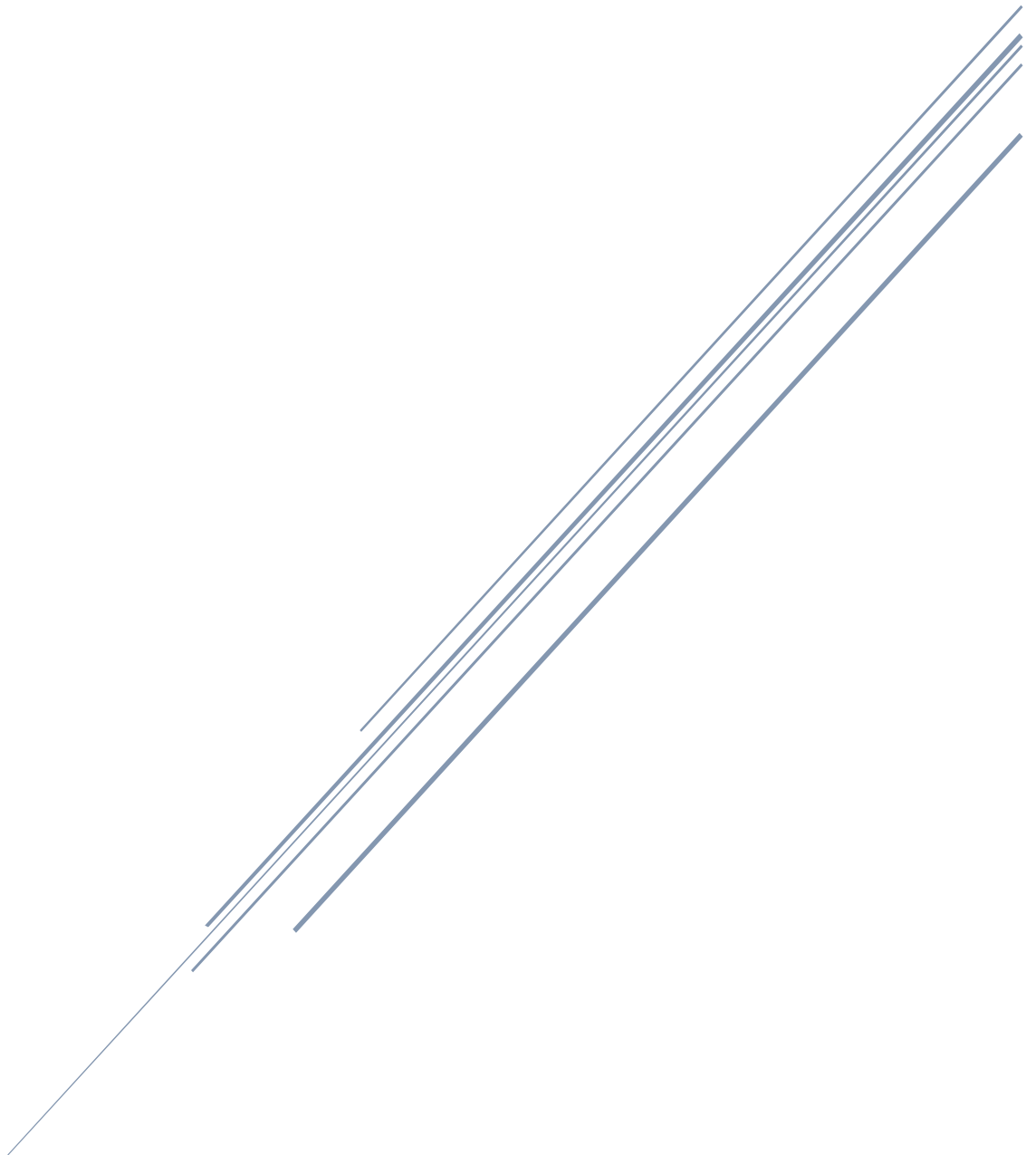


DESIGN FOR X PROJECT

ACMA5002



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Abstract

This study delves into the innovative use of Design for X methodologies in developing two products. The first is a robot gripper facing substantial increases in demand, which necessitates exploring more economical designs and manufacturing processes. The second is a motorcycle race team requiring a strong, lightweight footpeg in low quantities within a short time period.

Proven lean methodologies, such as Quality Functional Deployment (QFD) and Design Failure Mode and Effect Analysis (DFMEA), were successfully employed throughout product development. Design evaluation and creation tools, such as Finite Element Analysis (FEA) and Generative Design (GD), were also used. Decision matrices were extensively utilised due to their structured method of evaluating and comparing different options, such as design and manufacturing process selection.

Using the aforementioned tools, both products were redesigned to create solutions that satisfied the requirements created from the problem definitions. The robot gripper material and manufacturing process selections were meticulously optimised to meet production requirements, ensuring cost-effectiveness and maintaining product performance. Through the utilisation of additive manufacturing technology, the motorcycle footpeg underwent a redesign focusing on efficiency and lightweight construction.

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Task 1

Introduction

In 2022, Robotech, a company specialising in robotic tooling and equipment, launched a mechanical robot gripper assembly – illustrated in Figure 1. The gripper assembly was initially developed and manufactured for a single customer, requiring low production volumes (10 – 50 weekly units). However, other customers have been interested in the product since its inception, increasing the market demand. Robotech conducted market research highlighting a potential requirement of 1000+ units per week over a five-year period. Since the initial product was developed for low-scale production output, supporting these higher volumes was not financially viable.

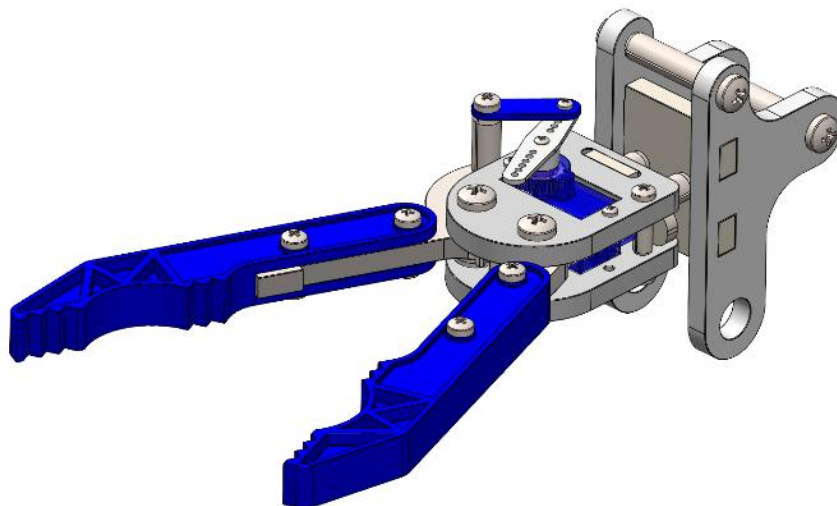


Figure 1: Original robot gripper assembly.

A redesign would ensure Robotech could support these higher production volumes. This redesign employed lean methodologies, such as design for manufacturing and assembly (DFMA), developed by Dewhurst et al. (1994), to help enhance the manufacturing and assembly stages of the product. This quantitative data analysis method is fundamental for contrasting various product design iterations. The bill of materials (BOM) in Figure 2 and key assembly metrics in Table 1 would be instrumental in the DFMA analysis.

The redesigning of componentry was assessed with suitable materials and manufacturing processes, ensuring the process was economically viable for the increased volumes required.

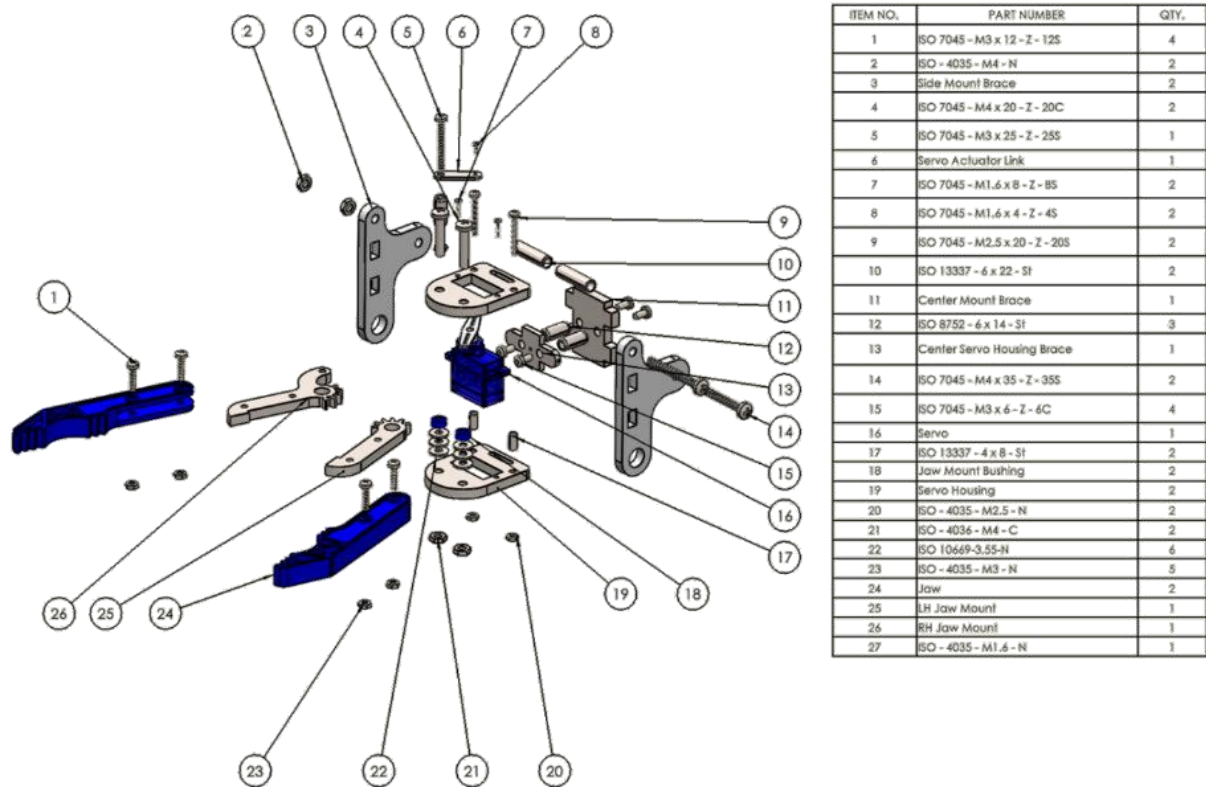


Figure 2: Original robot gripper bill of materials (BOM).

Table 1: Key assembly metrics of original robot gripper.

Metric Description	Value
No. of unique components	27
Total components	58
Length x width x height (mm)	190 x 50 x 70
Mounting pin width (mm)	22
Mounting pin diameters (mm)	6

Product Research

Robotic gripper arms – also referred to as ‘manipulators’ or end-effectors’ - were first developed in 1969 by Victor Scheinman, a Stanford University mechanical engineering student (Machine Design, 2009). The primary function is to hold and transfer objects from one position to another. Initial designs were largely developed for industrial applications, specifically mundane and dangerous tasks; the consensus was that humans, who were replaced by these robots, could focus on higher-value tasks that would further benefit the individuals and the organisation.

Robots can often perform tasks faster and more consistently than humans, as they are not subject to physical limitations such as fatigue. The gripper units attached to these robots come in many shapes and sizes, including two to five fingers, vacuum suction cups, electromagnets, bespoke tooling arrangements, and more. Common methods for actuating these mechanisms include electrical motors, hydraulics, and pneumatics (Universal Robots, 2020).

As advancements in robotic gripper technology progress, the scope of applications expands, particularly for tasks demanding high levels of dexterity, like the handling of grapes depicted in Figure 3 (Bush, 2019).

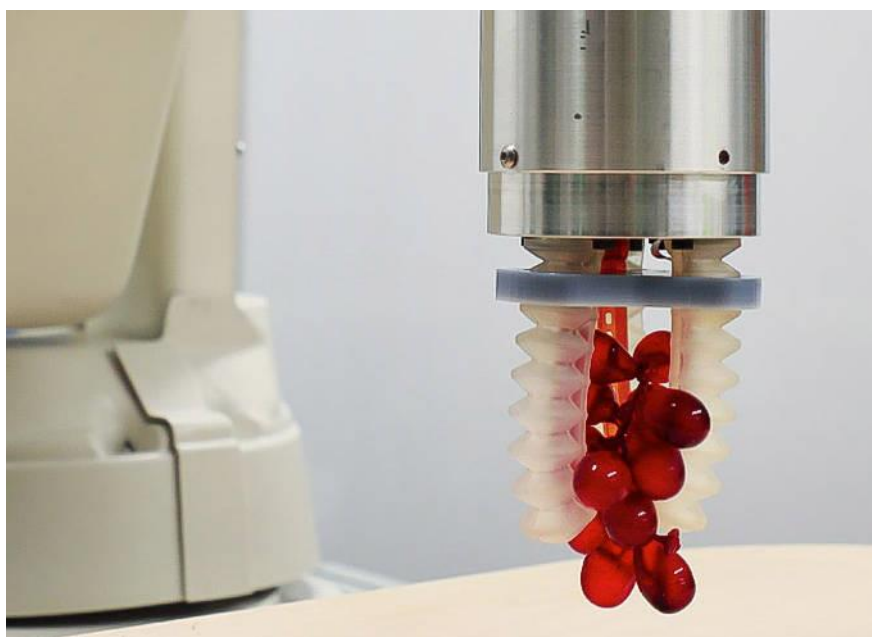


Figure 3: Dexterous robot gripper (Bush, 2019)

Before investigating alternative design solutions for Robotech's gripper assembly, the product design specification (PDS) needed to be compiled; benchmarking against similar products on the market is beneficial to ensure these specifications are, at minimum, in line with customer expectations. Two similar products were discovered, the details of which are shown in Tables 2 and 3, along with Figures 4 and 5.

Table 2: 2FG7 Finger/parallel gripper specifications (OnRobot, 2024).

Internal stroke	49 mm
Payload	11 Kg
Grip force	20 – 140 N
Price	£3,862
Operating hours	30,000
Weight	1.1 Kg
Size	145 mm H x 90 mm W x 71 mm L
Maintenance	Pad replacement 200k – 250k cycles
Operating temperature	-5°C to +50°C



Figure 4: 2FG7 Finger/parallel gripper (OnRobot, 2024).

Table 3: ROBOTIQ Hand-E gripper specifications (ROBOTIQ, 2024).

