FINAL REPORT

ADJUSTABIKE

OPEN SOURCE ADJUSTABLE BIKE

JAMIE TAYLOR

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UNIVERSITY OF BATH

MAJOR INDIVIDUAL DESIGN PROJECT

SUPERVISOR: JEREMY BONVOISIN

ASSESSOR: MICHAEL CARLEY

UNIVERSITY OF BATH

Department of Mechanical Engineering

1. SUMMARY

The primary aims of this report are to document the research and design tasks undertaken to achieve the project objectives to design an open source adjustable bike. The driving factors of this project are increasingly smaller living spaces, making bike storage a premium not obtainable for some, and increased concerns over climate change requiring more sustainable means of travel.

Research tasks were completed to inform the direction of the project, resulting in two project aims; designing a bike which can be built, from a kit, by the user and is adjustable for both size of rider and amount of cargo; and to document the designs for open source use. The kit had to be assembled using minimal tooling and be fully adjustable after assembly.

Further research was then conducted on standard bike geometries and existing solutions to understand the size and layout the frame was required to be, directly feeding into the design specification. This specification then informed the design journey and development of a frame that can be adjusted for both comfort and handling as well as size of rider. This was achieved through adjustable length tubes and pivoting bottom bracket and head tube joints, which could be used to change the angle of the seat tube and head tube and therefore the position of the contact points of the frame, altering the rider experience. The key features of the frame were then used to allow the standard bicycle frame to convert into a cargo bike with the addition of an attachment, fulfilling the adaptability for use case aim.

Force analysis was completed on key components of the frame with further work requiring the remaining joints to be completed to ensure the frame is safe to ride. The key geometry requirements identified in the specification were achieved, with future user testing able to determine the success of the adjustable nature of the frame, observing its effect on the users experience. Further development for features on the existing frame and new layout designs could be achieved with the help of expertise gained from collaborations with the project being made open source.

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5. INTRODUCTION

42% of the UK population own a bike, with many of this number requiring multiple for a variety of uses [1]. With both house prices and population rising, living space is become more of a premium and having multiple bikes is not feasible for many people. Furthermore, with growing concerns about global warming and climate change, increasing emphasis has been placed on more sustainable means of travel. Having one bike that could fulfil multiple needs and fit a wide variety of people could be the solution to both these problems.

The aim of this report is to document the research tasks, design journey and analysis of key components required to develop a bike that can be assembled by the user and can be adjustable for both the rider and the use.

This report will demonstrate the adjustability aspect by focusing on varying key geometries of a standard bike for multiple uses and the transformation from a standard bike into a cargo bike. This provides a good base for further development, on GitHub, for a wide range of bicycle layouts to cover an array of target markets.

5.1. INITIAL PROJECT BRIEF

The initial project brief was to design an open source bike which could be built by the user. This was broken down into two main aims that needed to be achieved.

- Design a bike that could be built using easily accessible materials and assembled with minimal tooling, similar to that used to build and service a regular bike.
- Make the designs publicly available so that anyone can study, modify, distribute, make and sell the design or hardware. [2]

5.2. MINI STUDY 1

To better inform the direction of the project and narrow down the scope, existing solutions and possible target markets were investigated for the first report [3].

First of all, potential target markets were researched to understand the key benefits that an adjustable bike could bring to the market to make it most appealing. The top three target markets were investigated further. These were the cargo market, student rental service market and the children's growing bike market.

From this, it was decided that the project direction would be to design an adjustable bike that could be adjustable for varying amounts of cargo and size of rider. This would make it fit both the cargo and student rental service markets, adding levels of adjustability not seen in these markets previously.

The majority of existing bicycle kits found were assembled with the use of lugs or large, complicated jigs, holding the bicycle frame in place before securing. This identified a need for the selected frame profiles to locate the joints in the correct orientation to assure quick and accurate assembly of the frame and easy adjustment after assembly. Profiles slotting into lugs was seen to be a good way to do this, providing the tubes were not circular as this offers no alignment, allowing the tubes to rotate freely until secured. Examples of bicycle building kits involving lugs and jigs are shown in Figure 1.

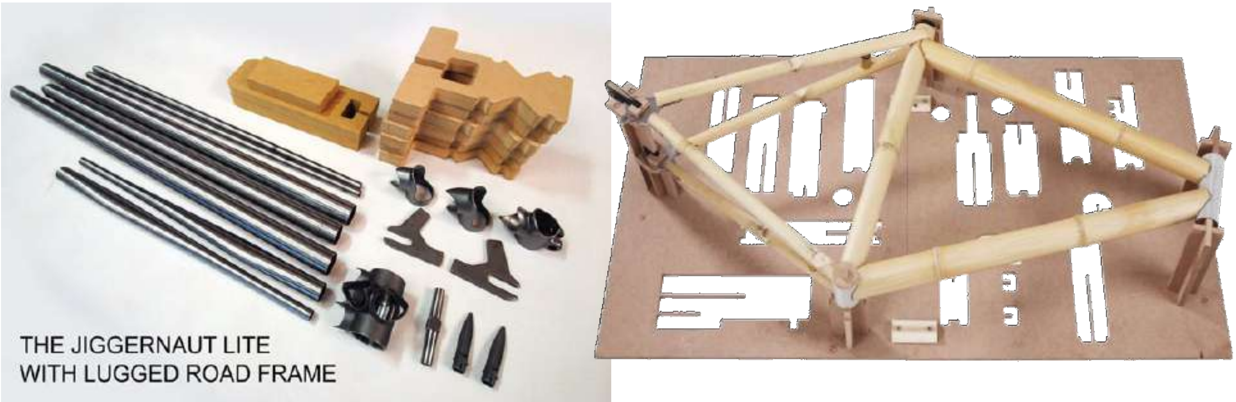


FIGURE 1 - EXAMPLE BICYCLE FRAME BUILDING KITS USING LUGS AND JIGS [4] [5]

Many of the bicycle building kits that people can buy have limited adjustability before assembly and little to none after assembly, which was identified as an area for improvement that should be focused on in this project.

The two build your own bicycle kits which showed most similarities with the aims of this project are shown in Figure 2 and Figure 3. The XYZ cargo bike, also with some open source models, uses bolted joints to create a variety of different cargo bikes for different needs. This offers adjustability before assembly but due to the destructive nature of the joining process, limited adjustability once assembled. The children's trike shown in Figure 3 is made by Infento, who sell a variety of kits of varying level which can be assembled into multiple configurations, making it highly adjustable after assembly.

FIGURE 2 - XYZ CARGO BIKES IN A VARIETY OF CONFIGURATIONS [6]

FIGURE 3 - INFENTO CHILDREN'S BIKE KIT [7]

This investigation showed how clamped joints could be utilised to allow adjustment and reconfiguration after assembly. Both examples use noncircular profiles to self-align the component, allowing for quick and accurate assembly every time. The XYZ bike is a very simple design compared to the Infento kit, but subsequently sacrifices on adjustability. This idea of a trade-off between simplicity and functionality was explored later when generating concepts.

5.3. MINI STUDY 2

It was decided early on that the design would utilise standard components where possible to aid maintenance and servicing of the bike to ensure a long life. Because of this, as shown in Figure 4, the frame and forks were selected as the key focus of the project, which should be designed in a way that would allow standard components to be installed to form the functional bicycle. Because of this, the second mini study [8] was focused on the geometries of these standard components and how these are arranged to adjust the riding experience for the rider.

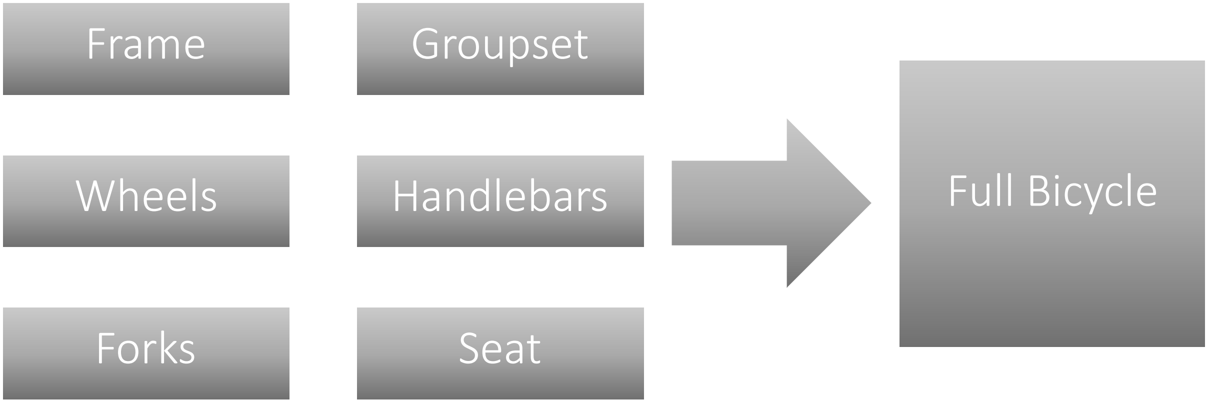


FIGURE 4 – HIGH LEVEL COMPONENT BREAKDOWN OF A BICYCLE [3]

The research found that there were no set standards for each component added to the frame. Instead there were a range to choose from, selected based on price and application. For the purposes of this project, the most common and easy to source options were chosen as the bike would not have the same high requirements as a performance bike.

There was a definite trend to the position of these components, dependant on the application. Figure 5 shows key measurements and how these vary for a hybrid, road and triathlon bike, with numerical figures found in Table 1 for size medium frames. The bicycle frame terminology and key geometries discussed in this table and throughout this report are shown in Figure 6.

FIGURE 5 - VISUAL COMPARISON OF FRAME GEOMETRIES [8]

TABLE 1 - STANDARD FRAME GEOMETRIES FOR 3 DIFFERENT BIKE APPLICATIONS [8]

Geometry	*Triathlon*	*Road*	*Hybrid*
Seat Tube Angle (°)	78	73.7	71
Head Tube Angle (°)	72.5	73	69.5
Head Tube Length (cm)	9	15.5	16.5
Bottom Bracket Drop (cm)	8	7	6
Chainstay Length (cm)	40	41	48.3
Fork Rake (cm)	4.5	4.5	4.5
Trail (cm)	6	5.6	8.6
Wheelbase (cm)	98.5	98.1	112.1
Standover (cm)	77.5	74.2	77.8
Reach (cm)	40.8	38.1	38.4
Stack (cm)	51.7	55.5	62.1

Table 1 shows that there is a definite trend in seat tube and head tube angles dependant on use. This demonstrates that higher angles for both features are optimum for faster, efficient riding and lower values tend towards a more comfortable ride. It was decided that these two angles should be the focus of the adjustable aspect of the bike design. Any adjustments to these would need to be done keeping the other key geometries within an allowable range.

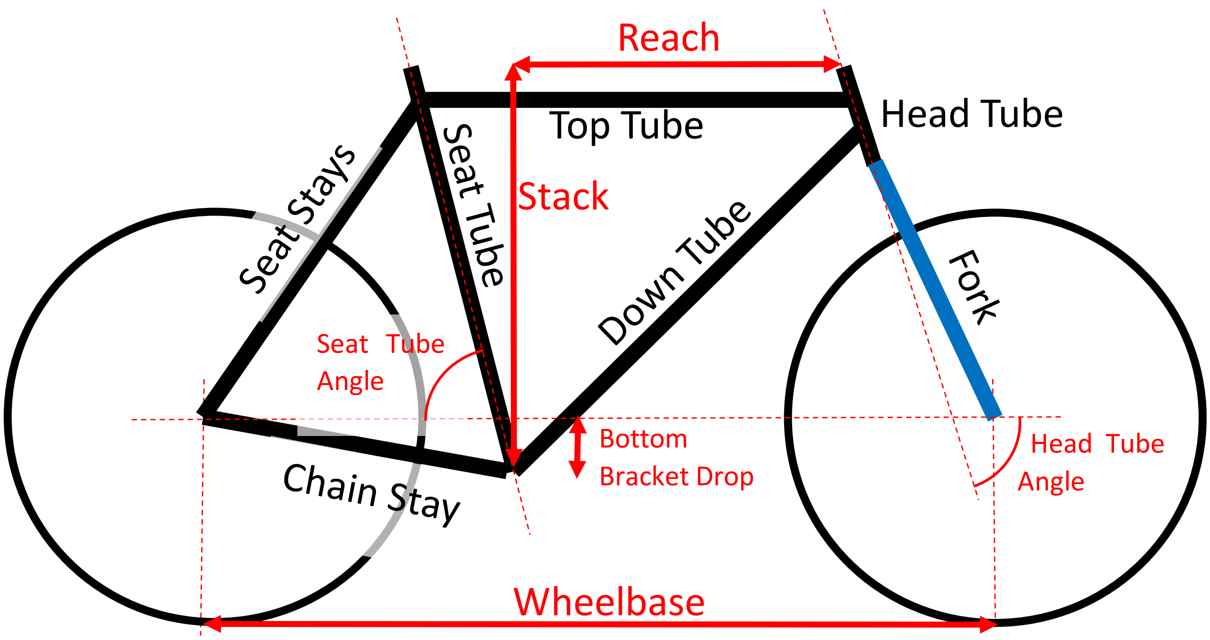


FIGURE 6 - BICYCLE FRAME TERMINOLOGY AND KEY MEASUREMENTS [8]

Geometry changes for size of user were also investigated so that the bike could be designed for the 95% percentile. It was important to design the standover height to accommodate the smallest rider, to ensure easy mounting and dismounting, while considering enough adjustment to allow the tallest rider to pedal efficiently.

These two studies highlighted the range of values that the bike could operate between so that the user could adjust for both handling and comfort, with key measurements in Table 2. To create a comfortable, slow riding position, the seat tube and head tube angles would lower with a longer wheelbase. For a faster, efficient and responsive position, the seat and head tube angles would increase, also increasing the bottom bracket drop, ideally, shortening the wheelbase.

TABLE 2 - KEY GEOMETRY ADJUSTMENT RANGES

Geometry	*Range to Achieve*
Seat Tube Angle	70° - 75°
Seat Tube Length	400mm – 700mm
Head Tube Angle	69° - 75°
Bottom Bracket Drop	10mm – 70mm

6. DESIGN SPECIFICATION

The findings from the two studies discussed above informed the design specification which was used throughout the design process to influence important decisions. This specification, shown in Appendix A, was split into 8 categories, with the important points relating to geometry requirements of the frame and the compatibility with standard components, researched and discussed in Mini Study 2 [8]. These are key for the bicycle to perform functions effectively, and directly impacts the users experience when in use.

7. CONCEPT GENERATION

Throughout the research stage, initial concepts were recorded, generated from the information found. Due to the new project direction identified from the market study, two different concept streams were formed. Initially, a variety of bike frame layouts were generated to identify geometries that would allow high levels of adjustability once built while still being simple for the user to assemble. Secondly, a variety of cargo additions were found, which could be added to these bicycle frames. A select few of these concepts are shown in Figure 7 and Figure 8.

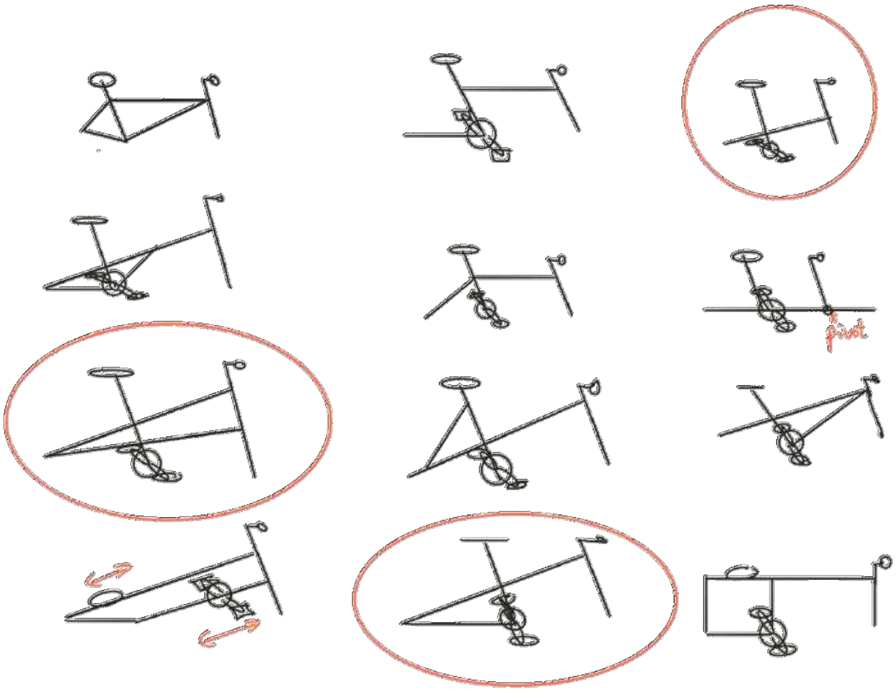


FIGURE 7 - CONCEPT FRAME LAYOUTS [9]

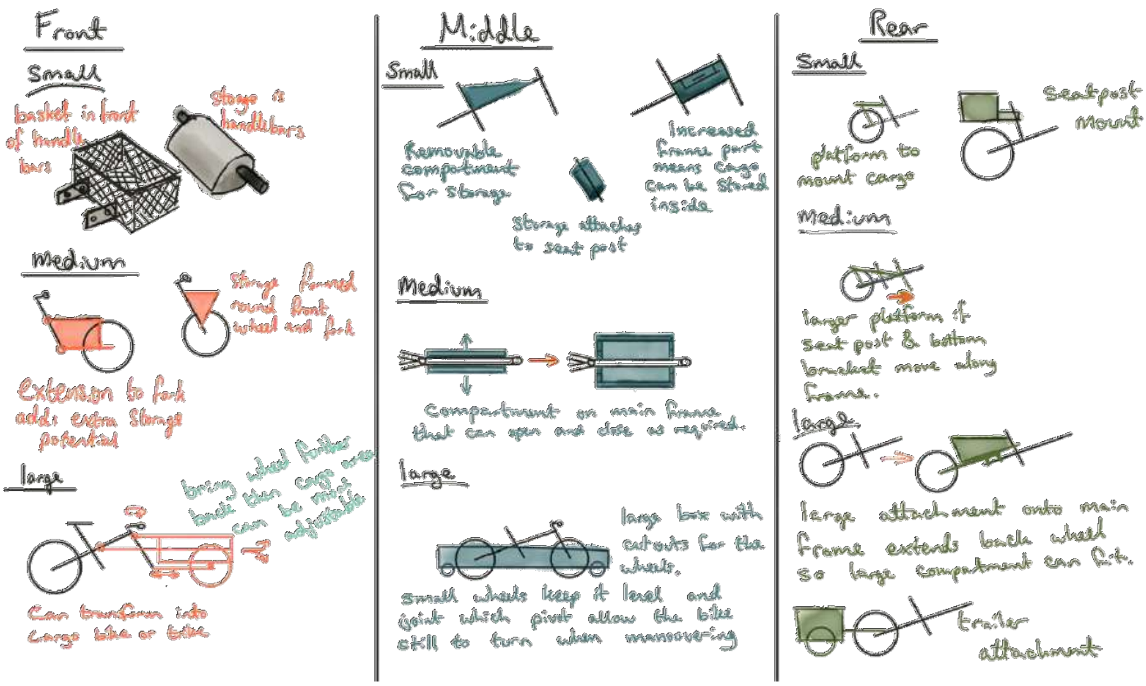


FIGURE 8 - CONCEPT CARGO ATTACHMENTS [9]

This order would be used throughout designing, where the standard bike would be designed first to provide the geometric information required for development of cargo attachments for the bicycle.

Figure 7 shows three frame concepts that were initially selected due to their simplicity while still maintaining potential for easy adjustment and strength. From this, these layouts were developed in more detail to find example solutions for each. At this stage in the design journey, the amount of work required by the user to build the bike was investigated. As mentioned in section 5.2, there is a pay-off between simplicity and functionality which needed investigating. As shown in Figure 9, the bicycle frame could be built from off the shelf stock materials, making the joints first before building. This would require the use of more tooling, some of which would not be standard, and this may also impact on the performance of the frame.

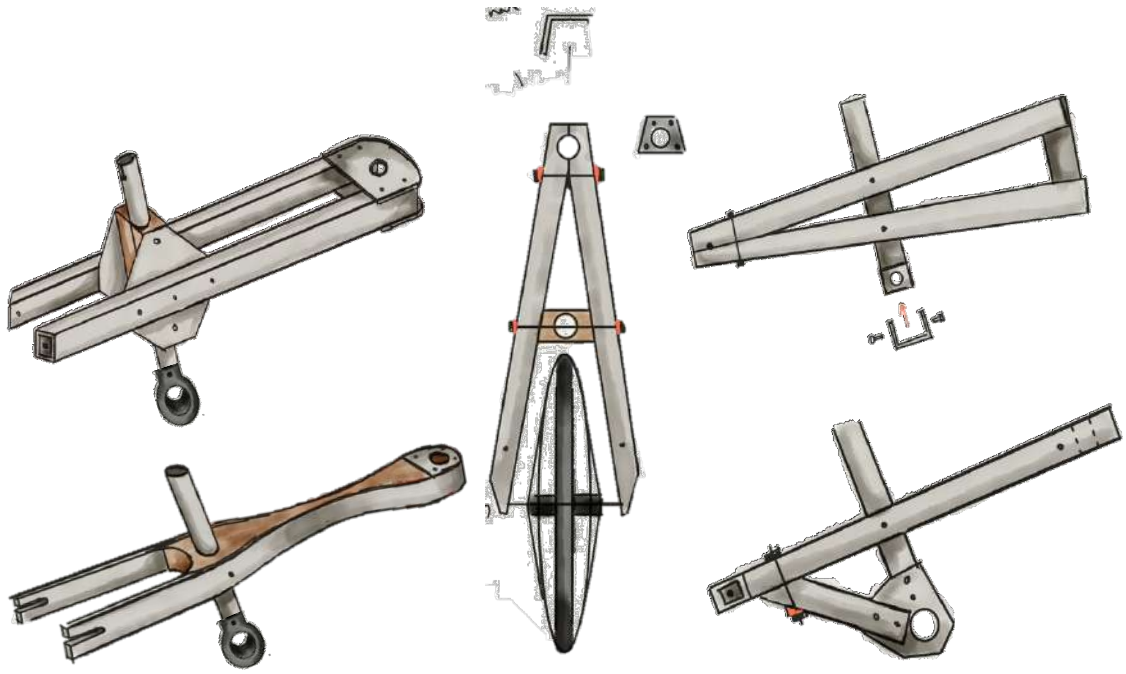


FIGURE 9 - DEVELOPED FRAME LAYOUTS USING STANDARD MATERIALS [9]

Because of this, it was decided that the aim of the project would be to design adjustable joints that could be used to assemble standard tubing together, similar to the lug method used on standard bicycle frames. The user would therefore not be required to manufacture the joints themselves and would purely need tools for fasteners, making it much more simple.

Due to the open source nature of the project, the joints that are designed would need to be documented in the correct manner to allow others to use, distribute or modify them for their own use.

8. TUBE PROFILE SELECTION

To effectively design the frame joints, the tube profile needed to be known. Selection of this was achieved by comparing the cross sectional area, relating to mass per length, and the second moment of area of a variety of profiles, shown in Table 3 and Table 4. Equation 1 shows that increasing the second moment of area decreases the stress for the same bending moment.

$$\sigma = \frac{My}{I} \qquad Equation\ 1$$

This meant that a higher second moment of area for a given mass would give the best profile. This comparison is shown in the far right column with a higher number representing a better combination. The square grooved profiles were ruled out straight away due to their extra mass. Although the circular tube has the best resistance to bending for the weight, the grooved circular profile (second profile) allows better alignment and fixation. This would mean that jigs would not be required for assembly and would allow easy adjustment, resulting in this profile being selected.

This profile also came in a 30mm diameter option which could be used in areas which do not require the larger tube, saving weight. Table 4 shows that it does not score as highly but there are good synergies between the two. The clamping geometry on both profiles is the same , resulting in any clamps being able to fit on both size profile, difficult to achieve with the circular or square profiles.

TABLE 3 - COMPARISON OF LARGER DIAMETER TUBE PROFILES

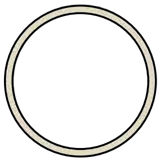
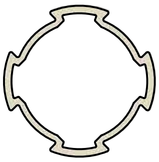
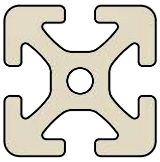
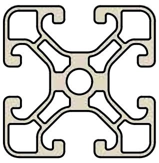
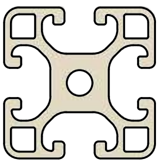
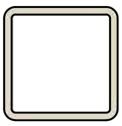
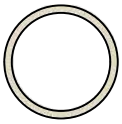
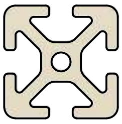
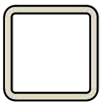
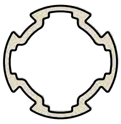
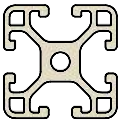
Tube Shape	**Dimension**	**Second Moment of Area**	**CSA**	**Mass/Length**	**Second Moment of Area / Mass**
	40	4.3	2.39	0.645	6.7
	40	3.88	2.45	0.66	5.9
	40	13.96	9.16	2.47	5.7
	40	7.38	5.07	1.37	5.4
	40	9	6.49	1.74	5.2
	30	2.94	2.24	0.6048	4.9

TABLE 4 - COMPARISON OF SMALLER TUBE PROFILES

Tube Shape	Dimension	Second Moment of Area	CSA	Mass/Length	Second Moment of Area / Mass
	30	1.73	1.76	0.475	3.6
	30	4.15	4.67	1.26	3.3
	25	1.63	1.84	0.4968	3.3
	30	1.71	1.97	0.532	3.2
	30	2.9	3.43	0.93	3.1

9. LAYOUT CONCEPT DEVELOPMENT

With the profiles selected, the sketched layouts were implemented into CAD for better visualisation, shown in Figure 10. Using this technique, the final concept layout was chosen and could then be developed. The reasoning behind these decisions is discussed in this section.

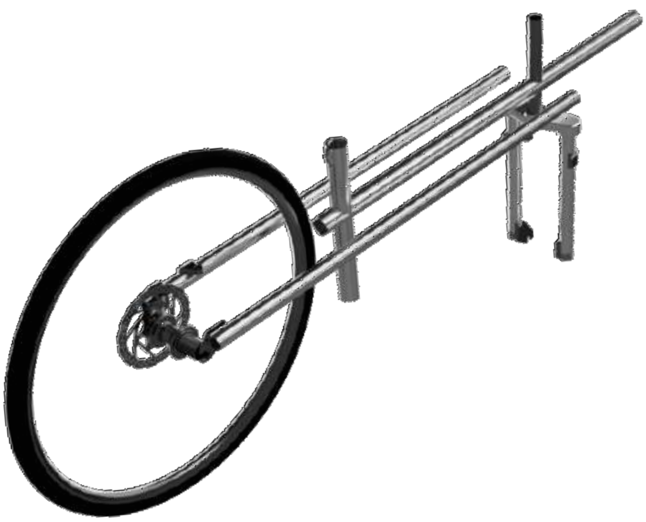


FIGURE 10 - TRIAL FRAME LAYOUT

Influenced by the geometric constraints of standard geometries, such as the rear hub width, the idea of having two profiles stretching the length of the frame was dismissed. The reason for this is demonstrated in Figure 11. With a rear hub width of 135mm, this would cause even the largest of riders knees to face outwards in order for the legs to get round the frame and onto the pedals. This would mean that the hip, knee and ankle would be out of alignment, causing discomfort for the rider. [10] [11]

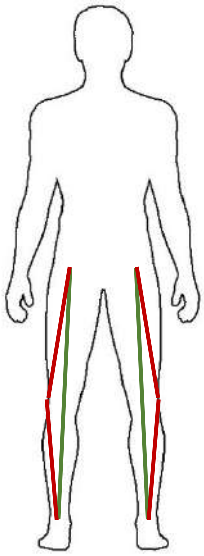


FIGURE 11 - HOW FRAME GEOMETRY EFFECTS THE RIDER[1]

This means that, to maintain comfort for the rider, there must be a single tube width between the seat tube and head tube. Therefore no tube can stretch from rear hub to head tube, as in the previous sketches, relying on a joint around the seat tube.

From this information, the first frame joints were designed and are shown in Figure 12. The main component of the frame is one joint, joining all tubes of the frame together. The joint fixed the rear stays to the down tube, rigidly, while allowing the seat tube to pivot to achieve the angle change defined in the specification of 5°.

FIGURE 12 - CROSS FRAME DESIGN WITH PIVOTING SEAT TUBE

[1] Body sketch taken from https://paintingvalley.com/blank-body-sketch#blank-body-sketch-24.jpg.

Two iterations of the joint were developed, shown in Figure 13. Both versions required a pivoting rod drilled through the seat tube, providing the centre of rotoation. The layout of the frame was evaluated after these had been developed and it was found that they posed a variety of problems and complications to the design, warrenting a rethink.

FIGURE 13 - DESIGN ITERATION OF CENTRAL JOINT

The main issue found was that, due to the pivot being located mid-way along the seat tube, it meant that the distance between the bottom bracket and rear hub did not stay constant, making it complicated to fit a chain between the two. Having a pin through the seat tube also meant that the retractable length of the seat post would be reduced. This would make it difficult to achieve the desired range of motion specified previously, limiting the range of users who could use the bike.

10. FRAME LAYOUT REDESIGN

With the knowledge learnt from the previous layout, improvements were implemented. The new design needed to keep the bottom bracket to rear hub distance constant when adjusting the seat tube angle. To achieve this, it was decided that the frame should utilise a rear triangle layout, as seen on a standard frame, and have the pivot about the bottom bracket. This would mean that when increasing the seat tube angle, it would increase the bottom bracket drop, a beneficial and coherent movement. To adjust this angle and to keep it locked, adjustable length bars would be used to adjust the distance between the seat tube and down tube at a given length. This layout is shown in Figure 14, overlaid on the previous layout.

