quality. The only negative was the 10-day delay from prototype testing that resulted in the presentation for the viva voice being written during a later time that would have been desired.

18 Conclusion

18.1 Project Conclusion

This project aimed to improve the design of an articulating barrier for our sponsor, PFL. The barrier's key objectives were to improve the aesthetics without increasing the lead time. The team developed a design that met all of PFL's objectives while remaining within their scope.

The literary review of existing barriers and the current PFL barrier provided the foundation that was required for the barrier to be designed. The primary research obtained through PFL was vital in understanding the problem we were solving.

The creation of customer needs and a PDS allowed for an effective understanding of the product requirements. They were also used during the evaluation state to determine the success of the project.

Ideation of a vast range of initial ideas, along with the use of a Pugh Matrix as an effective selection method, allowed the identification of an idea that aligned with the projects brief.

The concept was developed using a wide range of analytical and computer-simulated techniques. This was used to ensure that each opportunity was explored and that the design remained on track to be successful in later validation stages.

Prototyping one scale and one full-size model allowed for further development that could have only been identified through this process. Crucial problems were identified in the process, and improvements, such as the entry point, were suggested. The prototypes were also used later in the project to communicate the design.

Manufacturing, materials, and cost considerations were researched and evaluated to ensure the barrier could be integrated into PFL's product line. The costings were also used to justify design choices.

The evaluation of the design justifies the changes made to the original PFL barrier. The design meets most of the PDS points, but some further work is identified.

Key Successes of the project:

- Creation of a detailed barrier design that was thoroughly developed and well-resolved.
- Comprehensive calculations and FEA computer simulations were used to successfully validate design choices.
- The creation of a highly detailed CAD model was used to visualise and develop the design.
- The fabrication of two complete prototypes that validated our calculations was used to test specific objectives.

The success of the project proves that the team is capable of designing and developing a novel and complex product with mechanical, aesthetic and user requirements all considered.

Implications to the wider society:

- This project will provide a good foundation for PFL if they decide to continue developing it into their product line.

Overall, the project has produced a new articulating barrier design that is aesthetically pleasing and doesn't increase lead time for PFL. Through clever thinking and extensive calculation, this design has achieved what the project had aimed to do.

18.2 Individual Conclusions

18.2.1 Archie Buxton

Overall, I think the project was a huge success. The team managed to create a design that was both innovative and had all the calculations and computer simulations to back it up. We then created a full-scale prototype, which successfully demonstrated the effectiveness of the design. I'm happy with the detail that has been put into this design with time taken in the ideation phase all the way through to detailed work done by Oliver Squires in the CAD visualisation to help show our design. What I consider the project's greatest accomplishment was the detailed calculations led by Oliver Spencer and the rest of the team, being translated into a fully functional full-scale prototype which matched Oliver Spencer's calculations, thus showcasing the team's skill on the theoretical side as well as the physical fabrication side. This team was very good and keeping the driving going throughout which meant that the project always remained on track and never got behind. One thing that I felt could have been better was the communication with our sponsor PFL. As had, this had been better, I feel even more detail could have gone into ensuring the product was easier for them to adopt at the end.

Personally, I felt I played the role of team leader well. I've been impressed with how well we have all worked as a team. Nothing was ever taken personally, and conflicts were always discussed sensibly as a team. Communication was excellent with team meetings and online chat. Every member of the group contributed strongly and took advantage of the strengths and weaknesses of each other. Group meetings were always concise, with actions for the next meeting, meaning no time was ever wasted. Everyone also contributed to the project well, with nobody feeling left out or slacking at any time; this also resulted in great utilisation of the group.

18.2.2 Oliver Spencer

Throughout this project, I have been repeatedly impressed by how the team has maintained good communication and discussed conflicts thoroughly and responsibly. The team consistently reacted to unexpected obstacles, demonstrating flexibility and resilience. The team would have benefited from more consistent communication with PFL, which would minimise confusion. However, the team consistently took the initiative when necessary and overcame these challenges effectively.

While no official roles were delegated, the team members naturally took positions depending on the individuals' experience, and tasks were delegated to leverage team members' strengths and optimise team performance. For example, Archie's managerial and leadership skills naturally lead him to a team leader role, while Oliver Squires' strengths in CAD lead him to oversee the models and assemblies. All deadlines were met in a timely fashion with high-quality work.

My most significant contribution to the project is the hand calculations relating hinge dimensions to the movement and droopage of the beam. This allowed for design optimisation, proving the solution was of high quality and thoroughly thought through. In my opinion, the team's greatest achievement was manufacturing the prototype to such high quality, confidently proving the effectiveness of the proposed solution. A great team effort was put into manufacturing the prototype promptly, and the outcome was essential to the project.

Overall, the team created a robust and complete solution, arguably achieving shorter lead times, shorter assembly times and a better barrier aesthetic. With more time and a larger budget, I believe the team could take this project to a fully functioning product that could be sold to customers by PFL.

18.2.3 Lawrence Price

I think the project has gone very well and I feel that everyone has developed as engineering professionals. The team had regular meetings, both in person and online, with every member of the team making contributions and being involved discussions. We maintained a strong work ethic throughout the process and effectively navigated the hiccups that we experienced, including designing and manufacturing a whole new hinge for the prototype. The fact we were able to produce a working prototype, despite limitations stands as a testament to our teamworking, and the individual contributions made.

I provided significant contributions to numerical analysis throughout the project. I began by performing basic hand calculations to justify that a partially internalised cable design would be feasible to take forward. Once the idea had been selected by the group to take forward, I then calculated the minimum thickness the hinge would need to have a suitable fatigue life. As the design matured throughout the development stage, I progressed to more rigorous analyses for the individual components. I performed finite element simulations which identified areas that needed improvement, which supported the group's efforts to refine the design into its final version.

Towards the beginning of the FEA stage, I overcomplicated the problem, which resulted in an inefficient use of time. Had I been more efficient in the beginning, I could have helped other members of the group by becoming more involved in other aspects of the project. Nevertheless, once I simplified the analysis methods, I was able to gain invaluable knowledge on the performance of the critical components of the design.