Internal stroke	50 mm
Payload	5 Kg
Grip force	60 – 160 N
Price	£3,565
Operating cycles	5M
Weight	1 Kg
Size	157 mm H x 75 mm W x 75 mm L
Maintenance	Inspection: Monthly Rack & Pinion Cleaning: 2M cycles
Operating temperature	-10°C to +50°C



Figure 5: ROBOTIQ Hand-E gripper (ROBOTIQ, 2024).

Quality Function Deployment

A process called Quality Function Deployment (QFD) was employed to aid in defining the product. This is a systematic process used to create engineering specifications by listening to the customers' voices and acknowledging their needs. The process defines linkages between the customer's voices and engineering functions and specifications. Since its inception in the mid-1980s, QFD has proven to yield vast improvements in customer satisfaction while reducing product development time.

QFD is a four-phase process that incorporates the various undertakings throughout product development: product definition, product development, process development, and process quality control. Phase one was pursued during this study. During this phase, the subsequent 8-step process was implemented:

1. Identifying who the customers are.
2. Acquiring the customers' requirements.
3. Grasping what is essential to the customer.
4. Benchmarking with competitors' products.
5. Creating engineering specifications.
6. Defining linkages between engineering specifications and customer requirements.
7. Creating targets for engineering specifications.
8. Defining the linkages of engineering specifications.

(Ullman, 2018)

As illustrated in Figure 6, the eight steps mentioned above are collated into a QFD diagram, more commonly known as the house of quality.

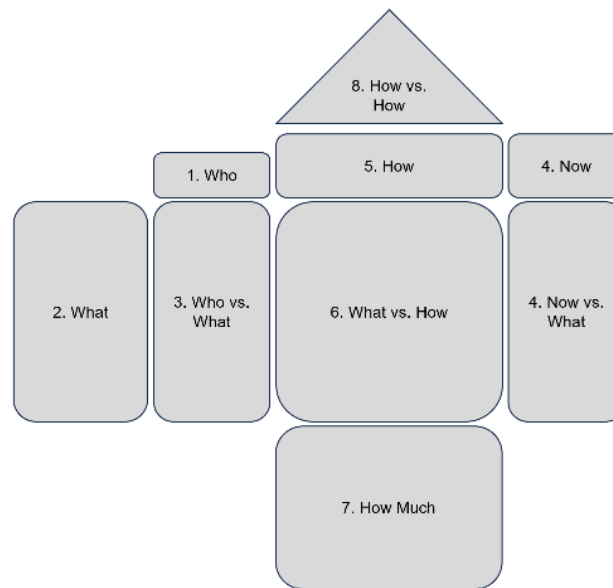


Figure 6: A QFD diagram (house of quality).

Throughout the product life cycle - development through to obsolescence - numerous internal and external stakeholders have input into the product design specification. The customer requirements can be categorised into basic, performance, and excitement (delighter) features using a Kano Model (Kano, 1984). Table 4 lists the type of customers, their requirements, the importance of the requirements (on a scale of 1 – 10), and the category in which they reside. These requirements are then illustrated as a Kano Model (Figure 7).

Table 4: Customer requirements of Robotech's robot gripper.

Customer(s)	Customer Requirement	Importance	Feature Type
End user	Securely holds items up to 60 mm wide	9.0	Basic
End user	Securely holds items up to 1 Kg	8.0	Basic
End user Manufacturer	Low cost	6.0	Performance
End user	Durable	6.0	Basic
End user Manufacturer Distributor	Lightweight	4.0	Performance
Manufacturer	Easy to assemble during manufacture	6.0	Performance
End user	Easy to mount gripper onto robot coupling	5.0	Performance
End user Manufacturer Distributor	Compact in size	4.0	Performance
End user	Low maintenance	5.0	Basic
End user	Compatible with robot coupling	10.0	Basic
End user	Operating temperature during use	6.0	Performance
End user	Securely hold items with a diameter up to 30 mm	8.0	Basic
Manufacturer	Ability to manufacture 1000+ units per week	8.0	Basic
End user	Good recyclability	5.0	Performance

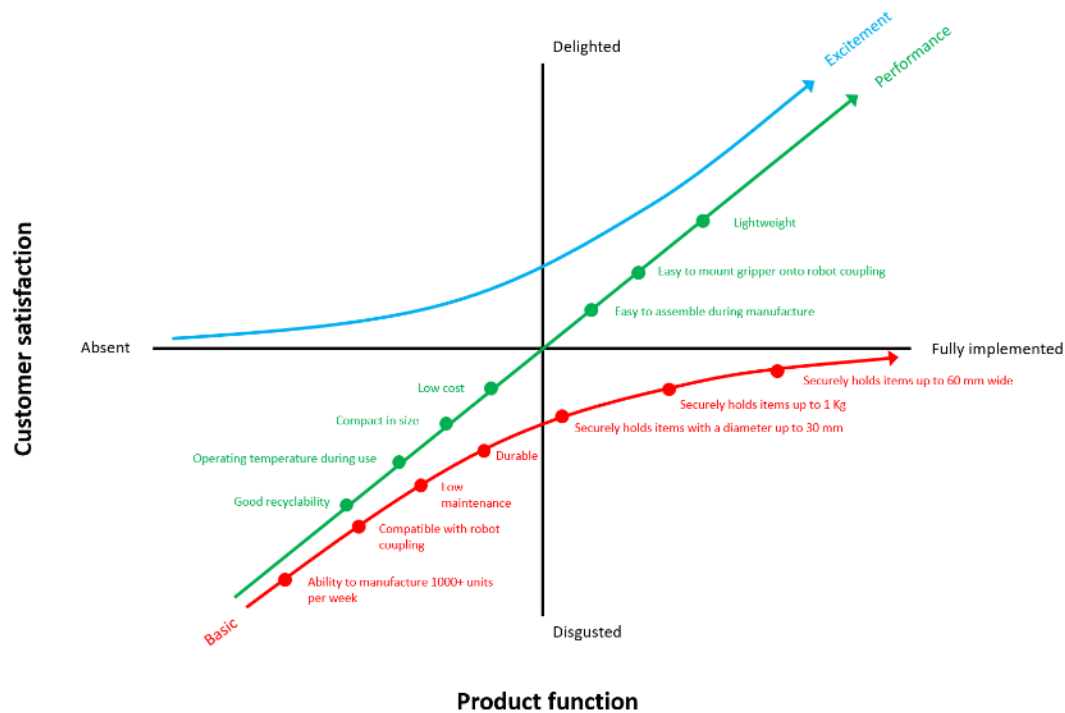


Figure 7: Kano Model of Robotech's robot gripper.

Competitor products are then benchmarked against these customer requirements to investigate opportunities for improvement. The scale for these ratings is 1 – 5 (5 meaning the product completely satisfies the requirement). The evaluation of two products discussed previously, along with Robotech's existing design, is presented in Table 5; blank cells indicate information that wasn't readily available.

Table 5: Competitor benchmarking analysis of the customer's requirements.

Customer Requirement	Existing Design	OnRobot 2FG7	ROBOTIQ Hand-E
Securely holds items up to 60 mm wide	4	3	3
Securely holds items up to 1 Kg	4	5	5
Low cost	3	1	1
Durable	3	5	5
Lightweight	4	4	4
Easy to assemble during manufacture	2		
Easy to mount gripper onto robot coupling	4	4	4
Compact in size	3	4	4
Low maintenance	3	5	4
Compatible with robot coupling	5		
Operating temperature during use	4	4	5
Securely hold items with a diameter up to 30 mm	4	4	4
Ability to manufacture 1000+ units per week	2		
Good recyclability	4		

The subsequent section involves generating engineering specifications that indicate a level of achievement against the customer's requirements; these specifications must be measurable, i.e., force in N, length in mm, etc. The relationship between the customer's requirements and the engineering specifications is evaluated to ensure both are sufficiently understood; requirements or specifications that don't exhibit a strong relationship are removed.

Completing the relationships discussed above allows the relative weighting of each engineering specification to be calculated. In collaboration with the assigned difficulty rating, the team can use this as guidance to determine which specifications to prioritise, especially when there are design conflicts.

Employing all the information obtained thus far, each engineering specification is assigned a target and/or limit value of acceptance. These values may be amended during the design creation/evaluation stage.

The final element of the QFD is identifying the relationships between the engineering specifications, if any. These relationships give guidance for trade-offs between specifications.

The final QFD (house of quality) for Robotech's gripper assembly is illustrated in Figure 8.

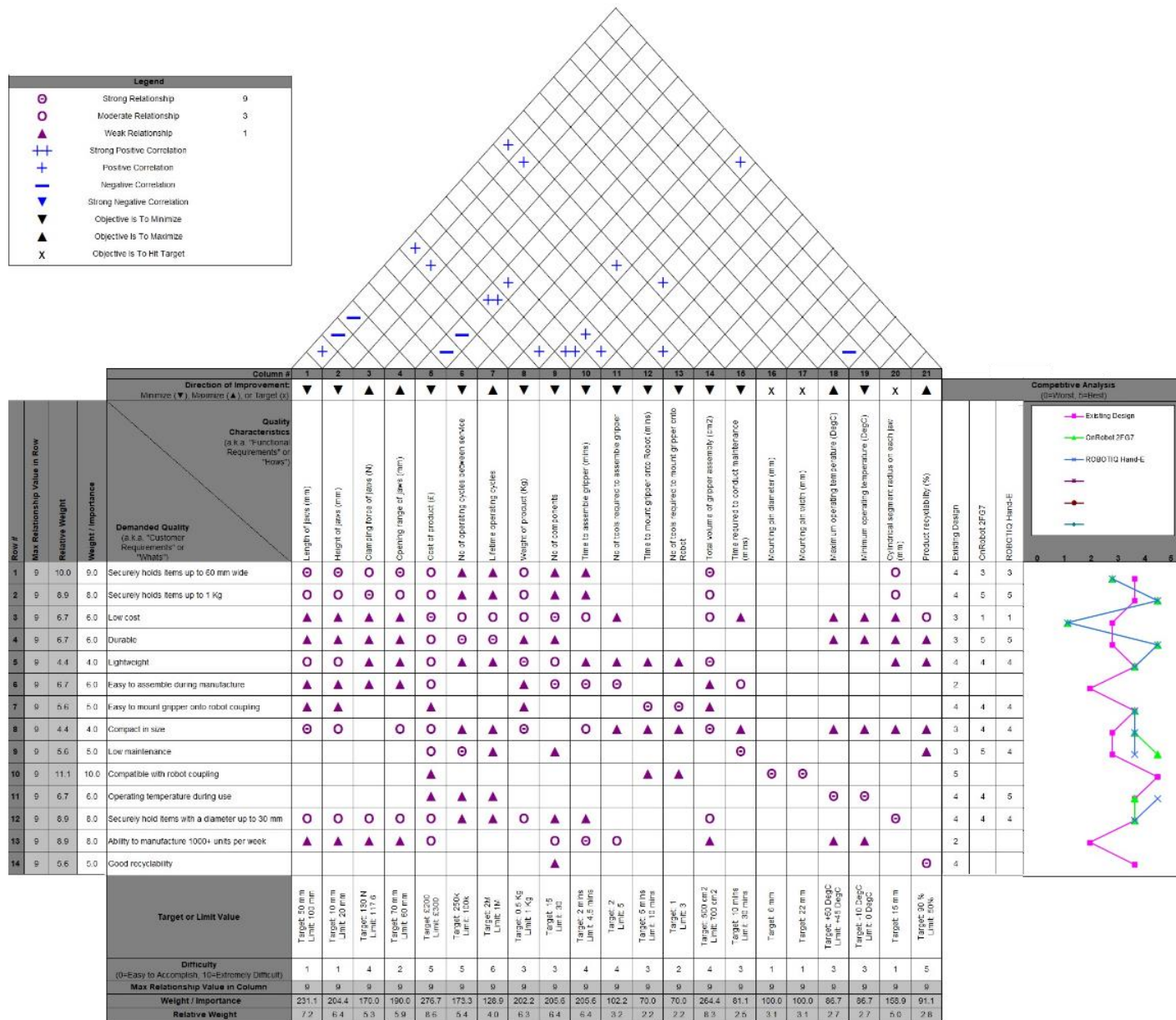


Figure 8: QFD of Robottech's gripper assembly (file format adapted from QFD Online, 2007).

Product Design Specification

The information obtained during the QFD stage was compiled into a product design specification (PDS), as displayed in Table 6. This acts as a guide for the designers and engineers during product development.

Table 6: Product Design Specification (PDS) for robot gripper.

Category		Requirement
1.0	Performance	1.1 The clamping force of the jaws must be between 117.7 N and 130 N.
		1.2 The opening range of the jaws must be between 60 mm and 70 mm.
		1.3 Fitment of the product should take no longer than 10 minutes.
		1.4 A maximum of three tools can be used to fit the product.
2.0	Environment	2.1 The product must operate sufficiently between 0°C and 45°C.
3.0	Product Life Span	3.1 The product will be on the market for at least 5 years.
4.0	Life in Service	4.1 The product must withstand a minimum of 1M operating cycles (ensuring maintenance is carried out at the relevant intervals).
5.0	Target Costs	5.1 The product cost to the end-user should be no greater than £300.
		5.2 The manufacturing costs should be no greater than 60% of the product costs (£180).
6.0	Volume/Demand	6.1 A minimum of 1,000 units will be required per week.
7.0	Maintenance	7.1 Maintenance intervals should be no less than 100k operating cycles.
		7.2 Time to conduct maintenance should be no greater than 30 minutes.
8.0	Size and Weight Restrictions	8.1 The length of the gripper jaws must not exceed 100 mm.
		8.2 The height of the jaws must not exceed 20 mm.
		8.3 The weight of the product must not exceed 1 Kg.
		8.4 The total volume of the product (L x W x H) must not exceed 700 cm ³ .
		8.5 The mounting pin diameter must be 6 mm in diameter and 22 mm long.
		8.6 The cylindrical segment of each jaw must have a radius of 15 mm.
9.0	Manufacturing Processes	9.1 There must be scope to manufacture up to 1,000 units per week (Mon – Fri) – the weekends will be reserved for peaks in demand and maintenance.
		9.2 Standardised, off-the-shelf components should be used where possible.
		9.3 The product should consist of no more than 30 components.
		9.4 Assembly of the product should take no longer than 4.5 minutes.
		9.5 A maximum of five tools can be used to fit the product.
10.0	Ergonomics	10.1 One person alone must be able to assemble the product.
		10.2 One person alone must be able to fit the product onto a robot.
11.0	Safety	11.1 The product must not have any sharp edges or burrs.
		11.2 The components and assembly processes must adhere to the Control of Substances Hazardous to Health Regulations (COSHH).
12.0	Testing	12.1 Testing must be carried out on 5% of all units manufactured.
13.0	Documentation	13.1 The product must be supplied with a user manual, which includes operational guidance, maintenance information, and a fitment guide.
14.0	Disposal	14.1 A minimum of 50% of the product must be recyclable.