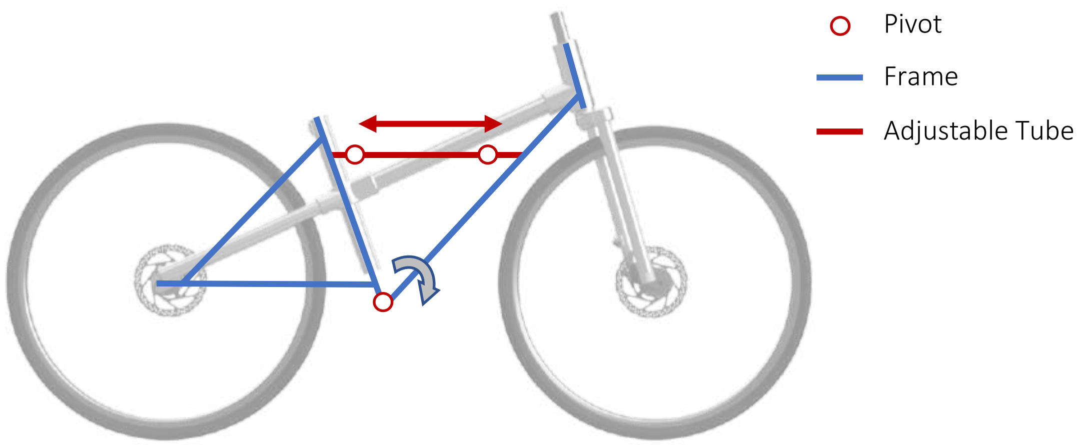


FIGURE 14 - FRAME LAYOUT REDESIGN

11. PROOF OF PRINCIPAL

11.1. TUBE LENGTHS

To ensure key geometry requirements are met, the length and size of tubes needs to be decided. Figure 15 shows the names of all the tubes involved in the frame and how the frame changes when adjusted. The tube lengths were designed for the layout on the left, taking into account how the adjustment would affect the key measurements, shown on the right, defined in the selected specification points in Table 5.

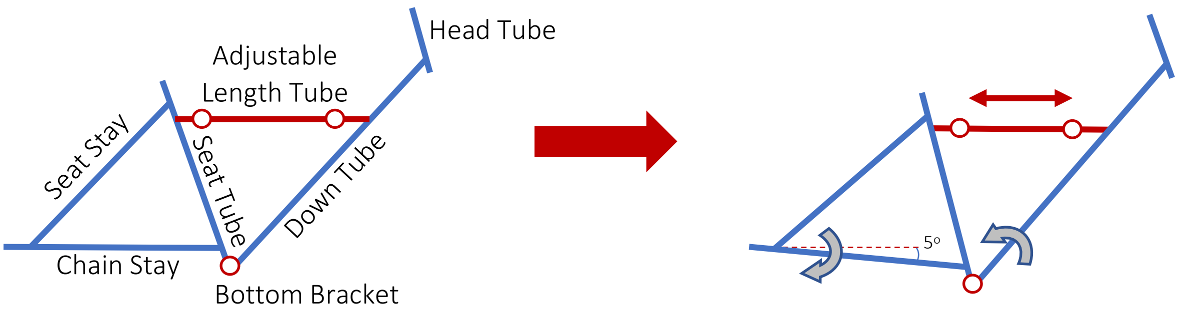


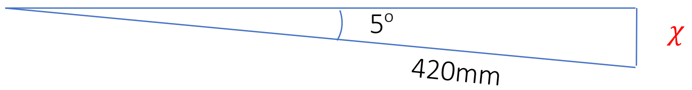
FIGURE 15 - FRAME LAYOUT AND MOTION

TABLE 5 - KEY SPECIFICATION POINTS FOR CALCULATING TUBE LENGTHS

Geometry & Ergonomics	G1	Angle between bottom bracket and top of the seat tube must vary between 70° and 75°
	G2	Distance between bottom bracket and saddle must cover the range 400mm - 700mm
	G8	The standover height of the frame must be <700mm
	G9	Frame reach must be between 360mm - 400mm
	G10	Frame stack must be between 520mm - 630mm
	G11	Bottom bracket drop must vary between 10mm – 70mm

Specification points G1 and G2 were achieved by having a seat tube of length 355mm. This allowed extra room for the saddle and bottom bracket joint, meeting the lower 400mm limit, with the upper limit being reached by extending a seat post. This would be secured in place with a clamp and allowed to slide the internal length of the tube. This tube was set at 70° to the chain stay, which was made horizontal and is required to be greater than 420mm to allow a 700c wheel to be mounted along its length. The adjustable length tube was set at 640mm from ground level, allowing a safe distance for the shorter users to step over. This results in a distance of 310mm from the bottom bracket, assuming a 10mm bottom bracket drop, the lowest value of the range shown in specification point G11.

The length and angle of the down tube was then dictated by the reach and stack requirements specified in G9 and G10. This is an important measurement for rider comfort and required more in depth investigation to achieve the best compromise. From the two values, the target reach should be 400mm and the stack of 520mm for the first layout, as the reach will shorten and stack increase with transition. To work out the change in angle of the down tube, and therefore the variation in reach and stack, the change in bottom bracket drop needed to be known, found from the chain stay length and angle, shown in Figure 16.



$$\frac{\chi}{sin(5)} = \frac{420}{sin(90)}$$

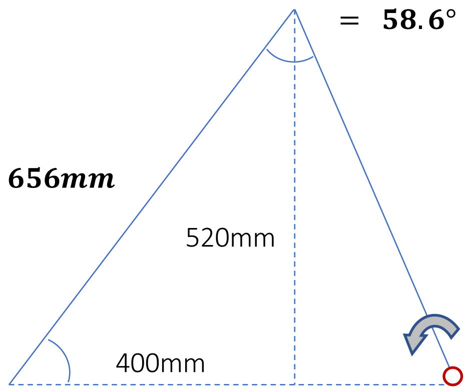
$$\boldsymbol{\chi = 36.6mm}$$

FIGURE 16 - CHANGE IN BOTTOM BRACKET DROP WITH A 5° INCREASE IN SEAT TUBE ANGLE

With a change in bottom bracket drop of 36.6mm, the movement of the front half of the bike could be analysed(Figure 17). From existing geometry studies, a smaller seat tube angle mainly linked with a smaller head tube angle and so 69° was chosen for this initial analysis. The distance between bottom bracket and front fork dropout was calculated, used to find the angle change in the down tube(Figure 18).

$$\beta = 37.6 + (90 - 69) = \mathbf{58.6°}$$

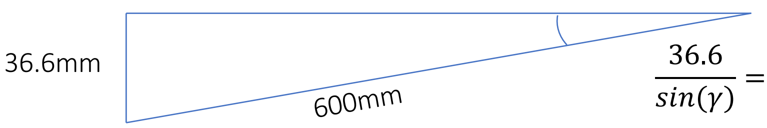
$$Hyp = \sqrt{400^2 + 520^2} = \boldsymbol{656mm}$$



$$\alpha = \tan^{-1}\frac{520}{400} = \mathbf{52.4°}$$

$$\frac{\Upsilon}{sin(58.6)} = \frac{656}{sin(69)} \quad \boldsymbol{\Upsilon = 600mm}$$

FIGURE 17 - ANALYSIS OF DOWN TUBE AND FORK GEOMETRY



$$\frac{36.6}{sin(\gamma)} = \frac{600}{sin(90)} \quad \boldsymbol{\gamma = 3.5°}$$

FIGURE 18 - CHANGE IN ANGLE OF DOWN TUBE DUE TO CHANGE IN BOTTOM BRACKET DROP

With the additional angle of 3.5° added to the initial 52.4°, the new stack and reach measurements were calculated and are shown in Table 6.

$$\frac{Reach}{\sin(34.1)} = \frac{656}{\sin(90)}$$

$$\frac{Stack}{\sin(55.9)} = \frac{656}{\sin(90)}$$

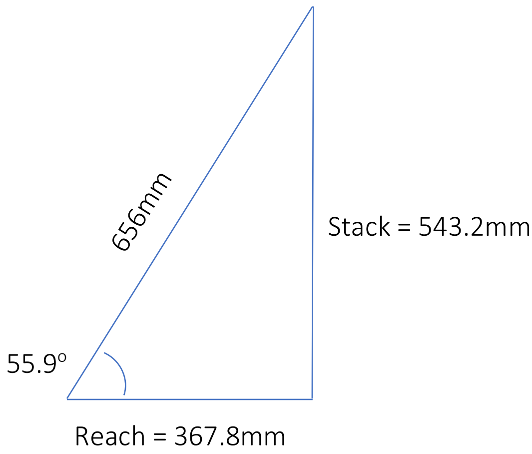


FIGURE 19 - NEW STACK AND REACH MEASUREMENTS

TABLE 6 - STACK AND REACH MEASUREMENTS FOR ADJUSTING SEAT TUBE ANGLE

	Initial	Final
Stack	520	543.2
Reach	400	367.8

From the values found, it shows that the stack and reach remain within the range defined in the specification points G9 and G10. From this, an initial down tube length of 600mm was selected to account for extra joint length.

11.2. BOTTOM BRACKET DESIGN

With the tube lengths decided, The key component, the pivoting bottom bracket, was designed. This was made from 4 main parts and was designed to allow the central component to house a threaded English 68mm bottom bracket. This part fits the bottom of the 40mm diameter seat tube and is held in place by a bolt through the centre. The two 30mm diameter chain stays are also attached to this piece and are clamped in place at a 20° angle in the vertical plane so they are horizontal while the seat tube is at 70°. The angle of divergence of the chain stays is set by this joint at 20°, to position them at the correct width for the rear drop outs to fix to the rear hub. This angle was obtained using Figure 20, showing how the 135mm and 145mm hub widths could fit on the frame at this angle with a 700c wheel allowing 10mm each side for rear drop out joints.

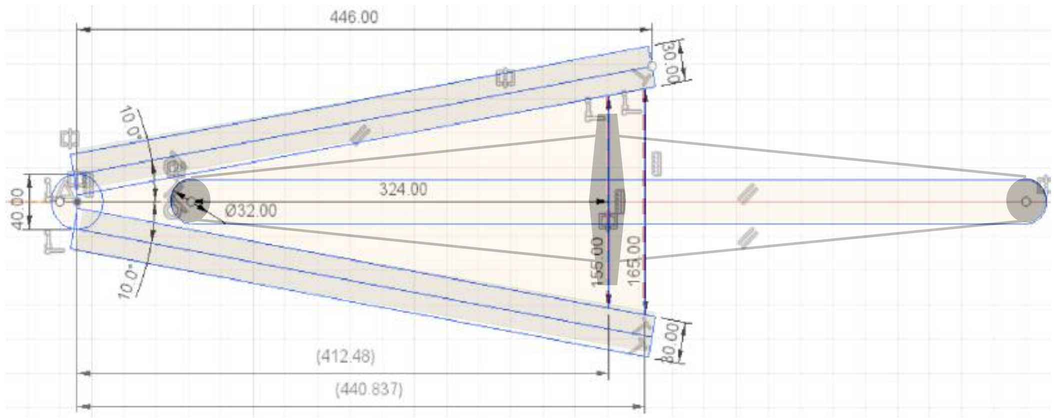


FIGURE 20 - CHAIN STAY LAYOUT TO SECURE MULTIPLE HUB WIDTHS

The pivoting section of this joint is created by the two blue pieces shown in Figure 21, which rotate around bearing surfaces on the outer most part of the bottom bracket, increasing the stiffness to bending. These two components clamp together over the central piece, and in doing so, also clamp the 40mm diameter down tube.

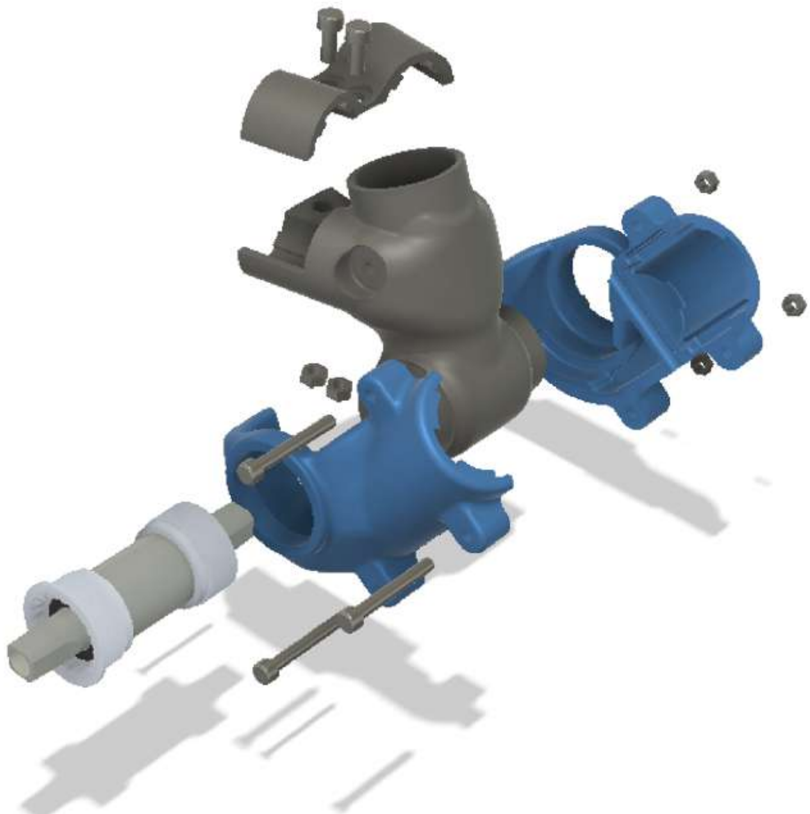


FIGURE 21 - BOTTOM BRACKET ASSEMBLY

To ensure a freely rotating joint without excess rattling or movement, reducing the rigidity of the frame, the correct mechanical tolerance needed to be selected between the rotating parts. From the limits and fits table(Figure 22) , an H7g6 fit was selected as the tightest fit while still allowing easy assembly. With a diameter of 40mm, the correct tolerances are highlighted.

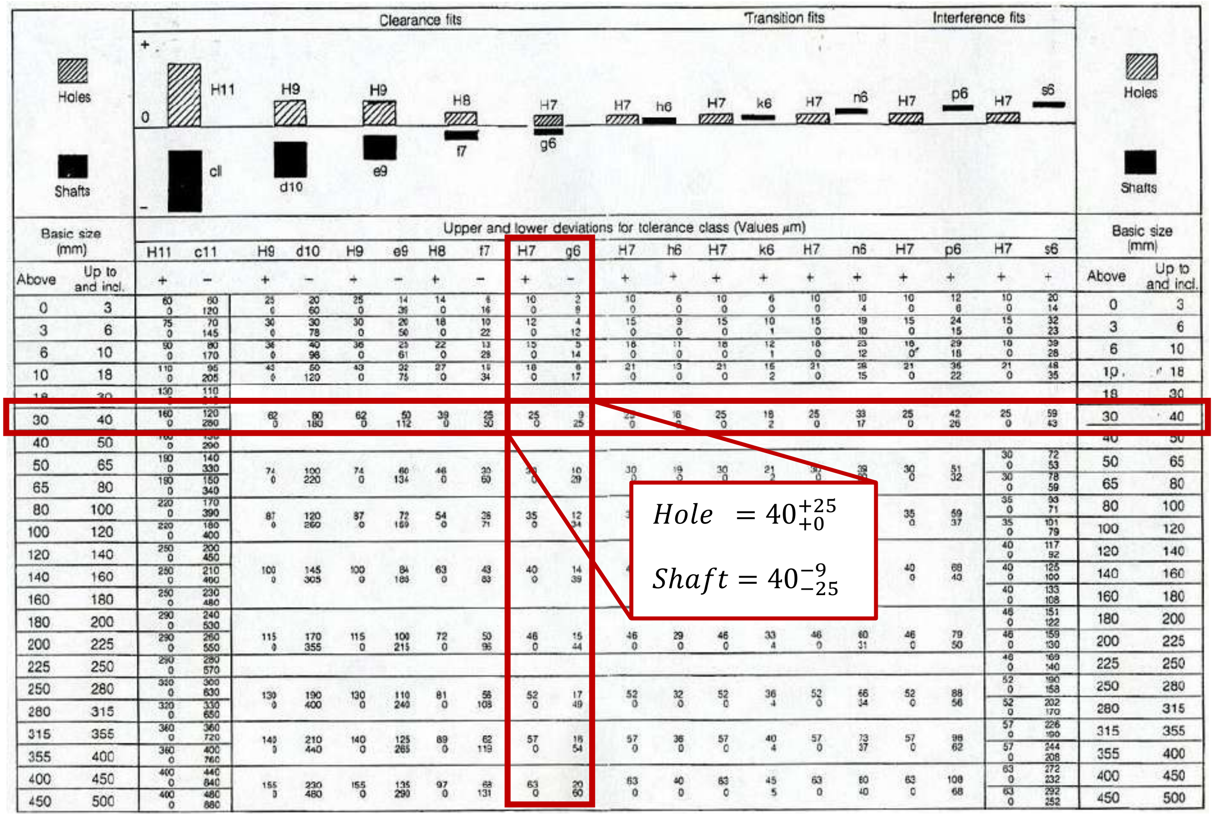


FIGURE 22 - LIMITS AND FITS TABLE [12]

11.3. ADJUSTABLE TUBE DESIGN

As mentioned in the redesign description, to constrain the movement of the bottom bracket angle, an adjustable length tube was required. Different methods were generated and evaluated with a selection shown in Figure 23. The threaded method was chosen as it allowed the tubes to be adjusted easily to any desired length, not discrete values.

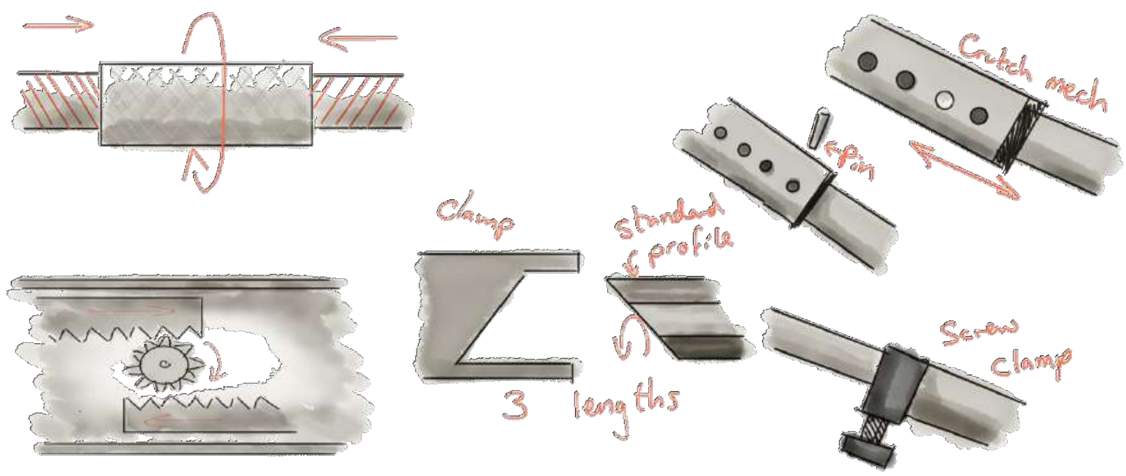


FIGURE 23 - ADJUSTABLE LENGTH CONCEPTS

Measurements relating to seat tube angle could be physically displayed, as shown in Figure 24, where the threaded middle section will partially cover the measurements, indicating the corresponding value.

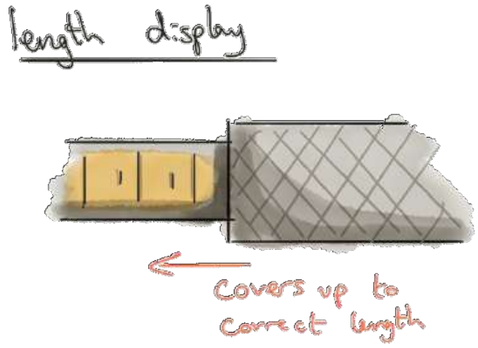


FIGURE 24 - MEASUREMENT DISPLAY METHOD

This lead to the development of the joints, shown in Figure 25, to hold the adjustable threaded tube. Joint A attaches to the seat tube and connects both of the 30mm diameter seat stays at the rear and the adjustable tube at the front. The angle and position of the seat stay clamps were dictated by the positioning of the chain stays to ensure alignment.

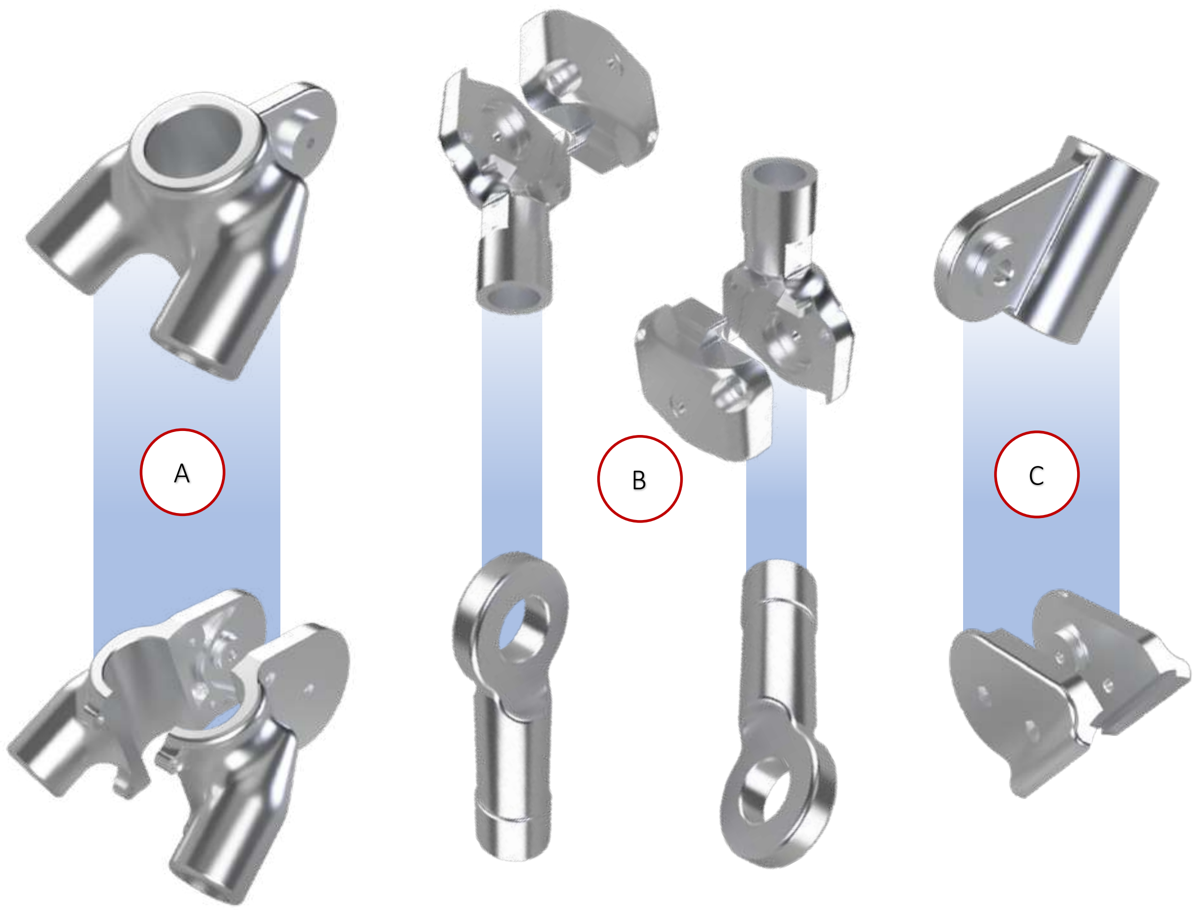


FIGURE 25 - FIRST ITERATION ADJUSTABLE LENGTH JOINT DEVELOPMENT

The adjustable tube is attached via the use of joint B, which clamps either side of the front extrusion of A with a bolt through the middle to secure in place. The two pieces slot together with the help of a dove tail feature, adding extra radial support to the bolt, the primary loading case for the part. A flat surface was added on the threaded cylinder to display measurements for the user, relating to seat tube angle. The thread of the two B type joints had to be opposite to each other to allow the shortening and lengthening of the tube.

Part C attached to the down tube and completed the main triangle of the frame. Further development of parts A and C split them in half to allow effective clamping to the main tubes, not previously possible. Having two halves meant that the clamping need not be achieved on part B, resulting in a much simplified solution.

As with the bottom bracket, an H7g6 fit was applied to the joints to ensure easy assembly and minimum rattling. With a diameter of 20mm, the same tolerance values could be used for this feature. The clearance distances in the axial direction were also derived from the same values in the table, ensuring the clamping of the joints does not restrict rotation.

11.4. FINDINGS

Combining the bottom bracket and adjustable tube design with the tube lengths calculated previously allowed for a proof of principle frame layout to be assembled, as shown in Figure 26, with the key joints highlighted. This showed that the motions and adjustments were possible and it was then time to develop each of the joints further into a full kit, applying the same adjustable length tube method for adjusting the head tube.

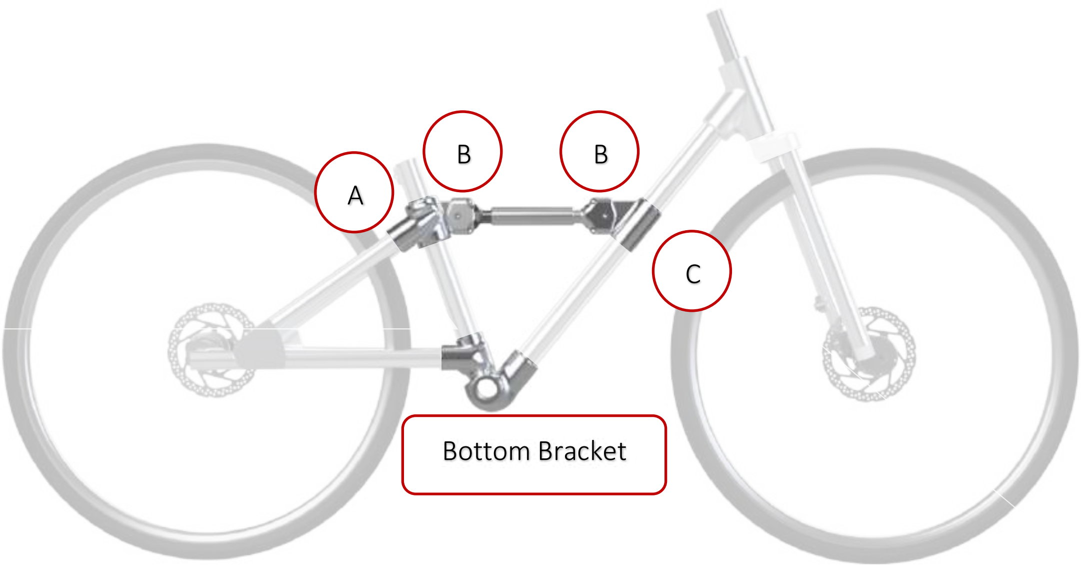


FIGURE 26 - FIRST ITERATION JOINTS IN SITU

12. DESIGN DEVELOPMENT

Looking back at the main objectives from this project, it was important to ensure that the bike could be simple and adjustable. The joints that had already been designed are large and rigid in nature, not allowing any level of adjustment to their use or position. To maximise the adjustability of the bike, these joints needed to be broken up and a joint that could be standard to the majority of the frame components needed designing. This joint could then have a method of attaching further parts onto it to adapt it for the given use on the frame. Achieving this would mean there would be less of an inventory of parts, making manufacturing simpler and cheaper. Any further layouts to be developed could then utilise this standard joint and just the attachments to this joint would need developing.

The locations for use of this standard component on the bicycle frame were then identified and shown in Figure 27 with coloured circles. Circles with the same colour represent joints which do the same thing and could therefore have the same attachments. Using this standard component would allow joints to move independently of each other, allowing for a greater level of adjustability.

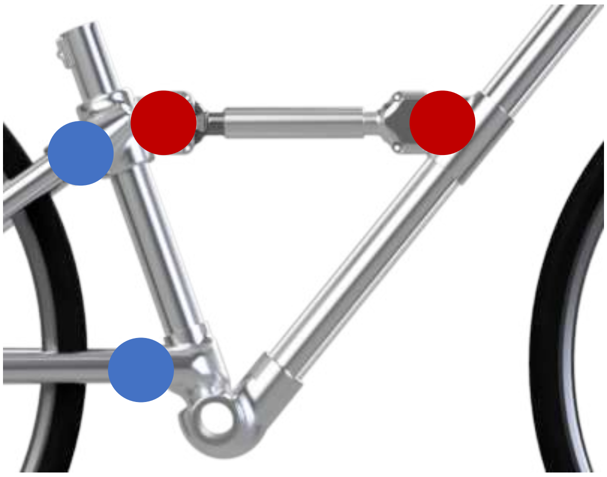


FIGURE 27 - STANDARD JOINT LOCATION AND TYPE

12.1. STANDARD JOINT DEVELOPMENT

Using the two example use cases identified in Figure 27, a standard joint was designed and is shown in Figure 28. It is made up of two identical pieces, clamping round the ridges of the tube profiles and securing in place with the use of 2xM6 bolts and nuts. The clamp pivots around a plateau at the rear to add extra stability and support and has a small extrusion with cut-out for alignment. The top surface of the part is angled at 10^{o} to maintain the same angle for the seat and chain stays as before and also adding additional support against tension, resisting attachments to the joints being pulled off. A groove is cut into the face to allow a T-slot nut to slide in and be secured and three concentric slots provide alignment and +/- 20^{o} rotation.