18.2.4 Oliver Squires

Overall, I am happy with how our team worked together to deliver a successful prototype and a developed concept for PFL. Communication was good and allowed for our work on different aspects of the project to run cohesively as we developed the solution.

I felt that I contributed significantly throughout the project. I took the lead for developing our solution into the final CAD models for both our prototype and proposed solution. I was on hand in the workshops to help ensure that we could bring our prototype visions to reality and adapt our design to overcome the challenges that we faced.

I am happy with my team members contributions. Archie stepped up and took the lead in project management, especially at the start of the project when our project direction was not as clear. The work done by the mechanical engineers was crucial in ensuring that our designs were functional, and communication between myself and them, meant that our designs were guided by FEA and engineering theory.

18.2.5 Ben McPherson

I believe the project to be a success in that we were able to design a barrier that PFL could take and move forward with, and the prototype validated that the design worked. The team overall worked brilliantly together, and I am thankful for the team that I have been given. They were all hard working and kept each other to a high standard with regular meetings and communication to ensure everyone was up to date and there were very few lulls in the year where the foot was taken of the pedal. In the concept generation stage, everyone was putting their ideas in the mix, and this meant that the final concept was one that it felt we had all been involved in creating.

For my part I had a hand in the calculations in the stage of design development to figure out the barrier's feasibility, I then took over the role of creating the cost function analysis for the prototype and the BOM of the finished design, I also devoted time to the prototype's manufacture and assembly,

followed by helping to test the two barriers. Overall, I am fairly happy with my performance in the project though there were many times where I felt that I was struggling to keep up with the hard work of my peers and ended up not having as much input as I would've liked to have had, nonetheless the project was a very good and challenging experience that I view as a success.

19 Future Work

If PFL decides to adopt the solution proposed in this report, there are several areas which would require addressing first, to ensure the product could maximise its potential and be competitive in the market. Three main areas for further work are identified, with recommended actions outlined.

19.1 Steps to take Final Design Through to Construction

As discussed in 8.8.1 Final Hinge FEA the design for hinge B would benefit from further investigations surrounding stress relief and/or the use of cost-effective alloys. The component is under significant load, with only the small pin to support it.

In order for the hinges to be sand cast, the mould cavities would need to be manufactured. PFL currently use an off-site supplier to carry out sand casting for their current barriers. Therefore, it would need to be confirmed that this supplier could also be used for sand casting the hinges. If this would not be possible, an alternative company would need to be found.

G-code files would need to be created for all of the components that would be machined. It would be ideal if these codes were compatible with the tooling configurations for the Hurico 4-axis CNC machines used by PFL.

Finally, it would need to be confirmed that all of the screws, bolts and other small fastening components could be sourced.

With all these steps addressed, the barrier could begin manufacture.

19.2 Redesign of the Barrier Housing Design

One of the main limitations in the project scope was that PFL did not want the design of the barrier housing and cast shoulder to be modified. As the concept development progressed, it became clear that this hindered the proposed solution from fully realising its potential. The design of the open entry point for the chain was a compromise which allowed cable to still run internally for much of the arm, while still significantly reducing the visual profile of the hinge. However, the fact that the cable is still visible negatively impacts the aesthetics of the design, and this is not helped by the need for a visible fastening plate at the base housing.

Were this design to be taken further, it is highly recommended that the base housing be modified to allow for a fully internal cable. A proposed solution would see the adapter and cast shoulder modified to provide space for a chain sprocket Figure 100. This would internalise the chain fastening by removing the need for a sheet that sticks out from the housing, and hide unsightly mechanical components from view. A light cover (potentially made from thin aluminium) would be placed over the cast shoulder and sprocket and would rotate with the arm, while the sprocket would be fixed. The cover could be cylindrical for a good visual profile and painted to not stick out from the rest of the housing. Calculations would be needed to determine the size needed for the sprocket – and as such the size of the cover, which may require the base housing to be further modified.



Figure 100 - A chain sprocket - a potential method for fastening the chain to the base. [23]

19.3 Adaptation of Design for the Smaller Cross-Section

PFL provide 2 separate beam dimensions. As the team was supplied with the larger beam dimensions, that is the beam size the design was built around. However, there is a possibility that the smaller beam dimensions could be used if required or preferred by PFL.

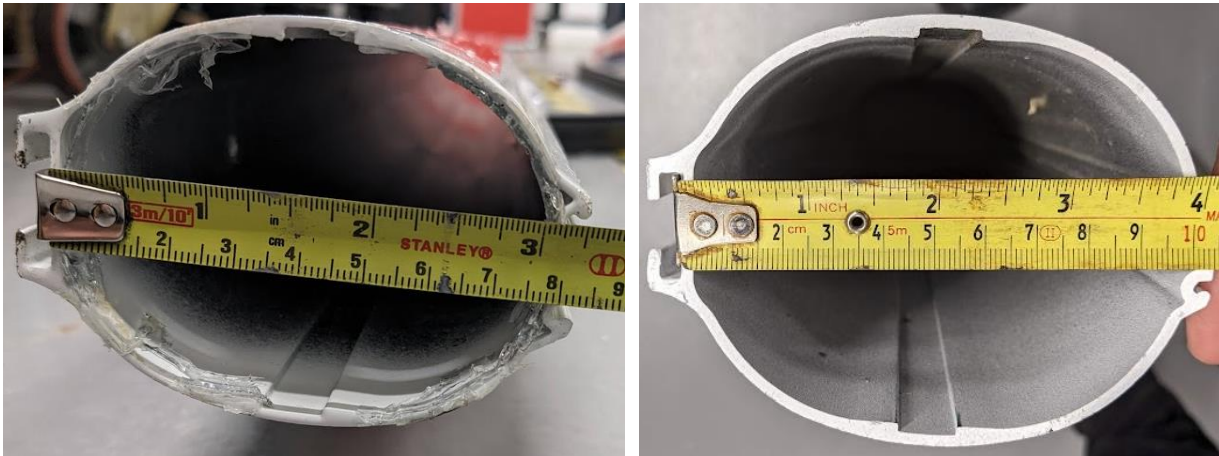


Figure 101 – An image showing the smaller beam profile (Left) and larger beam profile (Right) measured at 8 and 10 cm height respectively.