Design Failure Mode and Effect Analysis

Having compiled a PDS for the robot gripper assembly, the next stage was to analyse the existing product design for potential deficiencies using a DFMEA (design failure mode and effect analysis). DFMEAs are a systematic methodology used to pre-empt possible product failures, determine their effect on product performance, and prioritise actions to mitigate the associated risks. Much like the QFD, DFMEA is also conducted in teams at various stages throughout product development. When executed effectively, increases in product reliability, quality, and safety can be realised.

Table 7 illustrates the DFMEA completed by the Robotech team. The risk priority number (RPN) in all but one instance was under 100 (the company's target), for which failure mode additional testing was proposed to improve failure detection.

Table 7: DFMEA table of Rochtech's gripper assembly.

Item	Function	Potential Failure Mode	Potential Effect(s) of Failure	S e v	C I a s s	Potential Cause(s)/ Mechanism(s) of Failure	O c c u r	Current Design Prevention Controls	Current Design Detection Controls	D e t e c	R P N	Recommended Action(s)	Responsibility and Target Completion Date	Action Results				
														Actions Taken	S e v	O c c	D e t	R P N
Jaws	Grip workpieces up to 1 Kg in weight and 80 mm in width	Thermal degradation	Workpiece weight gripping capabilities reduced	6	S O	Inadequate thermal properties of material	2	Finite element analysis (CAE)	Performance testing with workpiece temperatures specified in PDS	2	24						0	
		Fatigue failure	Loss of functionality during operation	8	H A	Inadequate fatigue strength of material	3	Fatigue analysis (CAE)	Performance testing using 1.5 Kg workpiece (FOS = 1.5)	3	72						0	
		Wear and abrasion	Decreased lifespan of gripper jaws	5	S O	Inadequate surface hardness of material	4	Use of correct material thickness and grade	Hardness testing	4	80						0	
		Excessive flexibility	Reduced gripping capabilities - weight and size	6	S O	Inadequate material stiffness	2	Finite element analysis (CAE)	Performance testing using 1.5 Kg workpiece (FOS = 1.5)	2	24						0	
Jaw Mounts	Interfaces with servo motor linkage to allow actuation	Fracture from impact damage	Reduced performance	6	S O	Insufficient material toughness.	3	Use of correct material thickness and grade	Charpy impact test	4	72						0	
	Toothed sections ensure both jaws actuate synchronously, allowing jaws to grip workpieces up to 60 mm wide	Wear and abrasion of gear teeth	Decreased lifespan of jaw mounts	5	S O	Inadequate surface hardness of material	4	Use of correct material thickness and grade	Hardness testing of gear teeth	4	80	Introduce additional detection control - durability testing	J Smith	Durability testing introduced	5	4	2	40
			Reduced workpiece width gripping capabilities	5	S O	Incorrect backlash between gears	5	Gear and spacing specifications which allow for correct backlash	Performance testing using 1.5 Kg workpiece (FOS = 1.5)	3	75						0	
		Tooth breakage	Complete loss of gripper functionality during operation	8	H A	Inadequate surface hardness of material	4	Use of correct material thickness and grade	Hardness testing of gear teeth	4	128	Introduce additional detection control - durability testing	J Smith	Durability testing introduced	8	4	2	64
				Inadequate fatigue strength of material	8	H A	Fatigue analysis (CAE)	3	Performance testing using 1.5 Kg workpiece (FOS = 1.5)	3	72						0	
	Robot Mount Assembly	Connects the gripper assembly to the robot	Location pin fracture	Complete loss of functionality	8	H A	Insufficient material shear strength	4	Finite element analysis (CAE)	Performance testing using 1.5 Kg workpiece (FOS = 1.5)	2	64						0
Location pin becomes loose			Reduction in gripper accuracy	4	S O	Inadequate securing / fastening mechanism	5	Use of correct torque specification for fasteners	Performance testing using 1.5 Kg workpiece (FOS = 1.5)	3	60						0	
Servo Housing	Supports the servo motor, jaw mounts and robot mount assembly	Material fracture	Substantial reduction in performance (limited workpiece gripping capabilities)	7	H A	Inadequate material thickness	3	Finite element analysis (CAE)	Material analysis after performance tests	3	63						0	
				7	H A	Unsuitable material grade	3	Finite element analysis (CAE)	Material testing after performance tests	3	63						0	
		Fasteners become loose	Increased risk of dropping workpiece	4	S O	Insufficient torque specification	4	Use of correct torque specification for fasteners	Breakaway torque measurement after performance tests	3	48						0	
				4	S O	Vibration from normal operation	5	Use of correct torque specification for fasteners	Breakaway torque measurement after performance tests	3	60						0	
Jaw Mount Bushings	Provides a low-friction interface between jaw mounts and the mounting screws	Premature wear and abrasion	Reduction in gripper accuracy and/or force	6	S O	Intervals between service / replacement are too long	4	Use of PV calculations to predict bearing lifespan	Durability testing	4	96						0	
				6	S O	Dirt / dust ingress	5	Design encloses bushing between two surfaces	Durability testing	3	90						0	
				6	S O	Excessive radial load	4	Use of PV calculations to select suitable size/type of bushing	Durability testing	4	96						0	

Design for Assembly (original design)

Many researchers have concluded that around 70% of a product's final costs are locked in at the design stage, substantially reducing the scope for decreasing product cost during the manufacturing stages (Velling, 2021). Employing Design for X methodologies during the design creation stage is key to mitigating unnecessary costs by eliminating waste and increasing efficiency.

Boothroyd and Dewhurst's design for assembly (DFA) approach was used to analyse the manual handling and assembly/insertion actions necessary for product assembly; this is conducted using multi-disciplinary teams with input from manufacturing, engineering, quality, and other stakeholders. Through extensive analysis spanning a wide range of products, Boothroyd and Dewhurst developed a standardised list of estimated times for common operations. Assembly cost estimations can be generated by correlating these timings with labour rate. Post analysis, operations that include non-essential components and lengthy operation times are targeted for removal or improvement. The aim is to simplify the design without compromising the quality of the product.

The first stage of analysing the robot gripper design involved composing the assembly sequence. The servo motor was identified as the base component from which all other components would be assembled. In total, 59 operations were required to assemble the product. Figure 9 presents some of the assembly stages.

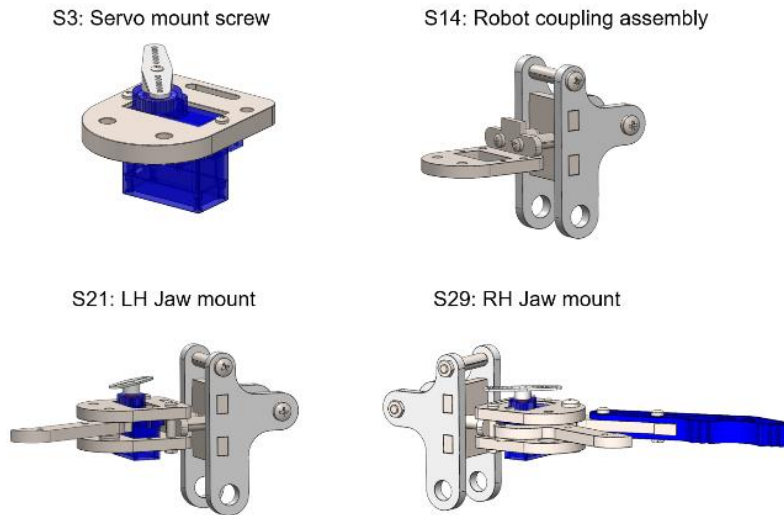


Figure 9: 3D models of four gripper assembly stages.

The subsequent step was assigning each assembly operation a code and time from the manual handling and insertion DFA tables (Dewhurst, et al., 1994). The handling and insertion times are combined to generate a total operation time multiplied by the operator rate/second to obtain the labour cost.

Next, the Minimum Part Criteria were assessed. Each discrete component was evaluated to determine whether it could be eliminated and/or combined with another component while ensuring the product can function as intended; fasteners automatically qualify for potential elimination. The full table of operations and their results are illustrated in Table 8.

Table 8: Robot gripper assembly analysis.

Step No	Item Name: Part / Operation	RP	HC	TH	IC	TI	TA	CA	NM	Description
1	Servo motor	1	30	1.95	00	1.5	3.45	2.48	1	Place in fixture (item 16)
2	Upper servo brace	1	20	1.8	12	5	6.8	4.90	1	Locate upper brace onto servo motor (item 19)
3	Servo motor screw	2	16	2.57	38	6	17.14	12.34	0	Add screw and fasten (item 7)
4	Center mount brace	1	10	1.5	00	1.5	3	2.16	0	Place in fixture (item 11)
5	Nut spacer	2	01	1.43	06	5.5	13.86	9.98	0	Add nut and locate against brace (item 12)
6	Center mount screw	2	11	1.8	38	6	15.6	11.23	0	Add screw and fasten (item 15)
7	Center servo housing brace	1	10	1.5	06	1.5	3	2.16	0	Locate onto center brace nut spacers (item 13)
8	Center mount screw	2	11	1.8	38	6	15.6	11.23	0	Add screw and fasten (item 15)
9	Side mount brace	2	30	1.95	02	2.5	8.9	6.41	0	Locate side mount brace onto center mount brace (item 3)
10	Side mount brace spacer	2	00	1.13	08	6.5	15.26	10.99	1	Add spacer and hold in position (item 10)
11	Side mount screw	2	10	1.5	38	6	15	10.80	0	Add screw (item 14)
12	Side mount nut	2	06	2.17	06	5.5	15.34	11.04	0	Add nut and fasten (item 2)
13	Lower servo brace	1	20	1.8	00	1.5	3.3	2.38	0	Place in fixture (item 19)
14	Robot coupling assembly	1	30	1.95	00	1.5	3.45	2.48	-	Locate into lower servo brace
15	Upper servo assembly	1	30	1.95	00	1.5	3.45	2.48	-	Locate onto servo housing brace
16	Servo brace spacer	2	01	1.43	02	2.5	7.86	5.66	0	Add spacer and hold in position (item 17)
17	Servo brace screw	2	11	1.8	38	6	15.6	11.23	0	Add screw (item 9)
18	Servo brace nut	2	06	2.17	06	5.5	15.34	11.04	0	Add nut and fasten (item 20)
19	Jaw mount washer	3	03	1.69	12	5	20.07	14.45	0	Add washer onto lower servo brace (item 22)
20	LH Jaw mount bush	1	01	1.43	06	5.5	6.93	4.99	0	Locate and hold jaw mount bushing into LH jaw (item 18)
21	LH Jaw mount	1	30	1.95	18	9	10.95	7.88	1	Locate and hold LH jaw into position (item 25)
22	LH jaw mount screw	1	11	1.8	38	6	7.8	5.62	0	Add screw (item 4)
23	LH jaw mount nut	1	06	2.17	06	5.5	7.67	5.52	0	Add nut and fasten (item 21)
24	LH Jaw	1	30	1.95	02	2.5	4.45	3.20	0	Locate jaw onto LH jaw mount (item 24)
25	LH jaw screw	2	12	2.25	38	6	16.5	11.88	0	Add screw (item 1)
26	LH jaw nut	2	06	2.17	06	5.5	15.34	11.04	0	Add nut and fasten (item 23)
27	Jaw mount washer	3	03	1.69	12	5	20.07	14.45	0	Add washer onto lower servo brace (item 22)
28	RH Jaw mount bush	1	01	1.43	06	5.5	6.93	4.99	0	Locate and hold jaw mount bushing into RH jaw (item 18)
29	RH Jaw mount	1	30	1.95	18	9	10.95	7.88	1	Locate and hold RH jaw into position (item 26)
30	RH jaw mount screw	1	11	1.8	38	6	7.8	5.62	0	Add screw (item 4)
31	RH jaw mount nut	1	06	2.17	06	5.5	7.67	5.52	0	Add nut and fasten (item 21)
32	RH Jaw	1	30	1.95	02	2.5	4.45	3.20	0	Locate jaw onto RH jaw mount (item 24)
33	RH jaw screw	2	12	2.25	38	6	16.5	11.88	0	Add screw (item 1)
34	RH jaw nut	2	06	2.17	06	5.5	15.34	11.04	0	Add nut and fasten (item 23)
35	Servo actuator link	1	13	2.06	06	5.5	7.56	5.44	1	Locate servo actuator link onto servo drive and hold (item 6)
36	Servo actuator screw	1	14	2.55	38	6	8.55	6.16	0	Locate servo actuator link screw (item 8)
37	Servo actuator nut	1	09	2.98	16	8	10.98	7.91	0	Add nut and fasten (item 27)
38	Servo jaw spacer	1	01	1.43	06	5.5	6.93	4.99	0	Locate between RH jaw and servo actuator link (item 12)
39	Servo jaw screw	1	12	2.25	38	6	8.25	5.94	0	Add screw (item 5)
40	Servo jaw nut	1	04	2.18	06	5.5	7.68	5.53	0	Add nut and fasten (item 23)

Key	
RP	No. of items / operations
HC	Manual handling code
TH	Handling time per item (s)
IC	Manual Insertion code
TI	Insertion time per item (s)
TA	Total operation time: $RP \times (TH + TI)$
CA	Total operation cost (pence): $TA \times OP$
NM	Figures for minimum parts required: 1 = Essential, 0 = Non-essential

The fully burdened labour cost used for the calculations was £25.92 per hour; this includes all the costs associated with employees: pension contributions, holiday pay, national insurance contributions, and other benefits (Lennox, 2023). The true assembly cost would also need to incorporate the machine rate, i.e., factory overheads such as rent and utilities.

In Table 9, a summary of the key metrics from the DFA analysis can be found.

Table 9: Robot gripper baseline design metrics.