FIGURE 28 - STANDARD JOINT EMBODIMENT

12.1.1. ATTACHMENT 1 – REAR STAY CLAMPS (BLUE)

As the standard joint already had the required angle built into it, the geometry of this attachment was simplified greatly. The first iteration of this can be seen on the left of Figure 29. The clamp for the stay was located in the centre of the attachment and 3 pins at the rear located the joint in the concentric grooves on the standard joint, rotated to 20^{o} to create the required angle between the seat tube and stays. Due to the central position of the clamp, the bolt location, for attaching to the standard joint, was located underneath where the tube would be clamped, making it difficult to remove and adjust.

When implemented into the frame model, it was found that the joint was too wide and caused clashes between the chain stay and chain ring, making the bike unrideable. As this component could not be made any narrower, the position of the clamp had to be changed, as shown on the right in Figure 29. The clamp was moved to the top surface, allowing the tubes to be located much closer together, providing clearing for the chain ring. This also meant that the bolt fixing to the standard joint was independent of the tube being attached, making a much easier joint for assembly and adjustment.

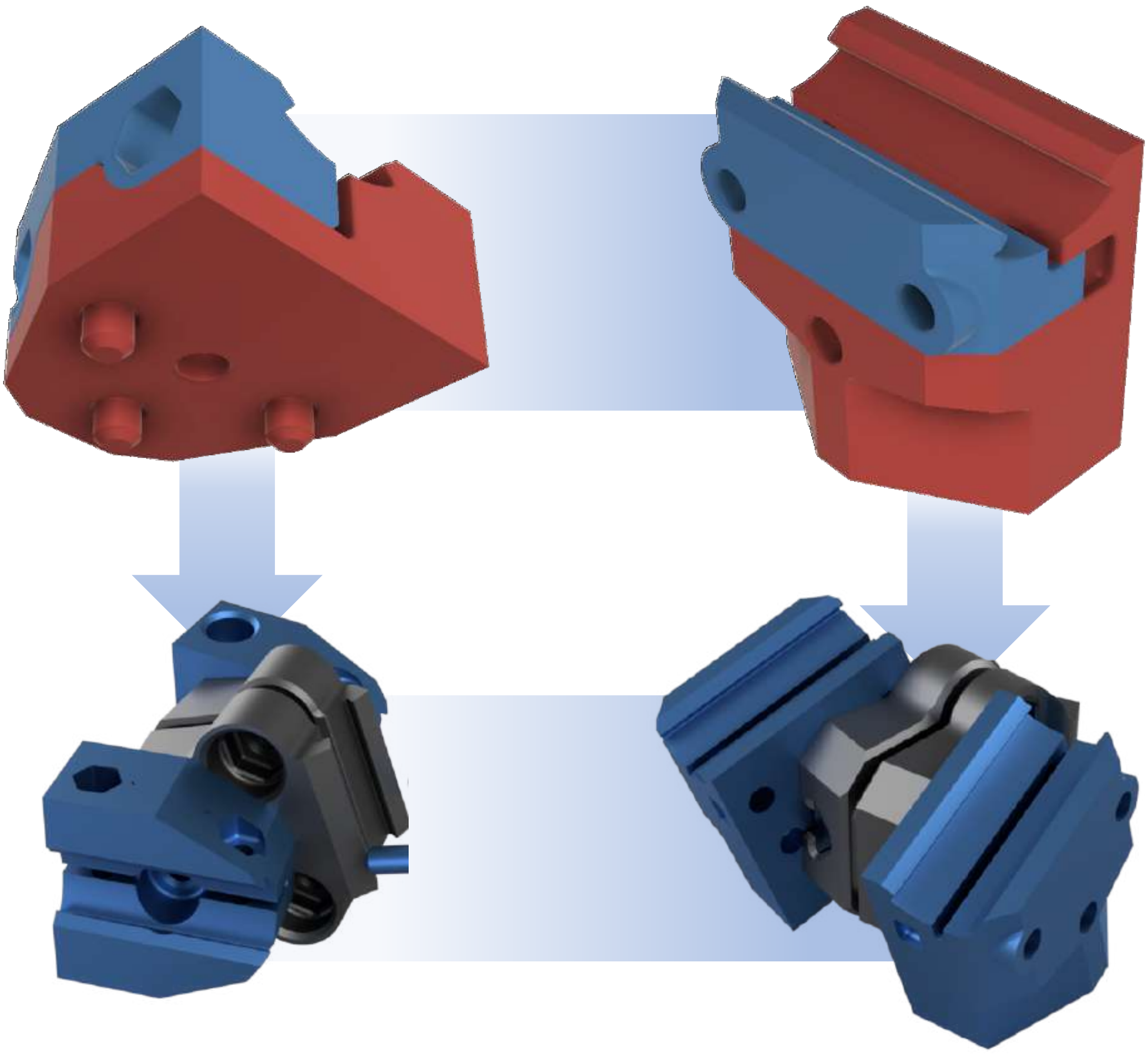


FIGURE 29 - REAR STAY ATTACHMENT DEVELOPMENT

12.1.2. ATTACHMENT 2 – ADJUSTABLE TUBE CLAMPS (RED)

For the second attachment, it was required to hold the pivoting end of the adjustable tube mount in line with the standard joint as shown in Figure 30. To achieve this, one part was designed that could be secured to the outside of either standard part, sandwiching the adjustable tube mount and securing in place with a bolt. The geometry of the standard joint was used to restrict movement of the attachment once secured in place with the T-slot nut. A cylindrical extrusion was used for the adjustable tube mount to locate to, as with the previous iteration, minimising the radial load on the securing bolt and strengthening the connection. This joint also used the same H7g6 tolerance on this feature. The designed part is shown in Figure 30 and it mounted to the standard joint shown in Figure 31.

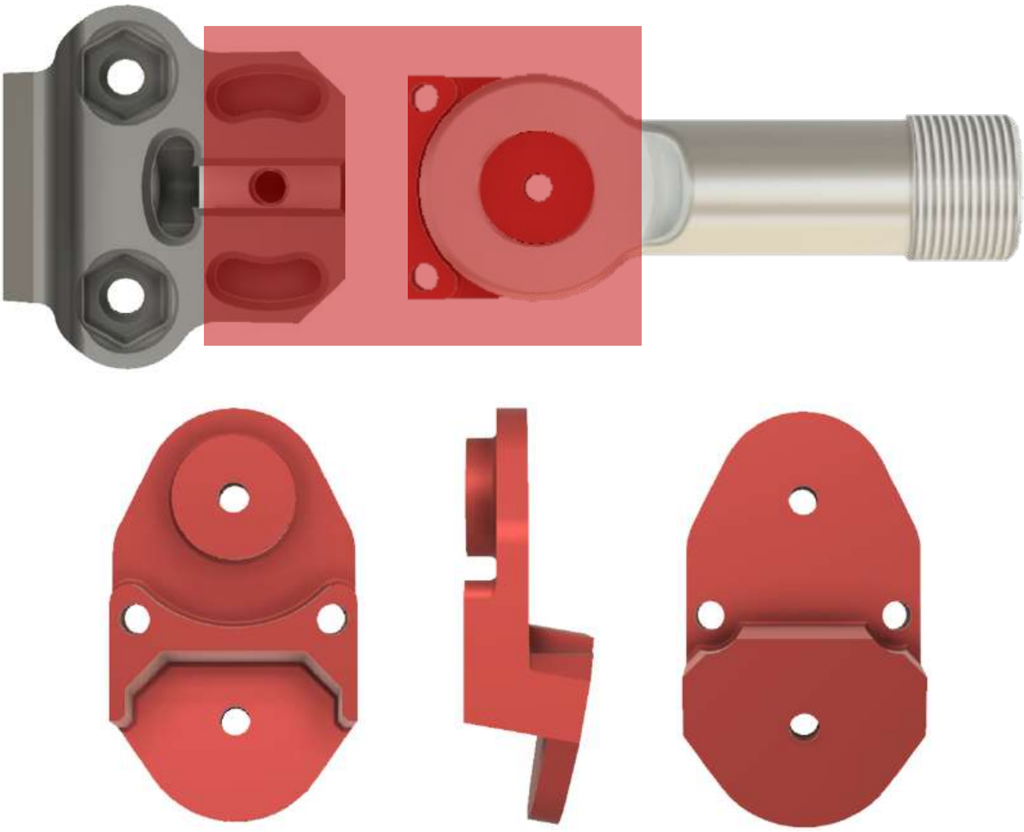


FIGURE 30 - ADJUSTABLE TUBE ATTACHMENT DEVELOPMENT

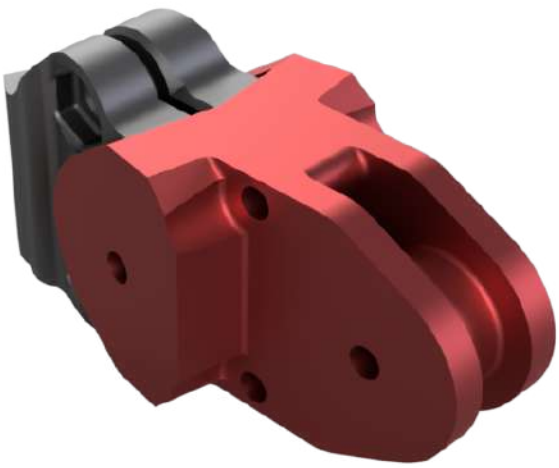


FIGURE 31 - ADJUSTABLE TUBE CLAMP IN SITU

12.2. BOTTOM BRACKET REDESIGN

With the standard joint and attachments designed, the bottom bracket required simplification to remove the chain stay clamps. With this feature removed, the geometry became more receptive to having additional clamping as well as bolts to secure in place. Because of this, an additional bolt hole was added through the seat tube and a method of clamping was added to the front of the tube(Figure 32). The grooves of the tube were used to grip to while the part is tightened. The rear of the part has a cut out, allowing small adjustments of the chain stay clamp to be made along the seat tube, resulting in a change in bottom bracket drop.

The down tube attachment to the main bottom bracket remained the same apart from small modifications to increase the range of motion of the joint to allow it to go horizontal, increasing the flexibility of the joint for any layout transformations.

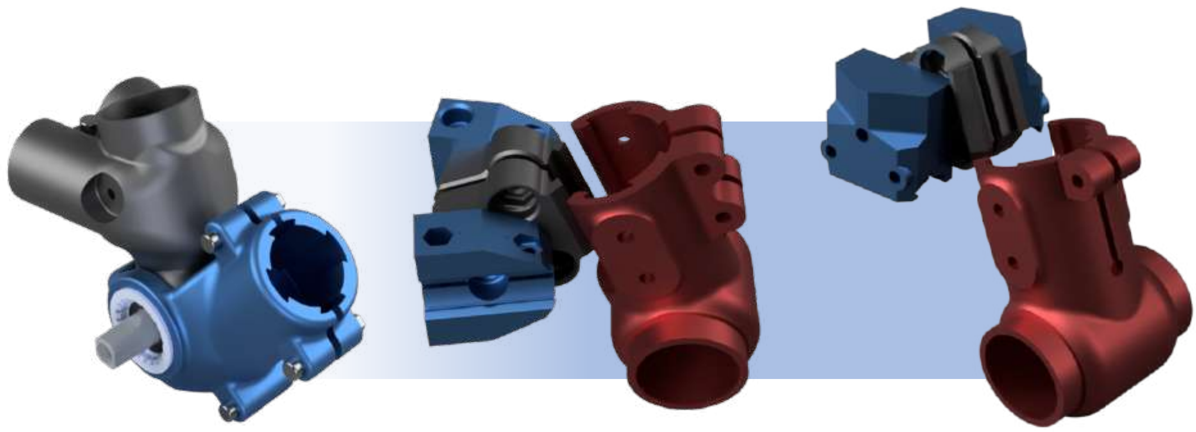


FIGURE 32 - BOTTOM BRACKET JOINT DEVELOPMENT

12.2.1. FORCE ANALYSIS

At this stage, it was important to understand the forces that would be going through this bottom bracket. This is the key component in the frame and the concept would not work without it. For this analysis, material properties of aluminium 6061 (Table 7) were used, due to its common use in bicycle frames, and it was assumed that all the load of 1500N would be going through the bottom bracket, supported by 1 of the 4 securing holes as a worst case.

TABLE 7 - ALUMINIUM 6061 MATERIAL PROPERTIES [13]

Property	*Value (MPa)*
Ultimate Tensile Strength	310
Tensile Yield Strength	276
Ultimate Bearing Strength	607
Bearing Yield Strength	386
Fatigue Strength[2]	96.5
Shear Strength	207

[2] 500 000 000 cycles completely reversed stress

To analyse the bottom bracket, lug calculations were used. This works out the forces involved with a pin going through a hole in a material and applying a force. This can be used for both the bottom bracket hole and the pin hole securing the joint to the seat tube. Analysis of both the joint and the seat tube holes would be required to determine the weakest component of the joint and its point of failure.

With lug calculations, there are three main causes of failure [14], listed below and shown in Figure 33. The calculations completed are simplified and will be further backed up by FEA. They do not take into account deformation of components which would cause contact areas to shrink and stress concentrations to arise. Because of this, and the fact that it is static loading and not dynamic, a large safety factor of 3 will be targeted to pass.

- Tension failure in one plane perpendicular to force direction
- Shear failure along two planes
- Bearing failure on contact surface

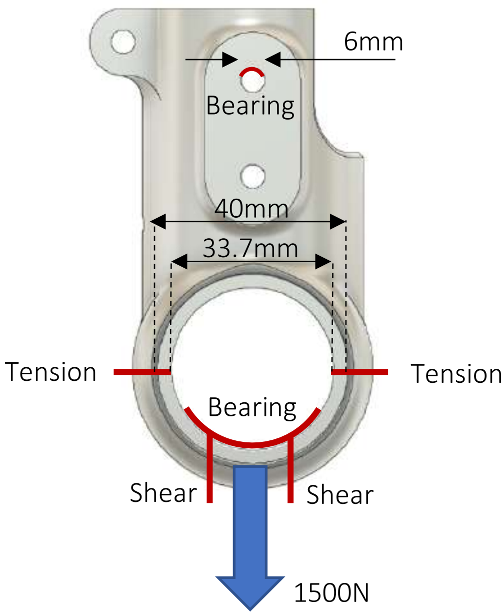


FIGURE 33 - COMMON LUG FAILURE TYPES

12.2.1.1. BOTTOM BRACKET HAND CALCULATIONS

For the calculations to do with the main bottom bracket hole, it was assumed that the thinnest thickness, found at the extremities, travelled the full thickness of 68mm. To find the critical load values, Equation 2 must be used, linking stress and force with area of action. For each type of loading, the area of action will vary, corresponding to the red lines shown in Figure 33, and the material property relating to the load type will be implemented. These values were then compared to the max loading of 1500N.

$$\sigma = \frac{F}{A} \qquad \textit{Equation 2}$$

12.2.1.1.1. BOTTOM BRACKET TENSION FAILURE

$$Area\ of\ Action = (40 - 33.7) \times 68 = \mathbf{428.4mm^2}$$

$$Tension\ Failure\ Load = Ultimate\ Tensile\ Strength\ \times\ Area\ of\ Action$$

$$= 310\ \times\ 428.4 = \mathbf{132\ 804}\boldsymbol{N}$$

$$Tension\ Yield\ Load = Yield\ Strength\ \times\ Area\ of\ Action$$

$$= 276\ \times\ 428.4 = \mathbf{118\ 238}\boldsymbol{N}$$

12.2.1.1.2. BOTTOM BRACKET SHEAR FAILURE

For the shear area of action, it was assumed that the length of the shear plane can be approximated by the difference in the two radii, slightly shorter than the exact value.

$$Area\ of\ Action = 2 \times (20 - 16.85) \times 68 = \mathbf{428.4mm^2}$$

$$Shear\ Failure\ Load = Shear\ Strength\ \times\ Area\ of\ Action$$

$$= 207\ \times\ 428.4 = \mathbf{88\ 679}\boldsymbol{N}$$

12.2.1.1.3. BOTTOM BRACKET BEARING FAILURE

The joint has been designed to fit a threaded bottom bracket. The selected model is threaded at either end and so is not in contact with the joint in the middle. As worst case, just one side of the thread will be in contact, reducing the area of action, so this will be used. This thickness was found to be 17mm and the effective diameter of the bottom bracket is 32mm.

$$Area\ of\ Action = 32\ \times\ 17\ = \mathbf{544mm^2}$$

$$Bearing\ Failure\ Load = Ultimate\ Bearing\ Strength\ \times\ Area\ of\ Action$$

$$= 607\ \times\ 544 = \mathbf{330\ 208}\boldsymbol{N}$$

$$Bearing\ Yield\ Load = Bearing\ Yield\ Strength\ \times\ Area\ of\ Action$$

$$= 386\ \times\ 544 = \mathbf{209\ 984}\boldsymbol{N}$$

12.2.1.1.4. JOINT PIN HOLE BEARING FAILURE

As the pin hole is in the centre of the joint, the tension and shear failure calculations would not apply to this and so just the bearing failure calculations needed to be completed. The pin going through the tube would be an M6 bolt and the thickness is 4mm.

$$Area\ of\ Action = 6 \times 4 = \mathbf{24mm^2}$$

$$Bearing\ Failure\ Load = Ultimate\ Bearing\ Strength \times Area\ of\ Action$$

$$= 607 \times 24 = \mathbf{14\ 568N}$$

$$Bearing\ Yield\ Load = Bearing\ Yield\ Strength \times Area\ of\ Action$$

$$= 386 \times 24 = \mathbf{9\ 264N}$$

This is by far the lowest value for yield on the joint. The safety factor, for a 1500N load acting on one pin joint would be 6.2, still above the target safety factor. As mentioned previously, the pin would also deflect under load, concentrating the load on a smaller proportion of the joint. As this was the point of likely failure, the stress was calculated, using Equation 2, so that it could be compared with FEA values.

$$\sigma = \frac{1500}{24} = \mathbf{62.5MPa}$$

12.2.1.2. BOTTOM BRACKET JOINT FEA

The scenario used above was then entered into CAD and used on the bottom bracket joint to complete FEA. Figure 34 shows this result which highlights the point made above about how stress can concentrate in areas if the force and hole are not in alignment or if there is deformation. Hand calculations assumed that the force was directly below the hole and the load was spread over the thickness. When put into FEA, the load was not aligned, resulting in a stress concentration on the inside edge of the hole, massively increasing the value to above the bearing yield strength.

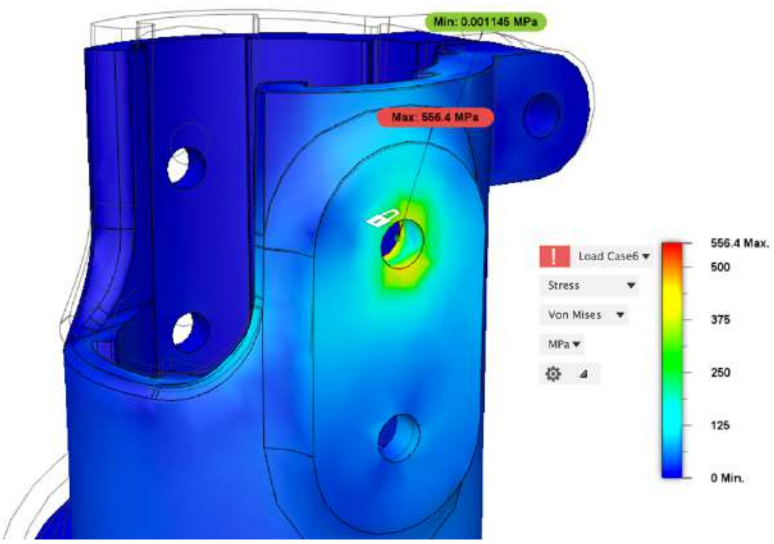


FIGURE 34 - FEA OF LOADING THROUGH SINGLE PIN SUPPORT ON BOTTOM BRACKET

In reality, the joint will be supported from both sides and this example can be seen in Figure 35. As this is now a symmetrical load case, the stress is spread evenly across the thickness and the value achieved is as expected at 27.16MPa, roughly half that of the single support, calculated in section 12.2.1.1.4.

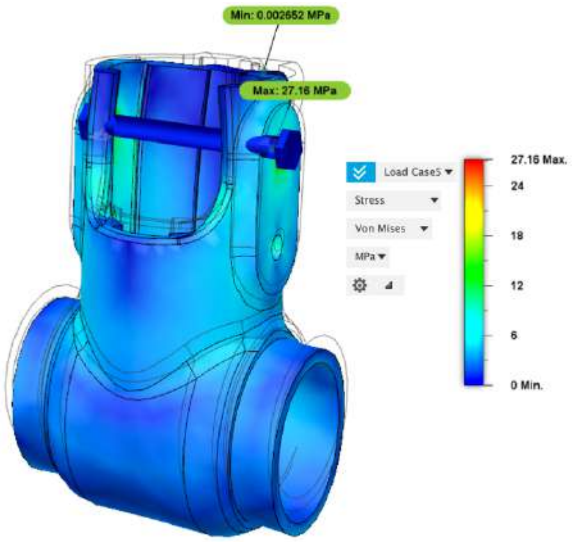


FIGURE 35 - FEA OF SYMMETRIC LOADING WITH TWO PIN SUPPORTS

12.2.1.3. FATIGUE STRENGTH

When the bicycle is in use, the user will be pedalling, causing cyclic loading on the joint. The loading is applied by the pedals at a distance of 100mm from the outer edge. This caused the loading to be asymmetrical unlike that which has already been calculated. Figure 36 demonstrates what effect this has on the maximum stress. It shows a maximum of 157.2MPa, almost 6 times as much as symmetric loading, having a bearing safety factor of 2.45 for the bearing yield strength of aluminium 6061. This demonstrates the need for the double set of bolts in the design with Figure 37 showing a drop in stress down to 93.5MPa corresponding to a safety factor of 4.1, larger than the target.

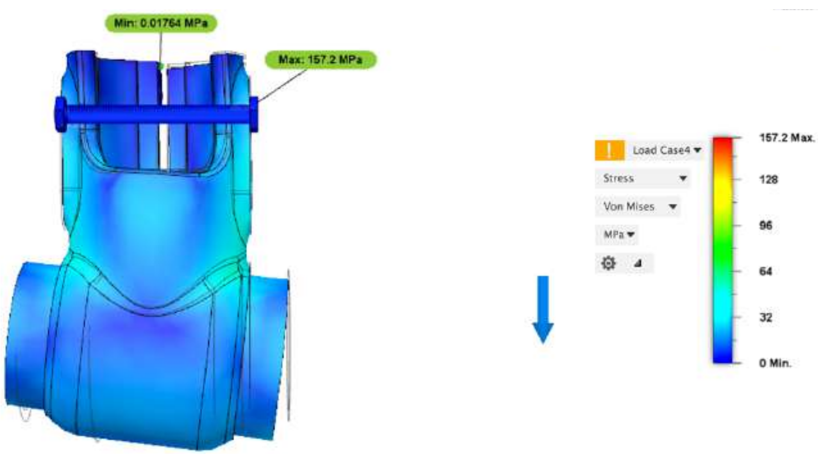


FIGURE 36 - ASYMMETRIC BOTTOM BRACKET LOADING THROUGH PEDAL – ONE PIN

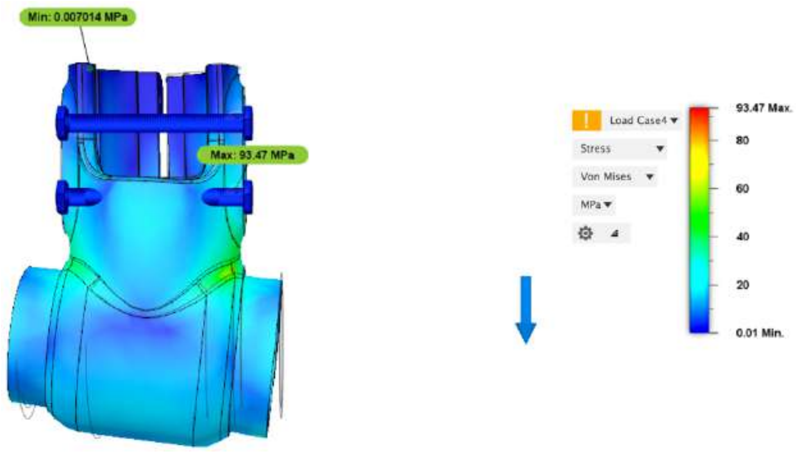


FIGURE 37 - ASYMMETRIC BOTTOM BRACKET LOADING THROUGH PEDAL – TWO PINS

When a material is subject to cycling loading, it weakens over time, known as fatigue. The change in strength can be plotted on an S-N curve such as Figure 38 for aluminium 6061 T6. The fatigue strength of a material can be defined for a set number of cycles. The fatigue strength of aluminium 6061 is 96.5MPa, from 500 000 000 cycles. The analysed bottom bracket joint was found to experience a maximum stress of 93.5MPa, therefore falling just below the fatigue strength of the material, ensuring a long life.

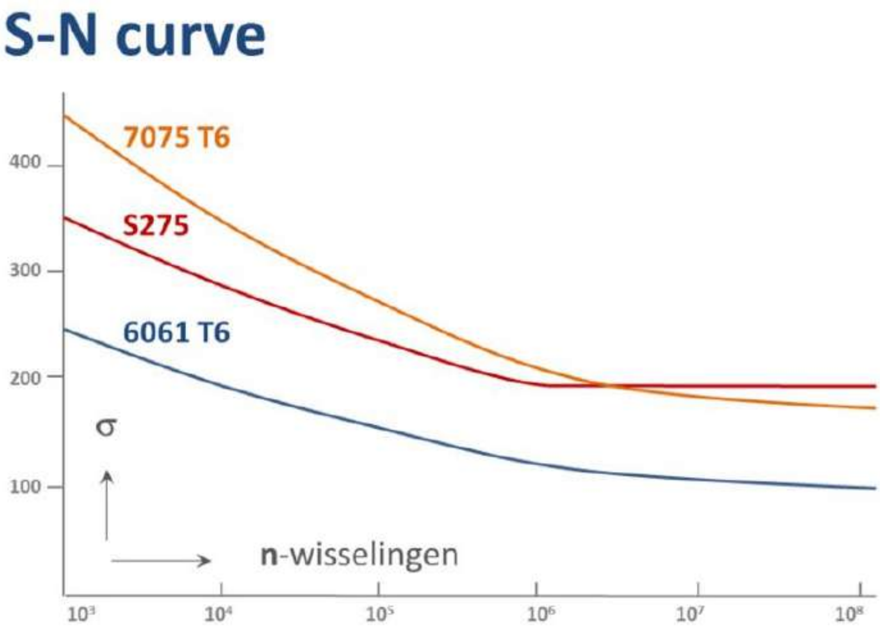


FIGURE 38 - EXAMPLE FATIGUE CURVE FOR ALUNIUM 6061 T6 [15]

12.2.2. PIN ANALYSIS

As well as analysing the joint, it was also important to look at the pin that would be securing it to the tube. Despite the fact there will also be a clamping force adding to securing the joint, this would be ignored for this calculation. Figure 39 shows the forces which would occur if all the load were going through one 6mm diameter pin, through both the joint and the tube. The calculations below show the shear stress through one side of the bolt, if the loading all went through this point, assuming an asymmetric loading condition.

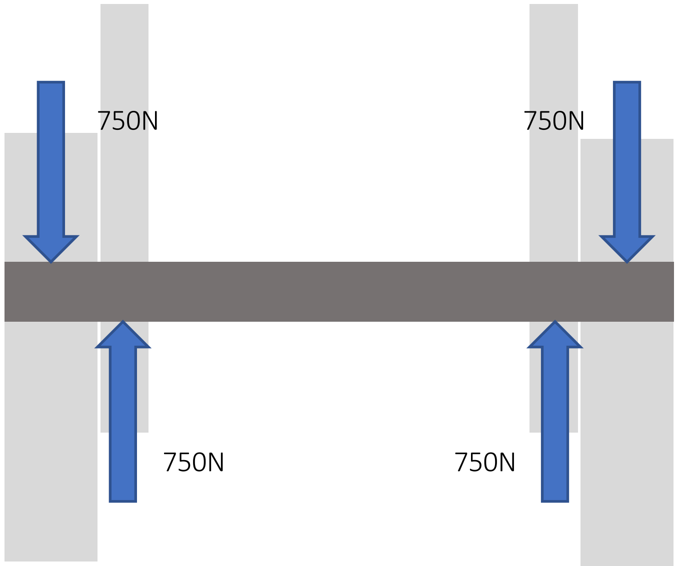


FIGURE 39 - LOADING THROUGH PIN OF BOTTOM BRACKET

$$Cross\ Sectional\ Area = \pi \times \frac{d^2}{4} = \mathbf{28.3mm^2}$$

$$\sigma = \frac{F}{A} = \frac{1500}{28.3} = \mathbf{53MPa}$$

For a standard 8.8 grade bolt, the ultimate tensile strength is 800MPa and shear strength is 80% of that. This gives a safety factor of 24, shown below. Therefore, the joint would fail first, before the bolt.