Applying the same tension calculations found in section Cable and Chain Calc for the smaller beam dimensions, it was found that the required tension for a 4m long 2nd beam and an 'x' distance of 0.15m the required tension is 730N. A 4mm diameter 17x9 stainless steel 316 cable would be required and would provide a factor of safety of 1.9. The required pulley diameter would therefore be 100mm. By scaling down our current design to fit the smaller beam dimensions, the maximum pulley diameter that would fit would be 50mm diameter. A pulley 50% of the recommended size will have adverse effects on the fatigue of the cable and is therefore not suitable. Therefore, with the smaller beam dimensions a chain would still be required.

From the chains available to purchase from 'The leaf chain specialists' with the smallest pitch (12.7mm) would require a pulley diameter of 63mm. The scaled down design would only allow for a pulley 80% of the recommended size. With the prototype on the larger beam dimensions (which was also designed to use the chain with the smallest available pitch), a pulley of size 60mm was used when a pulley diameter of 63mm was recommended. Therefore, the pulley is 95% of the recommended size and is mostly suitable.

There may be a suitable solution available using the smaller beam dimensions if further research was carried out, however, for this project the team decided to stick with the larger beam dimensions. However, it is important to note this would leave less space for the cables to pass through the hinge.

20 Acknowledgments

We would like to thank Paul King for his continued support throughout the project. He has gone above and beyond to help and guide this team, and we have learned a lot from him, both specifically to this project and generally as people.

We would also like to thank Joe Fletcher, Chris Jones and the rest of the team at PFL who sponsored this project for their advice, knowledge and support.

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22 Appendix

22.1 Refined PDS

PDS	CN	Specification	Ranking
Aesthetics			
1	1.14, 2.17	The barrier should be more aesthetic than its predecessor.	Primary
2	1.14, 2.17	Ugly joints should be hidden from the drivers view.	Tertiary
Company Constraints			
3a	1.1, 1.2, 1.3	The barrier should utilise existing company parts and processes as much as possible.	Primary
3b	1.1, 1.2, 1.3	The barrier should use the same company for outsourced parts where possible or provide justification as to the change.	Primary
4	1.9	Components must be assembled in existing company facilities.	Secondary
Cost			
5	2.17	The barrier should be sold cost less than £500 to manufacture.	Primary
6	2.4, 2.15	The barrier must be designed for easy maintenance.	Secondary
Installation			
7	1.12, 2.14	The barrier should not require any specialist tools.	Secondary
8	1.13, 2.10	The barrier should complete all required tests after installation .	Secondary
Legal/Statutory/ Patents			
9	1.4, 2.10	Comply with The Supply of Machinery Regulations.	Constraint
10	1.4, 2.10	The barrier must meet BS EN12978:2000	Constraint
11	1.4, 2.10	The barrier must meet BS EN 12453 (Safety in use, requirements)	Constraint
12	1.4, 2.10	The barrier must meet BS EN 12445 (Safety in use, test methods)	Constraint
13	1.4, 2.10	The barrier must meet BS EN 1760 (Safety edges)	Constraint
14	1.4, 2.10	The barrier must meet BS EN 12978 (Safety devices)	Constraint
15	1.4, 2.10	The barrier must meet BS EN 12604 (Mechanical aspects)	Constraint
16	1.5, 2.10	The barrier must not infringe on any existing patents. The barrier must not infringe on any existing barriers that have been identified through the competitor research.	Constraint
Life in Service/Maintenance			
17	2.4	The barrier must have a service life to match the standard current barrier (3 years).	Constraint
18	2.7, 1.12	The barrier must go at least 6 months without a service.	Constraint
19	2.16	The barrier should be easy to clean.	Tertiary

20	2.14	Should be easy to disassemble for maintenance.	Tertiary
Manufacture			
21	1.6	The barrier must be manufactured and assembled by PFL faster than its predecessor after an order has been placed (10- seconds).	Primary
22	1.10	Fiddly assembly steps should be eliminated.	Secondary
Performance			
23	2.3	Must open/close in under 10 seconds.	Primary
24	2.1	Structural factor of safety > 2.	Secondary
Quality and Reliability			
25	2.9	The barrier's arm should be inaudible by the driver.	Tertiary
26	1.14, 2.17	The barrier beams mustn't sag under normal use. (a droop of less than 10°)	Secondary
Safety			
27	2.6	The barrier should be operational under manual assistance.	Secondary
28	2.10, 2.11	The barrier must reverse its motion when its beams contact an object.	Constraint
Size/ weight			
29	1.1, 1.4	The second arm must be at least 1m long.	Constraint
30	2.2, 2.14	The barrier must have a length up to 4m.	Constraint
31	2.14	The barrier should go up to 6m in length.	Tertiary
32	2.1	The beam must be light enough for the existing motor to operate it.	Constraint

22.2 Report Contributions

Introduction	Ben
Summary of Preliminary	Ben
Synthesis of Concepts	Archie
Design Development	All
Development for Prototyping	Oliver Spencer, Oliver Squires
Prototyping	Oliver Spencer, Oliver Squires
Testing	All
Materials and Manufacturing Processes	Archie
Development Following Prototyping and Testing	Oliver Squires, Lawrence
Detailed Concept Design	Oliver Squires, Ben
Project and PDS Refinement	Archie
Design Evaluation	Ben, Archie, Oliver Spencer
Project Evaluation	Archie
Future Work	Lawrence, Oliver Spencer