Baseline Metrics	
Metric Description	Value
No. of unique components	27
Total components	58
No. of assembly operations	59
No. of tools required to assemble	6
Weight (g)	400
Theoretical minimum no. of parts	7
Total assembly time (s)	411
Total assembly cost	£ 2.96
Design Efficiency	5.1%

The manual assembly design efficiency was calculated using the following equation:

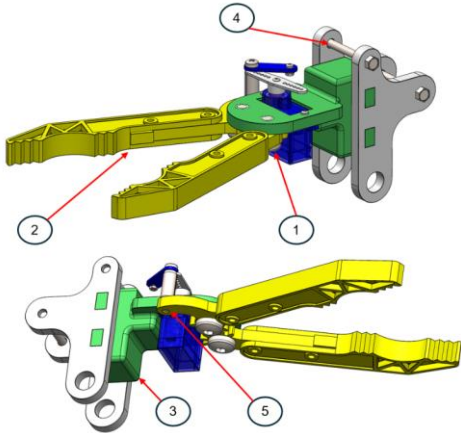
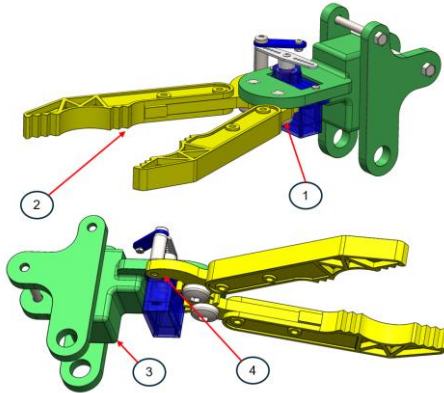
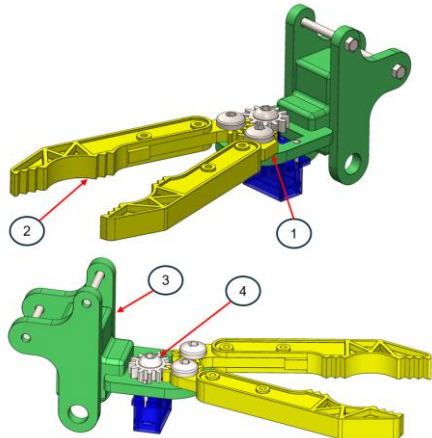
$$E_{ma} = N_{min} * (T_a / T_m)$$

Where N_{min} is the theoretical minimum number of parts, T_a is the ideal assembly time for one part, and T_m is the estimated assembly time for the actual product (Dewhurst, et al., 1994). The design efficiency of the robot gripper was a mere 5.1%, which came as no surprise considering the numerous fasteners and spacers integrated into the design.

Design Concepts

The design engineer created three concepts using the information collected in the previous sections. All of them needed to meet the requirements in the PDS while also aiming to reduce the product's complexity, increase design efficiency, and reduce the manufacturing cost. Table 10 illustrates the three design concepts along with their associated design metrics.

Table 10: Robot gripper design concepts and their associated metrics.

	Design 1	Design 2	Design 3
			
Metric Description	Value		
No. of unique components	14	13	9
Total components	19	17	14
No. of assembly operations	19	17	14
Theoretical minimum no. of parts	5	5	5
Total assembly time (s)	145	136	104
Total assembly cost	£ 1.04	£ 0.98	£ 0.75
Design Efficiency	10.4%	11.0%	14.4%

Design Selection

After compiling the three initial design concepts, the team chose one for further refinement. Each design was evaluated against the key DFA criteria using a decision-matrix method, with each criterion assigned relative importance weightings similar to the QFD process. Upon completing the scoring exercise, design no. 3 emerged as the most satisfactory, as shown in Table 11.

Table 11: Robot gripper design selection.

Design No.	Assembly time (weight: 4)	No. of unique components (weight: 4)	Design efficiency (weight: 3)	Assembly cost (weight: 5)	Total score
1	$4 \times 3 = 12$	$3 \times 4 = 12$	$2 \times 3 = 6$	$4 \times 5 = 20$	50
2	$4 \times 4 = 16$	$3 \times 4 = 12$	$2 \times 3 = 6$	$4 \times 5 = 20$	54
3	$5 \times 4 = 20$	$4 \times 4 = 16$	$3 \times 3 = 9$	$5 \times 5 = 25$	70

Material and Manufacturing Process Selection

This section includes a summary of the selection process for the materials and manufacturing methods for the bespoke components: jaws, servo gear and main housing. All other components, such as the bushings, servo motor, and fasteners, are off-the-shelf; it would not be economically viable to consider manufacturing these components solely for use in this product.

Jaws

Table 12 describes the process requirements for the jaws. Figure 10 illustrates the revised jaw design.

Table 12: Process requirements for robot gripper jaws.

Function:	Interact with workpiece Gear must mesh with the opposite jaw and servo motor.
Constraints:	Length (100 mm max) & height (20 mm max) Temperature range - 0°C and 45°C Stiffness >1 GPa
Objective:	Minimise cost Minimise mass
Free variables:	Choice of material

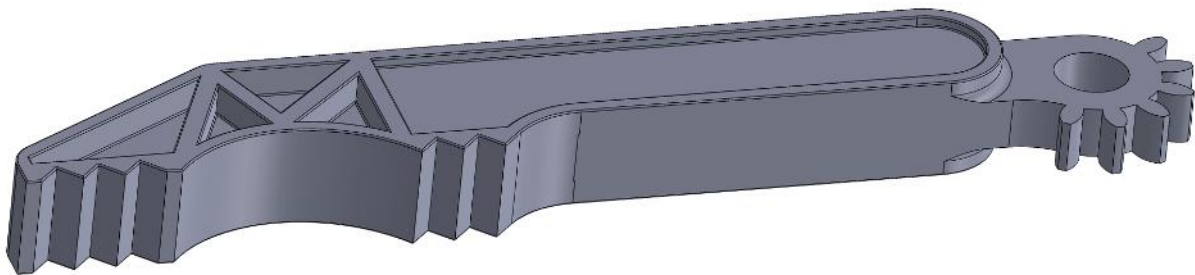


Figure 10: 3D model of revised robot gripper jaw.

While the objective was to minimise the material's cost and mass, the relative weighting from the QFD dictated that minimising cost was more important than minimising weight.

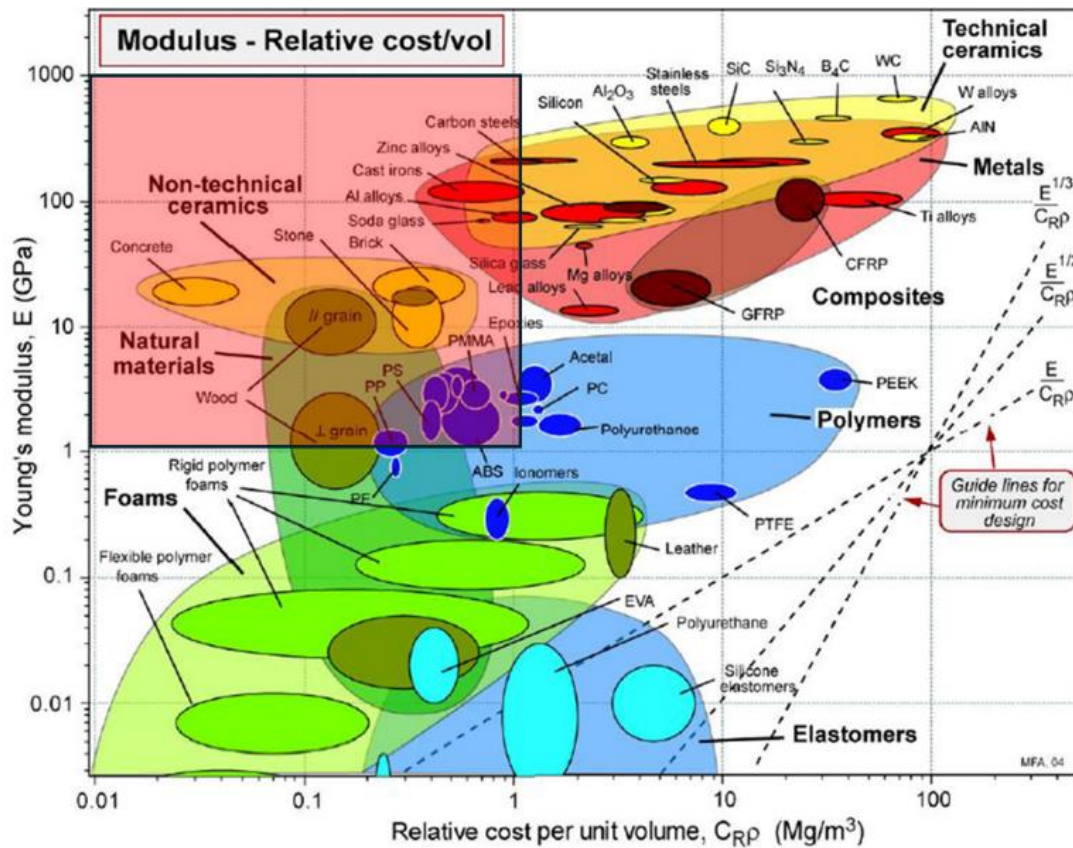


Figure 11: Young's modulus plotted against the relative cost per unit volume of materials (Ashby, 2017).

Figure 11 (Ashby, 2017) displays materials' stiffness (Young's modulus) against their relative cost per unit volume. The section highlighted in red contains materials considered candidates for the jaw assembly, summarised in Table 13.

Table 13: Potential robot gripper jaw materials.

Material	Stiffness (Gpa)	Relative cost per unit volume (Mg/m ³)
ABS	1 - 2	0.5 – 0.8
Al alloys	70 - 85	0.8 – 1.3
Carbon steels	200	0.8 - 2
Cast irons	100 - 150	0.4 - 1

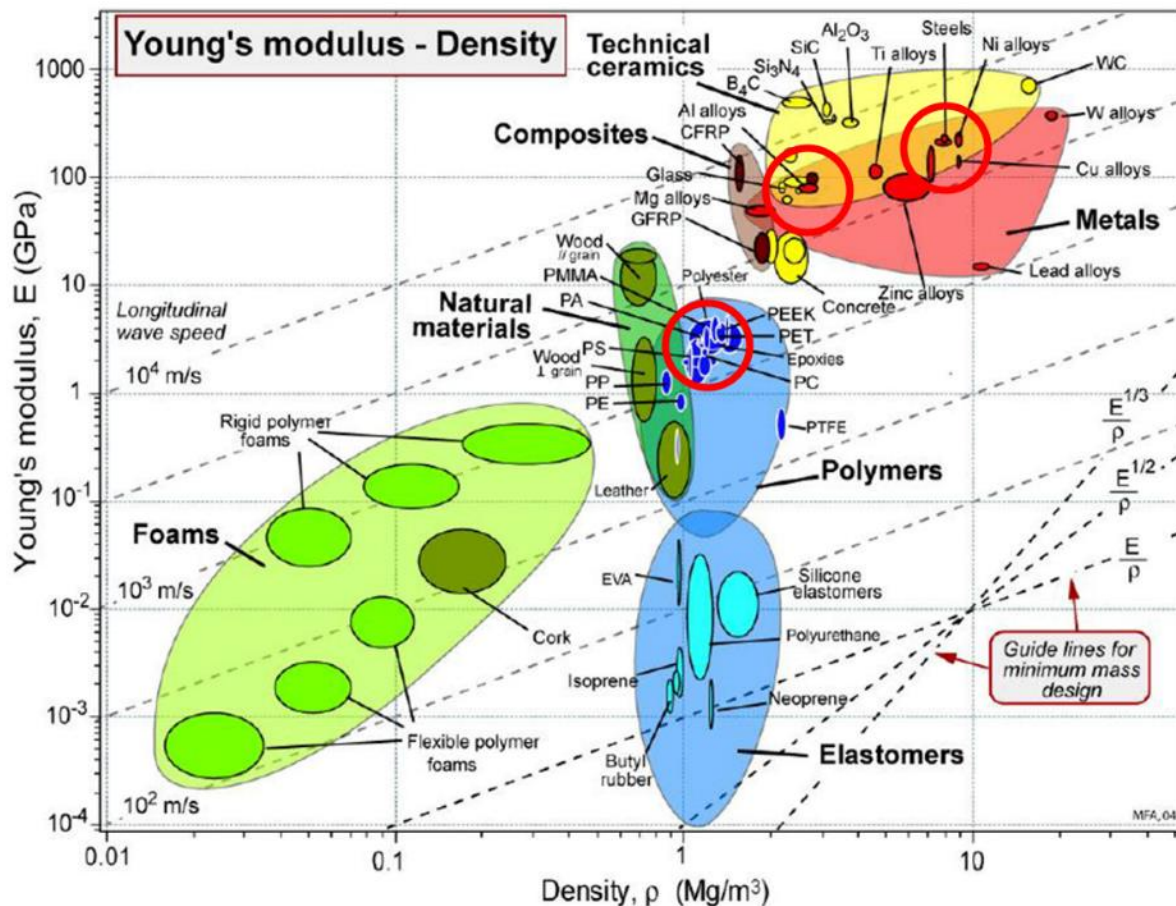


Figure 12: Young's modulus plotted against the density of materials (Ashby, 2017).

The subsequent step required choosing the lightest of the four chosen materials. Figure 12 (Ashby, 2017) displays the materials' stiffness (Young's modulus) against density. ABS polymer is the lightest material, so it was subsequently chosen to proceed with the manufacturing process investigation stage.

The selection criteria for suitable manufacturing processes depend on several key factors, including the shape of the desired product, tolerance requirements, material properties, and batch size. Until now, all of the necessary inputs, except the batch size, had been compiled; the team concluded on a requirement of 6,000 – 12,000 units.

Figure 13 (Ashby, 2017) highlights the polymer manufacturing processes capable of processing solid 3D components. These manufacturing processes were collated into Table 14 and with the aid of Figure 14 (Ashby, 2017), the team decided to use injection moulding.