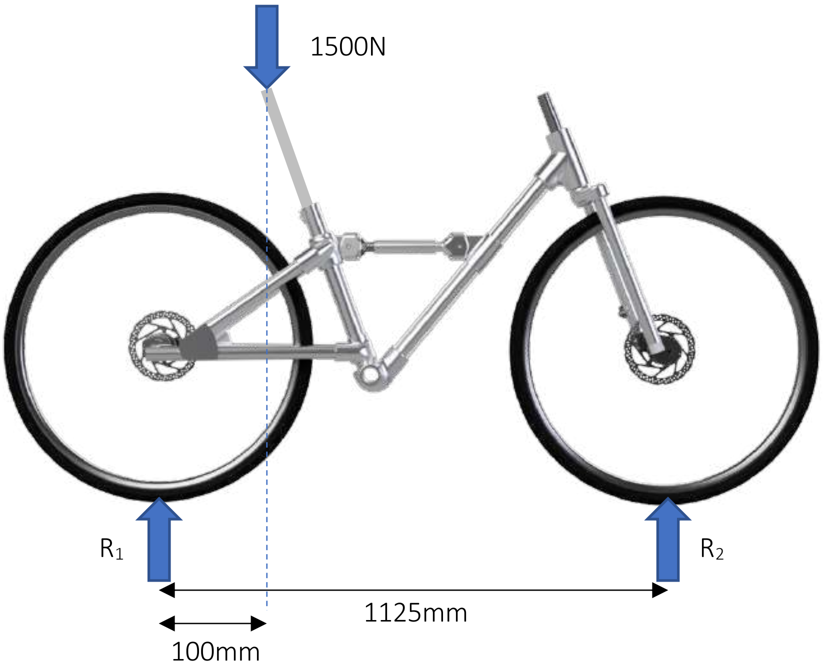
$$Safety\ Factor = \frac{640}{53} = \mathbf{12}$$

12.3. SEAT TUBE ANALYSIS

At this point, the seat tube was identified as the key linking component of the frame design, with majority of parts attaching to it. This tube was also the only tube that required adaptations with both a slot for seat post clamp and holes for the bottom bracket to bolt through. Because of this, the forces seen by the tube required investigation and will be calculated in this section.

12.3.1. EXTERNAL FORCES ACTING ON SEAT TUBE

To complete this, firstly, the full system needed analysing. For the worst case scenario of the seat tube, the seat post would be fully extended and the whole weight limit would be applied through the saddle. This would position the force 100mm from the rear hub, which was used to calculate the reaction forces, as shown in Figure 40.



$$R_1 = \frac{1025}{1125} \times 1500$$

$$\boldsymbol{R_1 = 1367N}$$

$$R_2 = \frac{100}{1125} \times 1500$$

$$\boldsymbol{R_2 = 133N}$$

FIGURE 40 - CALCULATING GROUND REACTION FORCES

Once this was completed, the smaller section of the components interacting with the seat tube could be investigated. At this stage, it was assumed that all internal forces are acting parallel to their corresponding beams, acting like a pin jointed frame. The frame geometry was also simplified to one rear triangle rather than the two in reality and so any forces seen for the rear seat stay and chain stay would be shared. Firstly the external forces of the sub-section were calculated, x and y in Figure 41, followed by the internal forces of the seat stay and chain stay, shown in Figure 42.

$$1500 - 1367 = y\,sin50$$

$$\boldsymbol{y = 174N}$$

$$x = y\,cos50$$

$$\boldsymbol{x = 111.9N}$$

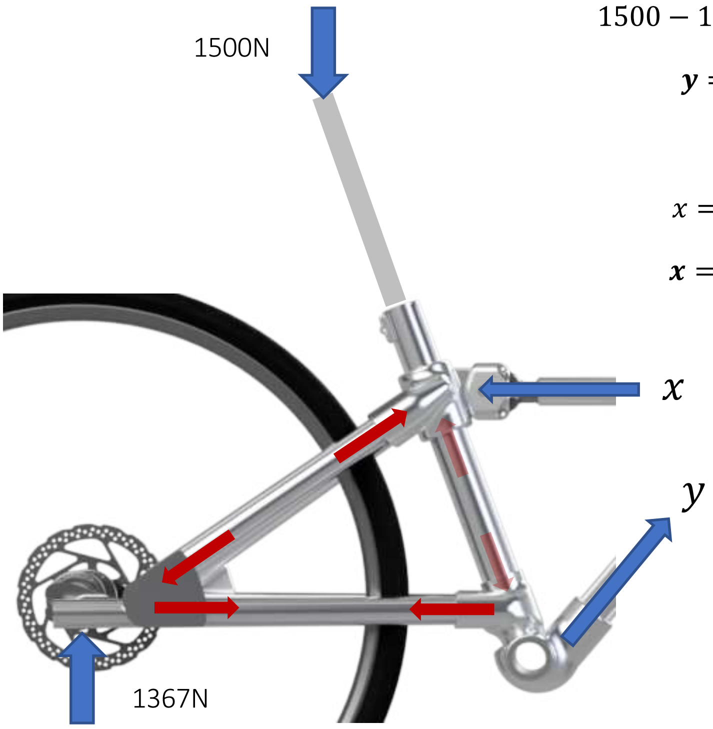
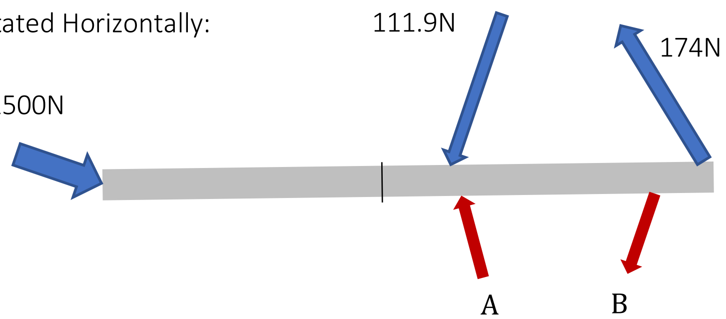


FIGURE 41 - EXTERNAL FORCES ACTING ON REAR TRIANGLE

Seat Tube Rotated Horizontally:



$$\text{res}\uparrow:\ 1500\text{sin}20 + 111.9\text{cos}20 + \ \text{B}cos20 = 174cos30 + \ Acos20$$

$$\text{A} - \ \text{B} = 497.5$$

$$res \rightarrow:\ 1500cos20 = 111.9sin20 + 174sin30 + \ Asin20 + \ \text{B}sin20$$

$$\text{A} + \ \text{B} = 3755$$

$$\mathbf{A = 2126.3}\boldsymbol{N} \qquad \mathbf{B = 1628.7}\boldsymbol{N}$$

FIGURE 42 - FORCE CALCULATIONS FOR SEAT TUBE

Using the calculated forces, and their distances along the tube, the axial force, shear forces and bending moments could be plotted, shown in Figure 43. The maximum values for each of these were then compared to the material properties of the tube material.

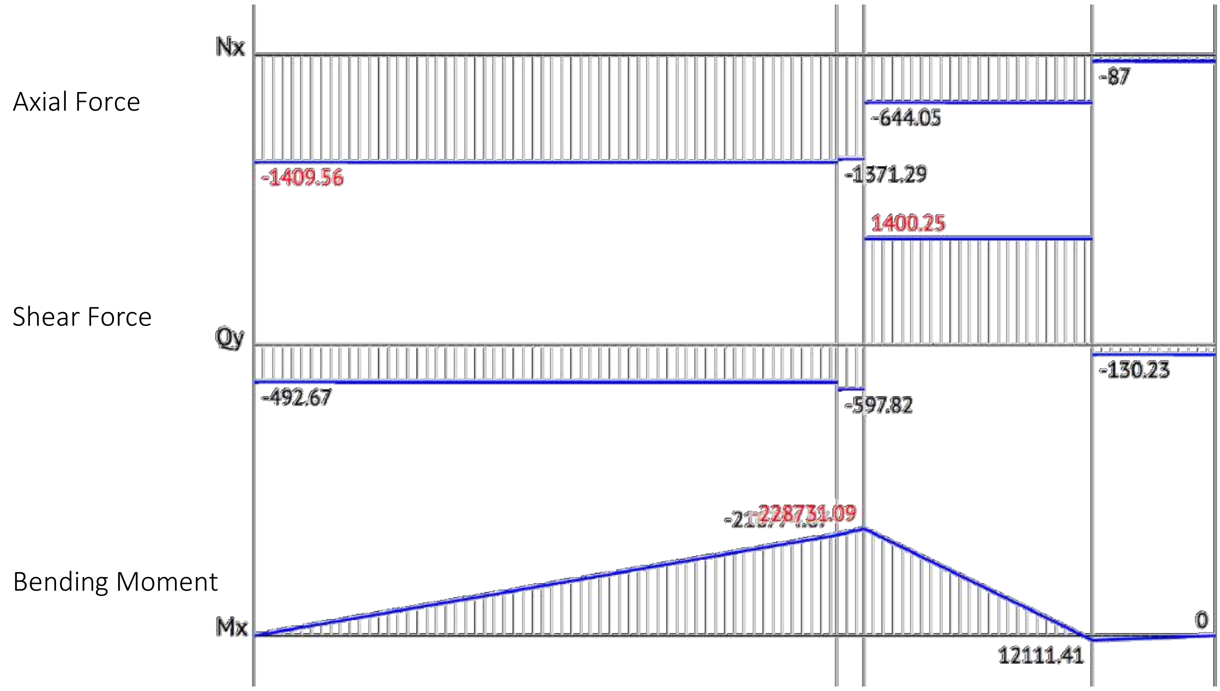


FIGURE 43 - FORCE ANALYSIS ALONG SEAT TUBE LENGTH[3]

The given material properties for the tube profiles are shown in Table 8. From this, the force to reach yield and failure could be calculated and compared with the values seen throughout the seat tube to obtain corresponding safety factors, shown in Table 9. It can be seen from the table that, if the seat tube were to fail, it would do so in bending. The location of this potential failure point was found to be at the top of the seat tube, where the seat stays connect. Although a low safety factor, this value was believed to be acceptable due to an insert for the seat post clamp being located there. This could be designed in a way to add additional strength to the tube.

TABLE 8 - TUBE PROFILE MATERIAL PROPERTIES

Property	*Units*	*Ø 40*	*Ø 30*
Tensile Strength	N/mm^2	245	
Yield Strength	N/mm^2	195	
Density	kg/dm^3	2.7	
Elastic Modulus	N/mm^2	70000	
Weight per Length	kg/m	0.66	0.53
Second Moment of Area	cm^4	3.88	1.71
Second Polar Moment of Area	cm^4	5.68	2.44
Cross Sectional Area	cm^2	2.45	1.97

[3] https://beamguru.com/online/beam-calculator/# used to create graphs from calculated values

Tensile Failure Load **=** Tensile Strength x CSA

= 245 x 245

= 60025N

Tensile Yield Load **=** Yield Strength x CSA

= 195 x 245

= 47775N

Shear Failure Load **=** 0.6 x Tensile Strength x CSA

(estimate) = 0.6 x 245 x 245

= 36015N

Bending Failure Moment

$$= \frac{\sigma_{ts}\, I}{y}$$

$$= \frac{245 \times 38800}{20}$$

$$= \mathbf{475300}\text{Nm}$$

Bending Yield Moment

$$= \frac{\sigma_{ys}\, I}{y}$$

$$= \frac{195 \times 38800}{20}$$

$$= \mathbf{378300}\text{Nm}$$

TABLE 9 - COMPARING CRITICAL MATERIAL VALUES TO CALCULATED TUBE LOADING VALUES

Measurement	*Failure / Yield Value*	*Calculated Max. Value*	*Safety Factor*
Tensile (Failure) (N)	60025	1410	42.6
Tensile (Yield Load) (N)	47775		33.9
Shear (Failure) (N)	36015	1400	25.7
Moment (Failure) (Nm)	475300	228731	2.1
Moment (Yield) (Nm)	378300		1.7

12.3.2. TORSIONAL EVALUATION OF SEAT TUBE

When in use, a bicycle frame is subject to torsional loading as a result of the pedalling action. Because of this, and the nature of the clamping joint, It was thought necessary to investigate torsional loading of a joint on the seat tube, as a key component of the frame. The seat tube secures three of the standard joints in place, each with a clamping length of 30mm and extending 85mm from the tube. A force of 500N was applied perpendicular to the bike frame on the front joint while constraining the rear joints. As can be seen in Figure 44, a large stress of 370MPa occurred around the top joint in the section between the groove and the outer diameter. This first test was done as a worst case but, in reality, there would be an insert added to the top of the tube to allow clamping of the adjustable seat post of diameter 27.2mm.

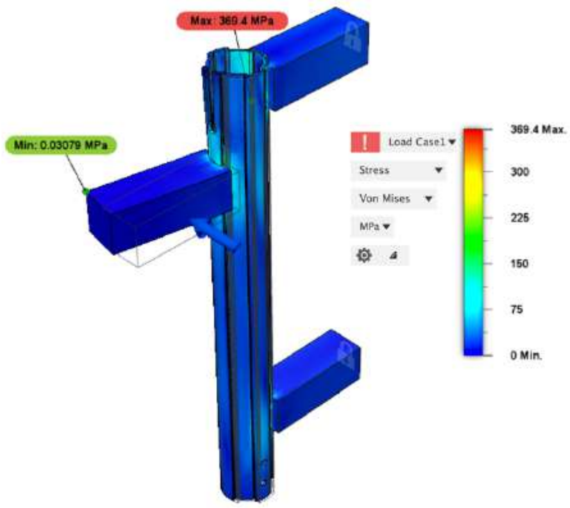


FIGURE 44 - TORSIONAL LOADING WITHOUT INSERT

This second load case had the insert added to the model(Figure 45). This insert extended 60mm into the tube, strengthening the area of the seat tube with the slot cut-out for clamping. For the purpose of this model, the insert was assumed to have the same material properties as the tube. In reality, it would be made from aluminium 6061, as with the rest of the joints, having significantly higher material properties. The insert reduced the stress seen by the tube by almost 25% and shifted the location down to the second joint, just below the length of the insert.

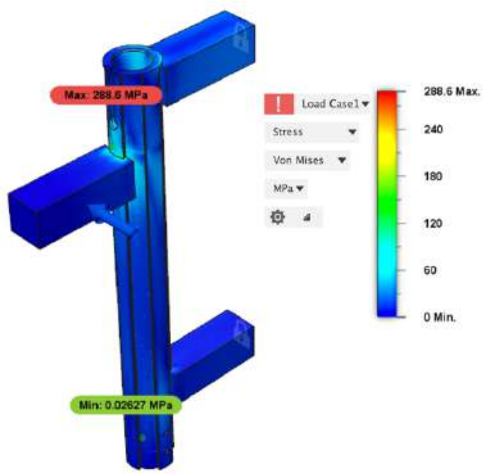


FIGURE 45 - TORSIONAL LOADING WITH STANDARD INSERT

As this was still larger than the ultimate tensile strength of the material of 245MPa, it was decided that the insert should be lengthened to 100mm into the tube. This would extend it just past the second joint, adding extra support. Implementing this study showed a further reduction in max stress, down to 129.2MPa(Figure 46), below the material limit with a safety factor of just under 2. The shift of the max stress position back to the first joint shows that further lengthening of the insert would not improve this value further. As further work, investigation into the effect of lengthening of the joint contact area, therefore increasing the area of action, could be completed to reduce the maximum stress seen by the tube(Equation 2).

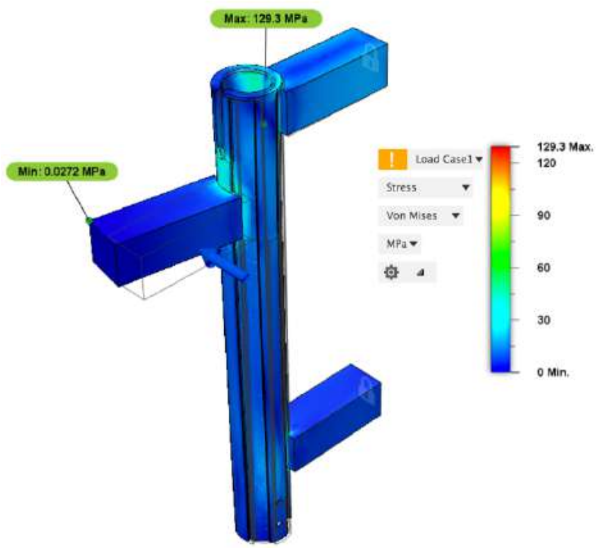
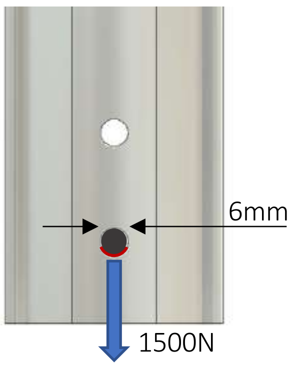


FIGURE 46 - TORSIONAL LOADING WITH LENGTHENED INSERT

12.3.3. SEAT TUBE PIN HOLE TO BOTTOM BRACKET BEARING FAILURE

As with the analysis of the bottom bracket joint, the pin holes through the seat tube to mount this also had to be investigated as a potential failure point. Using the wall thickness of 2mm and an M6 hole size, the area of action could be calculated. Using this, and the material properties in Table 8, the bearing failure load could be calculated(Figure 47). As the ultimate bearing strength of the material was not quoted, an approximation could be used by multiplying the ultimate tensile strength by 1.5 [14].



$$\boldsymbol{Area\ of\ Action = 6 \times 2 = 12mm^2}$$

$$Bearing\ Failure\ Load = UTS \times 1.5 \times Area\ of\ Action$$

$$= 245 \times 1.5 \times 12 = \mathbf{4410N}$$

FIGURE 47 - SEAT TUBE BEARING FAILURE ANALYSIS

These calculations show that each hole through the tube can withstand a 4410N load before failure if acting symmetrically. This gives a safety factor of 2.9. In the design, four of these holes are used, multiplying this to a safety factor of 11.8. As discussed in section 12.2.1.2, for the bottom bracket pin hole analysis, when in use, the maximum stress seen by the material will massively increase, justifying the need for 4 holes.

12.4. STRENGTH OF CLAMPED ATTACHMENTS

Key components on the bike frame rely on a clamped joint to secure in place, making it important to understand how these would behave under load. The joints use bolt tension to provide a clamping force, creating a friction force between the two surfaces, holding it in place. Equation 3 can be used to calculate this friction force, where the reaction force is equal to the bolt tension force. For the joint to stay in place, the force applied parallel to the surface must not exceed this friction force, as shown in Figure 48.

$$Friction\ Force\ F = Coef.of\ Friction \times Reaction\ Force = \mu R \qquad Equation\ 3$$

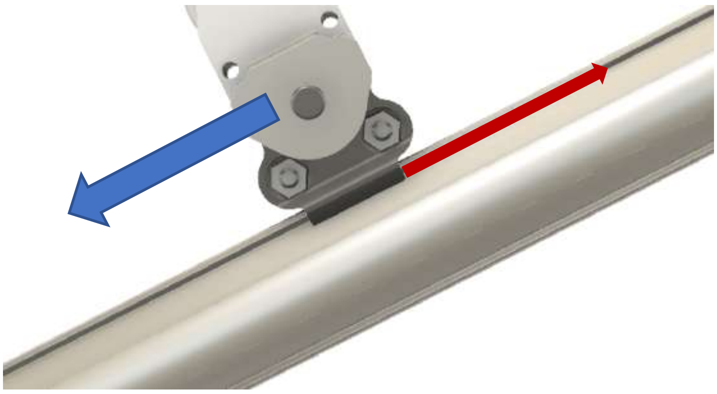


FIGURE 48 - FRICTION ON A CLAMPED JOINT

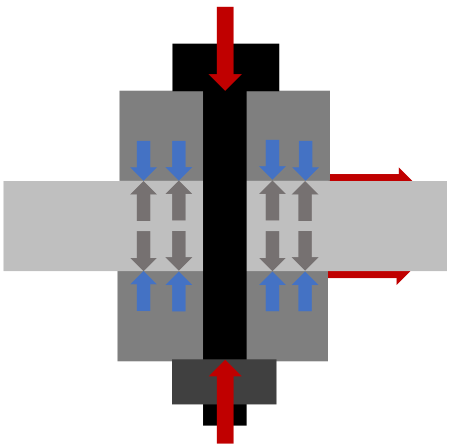


FIGURE 49 - FORCES INVOLVED IN A BOLTED CLAMP JOINT

Figure 49 shows the forces that each component exerts on the others. To calculate the maximum clamping force of the joint, the relationship between the bolt torque and the tension needed to be found. This was achieved using Equation 4 where P is the bolt tension, D is the bolt diameter and k is the nut factor. For a steel bolt, the value of k is 0.2 [16]

$$Torque = kDP \qquad\qquad Equation\ 4$$

There are recommended torque values for each size of bolt. In the design, M6 has been used which has a maximum tightening torque, for a grade 8.8 class, of 11.8Nm [17][4]. From this, a value of 10Nm would be set for the clamps, ensuring the bolt does not reach yield and can be adjusted multiple times after first use. Using these values, a maximum bolt tension of 8333N was calculated.

Equation 3 was then used to calculate the minimum force required to move the joint. To complete this, the coefficient of friction between the joint and the tube was required. The tube profiles have an anodised coating, making the coefficient of friction much less due to its hardness. It was assumed the joints would have a similar coating as a worst case and so a coefficient of friction of 0.17 was selected [18].

$$Friction\ Force = 0.17\ \times\ 8333N\ =\ \mathbf{1417}\boldsymbol{N}$$

With a maximum force of 1500N acting at a 20 degree angle to the seat tube, a parallel force of 1410N would be transferred, as shown previously in Figure 43. This force is supported by 3 clamped joints and the bottom bracket and should therefore be sufficient to hold the weight with a safety factor greater than 3.

The friction value does not depend on the area of the clamp, however, increasing the length of the clamp would spread the clamping force over a larger area, reducing the stress on both the clamp and the tube.

[4] Reaching 85% proof load

12.5. HEAD TUBE

Previously in the design process, the focus was on the adjustment of the seat tube and the rear of the bike, resulting in the head tube not being adjustable in the early stages and was purely used to aid key measurement gathering for the rear half of the bike. This simplified part is shown on the left in Figure 50. Now that the seat tube adjustment had proven to be effective, the same method could be applied to the head tube.

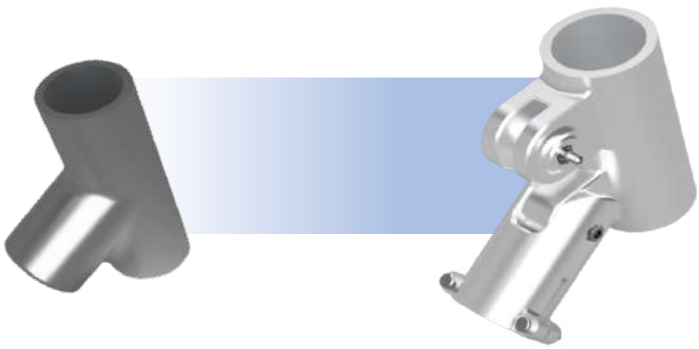


FIGURE 50 - HEAD TUBE JOINT DEVELOPMENT

The head tube was designed in 3 main parts(Figure 51), allowing adjustment by rotation about a down tube clamp. The angle is set by adjusting the length of an adjustable bar connected to the top half of the head tube. The adjustable tube mount, the same as used for the seat tube adjustment, is secured to a bracket at the top of the head tube with the use of a plug, secured in place with a bolt. As with the attachment 2, designed above, this plug minimises the radial forces acting on the bolt, strengthening the joint.

The head tube itself was designed to fit an internal 44mm diameter bearing at both the top and bottom, which would fit the specified 1-1/8 inch steering column.

The down tube clamp is made from one piece, with slits down either side of the cut-out of the profile to allow the part to be clamped to the tube with two bolts. It is secured to the head tube via an extrusion, which it slots around and is bolted in place. These features were made as wide as possible to increase the resistance to torsion, creating a more rigid fixing.

FIGURE 51 - ADJUSTABLE HEAD TUBE EXPLODED VIEW

12.6. ADJUSTABLE TUBE MOUNT MODIFICATION

With there now being two adjustable length tubes in the design, both requiring fixation on the down tube, the middle adjustable tube mount required a redesign. This was done so that they could both be fixed on the existing standard clamp without requiring a second, shown in Figure 52.

FIGURE 52 - HEAD TUBE ATTACHED TO BICYCLE FRAME

As the mounts at either end of the adjustable tube required threading in opposite directions, redesigning the mounts at one end would make this difference more obvious for the user as to which components pair together, aiding in assembly of the bicycle. To achieve this, the bearing profile thickness was halved and placed off-centre to allow the two mounts to interlock and fit in the space of the standard clamp, as shown in Figure 53.

FIGURE 53 - ADJUSTABLE TUBE MOUNT ADAPTATION

13. FRAME EVALUATION

13.1. GEOMETRY EVALUATION

The new design results in a greater number of varying geometries, with the seat tube and head tube angles no longer changing independently. To better understand this influence, a 2D model was created which could show key measurements and how they vary in relationship to each other, shown in Figure 54. This information would be key to understanding the required range of movement of the two adjustable tubes so that the part length can be set.

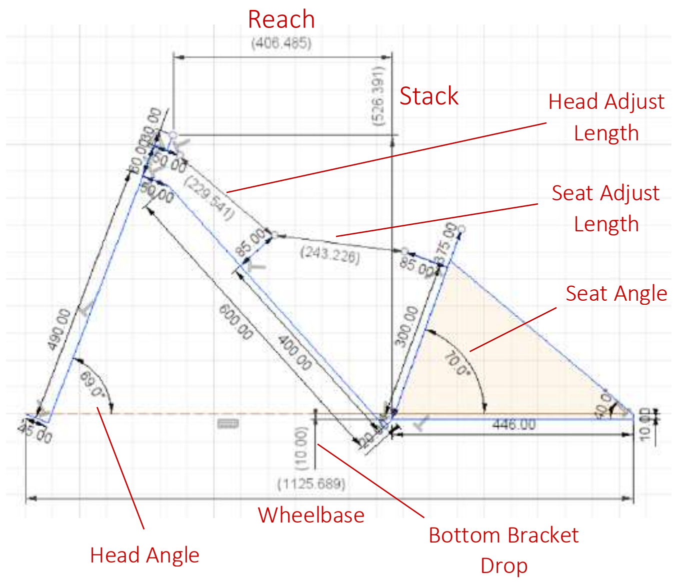


FIGURE 54 - 2D MODEL FOR GEOMETRY EVALUATION OF BIKE FRAME

Table 10 shows the various geometry changes for each measurement, with the largest and smallest value at the top and bottom of each column.

TABLE 10 - NUMBERICAL VALUES FROM BICYCLE FRAME EVALUATION

Seat Angle (°)	*Head Angle (°)*	*Seat Adjust (mm)*	*Head Adjust (mm)*	*BB Drop (mm)*	*Wheelbase (mm)*	*Reach (mm)*	*Stack (mm)*
70.0	*69.0*	243.2	229.5	10.0	1125.7	406.5	526.4
70.0	*74.5*	225.2	238.0	10.0	1058.0	389.6	550.2
75.0	*69.0*	186.1	235.0	48.8	1078.4	361.7	565.2
75.0	*74.5*	166.7	243.6	48.8	1004.7	338.8	589.0

With a maximum range of 76.5mm, each end of the adjustable tube would be required to travel just under 40mm to allow the bike frame to adjust to the specified geometries. With some adjustment to the length of the tube and mount, this was achieved, demonstrated in Figure 55.

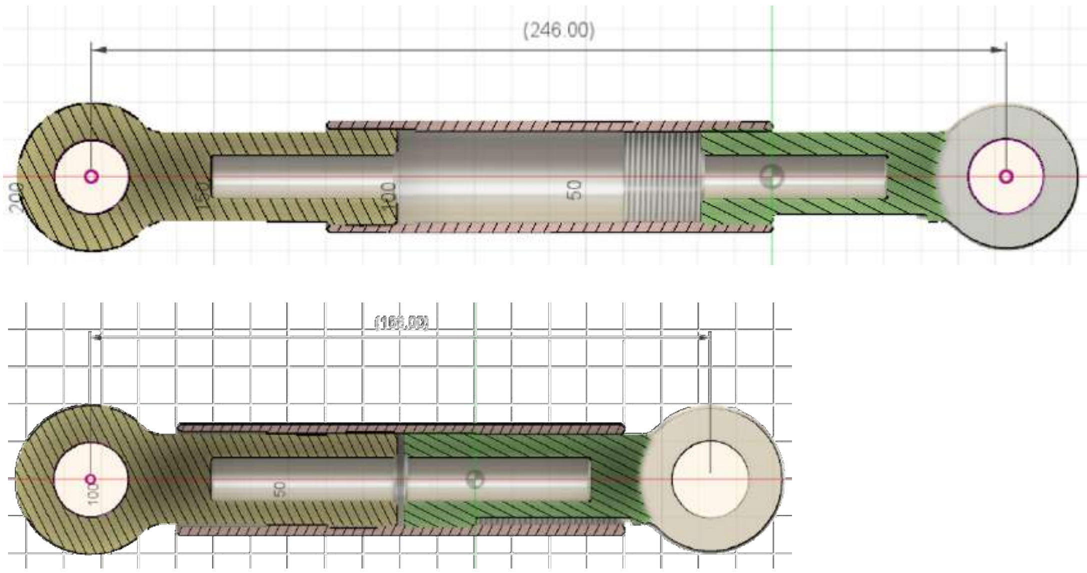


FIGURE 55 - ADJUSTABLE TUBE LENGTH RANGE

13.2. FRAME FEA

Now that the full geometry of the bicycle frame was known, FEA could be completed on the full frame, to better understand how all the tubes would behave, using the calculated values of the seat tube as a comparison check between methods. To simplify the model, getting much quicker results, the joints were modelled as blocks, as they were not the focus and the tubes were made circular. From this, the stresses seen by the circular tubes could be converted to that of the actual tube profile using Equation 1.

As the load distribution is always changing on the bike, static studies were carried out on 4 different load cases.