22.4 Pugh Matrix 2

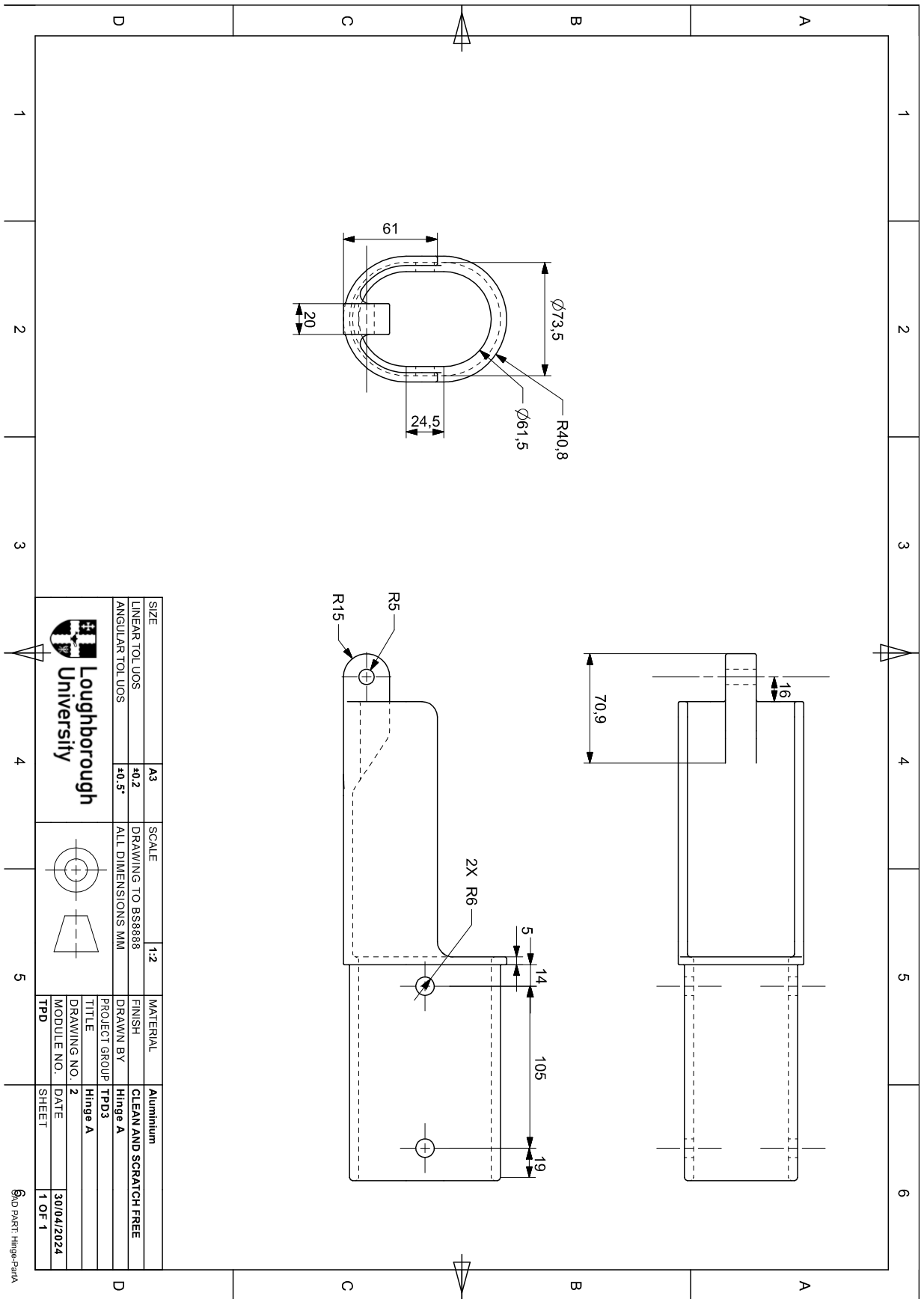
For more detail, see PughMatrix – Second Iteration.pdf.

	Current Solution	Idea 1 (Development)	Idea 2	Idea 3	Idea 4	Idea 5	Idea 6	Idea 7	Idea 8	Idea 9	Idea 10	Idea 11
Criteria												
Easy to manufacture	0	0	0	0	0	0	0	0	0	0	0	0
Low maintenance requirements	2	0	0	0	0	0	0	0	0	0	0	0
Barrier must look good	4	0	0	0	0	0	0	0	0	0	0	0
Barrier must transport easily	1	0	0	0	0	0	0	0	0	0	0	0
Weather resistance	1	0	0	0	0	0	0	0	0	0	0	0
Speed of operation	2	0	0	0	0	0	0	0	0	0	0	0
Weight/resistance	2	0	0	0	0	0	0	0	0	0	0	0
Speed of operation	2	0	0	0	0	0	0	0	0	0	0	0
Easy to adapt for a range of heights	2	0	0	0	0	0	0	0	0	0	0	0
Competitively priced	1	0	0	0	0	0	0	0	0	0	0	0
Innovation/creativity/uniqueness	2	0	0	0	0	0	0	0	0	0	0	0
Engineering science (advanced)	2	0	0	0	0	0	0	0	0	0	0	0
Net Score Ranking	2nd	1st	4	3rd	3rd	5th	5	6th	5	6th	7th	8
Weighting	5	0	0	0	0	0	0	0	0	0	0	0
Easy to manufacture	10	0	0	0	0	0	0	0	0	0	0	0
Low maintenance requirements	4	0	0	0	0	0	0	0	0	0	0	0
Barrier must look good	4	0	0	0	0	0	0	0	0	0	0	0
Barrier must transport easily	1	0	0	0	0	0	0	0	0	0	0	0
Weather resistance	1	0	0	0	0	0	0	0	0	0	0	0
Speed of operation	4	0	0	0	0	0	0	0	0	0	0	0
Weight/resistance	4	0	0	0	0	0	0	0	0	0	0	0
Speed of operation	4	0	0	0	0	0	0	0	0	0	0	0
Easy to adapt for a range of heights	4	0	0	0	0	0	0	0	0	0	0	0
Competitively priced	1	0	0	0	0	0	0	0	0	0	0	0
Innovation/creativity/uniqueness	4	0	0	0	0	0	0	0	0	0	0	0
Engineering science (advanced)	4	0	0	0	0	0	0	0	0	0	0	0
Net Score	2nd	1st	4	3rd	3rd	5th	5	6th	5	6th	7th	8