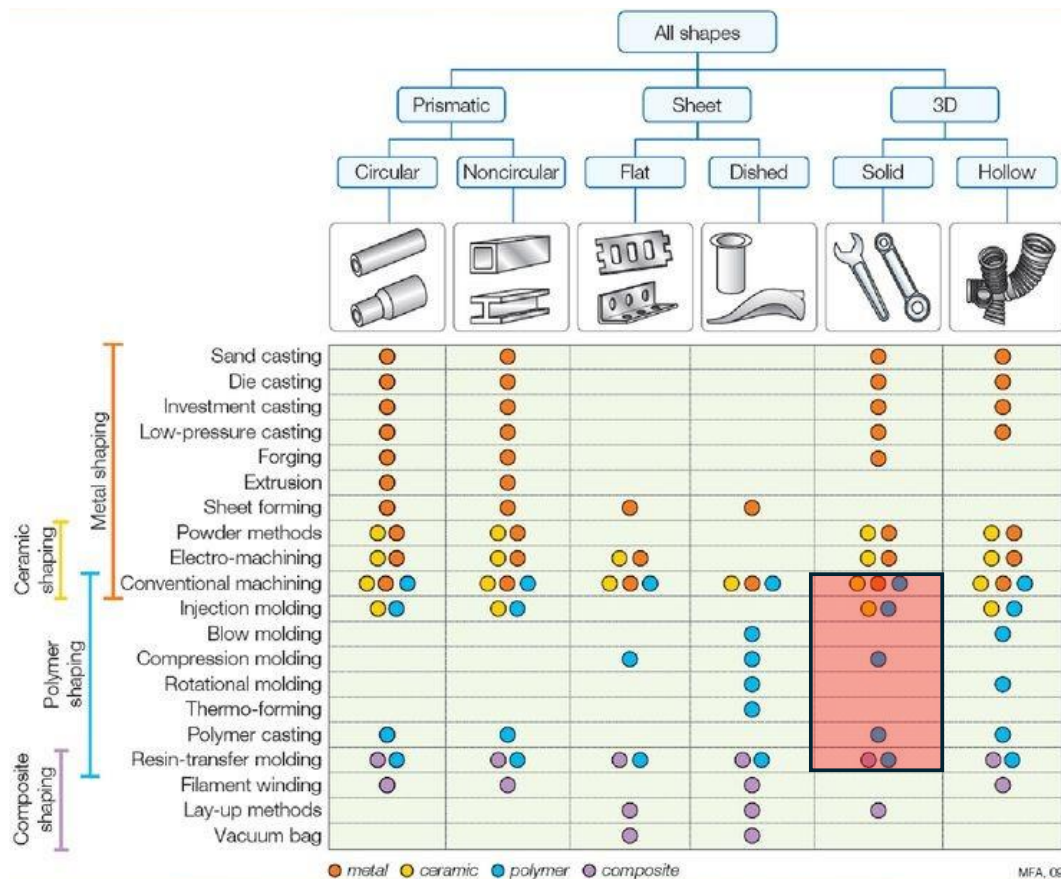


Figure 13: Process shape matrix (adapted from Ashby, 2017).

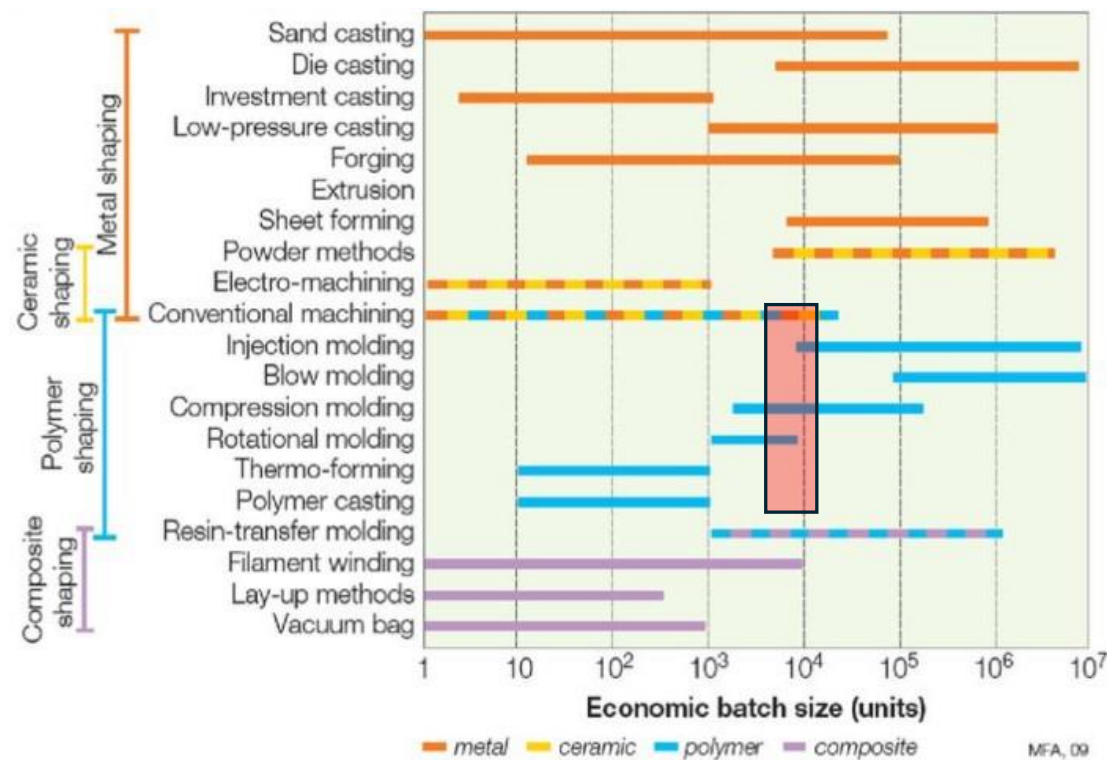


Figure 14: Economic batch-size chart of processes (adapted from Ashby, 2017).

Table 14: Robot gripper jaw process selection.

Material	Process	Compatibility with shape	Compatibility with batch size	Quality comment
ABS	Resin-transfer moulding	No	Yes	
	Polymer casting	Yes	No	
	Compression moulding	No	Yes	Surface finish and tolerance requirements cannot be met
	Injection moulding	Yes	Yes	
	Machining	No	Yes	

Servo gear and main housing

Using the same methodology as the jaw materials and manufacturing process selection, the team concluded that the servo gear (Figure 15) would also be manufactured using injection moulding with ABS. The main housing (Figure 16) would be made from aluminium using sand casting, with some post-processing required for the fastener threads.

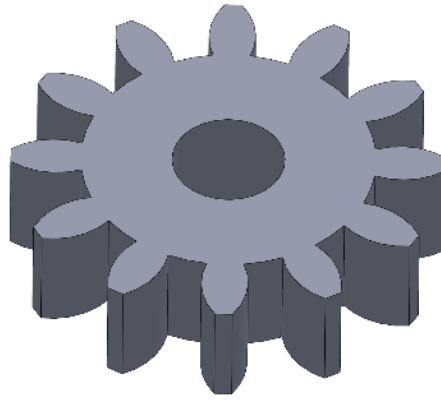


Figure 15: 3D model of robot gripper servo gear.



Figure 16: 3D model of revised robot gripper housing.

Final Design Summary

Using design concept no.3 as a reference, the design was further refined, adding and removing material where required and considering material and manufacturing process constraints.

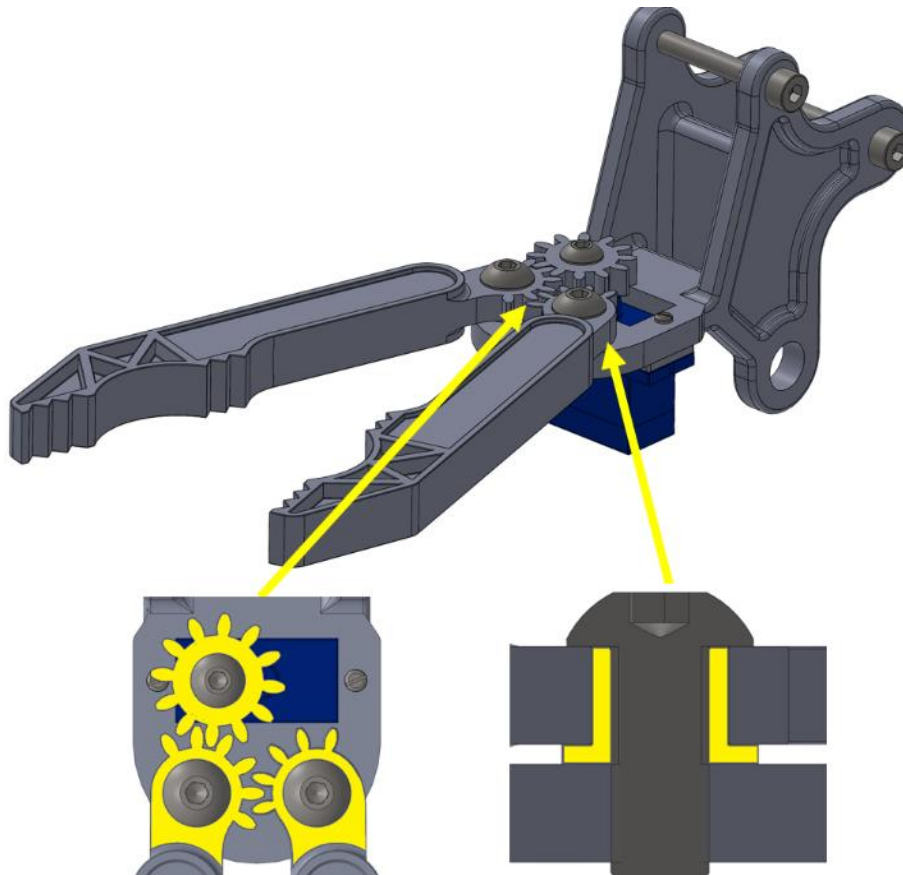


Figure 17: Assembly model of final robot gripper.

The linkage between the servo motor and the jaws was simplified by adding a drive gear (Figure 17) directly onto the servo, eliminating the need for the original design's linkage arms, dowels, bolts and nuts.

Another simple yet effective improvement was removing the three washers at the bottom of the gear mechanism on the jaws. A small flange was added to the bottom of the plain bushing (Figure 17) to support the load and act as a consumable wear item.

The greatest product complexity reduction was realised by combining all structural components and fasteners into one solid body, significantly reducing the assembly time.

Table 15 compares the DFA metrics from the original design against the new design. The new design significantly surpasses the original design in all metrics.

Table 15: Comparison of robot gripper's original and revised design metrics.

Metric Description	Original Design	New Design	Improvement
No. of unique components	27	9	67%
Total components	58	14	76%
No. of assembly operations	59	14	76%
No. of tools required to assemble	6	3	50%
Weight (g)	400	280	30%
Theoretical minimum no. of parts	7	5	29%
Total assembly time (s)	411	104	75%
Total assembly cost	£ 2.96	£ 0.75	75%
Design Efficiency	5.1%	14.4%	182%

Conclusion

The redesign of Robotech's mechanical robot gripper assembly has proven to be a strategic decision to meet the increasing market demand, transitioning from low-scale to high-volume production. The initial product, tailored for a single customer's requirements, required significant enhancements to support a projected demand of over 1000 units per week. Utilising Design for Manufacturing and Assembly (DFMA) methodologies, the team systematically addressed the product's design inefficiencies.

The redesign began with market research and competitor analysis, which aided in creating a Quality Function Deployment (QFD), converting customer requirements into measurable engineering specifications, and ensuring that the redesign met functional and performance criteria. The engineering specifications were compiled into a comprehensive Product Design Specification (PDS, a guideline to ensure the new design met customer expectations and industry standards.

Conducting a Design Failure Mode and Effects Analysis (DFMEA) identified potential failure points, leading to targeted improvements that enhanced product reliability and safety. The Design for Assembly (DFA) analysis highlighted numerous inefficiencies in the original design, prompting a reduction in the number of unique components and the complexity of the assembly process. The final design concept, selected through a rigorous decision matrix process, demonstrated superior assembly time, component count, design efficiency, and overall cost performance.

Material and manufacturing process selection further optimised the design for mass production, with ABS and aluminium identified as suitable materials for the jaws and main housing, respectively. Integrating injection moulding and sand casting processes ensured cost-effectiveness and quality in high-volume production.

Overall, the redesigned robot gripper assembly meets the current market demands and positions Robotech for future scalability and competitiveness in the robotic tooling and equipment industry. The final product showcases significant improvements in design efficiency, manufacturing cost, and assembly time, making it a robust and economically viable solution for high-volume production.

Task 2

Introduction

Since its inception in the mid-1980s, additive manufacturing (AM) has grown continually, with the technology improving yearly. Metal additive system sales, in particular, have grown exponentially over the past twenty years (Wohlers Associates, 2024) thanks to the ever-increasing range of applications.

HP Racing, an off-road motorcycle racing team, was designing its race bike in readiness for the following season. It wanted to capitalise on additive manufacturing because it could create lightweight and complex geometry components. One of the components chosen for upgrading was the footpegs, where the rider locates their feet. The team was unsure whether the original footpegs would be robust enough to handle the harsh environment they would be subjected to during the hard enduro racing events. Another objective was to minimise weight, where possible. With the support of computer-aided design (CAD) and computer-aided engineering (CAE) software programs, the team analysed the original design, considering the increased loads experienced during racing. Tools such as finite element analysis (FEA) and generative design (GD) would help redesign the product with weight efficiency in mind. Following design for additive manufacturing (DFAM) principles would ensure the design was manufacturable for the chosen AM process.

Figures 18 and 19 represent a replica of the original footpeg drawn using Autodesk 360 CAD software. This model would be the baseline when accessing new design iterations. The original footpeg is manufactured out of cast stainless steel 17-4 ph and weighs 243 g.

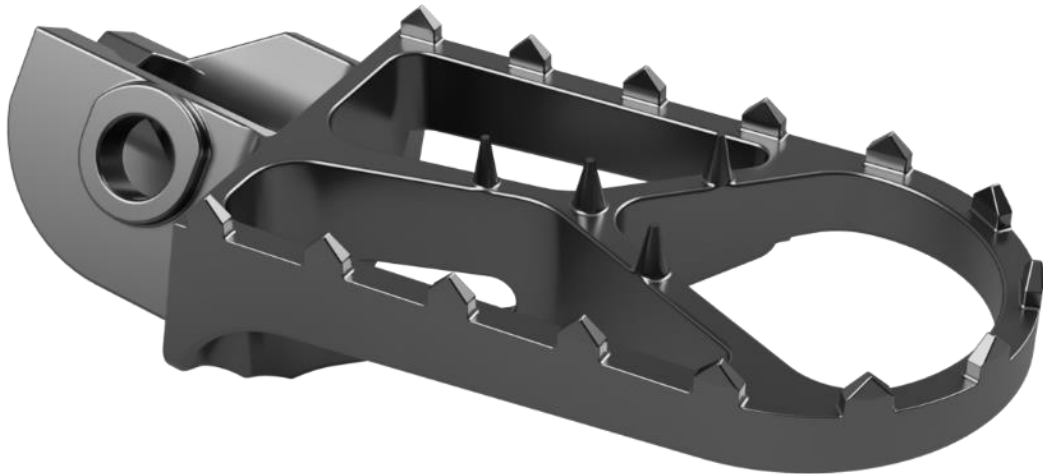


Figure 18: 3D model of the original footpeg design (view 1).