- 1500N through high saddle position
- 1500N through low saddle position
- 1500N through bottom bracket
- 1500N through Head Tube

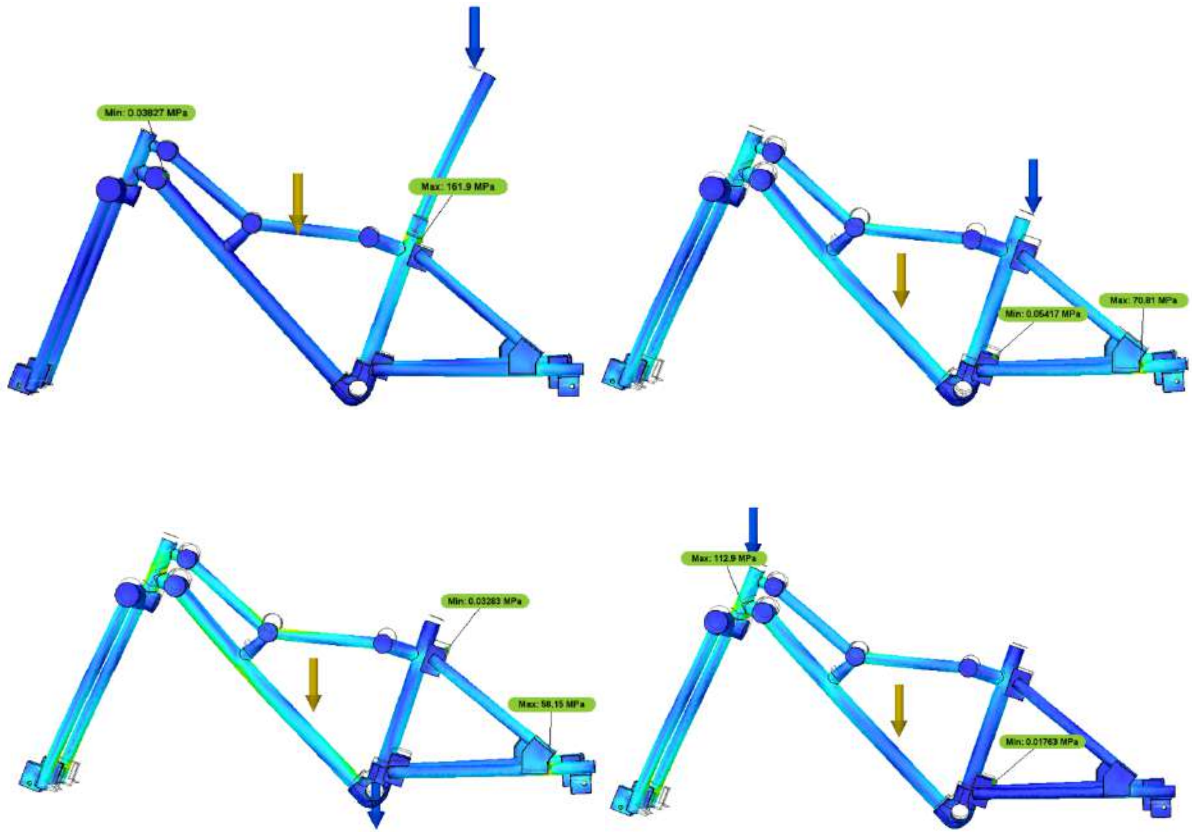


FIGURE 56 - FEA OF FULL FRAME – 4 STUDIES

These load cases are shown in Figure 56 with locations of maximum and minimum stress on the frame. All, apart from the head tube load case, had maximum stress occurring on a tube profile and so needed converting. As the head tube is a designed joint, this can be developed much easier than the profiles and so the other three cases were focused on. To convert this stress to that seen on the selected profiles, the second moment of area needed calculating for the circular profiles(Equation 5).

$$I_{tube} = \frac{\pi}{64}(D^4 - D^4) \qquad Equation\ 5$$

$$I_{t35} = \frac{\pi}{64}(35^4 - 31^4) = 2.34cm^4$$

$$I_{t25} = \frac{\pi}{64}(25^4 - 21^4) = 0.96cm^4$$

Equation 1 was then used to calculate the bending moment causing this stress and, using the profile's second moment of area, the subsequent stress that would act on the actual tube profiles.

$$\boldsymbol{I_{p40} = 3.88cm^4} \qquad \boldsymbol{I_{p30} = 1.71cm^4}$$

$$High\ Saddle\ Max.Bending\ Moment = \frac{\sigma_{hs}\ I_{t35}}{17.2}$$

$$= \ 220\ 314Nm$$

$$High\ Saddle\ Max.Actual\ Stress = \frac{M_{hs}\ \times\ 20}{I_{p40}}$$

$$= \ 113.6N/mm^2$$

$$Low\ Saddle\ Max.Bending\ Moment = \frac{\sigma_{ls}\ I_{t25}}{12.5}$$

$$= \ 54\ 382Nm$$

$$Low\ Saddle\ Max.Actual\ Stress = \frac{M_{ls}\ \times\ 15}{I_{p30}}$$

$$= \ 47.7\ N/mm^2$$

$$Bottom\ Bracket\ Max.Bending\ Moment = \frac{\sigma_{bb}\ I_{t25}}{12.5}$$

$$= 44\ 659Nm$$

$$Bottom\ Bracket\ Max.Actual\ Stress = \frac{M_{bb}\ \times\ 15}{I_{p30}}$$

$$= \ 39.2N/mm^2$$

As the majority of the time the highest forces would occur during dynamic loading, a high safety factor of 3, compared to the yield strength in Table 8, was made the target for these static load cases. Table 11 shows that, although the stresses are under the material limits, the high saddle max stress did not reach the target safety factor. This value was backed up by the hand calculations completed in section 12.3.1.

TABLE 11 - STRESS CONVERSION FROM FEA

Load Case	Max. Model Stress (MPa)	Bending Moment (Nm)	Max. Actual Stress (MPa)	Safety Factor
High Saddle	161.9	220314	113.6	1.7
Low Saddle	70.81	54382	47.7	4.1
Bottom Bracket	58.15	44659	39.2	5.0

From investigating the location of maximum stress in the multiple load cases, it was found that they occurred at either end of the seat stay, as predicted to be the largest load carrying component in section 12.3.1. As the stress was seen in the components attaching to the seat stay and not the seat stay itself, its position was extended to the extremity of both the seat tube and chain stay. This resulted in the rear triangle being larger, increasing the second moment of area and not allowing single members to take large loads without support.

FEA was then repeated, shown in Figure 57, on the new layout for the 3 load cases to observe how this would affect the maximum stress. The same method of calculating the actual profile stress was completed with final values shown in Table 12. The change in layout caused the case with full load through the bottom bracket to move its maximum to the head tube, not a profile, and so was omitted from the calculations. The maximum stress for high saddle position was also found to be on the removable seat post and therefore outside the scope of design. With further investigation, it was found that the maximum stress found on the frame for this case was roughly 56.5MPa, not the 88.5MPa found on the seat post. The results show that the adjustments made to the position of the seat stay have meant that all the static forces on the frame are now acceptable values, all achieving the target safety factor of 3.

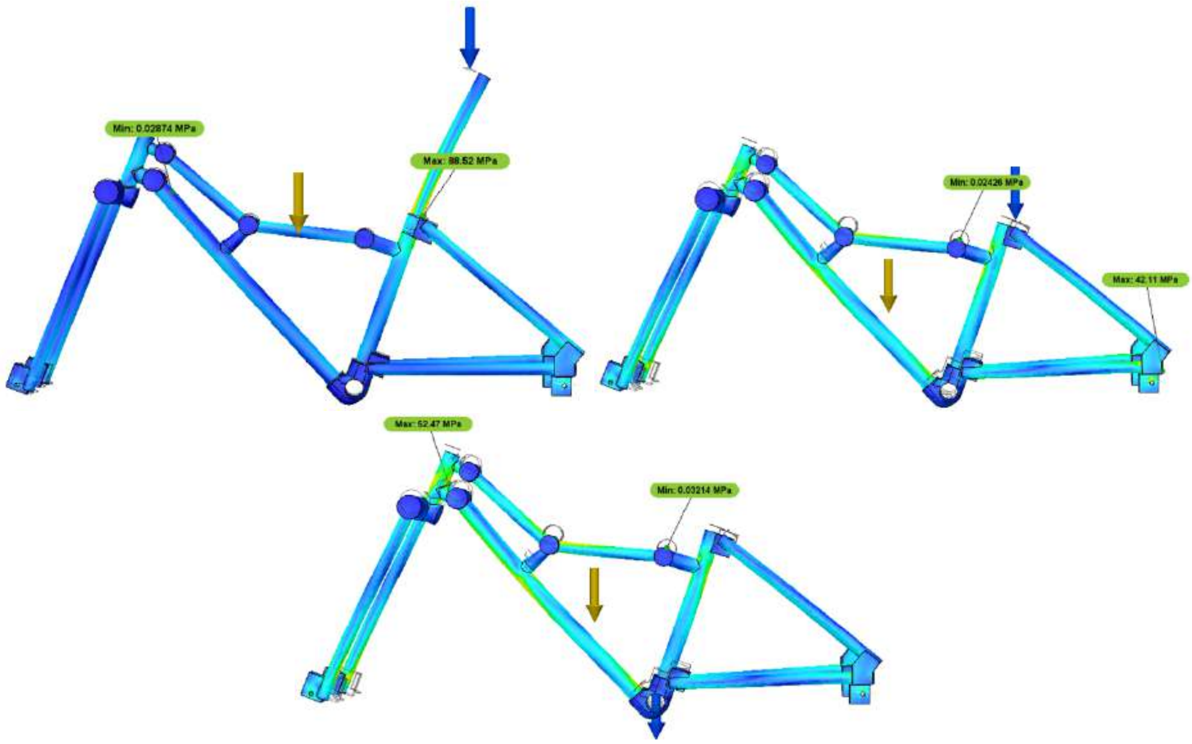


FIGURE 57 - SECOND FEA ON FRAME REDESIGN

TABLE 12 - REPEAT STRESS CONVERSION FROM FEA

Load Case	*Max. Model Stress (MPa)*	*Bending Moment (Nm)*	*Max. Actual Stress (MPa)*	*Safety Factor*
High Saddle (Seat Post)	88.52	120428	62.1	3.2
High Saddle (Frame)	56.5	76866	39.6	4.9
Low Saddle	42.11	32340	28.4	6.9

14. REMAINING FRAME JOINTS

As well as the main joints, required to achieve the geometry changes, discussed in the early part of the report, there were also many smaller joints designed which were key to the bike frame working and being able to withstand the required load.

14.1. REAR TRIANGLE CLAMP

With the seat stays and chain stays secured in place with the standard joint and attachment 1 (Section 12.1.1) a second joint was required to secure the two together at the rear of the bike, completing the rear triangle. This was essential for maximizing bike strength and stiffness. The designed clamp can be seen in Figure 58, designed to clamp on the outside of the profiles to maintain flexibility between profile sizes. The joint is made up of two clamps set at 40° from each other to receive the stays, both at 20° from the seat tube. The joint is made from two different components, the main body, which sets the angle, and two clamping components, standard for both sides, holding the tubes in place. Each clamp is secured with an M6 bolt threading into the main body.

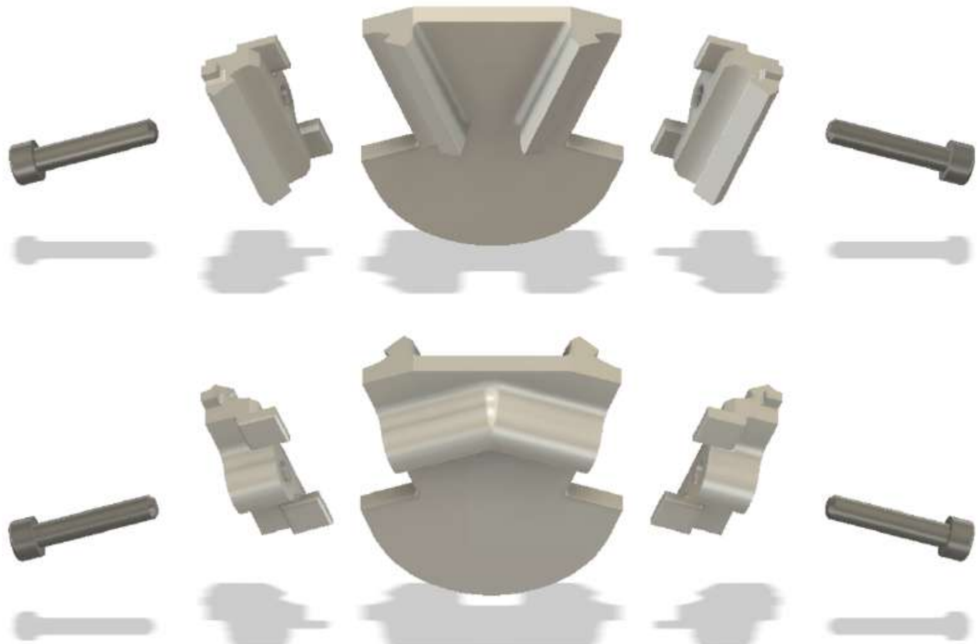


FIGURE 58 - REAR TRIANGLE CLAMP

14.2. DROP OUTS

Another key component are the drop outs, allowing the wheels to be secured to the frame, without which, the frame would not function. As with the other joints, these were designed to clamp onto the outside of the tube to maximise flexibility and adjustability. This allowed the position of the joints along the tube to be adjusted to suit a variety of wheel sizes and configurations.

14.2.1. FRONT FORK DROP OUT

The drop outs for the front fork are shown in Figure 59 and comprise of a main body, to secure the hub axle to, and a clamping element. The main body was mirrored for each side, with a circular cut-out to locate the wheel for the user while tightening the axle. The clamping element is standard for both, secured with an M6 bolt, threaded into the main body.

FIGURE 59 - FRONT FORK DROPOUTS

As mentioned above, the joint has been designed to clamp on the outside of the fork legs, creating adjustability for wheel size. For smaller wheels, the clamps can be lowered, maintaining the geometry requirements in the main frame, and vice versa for larger wheels. These joints were not designed to be adjustable for hub width as initial research suggested that front hub width did not vary as much as rear and was therefore thought unnecessary.

14.2.2. REAR FORK DROP OUTS

The rear fork drop outs were slightly more complicated to design than the front. This is due to them being attached to a tube at an angle. The drop out was set at a 10^{o} angle from the clamp and rotated 2^{o} to account for the twist in the tube as a result of the seat tube to stay clamp attachment being rotated 20^{o}. Several iterations of this joint were developed, the main two shown in Figure 60. The design started as a standard drop out that would be found on a single speed bike with a threaded hole next to where the rear axle would go to add tension to the chain once attached. It was later decided that a simplified version would achieve the same functions and be easier to manufacture. This was decided due to fact that the drop out is clamped to the side of the tube. This allows the position of the joint to be moved along the chain stay length, not possible on a standard bike. This lets the joints add chain tension and adjust for varying size of hub width. This is achieved without changing any of the key geometry measurements as the chain stay was designed to be parallel to the ground.

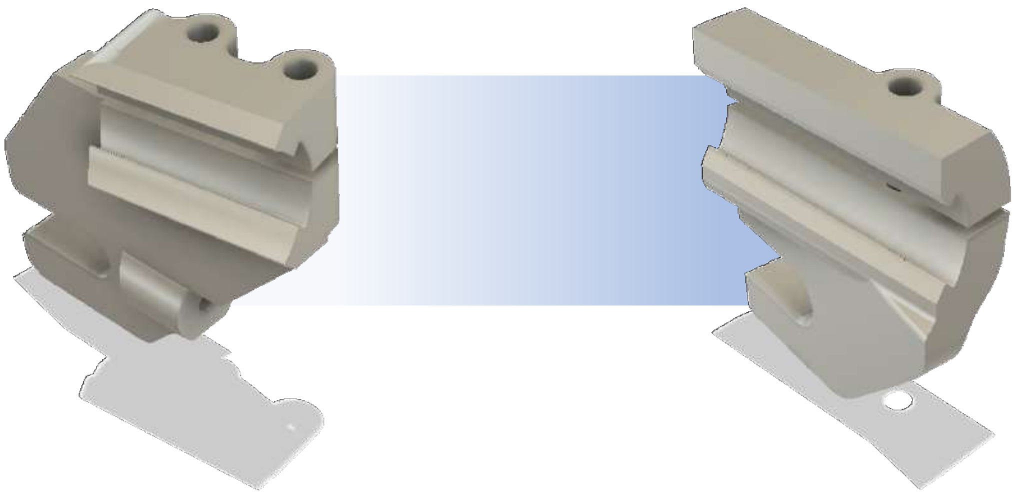


FIGURE 60 - REAR DROP OUT DEVELOPMENT

14.2.3. BRAKE BOSSES

A key safety aspect and requirement of the bike is for it to have two brakes on it, one on the front and one on the back. To keep with the adjustability theme, a solution was developed that could be used for both rim brakes, adjusting for multiple wheel sizes, and disc brakes, for multiple disc sizes. The design journey is mapped out in Figure 61 adding more design features throughout. The second iteration was developed to move the clamping area to the other side of the tube from the drop out, allowing a greater level of adjustability. Previously, the two joints would clash, causing the disc brake location not to work.

The final design is standard for both bosses and is comprised of 3 parts and two bolts. The central part connects to the clamping element and provides location for the boss components. This component has two setting it can sit at, to be used for either width of tube, critical for the cargo attachment discussed later. This was necessary due to the change in location of the clamping element to the far side of the tube from the boss, as shown in Figure 62.

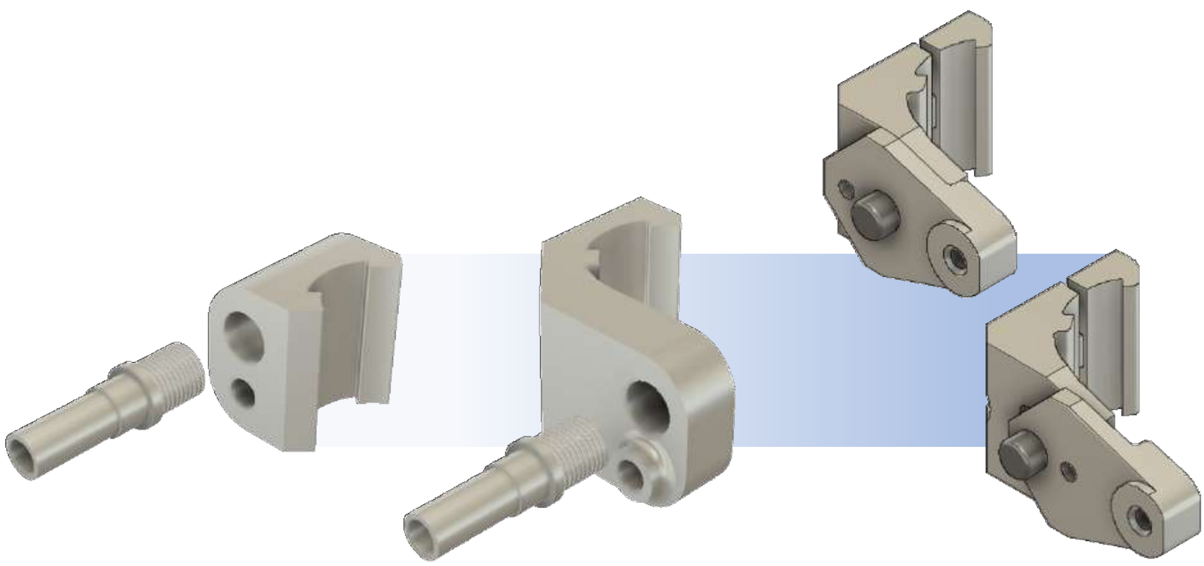


FIGURE 61 - BRAKE BOSS DEVELOPMENT

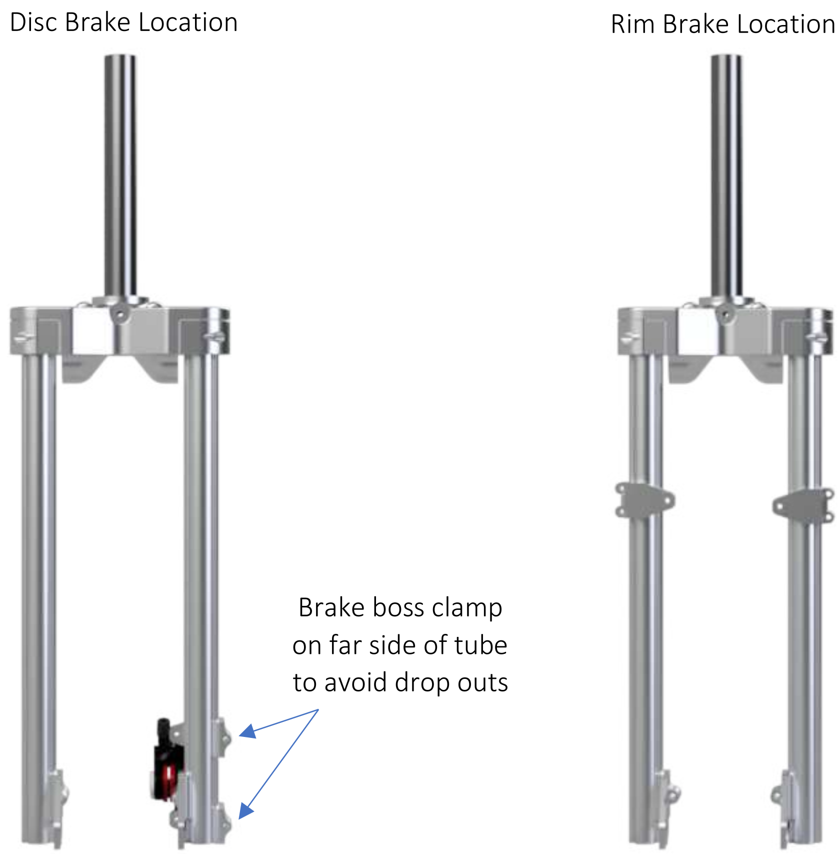


FIGURE 62 - TRANSITION BETWEEN RIM AND DISC BRAKES

These bosses can be used on the rear forks for rim brakes but due to the diagonal position of the stays, would not work for disc brakes. Because of this, a different top clamp for the left rear drop out was developed so that a disc brake calliper could be mounted, shown in Figure 63. This means that adjustments in drop out would also change the calliper position, ensuring it is in the right location. This results in standard adaptor plates being bought, as used on conventional bicycle frames, for different disc size.

FIGURE 63 - REAR BRAKE CALLIPER MOUNT

14.2.4. END CAPS

Lastly, the tube profiles required end caps to ensure that the insides of the tubes stayed clean, aiding maintenance of the bike, and covering sharp edges. Two example solutions for the 30mm and 40mm diameter profiles are shown in Figure 64.

FIGURE 64 - PROFILE END CAPS

15. CARGO ATTACHMENT

15.1. CONCEPT SELECTION

Once the standard bike frame design was completed, synergies were investigated between its components and a cargo bike to understand the best layout to develop. The goal of this was to reuse as many parts as possible from the standard bike to the cargo bike. From the cargo bike analysis undertaken in Mini Study 1 [3], multiple cargo bike types and their advantages and disadvantages were known. From this, the best compromise between synergies and advantages of the cargo bike was sought.

From the initial research, a large single cargo attachment was decided on rather than multiple smaller ones, increasing flexibility of items carried. It was also decided that the attachment should be at the front so the rider can see the cargo, letting them feel at ease. This means that the cargo area would need to be low to allow the rider to see over the top, making it safer to ride.

Analysing the cargo frame, it was found that the rear portion of the bike has limited adjustability and provides a sturdy base to any design and so the front half should be looked at for the transition between use cases. Looking at future examples, most cargo bikes with front attachments have a large horizontal tube from the bottom bracket to the cargo attachment. Having the adjustable bottom bracket allows this to be achieved easily with existing components of the bike. The head tube could also be used if required by adjusting this to the vertical position and acting as the steering axis, making the transition even easier and using all components on the frame.

The fork attachment requires a lot of work to take off and replace. To overcome this, it was decided that the front fork crown should be developed to transition in a way that would allow it to stay attached in the cargo layout.

15.2. CONCEPT DEVELOPMENT

15.2.1. ADJUSTABLE TUBE LENGTHENING

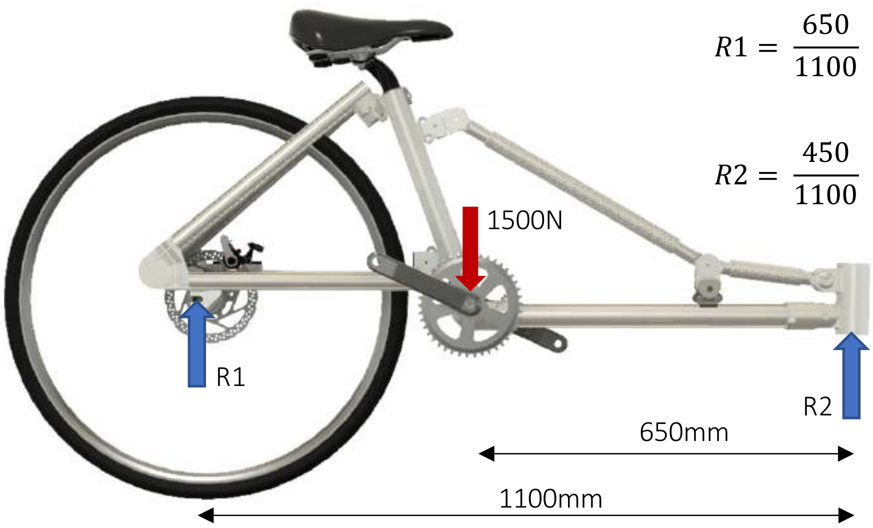
As mentioned above, the down tube is required to move horizontal to be used in the cargo layout. This could not be achieved with the existing adjustable tube length. A new tube was required, increasing the length from 120mm to 365mm, shown in Figure 65.

FIGURE 65 - LENGTH DIFFERENCE OF CARGO ADJUSTABLE TUBE

15.2.2. FORK CROWN REDESIGN

To allow the fork components to be reused in the cargo layout, the legs required securing in a horizontal position to connect to the cargo attachment, transmitting the turning input from the rider. Before the changes to the crown were entered, force analysis was completed on the fork legs to ensure they would be strong enough in this orientation.

To complete this, the bicycle reaction forces needed recalculating, with the load at R2 in Figure 66 being approximated to the load that the fork legs would see. The position of the maximum load was assumed to act through the bottom bracket, the furthest forward loading point on the frame as a worst case, as shown in Figure 66.



$$R1 = \frac{650}{1100} \times 1500 = 886N$$

$$R2 = \frac{450}{1100} \times 1500 = 614N$$

FIGURE 66 - RECALCULATING THE REACTION FORCES IN THE CARGO POSITION

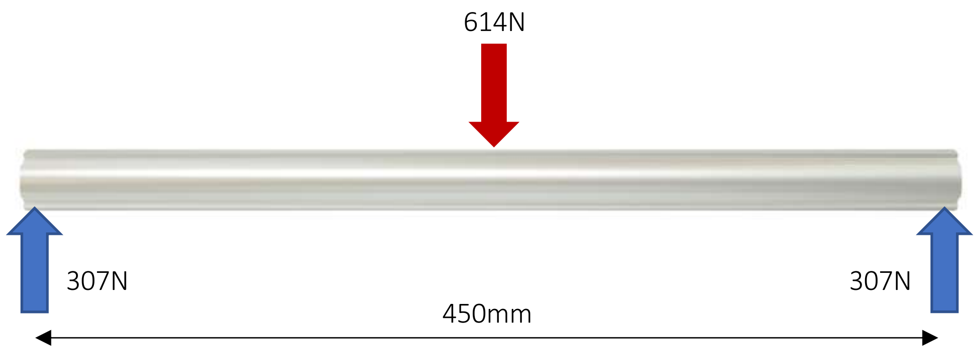


FIGURE 67 - LOADING OF THE FORK LEG IN THE CARGO POSITION

$$Max. Bending\ Moment = 307 \times 225$$

$$= 69075Nmm$$

Using Equation 1, the stress on the beam was then calculated to be 60MPa using the forces and positions shown in Figure 67. With a yield point of 195MPa, this gives a safety factor of 3.2. This is assuming all the load is going through one fork leg, as a worst case.

$$\sigma = \frac{My}{I} = \frac{69075 \times 15}{17100} = 60.6MPa$$

Once the layout was shown to be strong enough, the fork crown was redesigned to accommodate the new layout. The development of the fork crown throughout the project is shown in Figure 68.

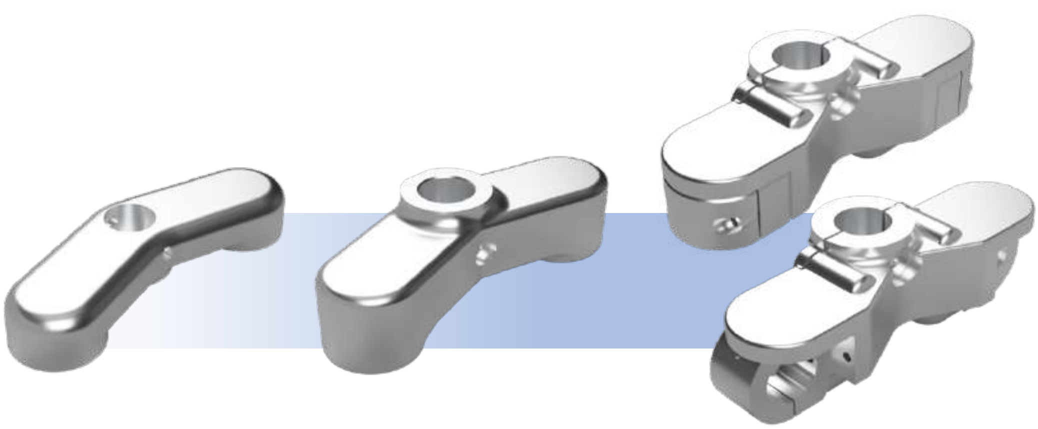


FIGURE 68 - FORK CROWN DEVELOPMENT

The redesigned crown for cargo layout involved removing the clamps from the main body, allowing them to be secured in two orientations for each set up. The material above the clamp remained attached to the main body to locate the fork legs in the standard position, adding extra support against vertical forces in both orientations, reducing the shear force on the bolts. When the clamps are removed, this opens the top of the clamp, allowing it to slide along the length of the leg into the position shown in Figure 69. The two layouts for the fork are demonstrate in Figure 70.