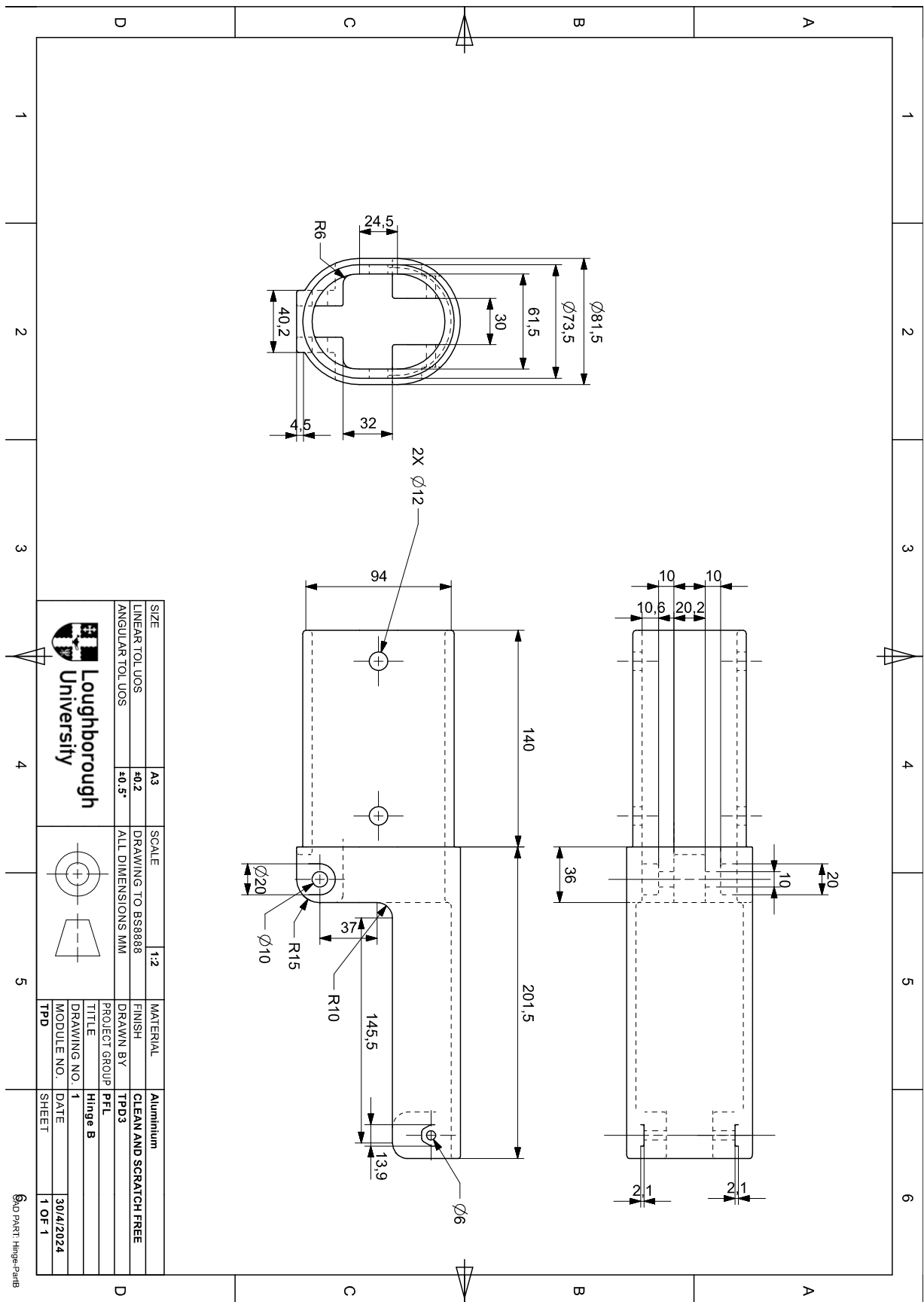
	Current Idea Baseline	Idea 1 (Development)	Idea 2	Idea 3	Idea 4 (Development)	Idea 5 (Development)	Idea 6 (Development)	Idea 7 (Development)	Idea 8 (Development)	Idea 9	Idea 10
Criteria											
Easy to manufacture	0	0	0	0	0	0	0	0	0	0	0
Low maintenance requirements	2	0	0	0	0	0	0	0	0	0	0
Barrier must look good	4	0	0	0	0	0	0	0	0	0	0
Barrier must transport easily	1	0	0	0	0	0	0	0	0	0	0
Weather resistance	1	0	0	0	0	0	0	0	0	0	0
Speed of operation	2	0	0	0	0	0	0	0	0	0	0
Weight/resistance	2	0	0	0	0	0	0	0	0	0	0
Speed of operation	2	0	0	0	0	0	0	0	0	0	0
Easy to adapt for a range of heights	2	0	0	0	0	0	0	0	0	0	0
Competitively priced	1	0	0	0	0	0	0	0	0	0	0
Innovation/creativity/uniqueness	2	0	0	0	0	0	0	0	0	0	0
Engineering science (advanced)	2	0	0	0	0	0	0	0	0	0	0
Net Score Ranking	1st	5	8	3rd	4	3	4	3	5	9	1
Weighting	0	1	5	1	10	3	10	1	5	9	1
Easy to manufacture	0	0	0	0	0	0	0	0	0	0	0
Low maintenance requirements	0	0	0	0	0	0	0	0	0	0	0
Barrier must look good	0	0	0	0	0	0	0	0	0	0	0
Barrier must transport easily	0	0	0	0	0	0	0	0	0	0	0
Weather resistance	0	0	0	0	0	0	0	0	0	0	0
Speed of operation	0	0	0	0	0	0	0	0	0	0	0
Weight/resistance	0	0	0	0	0	0	0	0	0	0	0
Speed of operation	0	0	0	0	0	0	0	0	0	0	0
Easy to adapt for a range of heights	0	0	0	0	0	0	0	0	0	0	0
Competitively priced	0	0	0	0	0	0	0	0	0	0	0
Innovation/creativity/uniqueness	0	0	0	0	0	0	0	0	0	0	0
Engineering science (advanced)	0	0	0	0	0	0	0	0	0	0	0