Figure 19: 3D model of the original footpeg design (view 2).

The location in which the right-hand footpeg is positioned on the motorcycle is illustrated in Figure 20 (KTM Malaysia, 2024) – the left-hand footpeg is symmetrical.



Figure 20: Original footpeg on a KTM EXC 300 motorcycle (KTM Malaysia, 2024)

Product Design Specification

A comprehensive PDS was developed with contributions from various stakeholders, as detailed in Table 16.

Table 16: Product Design Specification (PDS) for foot peg.

Category		Requirement
1.0	Performance	1.1 Must support a rider up to 180 Kg
		1.2 Can withstand twice the force of the original footpeg design.
		1.3 Teeth must securely grip into the rider's boot.
		1.4 Maximum allowable deflection – under loading – of 1 mm.
2.0	Environment	2.1 Must operate sufficiently between -20°C to +50°C.
		2.2 Must withstand regular use and harsh environmental conditions: impacts with rocky terrain and tree roots.
		2.3 Must resist rust and corrosion from exposure to water, mud, and road salts.
3.0	Product Life Span	3.1 The product will be on the market for at least 3 years.
4.0	Life in Service	4.1 The product must operate effectively for at least one year.
5.0	Target Costs	5.1 The manufacturing cost should be no greater than £200 per footpeg.
6.0	Volume/Demand	6.1 A total of twenty units are required (pairs).
7.0	Maintenance	7.1 The product should require no maintenance during its service life.
8.0	Aesthetics	8.1 The design should include smooth transitions between different geometric elements to ensure aesthetic coherence and structural integrity.
		8.2 The preferred colours are grey or silver.
9.0	Size and Weight Restrictions	9.1 The weight of the product must be less than 250 g.
		9.2 Must be compatible with the existing motorcycle fixture point (10 mm diameter pin).
		9.3 The foot mounting platform must be the same as the original design (50 mm x 90 mm).
10.0	Manufacturing Processes	10.1 Twenty pairs of footpegs need to be designed and manufactured within eight weeks.
		10.2 The product must be manufactured using an additive manufacturing process.
		10.3 The final design, material and process chosen should require minimal post-processing.
11.0	Ergonomics	11.1 The original design of the teeth must be used (boot contact area).
		11.2 One person alone must be able to fit the product.
12.0	Safety	12.1 The product must not have any sharp edges or burrs.
		12.2 Must be designed with a factor of safety of 2.
13.0	Testing	13.1 To validate the results obtained through the FEA analysis, destructive testing must be conducted on one pair of footpegs.
		13.2 Must undergo and pass tests for resistance to corrosion, UV light, and extreme temperatures.
14.0	Disposal	14.1 The product must be 100% recyclable.

Design Failure Mode and Effect Analysis

Following a thorough DFMEA review session, the team concluded that the design prevention and detection measures were satisfactory, instilling confidence in the design's robustness and eliminating the need for further actions, as presented in Table 17.

Table 17: DFMEA table for the footpeg.

Function	Potential Failure Mode	Potential Effect(s) of Failure	S e v	C l a s s	Potential Cause(s)/ Mechanism(s) of Failure	O c c u r	Current Design Prevention Controls	Current Design Detection Controls	D e t e c	R P N
Support the weight of the rider	Fatigue failure	Loss of functionality during operation	8	H A	Material has inadequate corrosion resistance properties	3	Selection of material that satisfies the environmental requirements in the PDS	Extensive field testing	3	72
					Material has inadequate thermal properties	3	Selection of material that satisfies the environmental requirements in the PDS	Extensive field testing	3	72
					Inadequate fatigue strength of material	3	Use of material with sufficient fatigue strength that satisfies the performance and life-in-service requirements	Fatigue analysis (CAE) of cyclic loading	2	48
	Material fracture	Reduction in performance	6	S O	Insufficient material thickness	4	Use of sufficient material in high stress areas	Finite element analysis (CAE) - minimum safety factor of 2	2	48
		Complete loss of functionality	8	H A	Use of material with unsatisfactory physical properties	3	Use of sufficient strength material that satisfies the performance requirements in the PDS	Finite element analysis (CAE) - minimum safety factor of 2	2	48
	Excessive flexibility	Reduced rider control due to varying foot positions	6	S O	Material lacks sufficient stiffness	2	Use of material with a satisfactory Young's modulus value - maximum allowable deflection of 1 mm	Finite element analysis (CAE) - maximum allowable deflection of 1 mm	2	24
Securely grip into the riders boot	Wear and abrasion of teeth	Reduction of rider's control due to reduced grip	6	S O	Inadequate surface hardness of material	3	Use of correct material thickness and grade	Rockwell hardness test	3	54
					Design of teeth are not suitable - insufficient surface area per tooth	2	Use original tooth design	Extensive field testing by numerous professional athletes	4	48
					Inadequate tooth design - not sharp enough to penetrate boots	2	Use original tooth design	Extensive field testing by numerous professional athletes	4	48
	Tooth breakage	Complete loss of functionality due to numerous tooth breakages	8	H A	Inadequate surface hardness of material	3	Use of correct material thickness and grade	Rockwell hardness test	3	72
					Design of teeth are not suitable - insufficient surface area per tooth	2	Use original tooth design	Extensive field testing by numerous professional athletes	4	64
					Inadequate fatigue strength of material	3	Use of material with sufficient fatigue strength that satisfies the performance and life-in-service requirements	Fatigue analysis (CAE) of cyclic loading	2	48
Protect the sole of the riders foot	Fracture from impact damage	Reduction in performance	6	S O	Insufficient material toughness	3	Use of correct material thickness and grade	Extensive field testing by numerous professional athletes	4	72
		Complete loss of functionality	8	H A	Inadequate design - lack of structure/bracing	4	Use of sufficient material in high-stress areas, and support structures	Finite element analysis (CAE) - minimum safety factor of 2	2	64

Finite Element Analysis (existing design)

Finite Element Analysis (FEA) was employed before investigating alternate designs of the footpeg. This allows engineers to anticipate an object's behaviour, considering its environmental aspects. FEA is predominantly used to analyse complex systems and structures that would be arduous or even unfeasible to assess using manual computations. It can be used for analysing solid mechanics, fluid mechanics, heat transfer, and electromagnetics.

The finite element method (FEM) is the backbone of FEA. It uses maths to break down complex structures into smaller pieces or elements, also known as discretisation. This is converting the solid body into a mesh, consisting of tetrahedral (best suited for complex geometries) or hexahedral (more precise with fewer elements); the points or corners in which the elements interface are called the nodes. Analysing all model features, such as a branding plate or a non-structural feature, may not be necessary. The user decides which features of the model need to be converted into a mesh. The capability of computers and FEA software then apply differential equations to each element, resulting in an output of the desired field variable (stress, strain or displacement, to name a few). The accuracy of the model's results relies heavily on the quality of the inputted data, such as the material properties, geometry, analysis type, and environmental elements (temperature, force, etc) (Ansys, 2021; Dixit, 2009).

The footpeg's FEA was conducted using Autodesk Fusion 360. The first assessment used the original force rating (dynamic force multiplier of two).

The next step involved assigning the constraints to the part. The internal faces of the mounting pin location were fixed, as illustrated by the yellow arrows in Figure 21.

Load Calculation (original specification)

Maximum permissible rider weight = 180 kg

Dynamic force multiplier = 2

Force calculation:

$$F = m \times g$$

Where f = force in Newtons, m = mass in kg and g = gravity in m/s^2

$$F = 180 \times 9.81$$

$$F = 1766 \text{ N}$$

Force calculation, including the dynamic force multiplier:

$$F = 1766 \times 2$$

$$F = 3532 \text{ N}$$

However, since the motorcycle has two footpegs, the force is distributed between them:

$$F = 3532 / 2$$

$$F = 1766 \text{ N}$$

As illustrated by the blue arrows in Figure 21, a load of 1766 N was evenly distributed across the 18 contact pins.

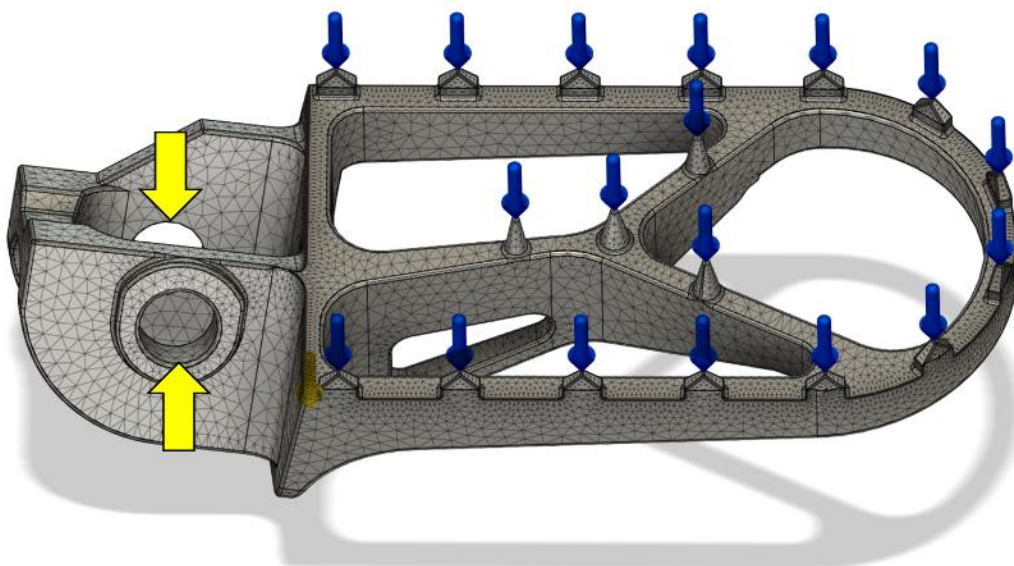


Figure 21: Constraint and load application points for FEA of the original footpeg design.

A mesh element size of 5% was selected, the result of which is visualised in Figure 22. Due to the complex geometry, a tetrahedral mesh was employed.

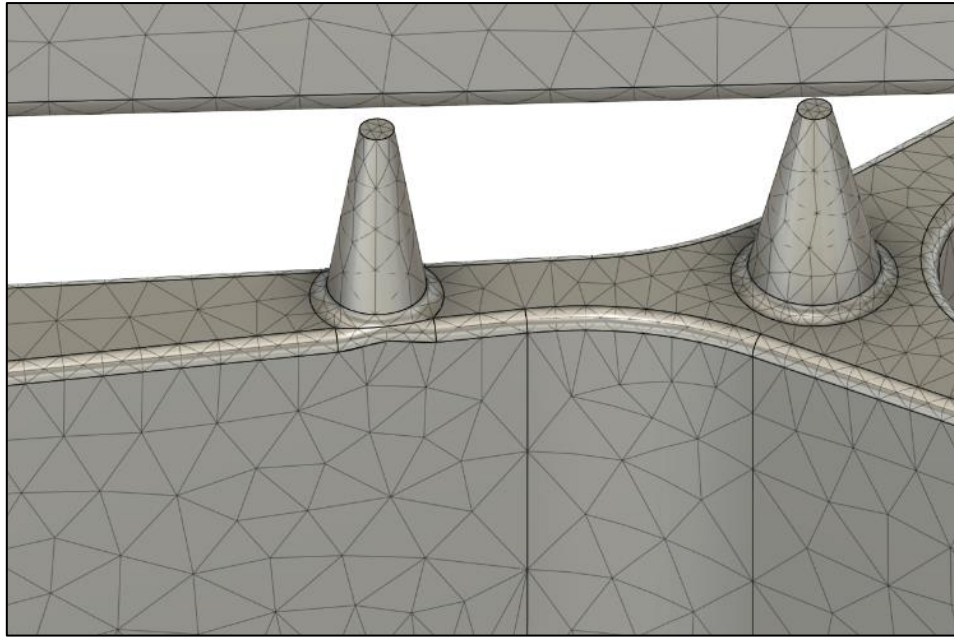


Figure 22: A 3D mesh of the original footpeg design.

After entering all the relevant inputs, the software begins solving the problem. The convergence plot displayed in Figure 23 confirms that the convergence target was achieved in the second solution step; the finer the mesh, the more accurate the value.

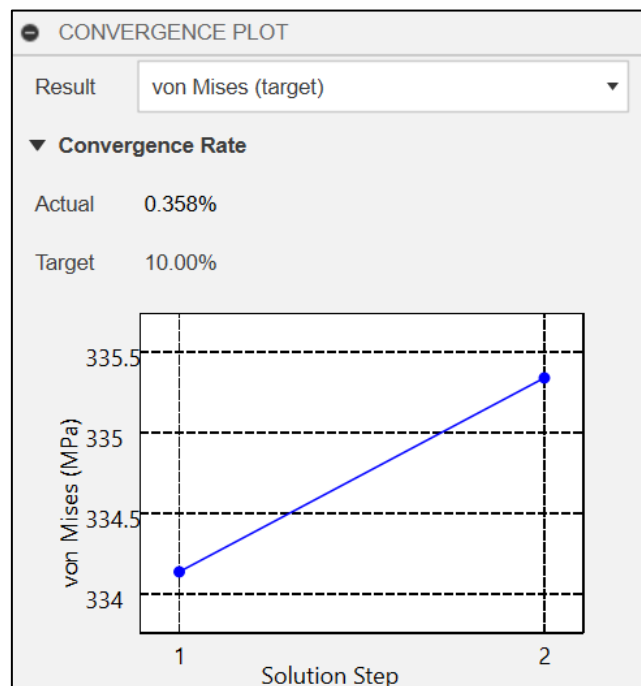


Figure 23: Convergence plot.

Figure 24 illustrates the FEA's final result. The colour mapping gives the engineer a visual depiction of the results. In this instance, the desired output was the safety

factor—the ratio between the strength of the material and the stress in the component. The lowest FOS result was 1.789, which was located on top of the lower support brace. The result was slightly under the requested value of 2; this could be attributed to inaccuracies in replicating the original component.