FIGURE 69 - CARGO FORK POSITION

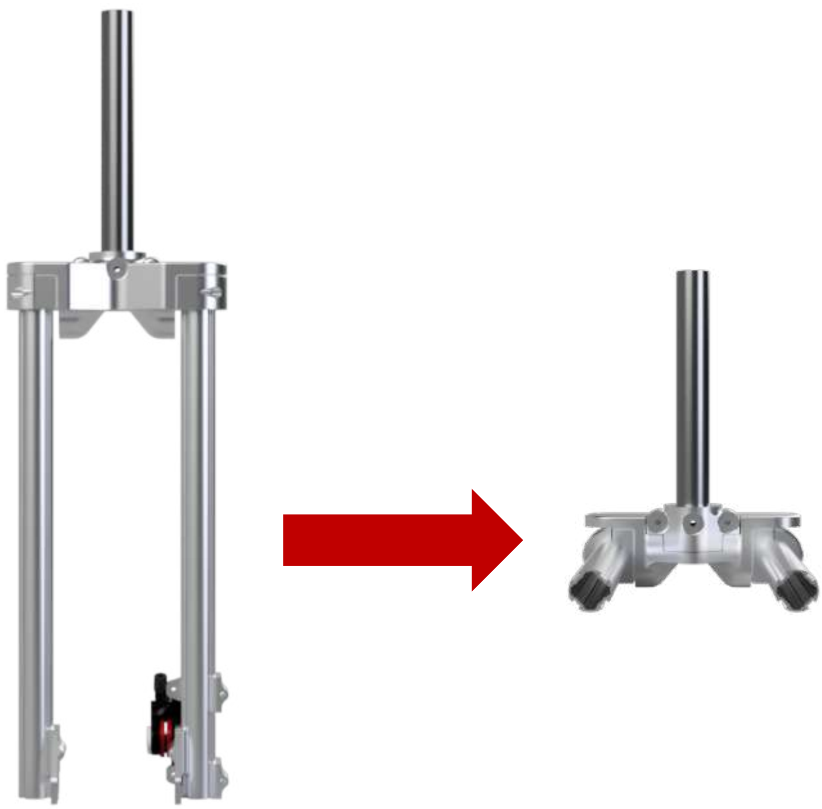


FIGURE 70 - FORK LAYOUTS

15.2.3. CARGO ATTACHMENT DESIGN

15.2.3.1. 90° JOINT

With the basic cargo design decided in section 15.1, a joint to hold tubes at 90º to each other was required. Due to the shape of the profile, a clamping joint could be standard, holding both sizes of tube, shown in Figure 71. The two tubes are secured in place with an M6 bolt for simplicity and the clamp has an extrusion on the inside edge to align the two components, aiding the user when assembling.

FIGURE 71 – 90° JOINT

15.2.3.2. TUBING

With the fork crown redesigned, the cargo attachment could be developed using the length of the front fork legs. The final frame design was primarily made from just two profiles. The longer 40mm diameter tubes are 800mm long and the shorter 30mm diameter tubes are 450mm(Figure 72), the same length as the fork legs and rear stays. The larger tubes are used for the main base, taking the majority of the potential cargo load with the smaller tubes adding shape to the box. The one tube of a different length is the one positioning the handlebars at the maximum value for stack of 630mm, requiring a shorter length of 300mm. Having a vertical tube to secure the handlebars allows easy adjustment for a variety of rider sizes.

FIGURE 72 - CARGO FRAME

The position of the fork wants to be far back to stop the handlebars having to move large distances to turn. The wheels also want to be as close to this steering axis as possible to improve handling. The factor determining the position relative to each other are the brake bosses, which share the same attachment tube as the fork. To ensure these components do not interfere, the drop outs need to be positioned 45mm in front of the steering axis, allowing the brake bosses to sit inside the fork legs, as shown in Figure 73.

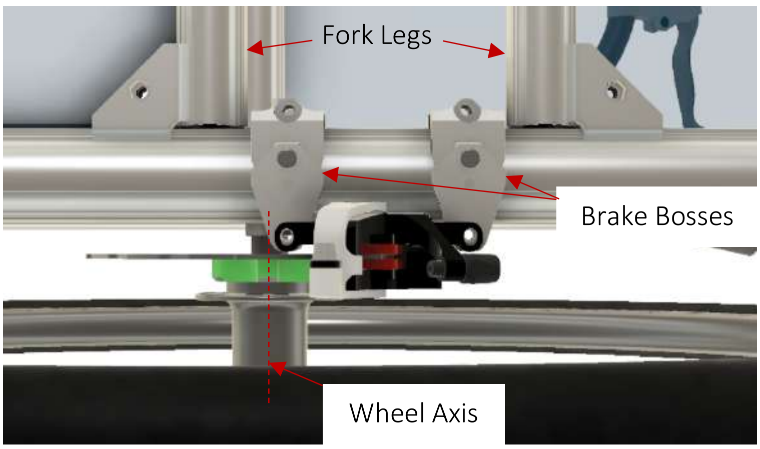


FIGURE 73 - WHEEL POSITION IN RELATION TO FORK LEGS

The position of the transformed front fork was decided based upon the size of the largest potential wheel size. Having the seat tube at 70° and the down tube horizontal allows the head tube to sit perpendicular to this and 20 inch wheels to be fitted to the standard front fork drop outs.

As well as this, the cargo attachment was designed to cope with multiple wheel sizes with an increase in angle of down tube adjusting for bigger wheels without changing the seat tube angle. Because of this, the position of the fork should depend on the largest wheel size, 700c(Figure 74). The position was moved as far back as possible without interfering with the rear tube.

FIGURE 74 - FORK POSITIONING ON CARGO FRAME FOUND FROM WHEEL SIZE

15.2.3.3. PANELS

Once the frame geometry was known, the panels could be designed to hold the cargo. The rear of the attachment was required to stay open to allow the down tube to go through and attach to the fork and so the area for cargo has a step in it. This means that it can be used as a seat for children to sit on as well as standard cargo.

The panels designed are shown in Figure 75 in their intended layout, secured together with a variety of support joints. It was important to ensure the size of the panels was not too large, catching the wind when ridden. The largest side panel has an area of 0.26m^2, a quarter of the specified maximum of 1m^2. The tallest part of the cargo attachment is under 770mm from the ground ensuring good visibility for the rider.

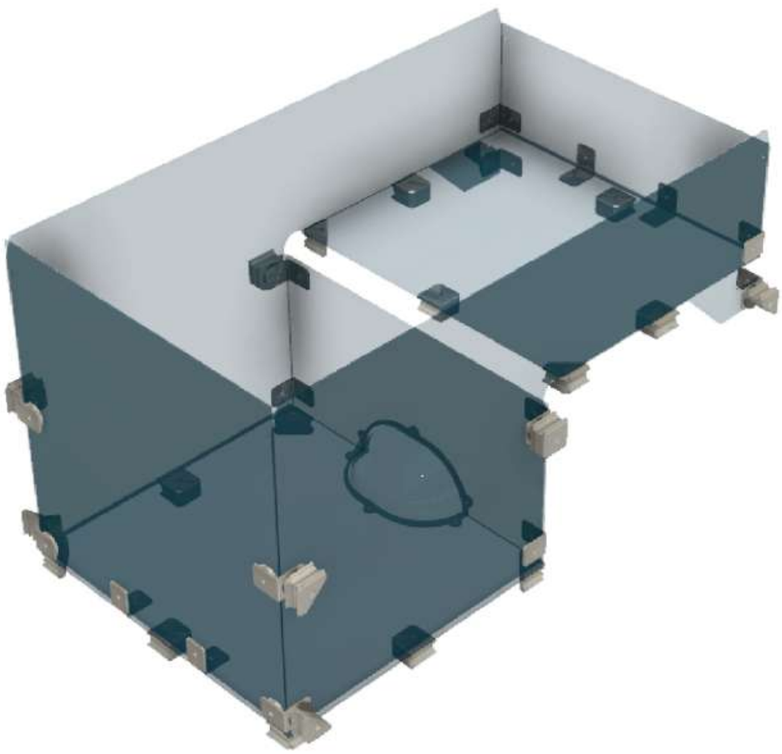


FIGURE 75 - PANEL DESIGN LAYOUT

15.2.3.3.1. SUPPORT JOINTS

To secure the cargo panels together(Figure 75), 90^{o} corner fasteners were used(Figure 76). This ensuring no large gaps appear under loading, causing cargo to potentially fall out.

To secure the panels to the tubes, both the corner pieces and the piece shown on the right in Figure 76 were used. Both these joints are clamped to the side of the tubes and using a longer bolt to both clamp the joint and secure the panels in place.

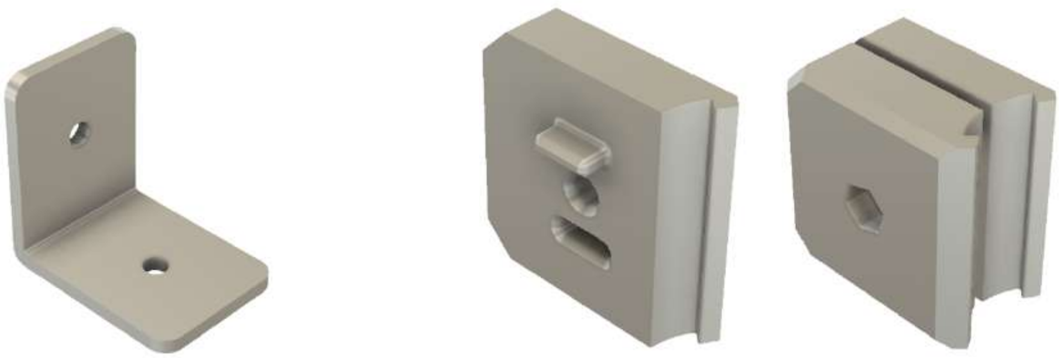


FIGURE 76 - SUPPORT JOINTS FOR PANELS

16. PROTOTYPE

With the final design complete, a prototype was produced so that it could be visualised and inspected in actual size. Due to time and funding constraints, the joints were 3D printed out of plastic, resulting in the bike being too weak to ride and test. This meant that only the geometry changes could be tested along with the testing of joint assembly.

When the tube profiles were ordered, standard aluminium clamps were also bought to get a better idea of the actual rigidity the joints would have, shown in Figure 77.

FIGURE 77 - STANDARD ALUMINIUM JOINTS

A selection of the 3D printed joints are shown in Figure 78 showing them assembled with bolts. Due to the fragility of the parts, bolts could not be properly tightened but access to them could be evaluated. An example of this is for the green joint in Figure 78, the white standard joint could be tightened and loosened with the green part attached, making assembly much easier.

FIGURE 78 - 3D PRINTED PROTOTYPE JOINTS

The prototype bike frame, shown in Figure 79, was assembled with 700c wheels. The bottom bracket joint fit the standard bearing as intended with room to add pedals and chain ring without interfering with the chain stay. The wheels fit onto the bike, adjusting the rear drop outs to fit the 135mm hub and having tyre clearance at the seat tube.

FIGURE 79 - STANDARD BIKE FRAME WITH 700C WHEELS ATTACHED

Instead of manufacturing the threaded adjustable tubes, plastic syringes were cut into tubes and electrical tape was added to the outside of the adjustable tube connectors to add grip. The tubes could then slide and adjust easily but would be held in the position they were set, to carry out quick testing.

The stand, shown in Figure 80, was used to evaluate the performance of the frame against the geometry and ergonomics section of the specification points (Appendix A). It held the rear drop outs, allowing the bike to pivot around it, like a wheel, so that seat tube angle and bottom bracket drop could be measured against the lines marked out. The front stays were able to slide parallel to the ground, allowing the head and seat tube adjustments to be carried out unimpeded. Angles were also displayed in front of the fork to observe their position. The frame was able to achieve all the specification points apart from the reach. The target range was between 360mm – 400mm whereas the actual range was within 340mm – 410mm. Further investigation with a prototype out of the intended material would determine whether this is acceptable or whether it makes it difficult to ride. The bike was designed to be used with reversible handlebars, changing from bull horn to cruiser orientation(Figure 81). This would solve the problem for hand position but leg room for the larger rider would need to be investigated at the shorter reach distance.

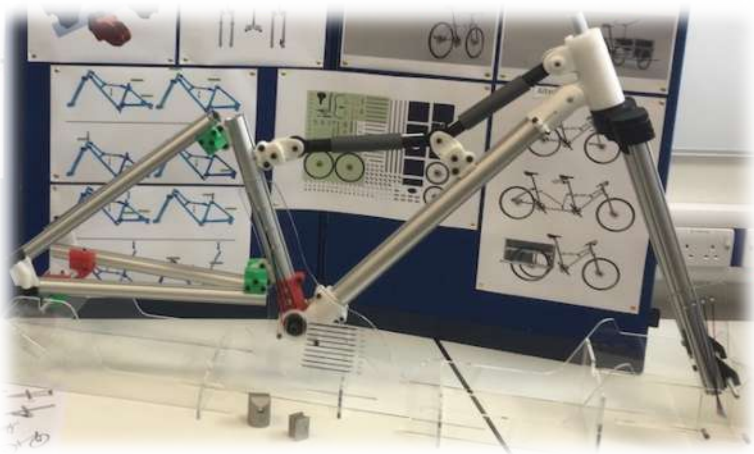


FIGURE 80 - GEOMETRY CHANGE TESTING RIG

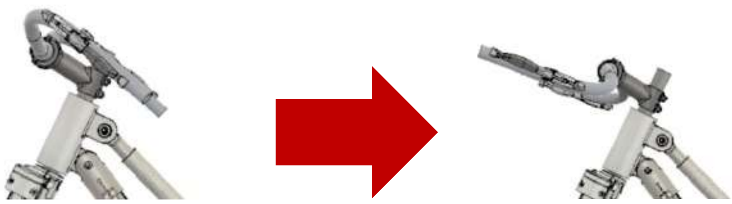


FIGURE 81 - REVERSIBLE HANDLEBARS

17. FINAL SOLUTION

The final solution for both the standard bike and the cargo bike can be seen in Figure 82 and Figure 83 with the key geometry features summarised in Table 13. Assembly and sub-assembly drawings for the frame and joints can be found in Appendix B.

FIGURE 82 - FINAL BICYCLE DESIGN

FIGURE 83 - FINAL CARGO BIKE DESIGN

TABLE 13 - FINAL DISIGN ACHIEVEMENTS

Measurement	*Value Range*
Seat Tube Angle (°)	70 – 75
Seat Tube Length (mm)	400 – 700
Head Tube Angle (°)	69 – 74.5 (90 for cargo)
Bottom Bracket Drop (mm)	10 – 50
Reach (mm)	340 – 410
Stack (mm)	525 – 590
Wheelbase (mm)	1005 – 1125 (1145 for cargo)
Bike Frame Weight (kg)	6.5
Cargo Attachment Weight (kg)	16

17.1. COMMERCIAL CONSIDERATIONS

This bicycle frame would be sold as a kit for the user to assemble to the geometry they want. Example kits could be the components for a standard bike or they could pay more for a larger kit which is for a standard bike and cargo bike. This example is shown in Figure 84, where the green area is for a standard bike and all components are needed for the cargo bike.

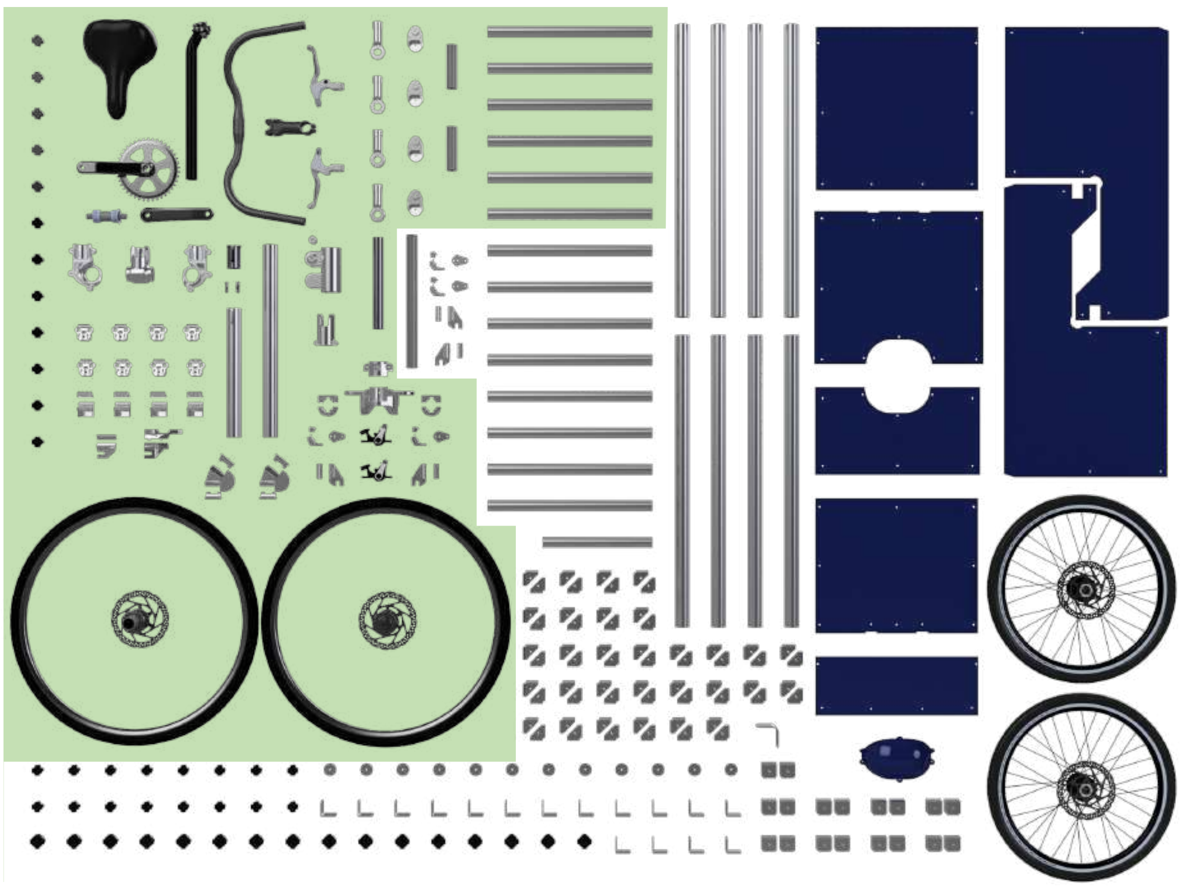


FIGURE 84 - COMPONENT LAYOUT

For a kit to be assembled effectively, a set of instructions and pictures would need to be completed, giving the user a step by step guide to the easiest way to assemble each configuration.

The majority of the joints are located at the end of profiles but to aid assembly of the others, key geometry measurements could be marked on the tubes in the kit so that the user does not have to measure set distances, with an example shown in Figure 79 for the white joint. This could be done on the seat tube and head tube as well as on the fork to show a variety of options for brake boss position.

17.2. OPEN SOURCE ASPECT

From the beginning, it was known that the project material would be made publicly available for people to use and modify. It was decided that GitHub would be used to achieve this and an account and repository was created for the files at the beginning of the project. The focus then became creating a first layout and an example layout change to demonstrate the concept aims. This resulted in the open source aspect of the project being completed later on, allowing the progression of the project to continue in the future. Figure 85 shows the Adjustabike repository with corresponding README file, giving information to the public about the project for them to study. A suitable license still needs to be applied, such as CC-BY or TAPR Open Source Hardware License.

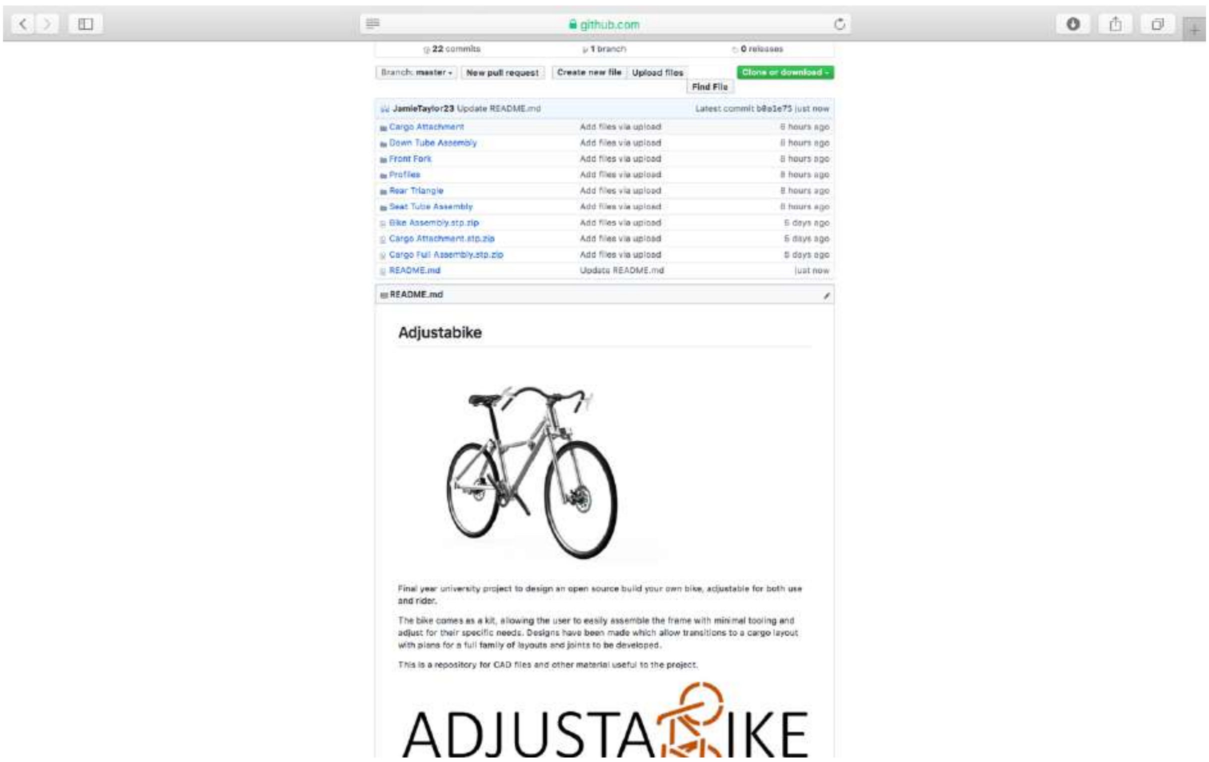


FIGURE 85 - GITHUB REPOSITORY FOR ADJUSTABIKE

17.3. EVALUATION

17.3.1. COMPARISON WITH EXISTING SOLUTIONS

Looking back to Mini Study 1 [3], two existing solutions were identified as successful, similar to the direction of this project. It was therefore important to evaluate and compare the final design against the two, shown in Figure 2 and Figure 3.

It was concluded in this mini study that more adjustability and fewer destructive joining processes were required over the XYZ cargo bike and a higher load capacity and more functional layouts should be developed over the Infento kit.

The final design uses clamped joints where possible, maximising the adjustability after first assembly and minimising destructive processes. For the joints analysed so far, the load capacity is greater than the Infento kit and the developed layouts are much more functional, tailored towards the adult market.

17.3.2. COMPARISON WITH SPECIFICATION

Comparing the final design against the specification produced the values shown in Table 14. The majority of the points were achieved, including the key geometry and compatibility requirements, key to the bike functioning correctly

TABLE 14 - SPECIFICATION CHECK

	Number
Achieved	54
Unobtained	2
Requires Future Work	13

The two unobtained points are shown in Table 15. The first point, G9, has been discussed in Section 16 where future testing with a user would show whether this is an acceptable range. F8 was not achieved, with a cargo area of $0.12m^3$. This was mainly due to the width restrictions of the cargo so that it could be easily operated (Spec point O11). The achieved cargo size is ideal for a child to sit in and to carry a weekly shop home and was therefore deemed acceptable and a vast improvement over the standard bike cargo capabilities.

TABLE 15 - UNOBTAINED SPECIFICATION POINTS

G9	Frame reach must be between 360mm - 400mm	Mini Study 2	D		5/12/2018
F8	The cargo attachments must hold a volume of at least $0.2m^3$	Existing product comparison	D		31/10/2018

18. FUTURE WORK

With the majority of the layout decisions decided, the remaining work involves completing further analysis of the joints to ensure the frame is strong enough, a key factor for the bike to function. The force analysis so far has been to apply static loading and ensuring a significant safety factor. Manufacturing the frame out of the intended material would allow dynamic loading to be applied, similar to how it would actually be ridden, giving a better idea of success.

Length of clamping surfaces may also need to be investigated further to reduce stresses on components, applying the force over a larger area. Figure 86 demonstrates this effect, with the same loading conditions as Section 12.3.2, but with two thirds of the maximum stress due to an increase in clamp length from 30mm to 50mm.

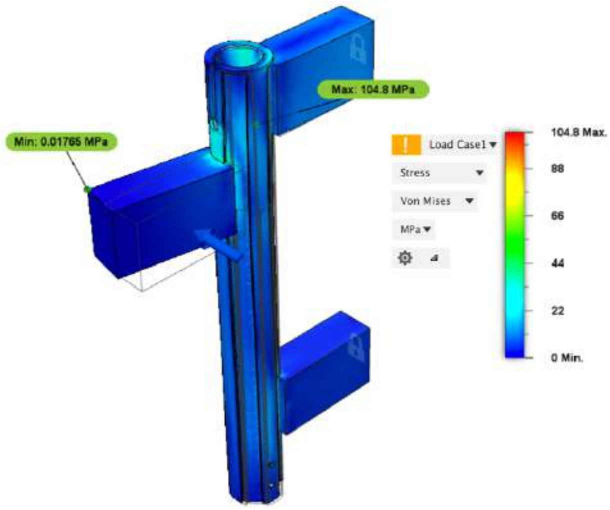


FIGURE 86 - INCREASED CLAMPING AREA ON SEAT POST

Once all joint forces have been analysed and approved, user testing could be completed to fully understand the effect of the changing geometries of the bike. It would also be important to understand how often a user would want to adjust tube angles on the standard bike, or whether the adjustable tube could become a set length that the user decides when they buy the kit with a different standard length for bicycle and cargo frame layouts.

Materials and manufacture would also need to be investigated further. Throughout the joint development process, it was assumed that the designed components would be cast aluminium, the same as the standard joints used by the profile manufacturer and many standard bicycle frames. Its light weight properties and strength lend itself well to this application but further analysis should be completed to ensure this is the optimum material. This would then inform the final cost and price of the full kit.

Possible further development of the existing layouts, to allow folding up, or development of new layouts, such as in Figure 87, Figure 88 and Figure 89 should be developed which could lead to the creation of a wide range of kits, similar to Infento. On top of this, small attachments to the frame for water bottle holders and other standard fixtures could be developed.

FIGURE 87 - SMALL CARGO ATTACHMENT LAYOUT

FIGURE 88 - TANDEM BIKE LAYOUT

FIGURE 89 - REAR CARGO ATTACHMENT LAYOUT

A key issue with the concept, identified early on, is the safety of the bike when locked up. Due to the adjustable nature of the frame, it is easy for it to be dismantled, making it difficult to secure safely in a public place. To overcome this, investigation into adding a locking element to key components of the bike should be completed. This could be done to the bottom bracket so someone cannot cycle away with the bike. An internal cabling system could also be implemented, shown in Figure 90, securing the key profiles together, creating a secure rear triangle to lock through.

All the future work can be assisted by making it open source on GitHub. This opens up the project to new ideas and knowledge, developing it further.

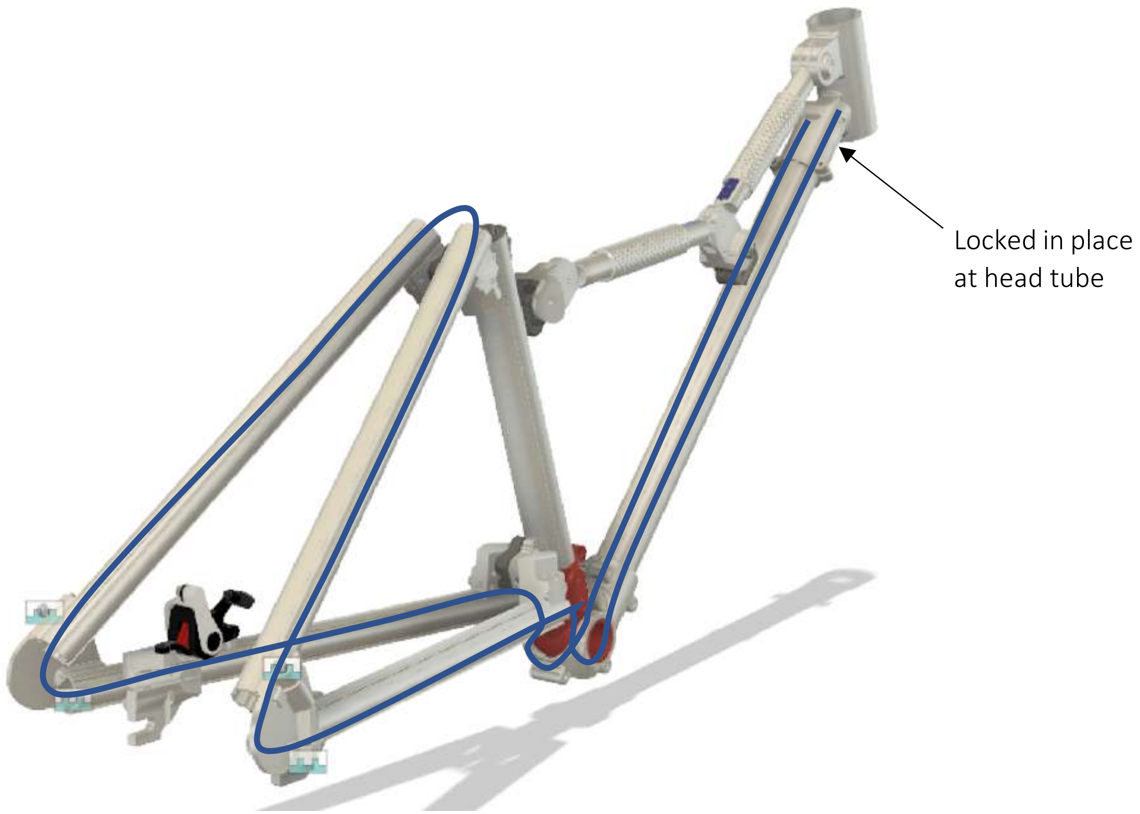


FIGURE 90 - CABLE ROUTING TO SECURE FRAME

19. CONCLUSION

The primary aims of the project were to design an adjustable bike for both use and user and make these designs available to the public for future use and development. The driving factor behind this project was the amount of space used for storing multiple types of bicycle, when space is of a premium. Having a bike that can be fully adjustable, minimises this used space by removing duplicate components.