	Current Idea	Idea 1 (Development)	Idea 2 (Development)	Idea 3	Idea 4	Idea 5 (Development)	Idea 6 (Development)	Idea 7 (Development)	Idea 8 (Development)	Idea 9	Idea 10
Criteria											
Easy to manufacture	0	0	0	0	0	0	0	0	0	0	0
Low maintenance requirements	2	0	0	0	0	0	0	0	0	0	0
Barrier must look good	4	0	0	0	0	0	0	0	0	0	0
Barrier must transport easily	1	0	0	0	0	0	0	0	0	0	0
Weather resistance	1	0	0	0	0	0	0	0	0	0	0
Speed of operation	2	0	0	0	0	0	0	0	0	0	0
Weight/resistance	2	0	0	0	0	0	0	0	0	0	0
Speed of operation	2	0	0	0	0	0	0	0	0	0	0
Easy to adapt for a range of heights	2	0	0	0	0	0	0	0	0	0	0
Competitively priced	1	0	0	0	0	0	0	0	0	0	0
Innovation/creativity/uniqueness	2	0	0	0	0	0	0	0	0	0	0
Engineering science (advanced)	2	0	0	0	0	0	0	0	0	0	0
Net Score Ranking	1st	1	4	5	2nd	4	3rd	5	3	6	1st
Weighting	0	0	0	0	0	0	0	0	0	0	0
Easy to manufacture	0	0	0	0	0	0	0	0	0	0	0
Low maintenance requirements	0	0	0	0	0	0	0	0	0	0	0
Barrier must look good	0	0	0	0	0	0	0	0	0	0	0
Barrier must transport easily	0	0	0	0	0	0	0	0	0	0	0
Weather resistance	0	0	0	0	0	0	0	0	0	0	0
Speed of operation	0	0	0	0	0	0	0	0	0	0	0
Weight/resistance	0	0	0	0	0	0	0	0	0	0	0
Speed of operation	0	0	0	0	0	0	0	0	0	0	0
Easy to adapt for a range of heights	0	0	0	0	0	0	0	0	0	0	0
Competitively priced	0	0	0	0	0	0	0	0	0	0	0
Innovation/creativity/uniqueness	0	0	0	0	0	0	0	0	0	0	0
Engineering science (advanced)	0	0	0	0	0	0	0	0	0	0	0