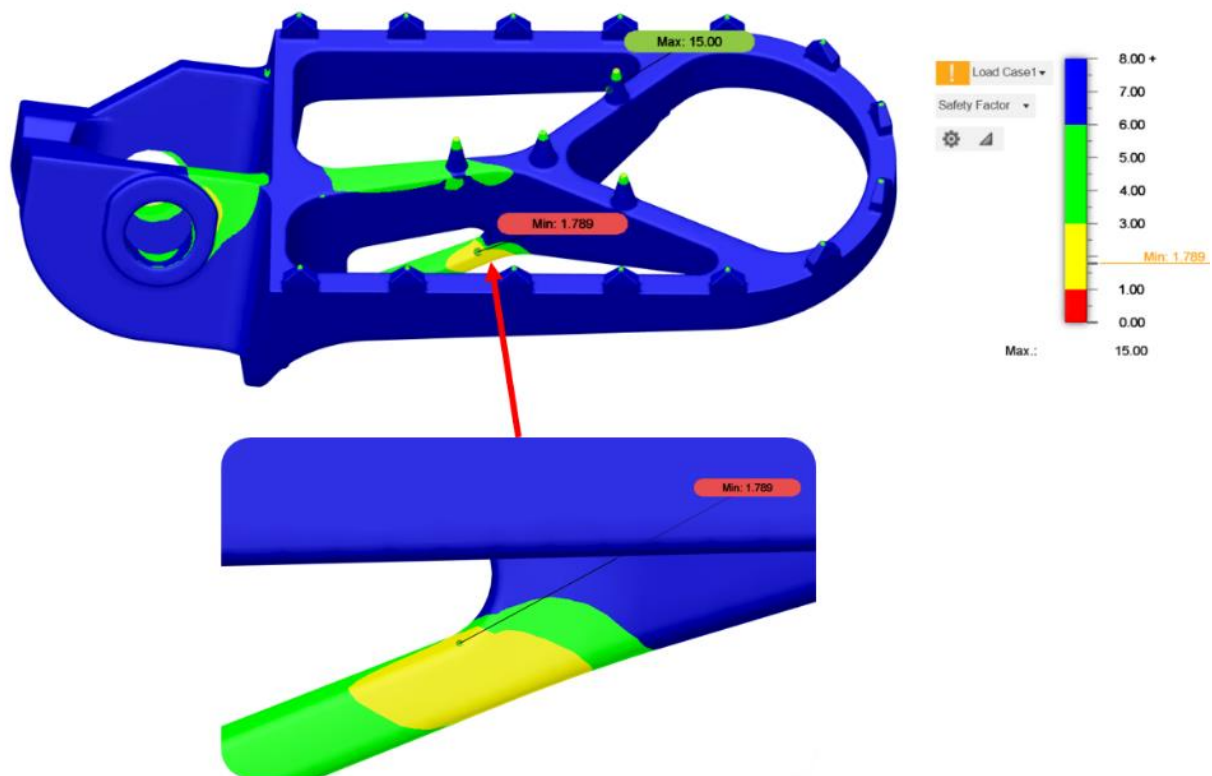


Figure 24: FEA of original footpeg design (2x dynamic force multiplier).

Load calculation (new specification)

Force calculation, including the dynamic force multiplier:

$$F = 1766 \times 4$$

$$F = 7064 \text{ N}$$

However, since the motorcycle has two footpegs, the force is distributed between them:

$$F = 7064 / 2$$

$$F = 3532 \text{ N}$$

The second FEA, conducted at a peak force twice that of the original test to simulate the stresses of hard enduro racing events, revealed a critical finding. The minimum FOS was halved, indicating a potential product failure under peak loads. The FEA color-mapped result, shown in Figure 25, clearly highlights areas for strength improvement (yellow) and potential material reduction (blue).

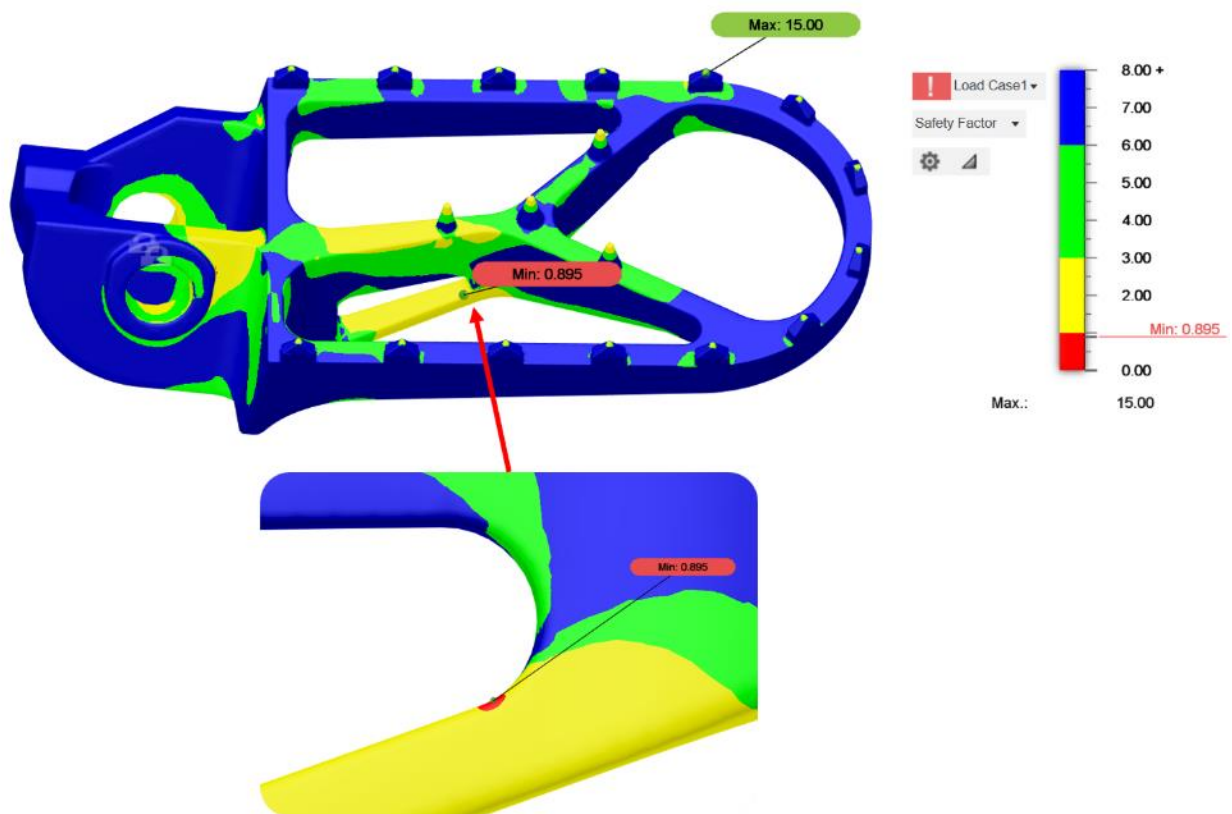


Figure 25: FEA of original footpeg design (4x dynamic force multiplier).

Additive Manufacturing Process Selection

Traditional, well-understood manufacturing processes, such as formative (i.e., casting) and subtractive (i.e., machining), have existed for many millennia; continuous technological advancement in these processes has resulted in increased precision and efficiency, contributing towards improvements in the quality, availability, and diversity of products. AM differs from these processes because it adds material layer by layer. Some of the key benefits of AM over traditional manufacturing processes include:

- Optimisation of lightweight architectures
- Consolidation of supply chains
- Accelerated design-to-manufacture timelines
- Consolidation of multiple components into a single part

One of the significant disadvantages of AM is its limited ability to scale, especially when compared to traditional, high-volume manufacturing processes such as die-casting and injection moulding. Figure 26 (Protolabs Network, 2024) illustrates the cost-effectiveness of the three main manufacturing categories against production volume requirements. AM remains economically viable for batch quantities in the hundreds, so AM was chosen to manufacture the redesigned foot pegs—twenty pairs were required.

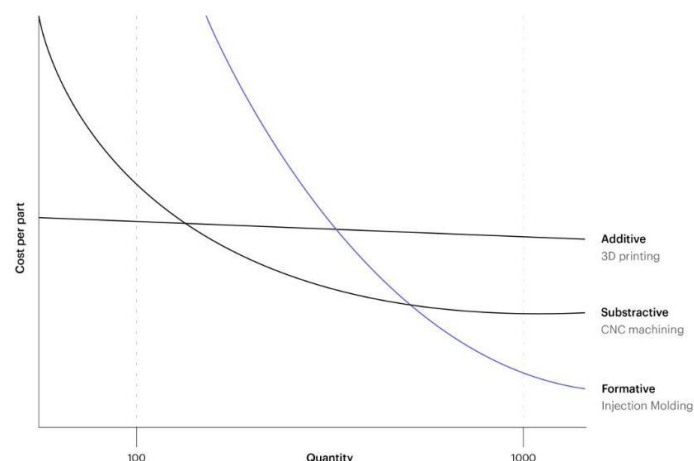


Figure 26: Chart of cost Vs quantity of AM, subtractive and formative processes (Protolabs Network, 2024).

While still in its infancy, seven ISO/ASTM-recognised AM manufacturing processes already exist. Due to this product's requirements, three categories will be discussed, all of which can produce metallic structures.

Powder Bed Fusion (PBF)

A typical metal Powder Bed Fusion (PBF) process involves spreading a metal powder of 0.02 – 0.05 mm thickness across a platform using a counter-rotating roller mechanism. Depending on the machine type, a laser or electron beam fuses the metal particles together, including the subsequent layer. Laser beam machines require the build chamber to be sealed with an inert gas such as argon or nitrogen, while electron beams require a vacuum environment with higher temperatures. The part must be fused to the baseplate to mitigate the effects of part distortion from residual stresses. Heat treatment processes are often required to reduce residual stresses within the component. Figure 27 illustrates the PBF process (Dassault Systems, 2018).

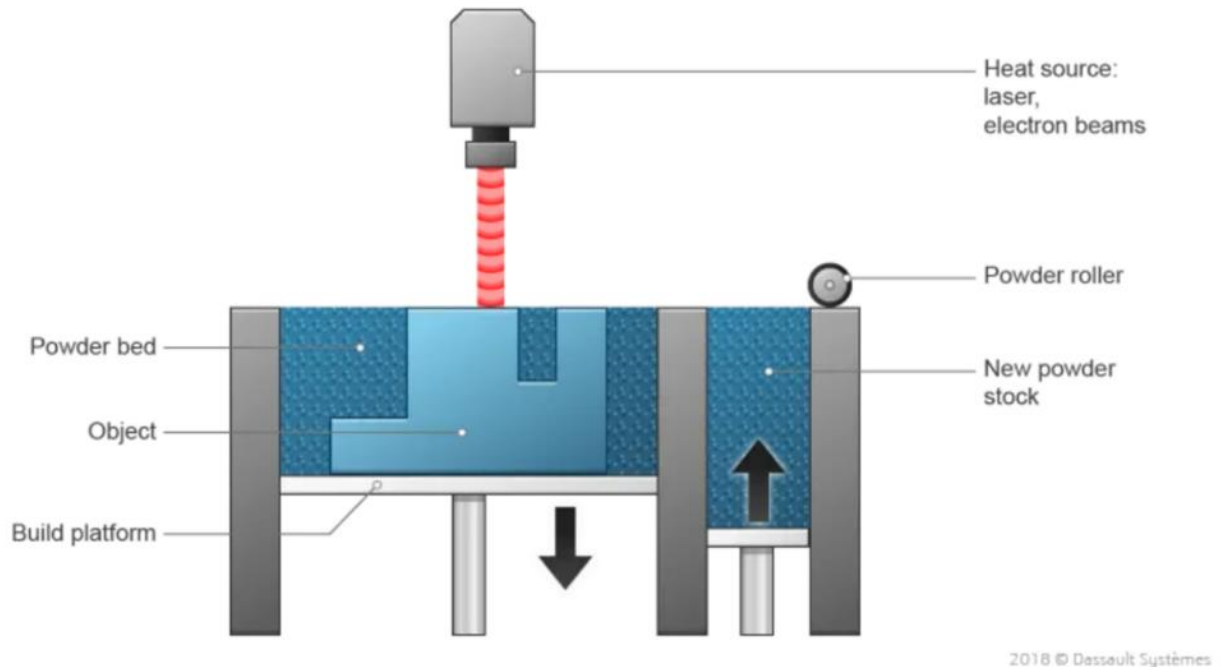


Figure 27: Schematic of Powder Bed Fusion (PBF) manufacturing process (Dassault Systems, 2018).

Binder Jetting (BJ)

Binder Jetting (BJ) is a similar concept to inkjet printing but with the addition of stacked layers to create a 3D object. Like PBF, a layer of powdered material is spread across a build platform using a counter-rotating roller mechanism. However, instead of melting the powder, a binding agent is deposited through a series of nozzles, forming spherical agglomerates of powder particles and binder liquid. It is often compared to the soldering of metals, where the materials are not physically fused together. Figure 28 depicts the BJ process (Dassault Systems, 2018).

Upon completion of the printed parts, further post-processing is required using one of two steps:

- **Infiltration:** This involves heating the component in a hot furnace for several hours to burn off the polymer binder (~60% dense part). The final step comprises placing a bronze ingot onto the part and heating it in the furnace once again; the bronze fills the porous regions of the part (~90% dense part).
- **Sintering:** To further improve the mechanical properties, the part can be heated in a furnace at a higher temperature than the infiltration step, burning off the binders and fusing the metal particles. This results in 3% porosity and better corrosion resistance. However, parts often shrink around 20%.

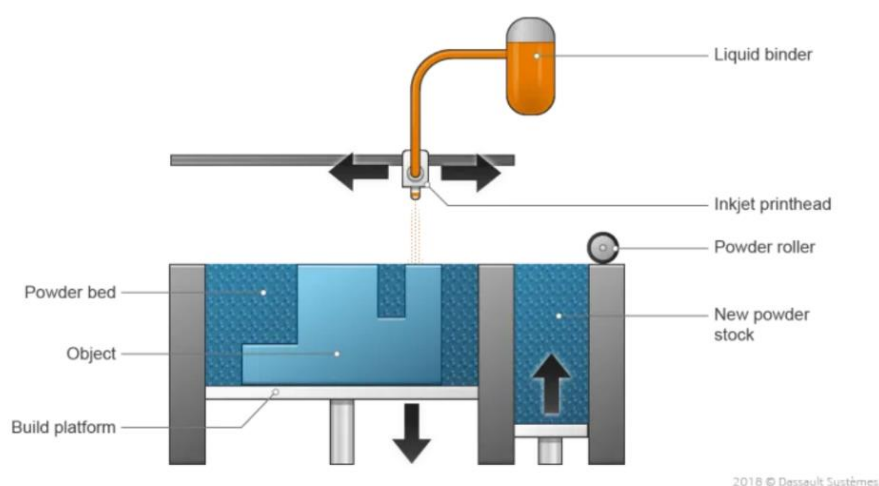


Figure 28: Schematic of Binder Jetting (BJ) manufacturing process (Dassault Systems, 2018).