A final concept was developed which utilised clamped joints to create the basic shape of the bicycle frame. The frame had a pivoting bottom bracket and head tube which could be adjusted, changing seat tube and head tube angles by 5^{o}, affecting both comfort and handling for the rider.

The pivoting bottom bracket, and adjustable fork crown were then utilised to transform the standard bike frame into a cargo bike, using all the previous components plus the addition of a $0.12m^{3}$ attachment, fixing to the front fork. This demonstrates the flexibility of the design to multiple use cases, adjusting between the two layouts in a matter of minutes.

Static force analysis was completed on the seat tube and bottom bracket, believed to be the key components of the frame. Further analysis of the remaining joints needs completing as well as physical dynamic loading tests. The project could be developed further and expanded, allowing other bicycle layouts to be developed, with the files uploaded to GitHub, providing fresh knowledge and expertise to the project.

20. ACKNOWLEDGMENTS

I would like to offer my special thanks to a variety of people who have helped me throughout this project:

Firstly to Jeremy Bonvoisin, for initialising the project and for our regular meetings and discussions about the project. The feedback and suggestions helped me to understand the direction I wanted to take the project and giving me knowledge on important areas.

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22. APPENDICES

22.1. APPENDIX A – DESIGN SPECIFICATION

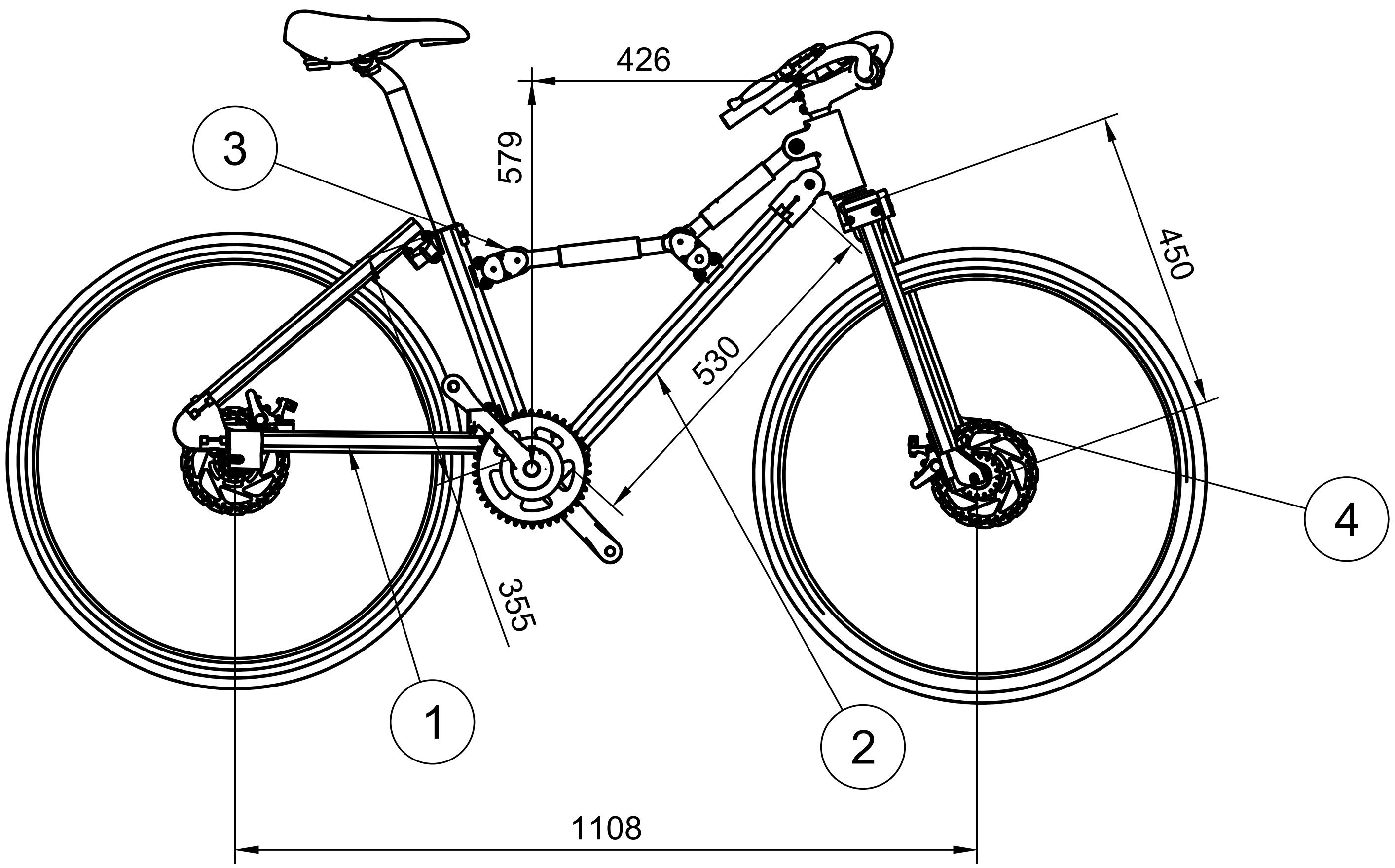
Category	Ref.	Specification Point	Justification	D/W	Weight	Date
Function	F1	Must be propelled by pedalling	Definition of a bike	D		10/12/2018
	F2	Must be able to manoeuvre using handlebars	Definition of a bike	D		10/12/2018
	F3	Must operate on at least 2 wheels	Definition of a bike	D		10/12/2018
	F4	Must be able to carry a total load of 150kg (frame, rider and cargo)	Taken from existing products	D		31/10/2018
	F5	Front cargo must sit below the handlebars of the bike	To aid vision and stability	D		10/12/2018
	F6	Frame must allow cargo attachments to be fitted in under 3 minutes	Arbitrary value set as target from	D		10/12/2018
	F7	A frame geometry adjustment must be done in under 1 minutes	Comparable to seat post adjustment	D		10/12/2018
	c	The cargo attachments must hold a volume of at least 0.2m^3	Existing product comparison	D		31/10/2018
	F9	Must be comfortable to cycle 7.5km while fully loaded	Average shopping distance	D		10/12/2018
	F10	The frame must last more than 5 years	Lifetime of aluminium frames	D		10/12/2018
	F11	Full bike assembly with cargo attachments must be under 30kg	Existing product comparison	D		5/12/2018
	F12	Bike must be capable of travelling 15km/h on a flat surface	Comparable to existing solutions	D		10/12/2018
Geometry & Ergonomics	G1	Angle between bottom bracket and top of the seat tube must vary between 70° and 75°	Mini Study 2	D		5/12/2018
	G2	Distance between bottom bracket and saddle must cover the range 400mm - 700mm	Mini Study 2	D		5/12/2018
	G3	Headset angle must be between 69° and 74.5°	Mini Study 2	D		5/12/2018
	G4	Front and rear wheel must be the same size	Mini Study 2	W	H	5/12/2018
	G5	Bicycle wheelbase must be between 950mm-1150mm	Mini Study 2	D		5/12/2018
	G6	The trail of the front wheel must be between 50mm - 90mm	Mini Study 2	D		5/12/2018
	G7	The fork must have a rake of 45mm	Mini Study 2	D		5/12/2018
	G8	The standover height of the frame must be <700mm	Mini Study 2	D		5/12/2018
	G9	Frame reach must be between 360mm - 400mm	Mini Study 2	D		5/12/2018

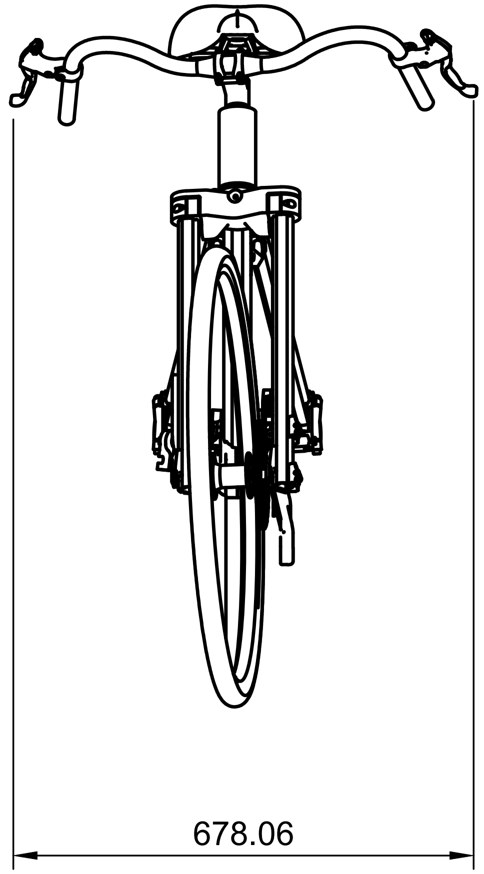
	G10	Frame stack must be between 520mm - 630mm	Mini Study 2	D		5/12/2018
	G11	Bottom bracket drop must be between the range of 10mm-70mm	Mini Study 2	D		5/12/2018
	G12	All load bearing components must be able to withstand 136kg	Mini Study 2	D		5/12/2018
Compatibility	C1	Frame must hold a seat tube of diameter 27.2mm	Mini Study 2	D		5/12/2018
	C2	Headset must be suitable for a 1-1/8inch diameter steering column	Mini Study 2	D		5/12/2018
	C3	Forks must fit 700c wheels with 17mm bead width	Mini Study 2	D		5/12/2018
	C4	Bike forks and brakes must accommodate 32c tyres	Mini Study 2	D		5/12/2018
	C5	Front fork spacing must be 100mm	Mini Study 2	D		5/12/2018
	C6	Rear fork must have spacing for a 135mm hub	Mini Study 2	D		5/12/2018
	C7	Rear hub could be adjustable for smaller sized hubs	Mini Study 2	W	L	5/12/2018
	C8	handlebar must have a stem clamp diameter of 31.8mm	Mini Study 2	D		5/12/2018
	C9	handlebar must have a grip diameter of 22.2mm	Mini Study 2	D		5/12/2018
	C10	Frame must utilise two 8mm brake bosses to mount v-brakes	Mini Study 2	D		5/12/2018
	C11	Must utilise long pull brake levers	Mini Study 2	D		5/12/2018
	C12	Brake bosses could be movable to accommodate disk brakes	Mini Study 2	W	M	5/12/2018
	C13	Bottom bracket shell must have a diameter of 35mm with 24TPI (English style)	Mini Study 2	D		5/12/2018
	C14	Bottom bracket shell must be 68mm or 73mm wide (English style)	Mini Study 2	D		5/12/2018
	C15	Standard bicycle accessories must be mountable to the frame	Making the bike attractive to users	W	M	10/12/2018
	C16	Crank arm must be 170mm	Mini Study 2	D		5/12/2018
Safety	S1	Frame component ends must be covered to hide sharp edges	Safety of user	D		10/12/2018
	S2	Loose fixtures cannot cause accidents when in use	Design for error	D		10/12/2018
	S3	Bike must be equipped with two brakes	Bike safety regulations	D		10/12/2018
	S4	Bike must have mounting positions for compulsory reflectors and bell	Bike safety regulations	D		10/12/2018
	S5	IP32 on frame components	To stop fingers getting trapped	D		10/12/2018
Economics	E1	Product to be priced under £2500	Existing Products	D		10/12/2018
	E2	Frame material costs no more than £800	Arbitrary value based on target price	D		10/12/2018
	E3	standard components cost no more than £800	Arbitrary value based on target price and component research	D		10/12/2018

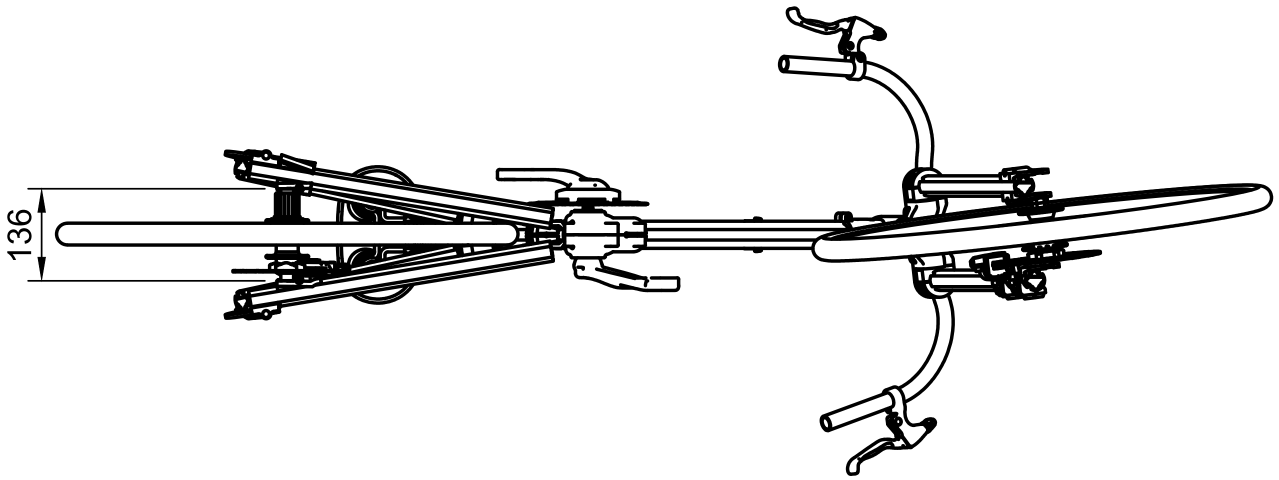
	E4	Maintenance costs should average under £100 per year	Comparing to standard bikes	D		10/12/2018
Materials & Manufacture	M1	Joints must be easily manufacturable		W	L	10/12/2018
	M2	Minimise the use of jigs	Mini Study 1	W	H	31/10/2018
	M3	Must be assembled using standard tooling	Mini Study 1	D		31/10/2018
	M4	Minimise destructive processes for user during assembly process	Mini Study 1	W	H	31/10/2018
	M5	Bike must be aesthetically pleasing		W	M	10/12/2018
	M6	User must be able to assemble the bike in under 2 hours	Arbitrary value set as target	D		10/12/2018
Operating Environment	O1	Must function between -5℃ - 40℃	Outdoor temperature range	D		10/12/2018
	O2	Cannot be damaged by UV light	Use in the sun	D		10/12/2018
	O3	Cannot have panels larger than $1m^2$	Wind making it unrideable	D		10/12/2018
	O4	The frame must have a ground clearance of 150mm	Uneven surface use - curb height	D		10/12/2018
	O5	Must operate effectively on tarmacked surfaces	Mini Study 1	D		31/10/2018
	O6	Could work or gravel / unmade roads		W	L	10/12/2018
	O7	Must be weatherproof: IP65 on critical moving components	Projected water protection	D		10/12/2018
	O8	Must be weatherproof: corrosion resistant material or coating	Outdoor use	D		10/12/2018
	O9	Fixtures must stay secure when subjected to vibration acceleration of 8m/s^2	Uneven surface use	D		10/12/2018
	O10	Bike must stay rigid when subjected to 2kN (1.2kN loading + 0.8kN braking)	150kg bicycle loading plus braking force from 15km/h to 0km/h in 1s	D		10/12/2018
	O11	Bike width must be less than 1m with cargo attachments	Arbitrary value set for stability and accessibility	D		10/12/2018
Life & maintenance	L1	Frame components cannot be fixed permanently	Allow easy maintenance and replacement	D		10/12/2018
	L2	standard components must be accessible and removable	Allow easy maintenance and replacement	D		10/12/2018
	L3	Maintenance time and frequency should be kept to a minimum		W	H	10/12/2018

22.2. APPENDIX B – ASSEMBLY AND SUB-ASSEMBLY DRAWINGS

Parts List			
Item	Qty	Name	Description
1	1	Rear Triangle Assembly	Consisting of seat tube with bottom bracket and rear stay assembly
2	1	Down Tube assembly	Consisting of head tube, adjustable tube assembl, and connection to bottom bracket
3	1	Adjustable Joint Assembly	Connects adjustable tube to seat tube
4	1	Front Fork Assembly	fork and handlebars

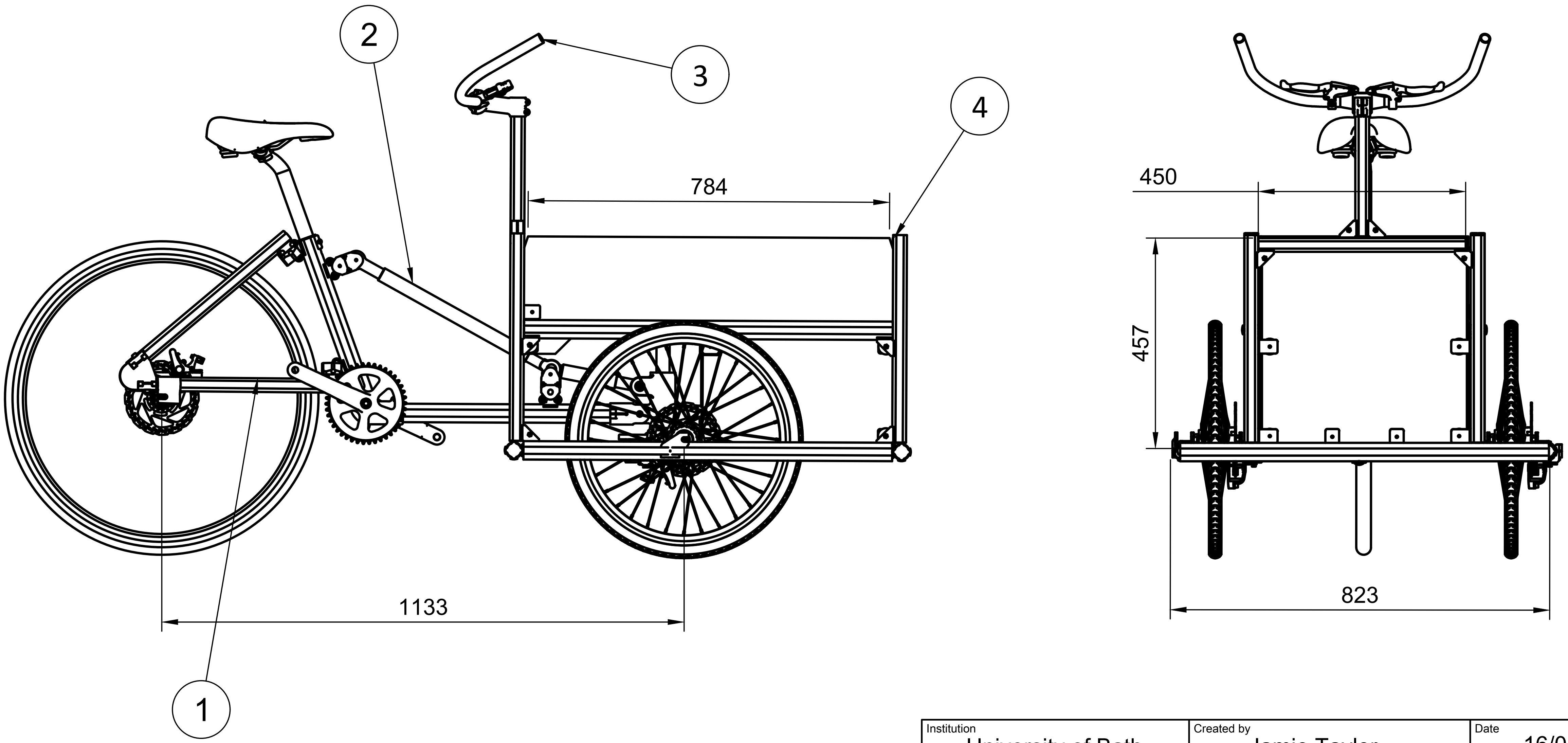




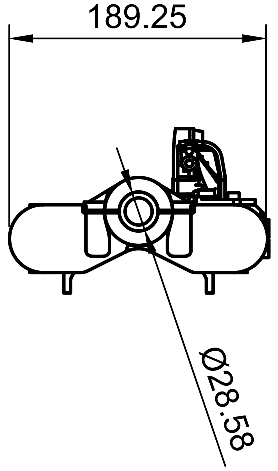


Institution: University of Bath	Created by: Jamie Taylor	Date: 16/04/2019
Project: Adjustabike - Open source adjustable bike	Document type: Assembly Drawing	Document status: Complete
	Title: Standard Bike Assembly	DWG No.
		Scale: 1:10 — Sheet: 1/1

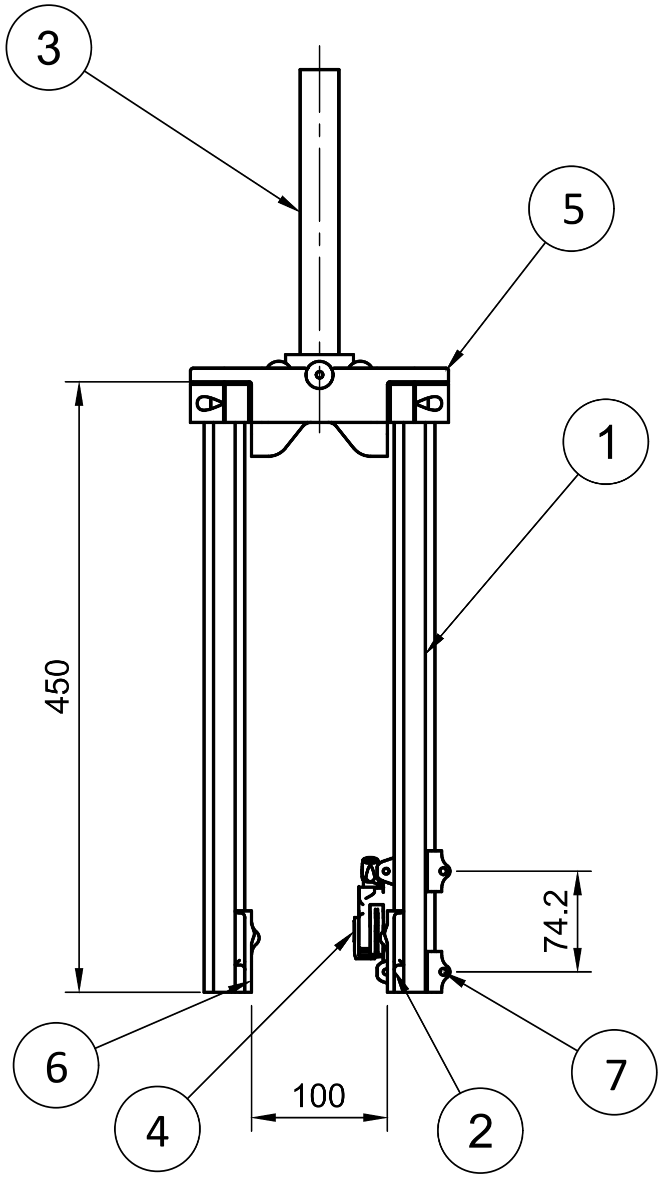
Parts List			
Item	Qty	Name	Description
1	1	Standard Bike Frame	All components used on cargo bike from standard
2	1	Long Adjustable Bar	Replaces short bar from standard bike
3	1	Handlbar Attachment	Handlebars reused for cargo attachment
4	1	Cargo Attachment	Attaches to transformed front fork legs

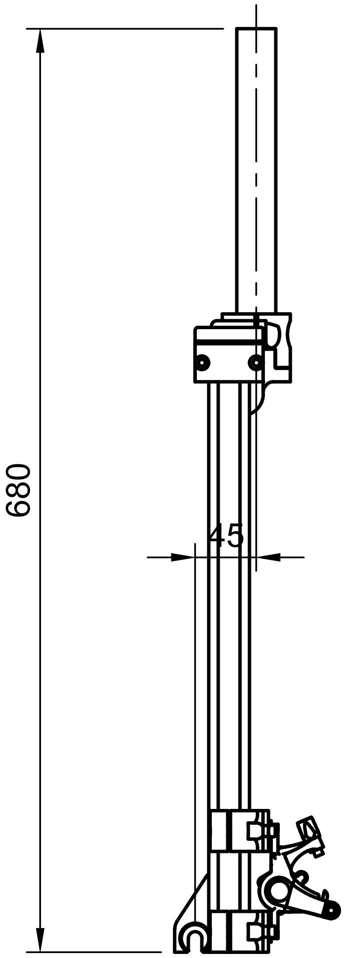


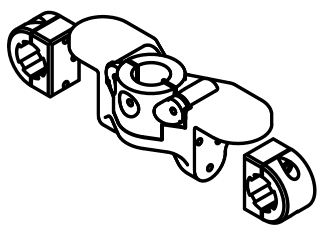
Institution University of Bath	Created by Jamie Taylor	Date 16/04/2019
Project Adjustabike - Open source adjustable bike	Document type Assembly Drawing	Document status Complete
	Title Cargo Bike Assembly	DWG No.
		Scale 1:10 / Sheet 1/1

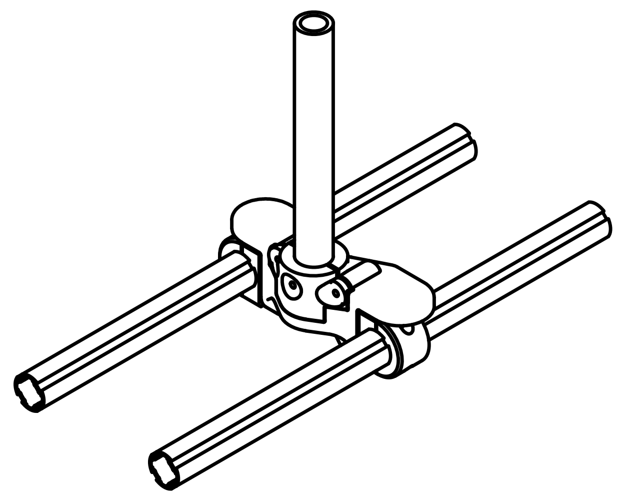


Parts List			
Item	Qty	Name	Description
1	2	450mm Tube Profile	Aluminium Extrusion
2	1	Right Fork Drop Out	Aluminium, clamps to tube profile
3	1	Steering Column	1-1/8 inch
4	1	Disc Brake Caliper	Bought Component
5	1	Fork Crown Assembly	Aluminium, clamps steering column and profiles
6	1	Left Fork Drop Out	Aluminium,clamps to tube profile
7	2	Brake Boss Clamp	Aluminium, clamps to tube profile





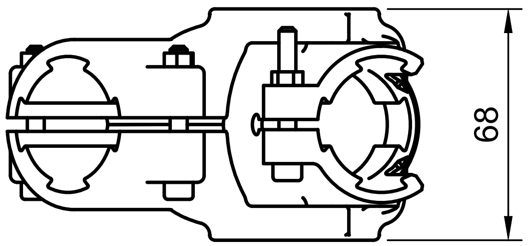


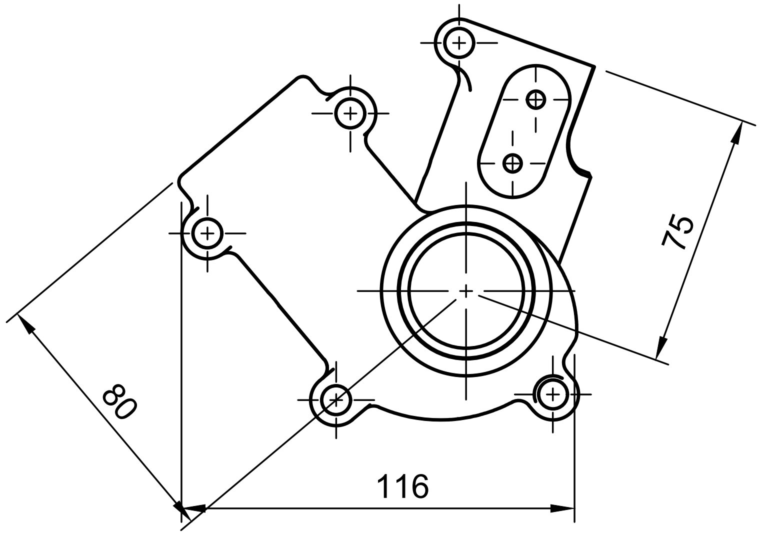


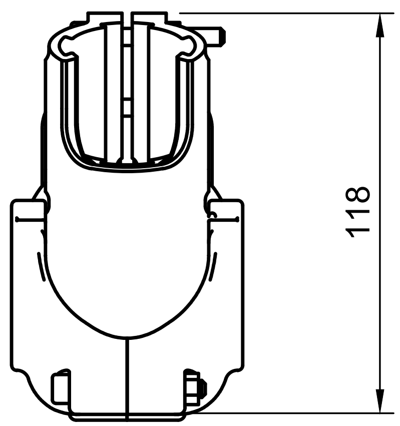
Institution: University of Bath	Created by: Jamie Taylor	Date: 16/04/2019
Project: Adjustabike - Open source adjustable bike	Document type: Assembly Drawing	Document status: Complete
	Title: Fork Assembly	DWG No.
		Scale: 1:5 / Sheet: 1/1