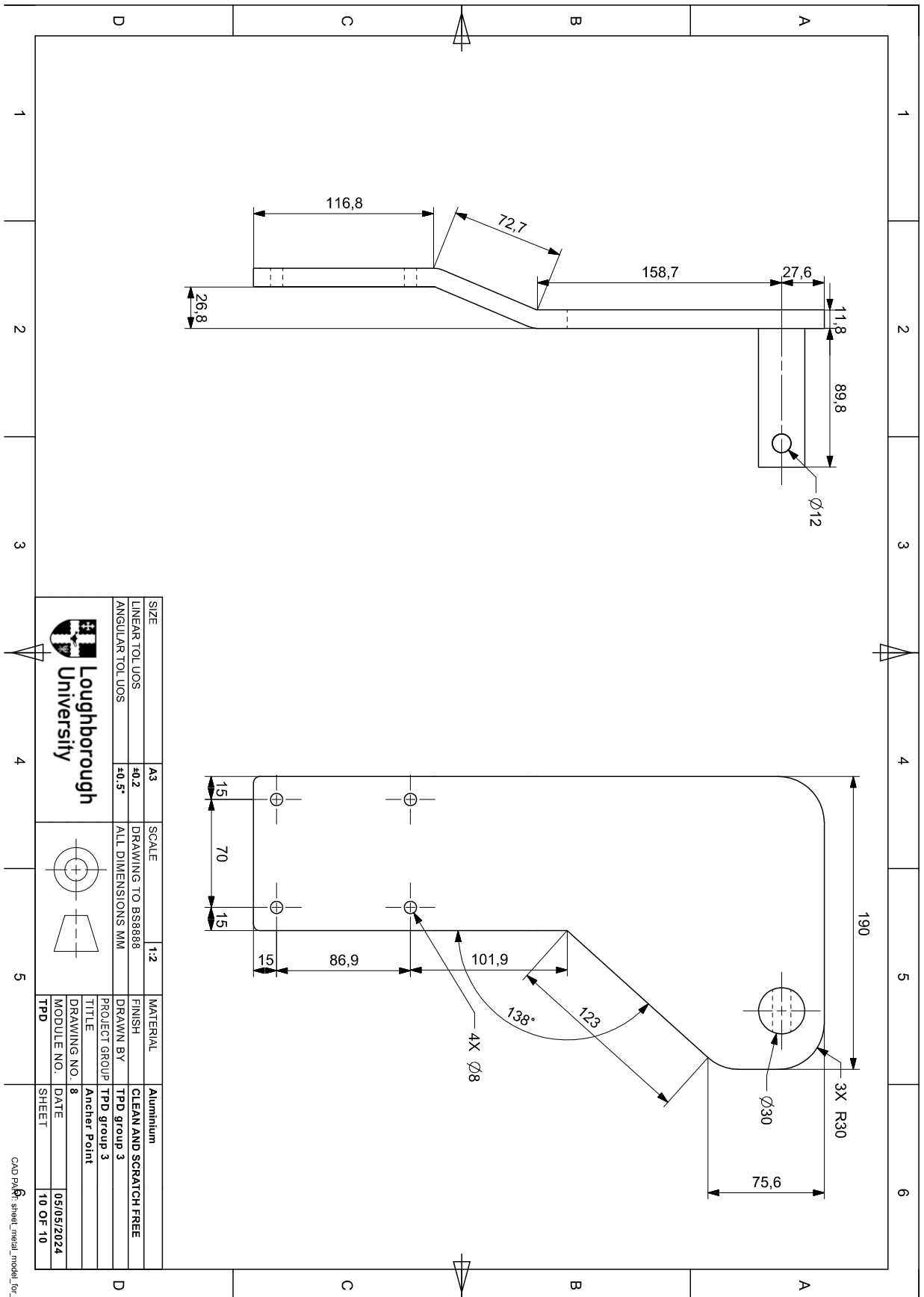
22.5 Engineering Drawing – Hinge A



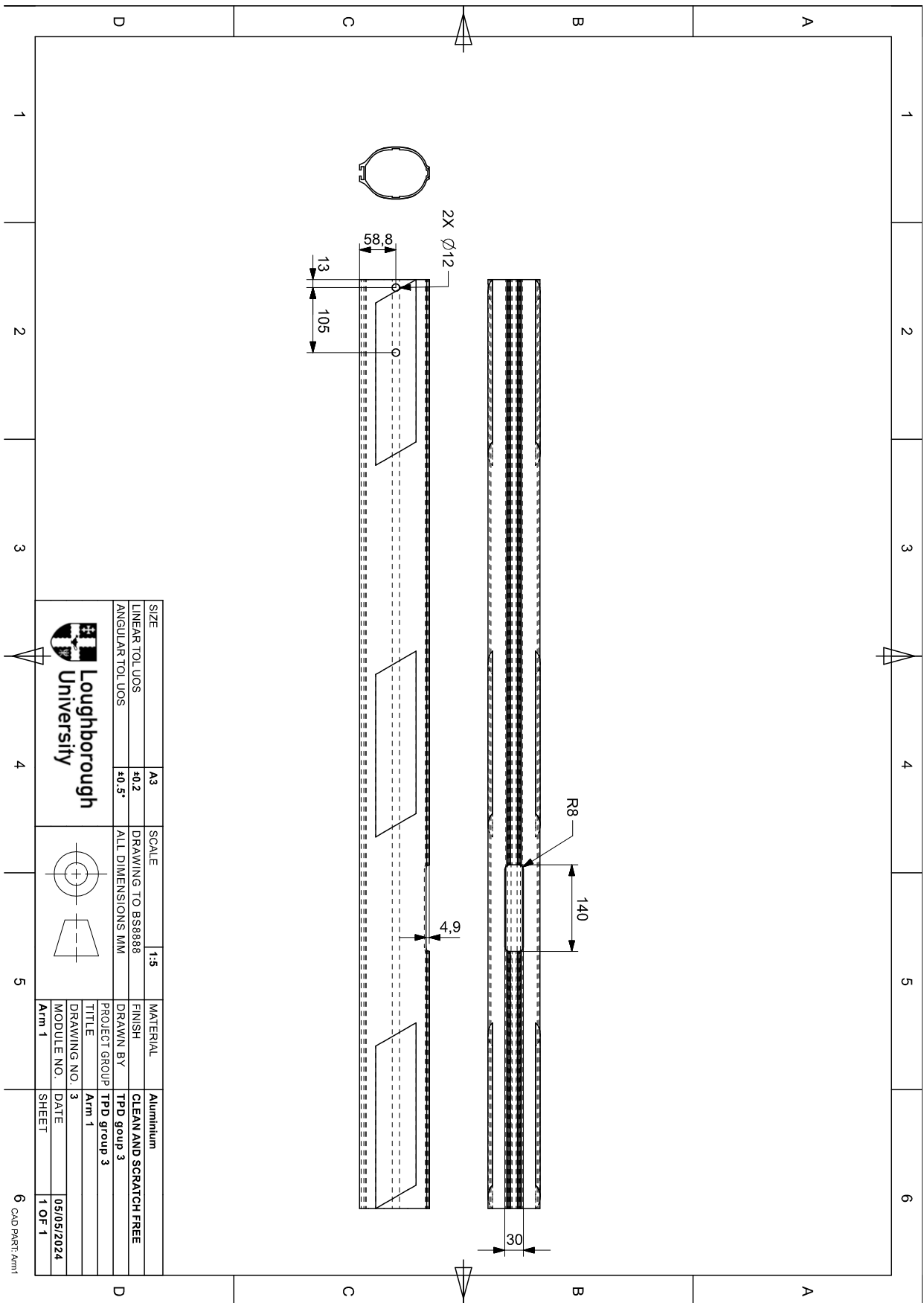
22.6 Engineering Drawing – Hinge B



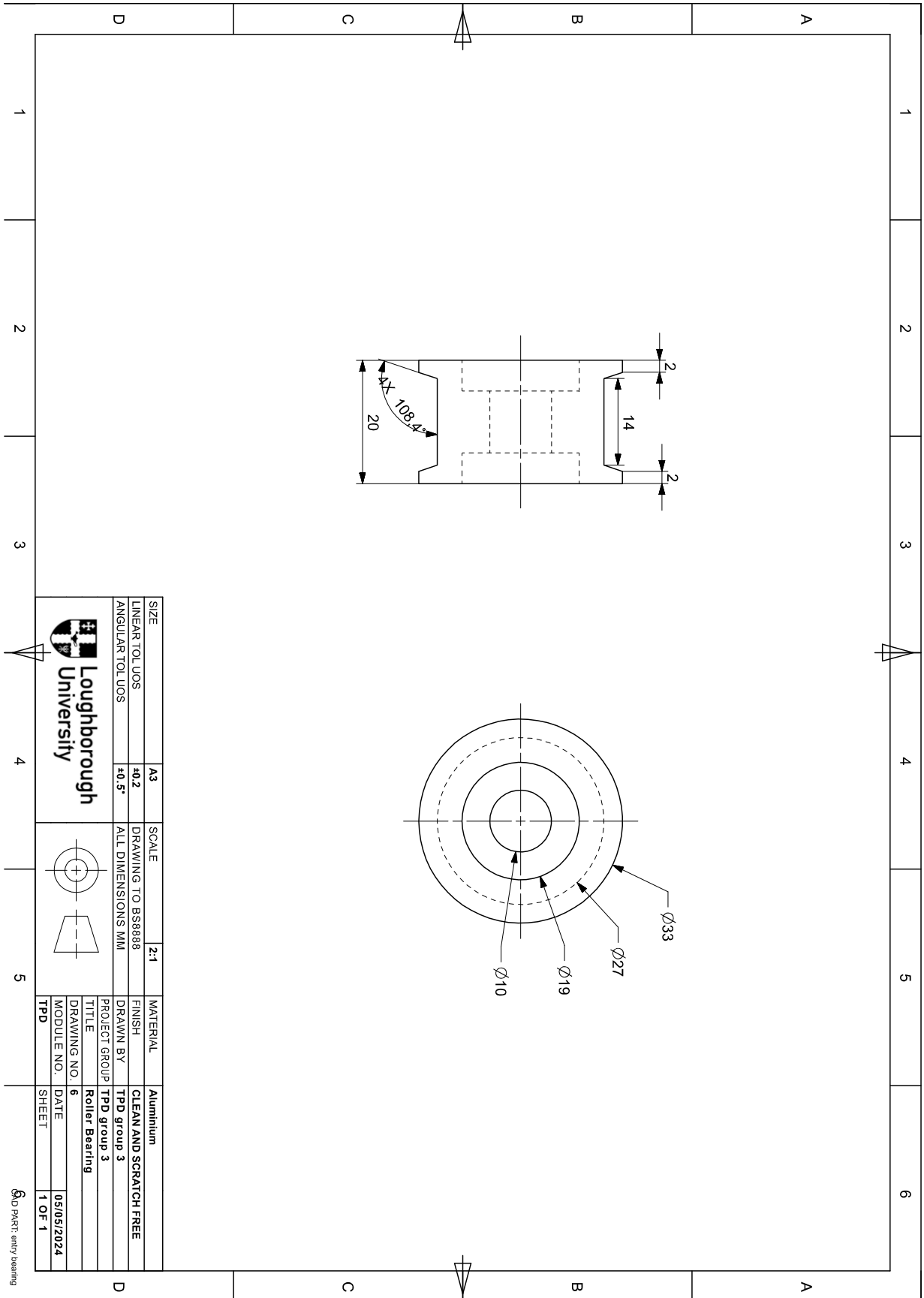
22.7 Engineering Drawing – Attachment Point



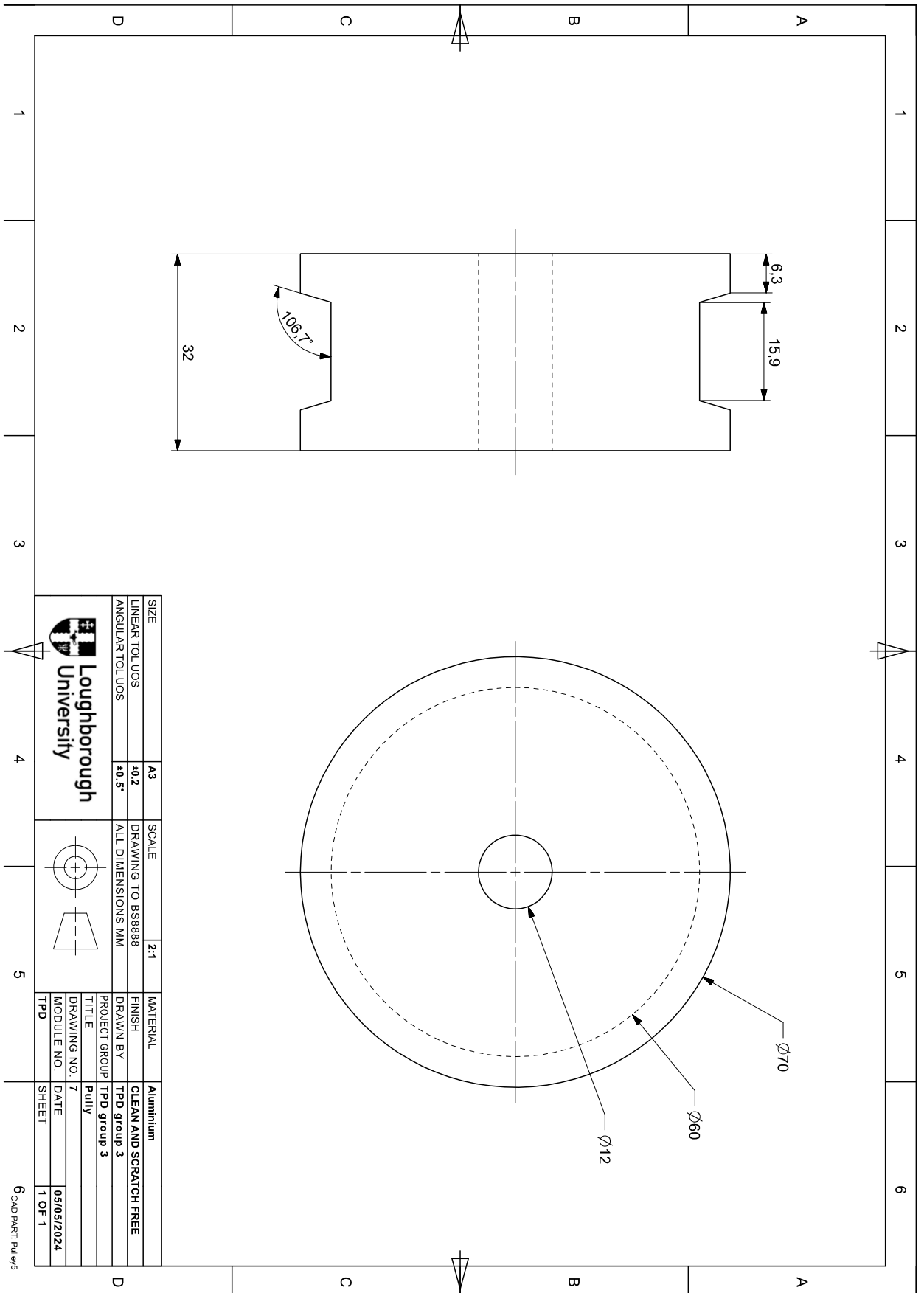
22.8 Engineering Drawing – Arm Entry Point



22.9 Engineering Drawing – Entry Way Bearings



22.10 Engineering Drawing – Pulley



22.11 Engineering Drawing – Entry Point