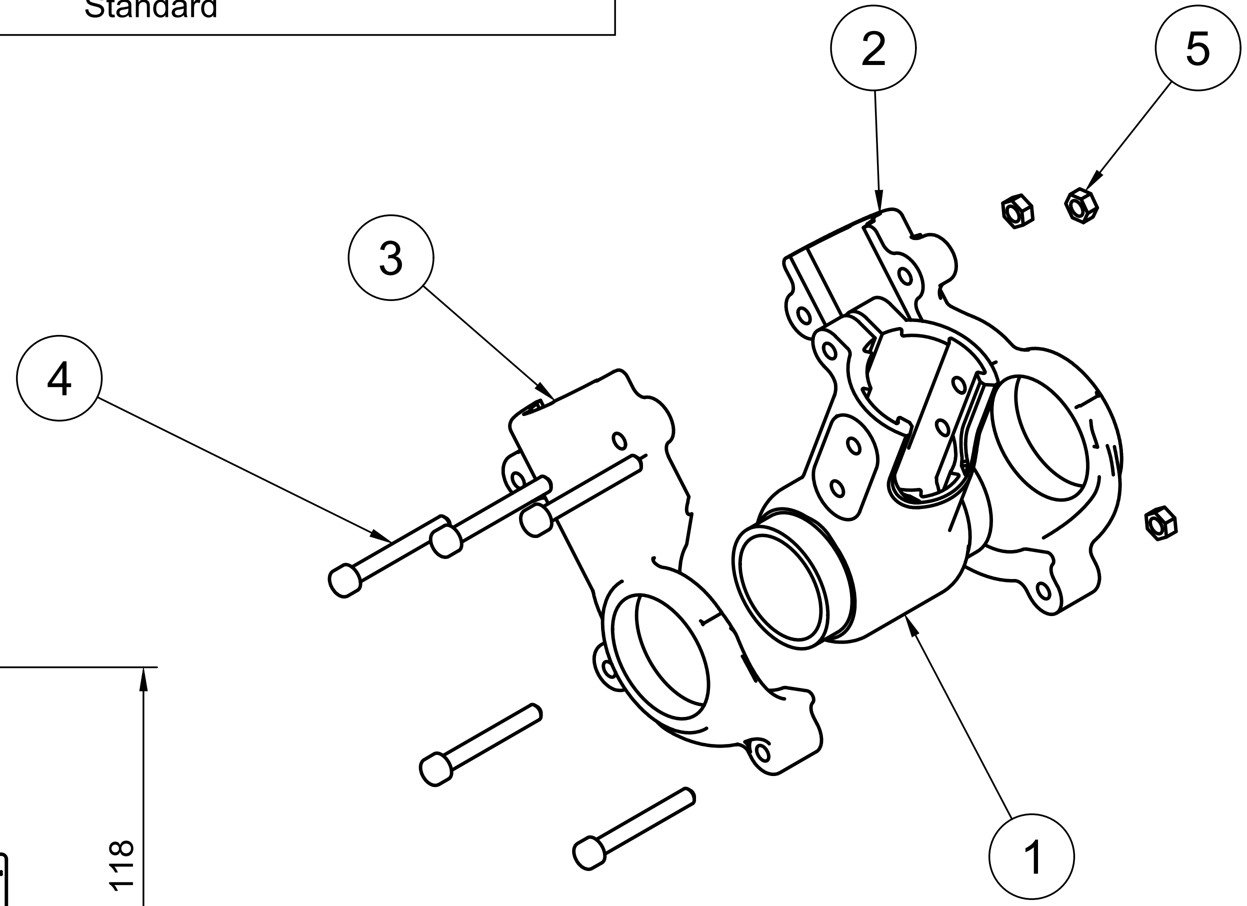
Parts List

Item	Qty	Name	Description
1	1	Bottom Bracket	Aluminium bolted and clamped to seat post
2	1	Right Down Tube Connector	Aluminium, Bolts to Left Half around BB
3	1	Left Down Tube Connector	Aluminium, Bolts to Right Half around BB
4	5	M6 x 30mm Bolt	Standard
5	5	M6 Nut	Standard



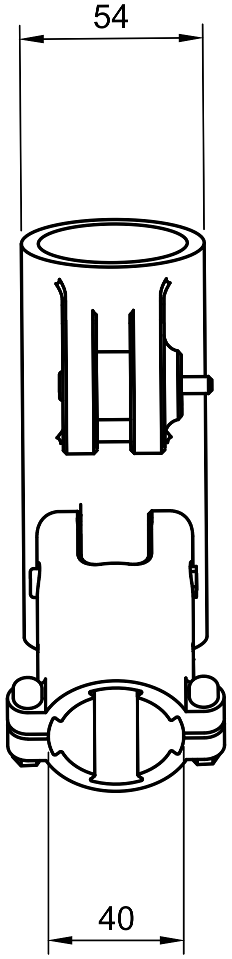


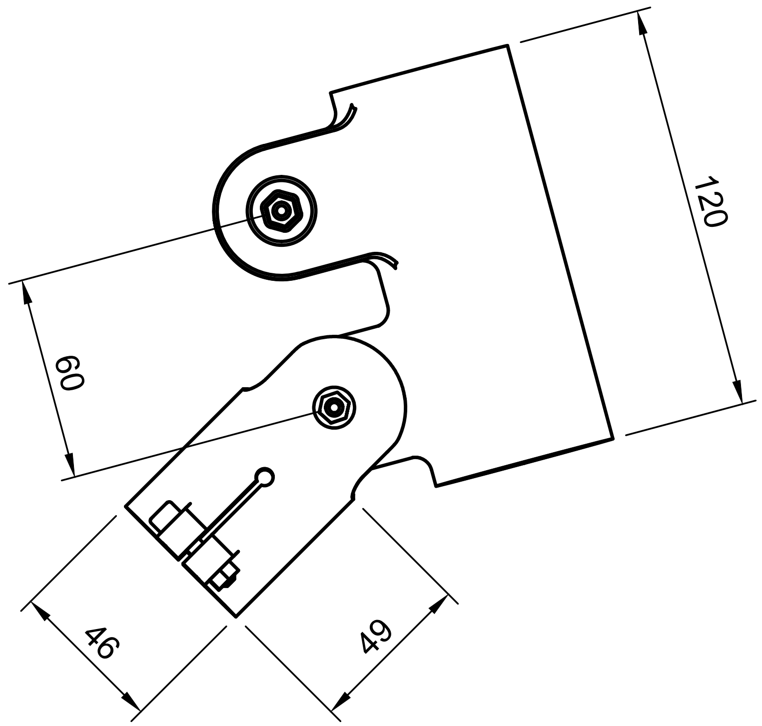


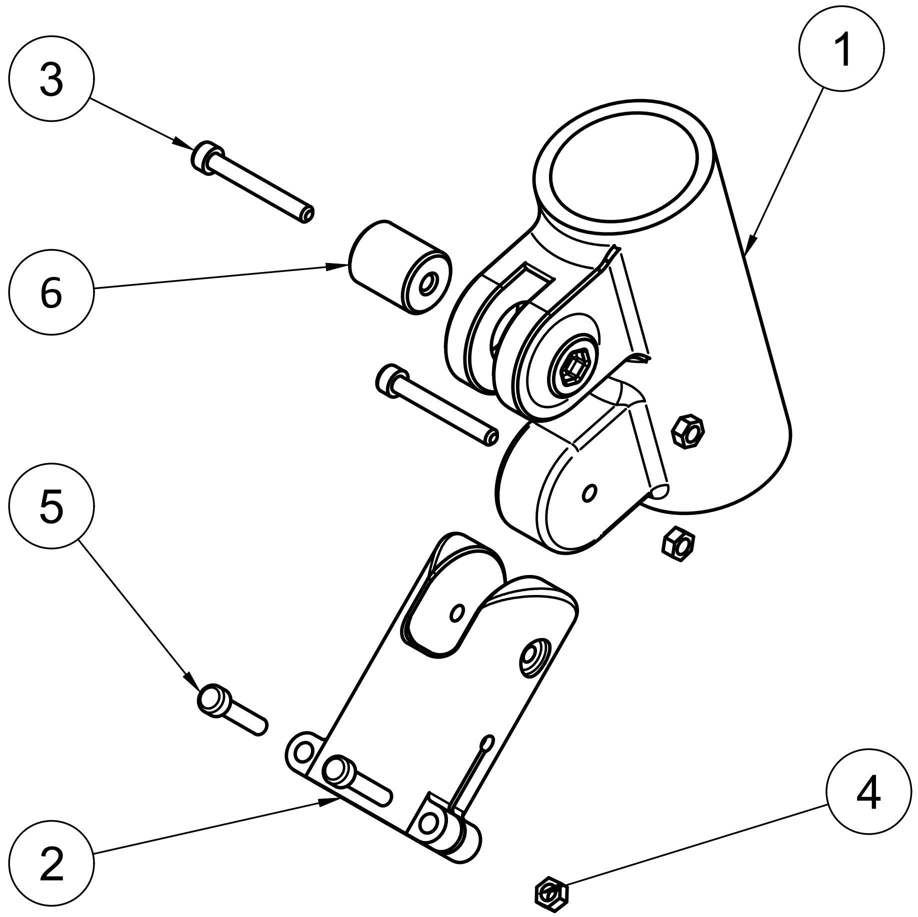


Institution: University of Bath	Created by: Jamie Taylor	Date: 16/04/2019
Project: Adjustabike - Open source adjustable bike	Document type: Assembly Drawing	Document status: Complete
	Title: Bottom Bracket Assembly	DWG No.
		Scale: 1:2 — Sheet: 1/1

Parts List			
Item	Qty	Name	Description
1	1	Head Tube	Aluminium component, fixing frame to fork
2	1	Down Tube to Head Clamp	Aluminium clamp secured to head with bolt
3	2	M6 x 30 Bolt	Standard
4	4	M6 Nut	Standard
5	2	M6 x 25 Bolt	Standard
6	1	Head Connecting Plug	Aluminium, secures adjustable tube

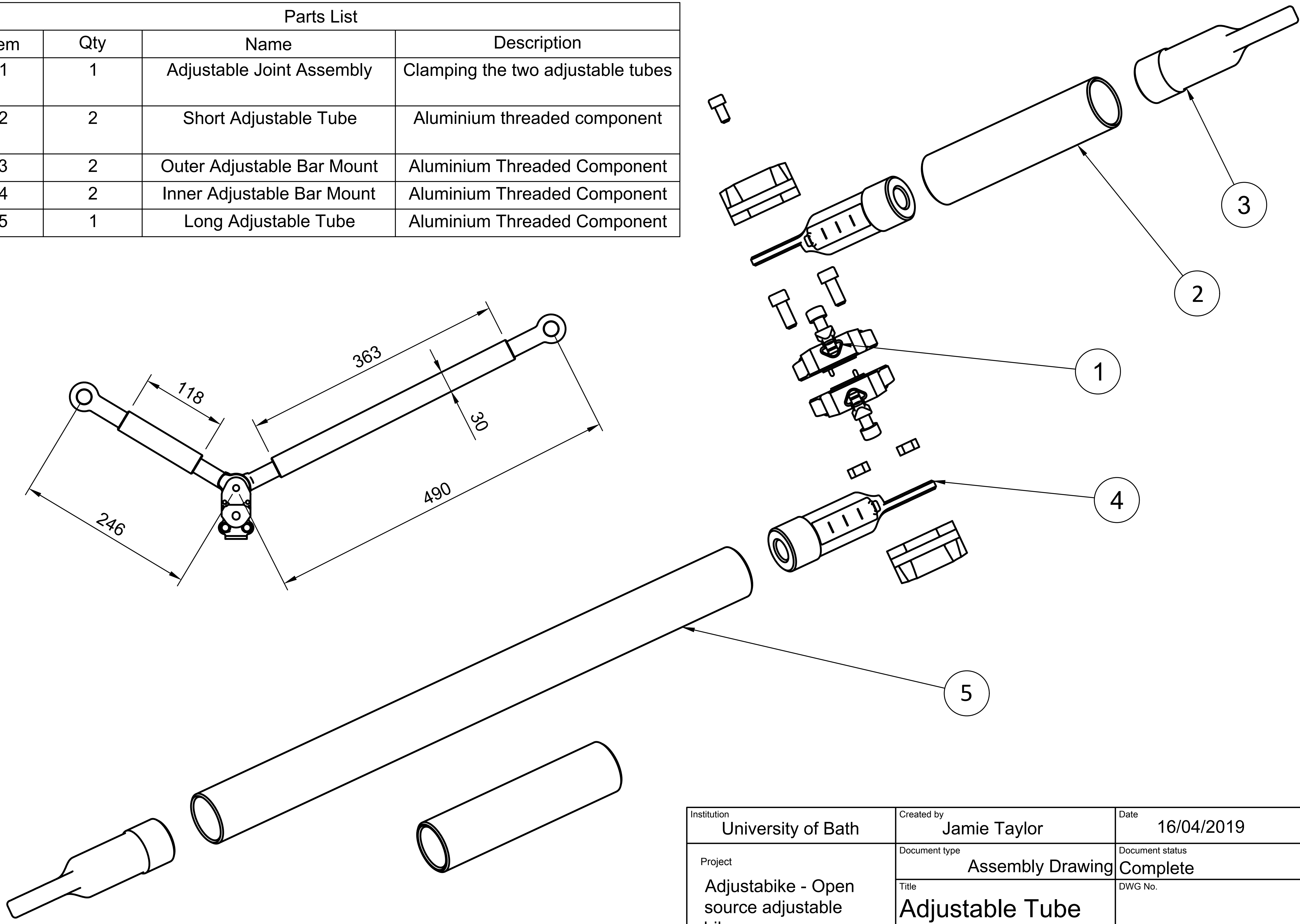






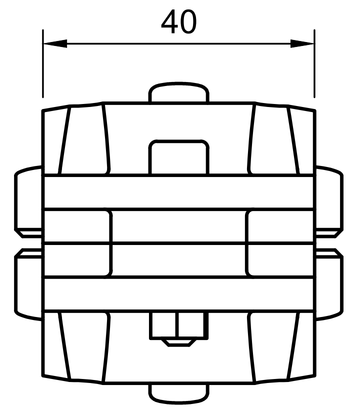
Institution: University of Bath	Created by: Jamie Taylor	Date: 16/04/2019
Project: Adjustabike - Open source adjustable bike	Document type: Assembly Drawing	Document status: Complete
	Title: Head Tube Assembly	DWG No.
		Scale: 1:2 / Sheet: 1/1

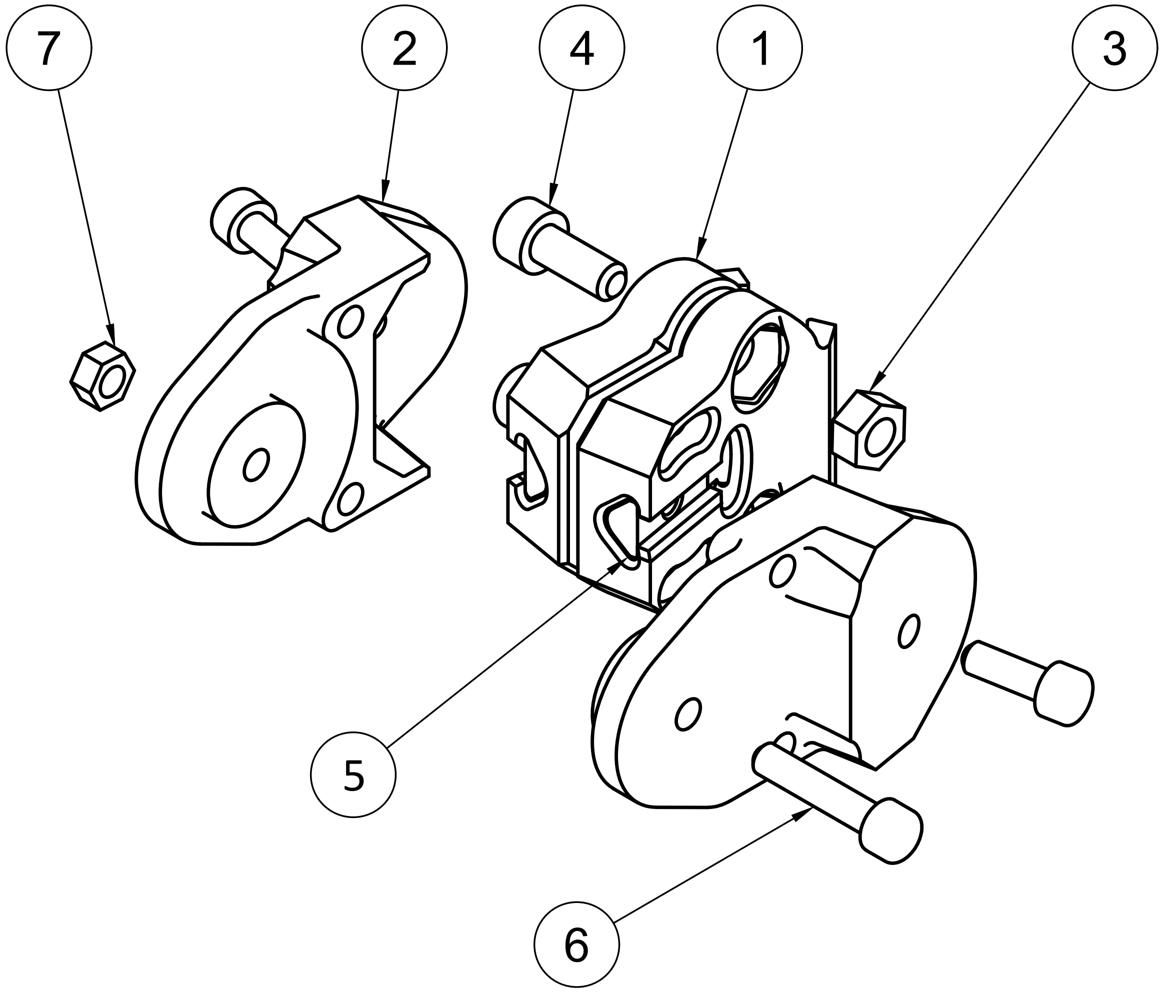
Parts List			
Item	Qty	Name	Description
1	1	Adjustable Joint Assembly	Clamping the two adjustable tubes
2	2	Short Adjustable Tube	Aluminium threaded component
3	2	Outer Adjustable Bar Mount	Aluminium Threaded Component
4	2	Inner Adjustable Bar Mount	Aluminium Threaded Component
5	1	Long Adjustable Tube	Aluminium Threaded Component

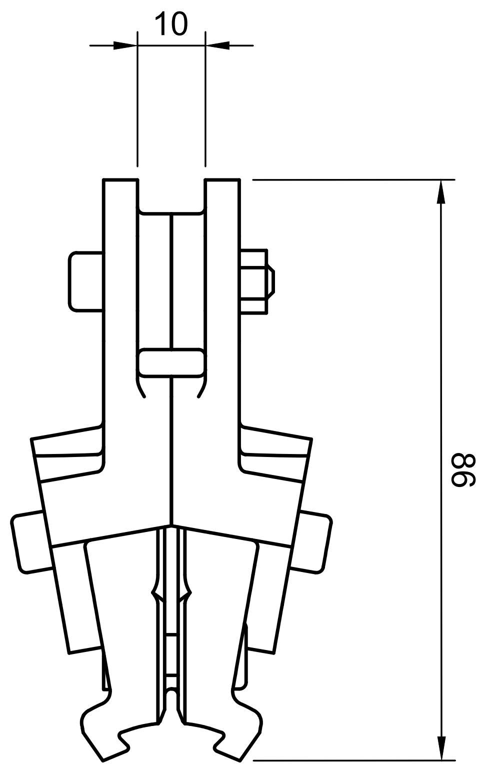


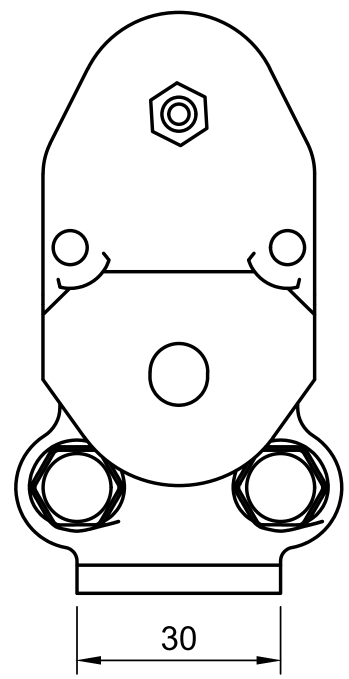
Institution: University of Bath	Created by: Jamie Taylor	Date: 16/04/2019
Project: Adjustabike - Open source adjustable bike	Document type: Assembly Drawing	Document status: Complete
	Title: Adjustable Tube Assembly	DWG No.
		Scale: 1:2 — Sheet: 1/2

Parts List			
Item	Qty	Name	Description
1	2	Standard Joint	Aluminium bolted clamp
2	2	Adjustable Bar Joint	Aluminium, secured with T-slot nut to standard joint
3	2	M6 Nut	Standard
4	4	M6 x 15mm Bolt	Standard
5	2	M6 T-Slot Nut	Standard
6	1	M5 x 25mm Bolt	Standard
7	1	M5 Nut	Standard



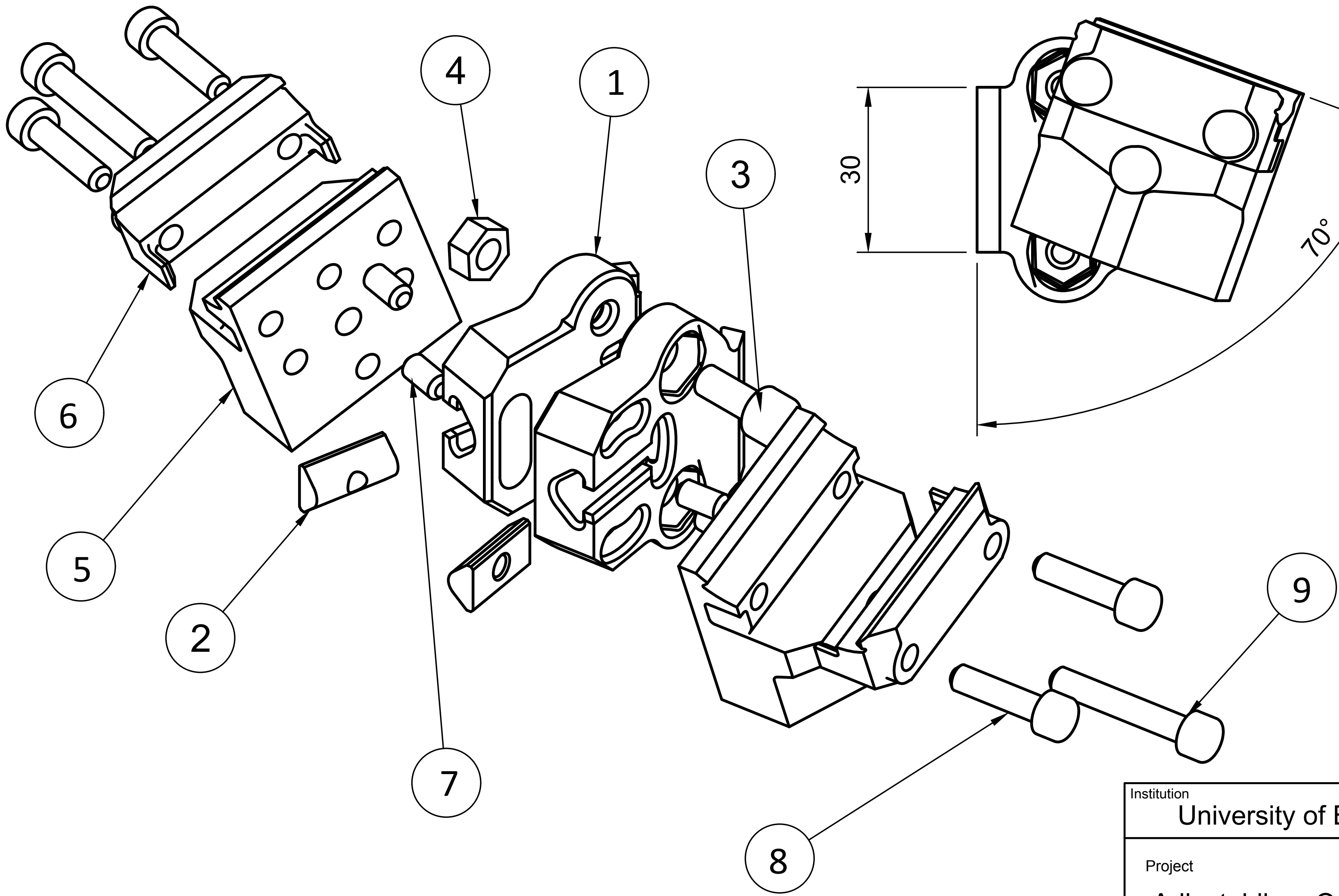


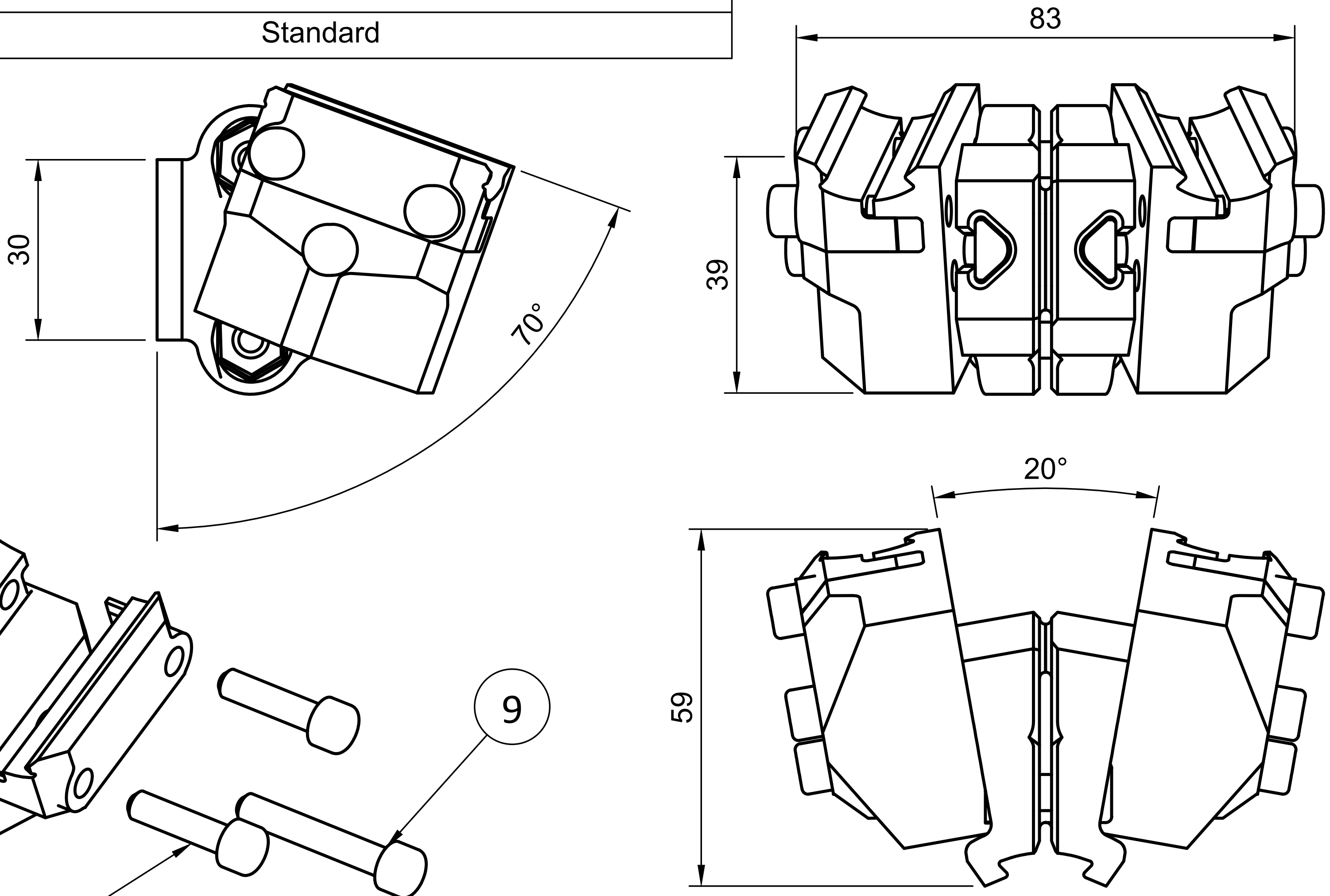




Institution	Created by	Date
University of Bath	Jamie Taylor	16/04/2019
Project: Adjustabike - Open source build your own bike	Document type: Assembly Drawing	Document status: Complete
	Title: Adjustable Bar Joint	DWG No.
		Scale: 1:1 / Sheet: 1/1

Parts List			
Item	Qty	Name	Description
1	2	Standard Joint	Aluminium bolted clamp
2	2	T-slot Nut	Aluminium, secured with T-slot nut to standard joint
3	2	M6 x 15mm Bolt	Standard
4	2	M6 Nut	Standard
5	2	Rear Stay Attachment	Aluminium, secured with T-slot nut to standard joint
6	2	Rear Stay Clamp	Bolted to Rear Stay Attachment
7	4	10mm Dowel	Steel
8	4	M5 x 25mm	Standard
9	2	M6 x 35mm	Standard





Institution University of Bath	Created by Jamie Taylor	Date 16/04/2019
Project Adjustabike - Open source adjustable bike	Document type Assembly Drawing	Document status Complete
	Title Rear Stay Clamp Assembly	DWG No.
		Scale 1:1 / Sheet 1/1