Directed Energy Deposition (DED)

Directed Energy Deposition (DED) processes use a directed energy heat source (usually an electron beam or laser) that is focused onto the base material, melting it and the material (powder or wire) that is simultaneously being deposited – powder being more commonly used for metals. Powder particles fed through the nozzle undergo kinetic energy greater than the powders during flight, allowing deposition to occur at multiple angles, unlike many other AM processes that require vertical deposition. Figure 29 demonstrates the DED process (Dassault Systems, 2018)

Subsequent layers deposit material in orientations that differ from the previous layer. These layer-to-layer changes in orientation alleviate preferential grain growth and lessen the likelihood of residual stresses. To a certain extent, grain structures can also be manipulated by altering beam energy and traverse rates, resulting in varying degrees of cooling.

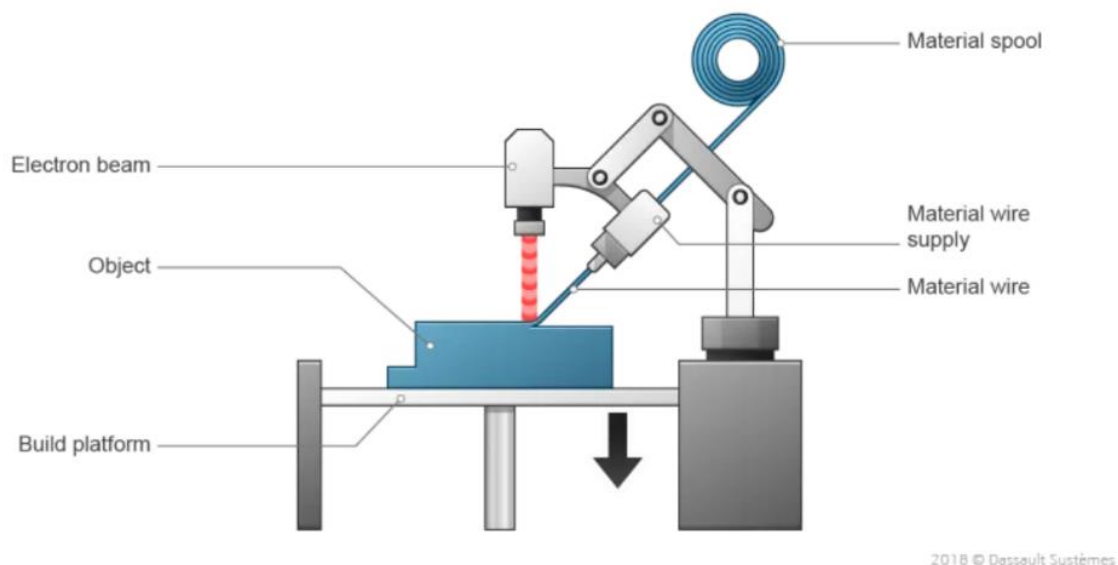


Figure 29: Schematic of Directed Energy Deposition (DED) manufacturing process (Dassault Systems, 2018)

The choice of AM process dictates specific design guidelines, necessitating its selection before designing the new foot peg. Table 18 (Adapted from Sun, et al., 2019; Protolabs Network, 2024; Mostafaei, et al., 2020; TWI, 2024; Gibson, et al., 2015; Metal AM, 2024; Templeton, et al., 2023) consolidates critical features pivotal in determining the suitable AM process.

Table 18: Summary of key features for different metal additive manufacturing (AM) processes (Adapted from Sun, et al., 2019; Protolabs Network, 2024; Mostafaei, et al., 2020; TWI, 2024; Gibson, et al., 2015; Metal AM, 2024; Templeton, et al., 2023)

Process Classification	Compatible Materials (Metals)	Positives	Negatives	Shrinkage %	Typical surface quality	Layer thickness	Minimum wall thickness	Dimensional accuracy	Typical build volume capability	Relative cost (per Kg)
Powder Bed Fusion (PBF) <i>Machine types:</i> - Selective Laser Melting (SLM) - Selective Laser Sintering (SLS) - Direct Metal Laser Sintering (DMLS) - Electron Beam Melting (EBM)	Generally, if a material can be welded, it is suitable for PBF. - Stainless steel - Aluminium (laser beam only) - Titanium alloys - Nickel-base alloys - Cobalt chrome alloys	- Good dimensional accuracy when compared to other AM processes. - Supports a wide array of materials. - Efficient recyclability of unused powders. - Able to manufacture components with hybrid structures using multiple materials of varying compositions.	- Lots of post-processing required: cleaning excess powder from the part, heat treatment to relieve stresses, cutting part from the build plate and removal of support structures - Machine, drilling, grinding, etc is often required due to the rough finish. - The powder poses health and safety risks, such as respiratory issues and flammability hazards. Strict H&S processes must be adhered to. - Surface finish is reliant on powder grain size.	1 - 3 %	10 µm (Ra)	0.02 - 0.05 mm	0.4 mm	+/- 0.1 mm	300 mm³	2.92
Binder Jetting (BJT)	- Nickel-base alloys - Cobalt chrome alloys - Stainless steel - Titanium alloys - Copper alloys	- Often, no support structures are required. - Lower energy usage when compared to PBF. - Fast print speeds due to the possibility of numerous ejection nozzles. - No residual thermal stresses. - Isotropic microstructure. - Highly scalable due to the uncontrolled atmospheric environment.	- Weaker mechanical properties than other metal AM processes as the powder particles aren't fused together. - Post-processing cycles are required (infiltration or sintering)	~20% shrinkage between green part and sintered part. ~2% shrinkage between a green part and an infiltrated part. This can be accommodated somewhat in the initial CAD design by scanning post-sintered parts and altering the scale to suit the required geometry.	6 µm (Ra)	0.035 - 0.05 mm	1.0 mm	+/- 0.2 mm	500 mm³	1
Directed Energy Deposition (DED)	The majority of weldable metals: - Stainless steel - Aluminium alloys - Titanium alloys - Nickel-base alloys - Cobalt chrome alloys - Refractory metals (tungsten, molybdenum)	- Fewer design rules when compared to other metal AM processes. - Capable of controlling the grain structure with rapid solidification theory. - Able to manufacture components with hybrid structures using multiple materials of varying compositions. - Ability to produce large structures. - Can be used to repair existing parts. - Low material wastage.	- Poor surface finish when compared to other metal AM processes. - Low build speeds. - Post-processing machining operations are often required. - Residual stresses can be highly non-uniform due to the fast cooling rates and elevated thermal gradients. - Porosity can occur from a lack of fusion (insufficient melting of the pool into base material) or keyholes (from localised vaporisation due to excessively high energy density); these can be mitigated with correct process parameters.	0.5 - 2 %	20 µm (Ra)	0.02 mm	1.0 mm	+/- 0.25 mm	1000 mm³	1.15

Each process was scored against these key features:

- Shrinkage: The percentage difference between the nominal geometric profile and the manufactured component.
- Surface quality
- Layer thickness: A measure of the material thickness per horizontal layer.
- Minimum wall thickness
- Dimensional accuracy
- Manufacturing cost: This is a relative cost per kg of product, considering raw materials, printing, and post-processing costs.

The cross-functional team assigned importance weightings to each feature and scored processes on their performance in each category. Table 19 contains the final results of the selection process.

Table 19: Metal AM process selection matrix.

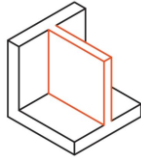
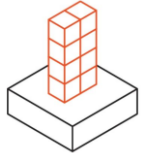
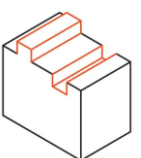
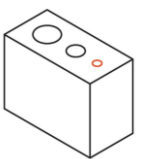
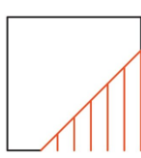
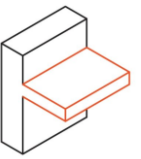
Process Feature	Weighting (1 - 5)	Process		
		Powder Bed Fusion	Binder Jetting	Directed Energy Deposition
Shrinkage	3	12	9	15
Surface quality	4	12	16	8
Layer thickness	3	9	9	12
Minimum wall thickness	5	25	15	15
Dimensional accuracy	5	20	15	15
Manufacturing cost	3	6	15	12
Total Weighted Ratings		84	79	77

The team concluded that a Powder Bed Fusion manufacturing process would best suit this product's requirements.

Powder Bed Fusion Design Rules

Through extension research and development, engineers have created design rules applicable to each AM process. The PBF design rules, illustrated in Table 20 (Protolabs Network, 2024), were used in the design creation stages that followed.

Table 20: Powder Bed Fusion (PBF) design rules (Protolabs Network, 2024).

Feature	Specification	Visual Aid
Minimum wall thickness	0.4 mm	
Maximum aspect ratio	8:1	
Minimum feature size	0.6 mm	
Minimum detail size	0.4 mm	
Minimum hole diameter	Ø1.5 mm	
Maximum overhang angle	50°	
Unsupported edges	0.5 mm	

Generative Design

Human-driven design, while valuable, is heavily reliant on the designer's skill level and is often constrained by the limits of human creativity. This can lead to several undiscovered design solutions, restricting the potential for innovative design outcomes. In contrast, generative design (GD) can overcome these limitations and unlock new design possibilities with its complex algorithms and computational power. Initially applied by the architectural industry, it is now employed by various other sectors, such as the aerospace and automotive industries. In these industries, GD has proven its worth by generating designs that usually result in the use of less material, reduced post-processing requirements, and enhanced strength in multiple directions while reducing design-to-manufacturing lead times, all of which aid in reducing cost (Bendoly, et al., 2023).

GD is commonly believed to be synonymous with topology optimisation, although this is not true. Topology optimisation requires the engineer to produce a 3D model from the outset, after which constraints and loads are applied. The software then optimises the design by removing or adding material where required, unlike GD, which doesn't require a complete 3D base model.

GD has three essential components: an organised design framework, a means of producing divergence, and a method of determining the desirable result (Jaisawal & Agrawal, 2021). Key parameters are entered into the software. The computer then solves complex challenges, such as reducing mass or increasing stiffness through an iterative design process until convergence has been achieved – this process is summarised in Figure 30. The designs are typically of an organic-type structure, like nature-based features, due to the software using algorithms based on bone and plant growth; these designs often cannot be constructed using conventional formative and subtractive manufacturing processes, such as casting and machining. Its robust interoperability lies with additive manufacturing (3D printing).

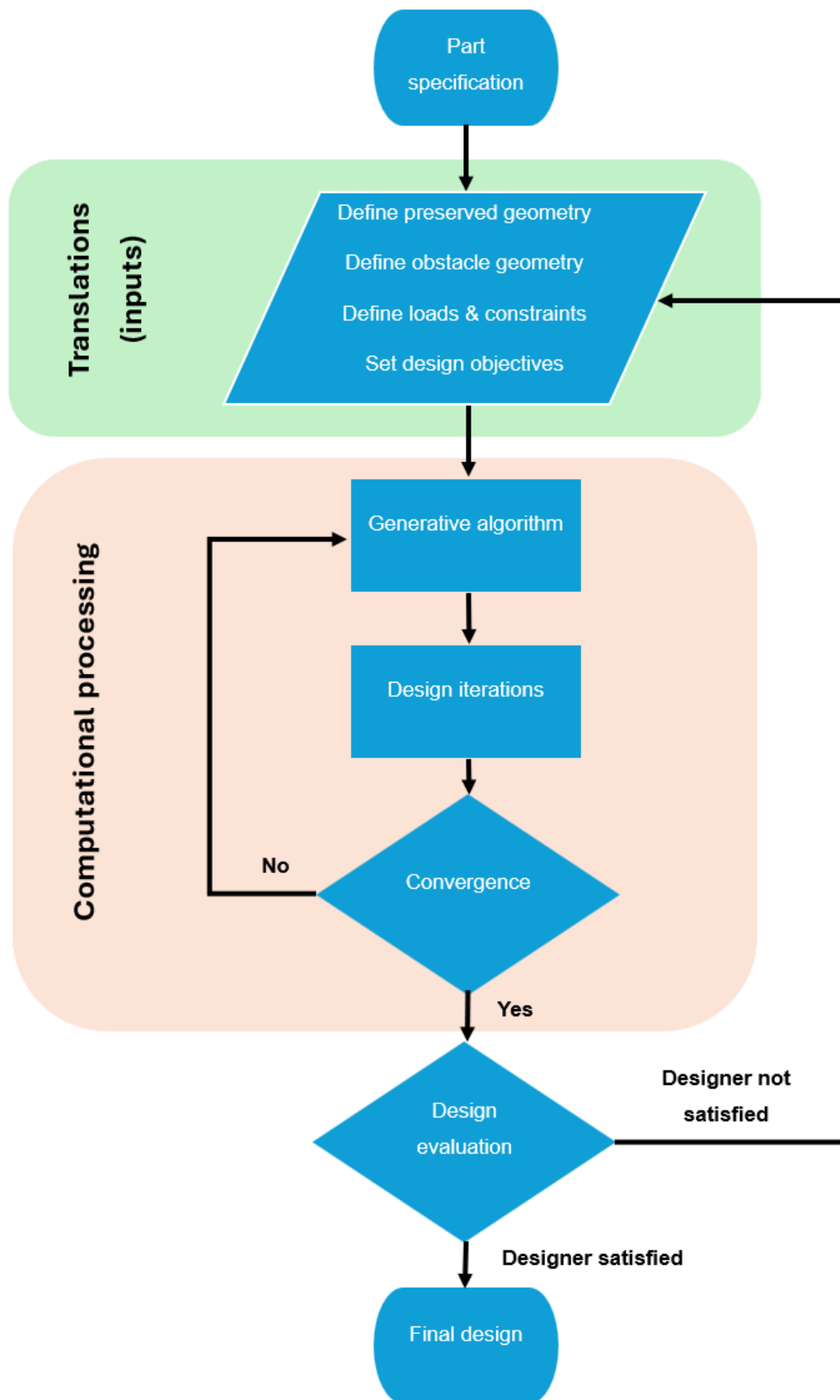


Figure 30: Generative design process flowchart (adapted from (Jaisawal & Agrawal, 2021)).

The team leveraged GD in the foot peg design due to its strength-to-weight advantages and compatibility with AM processes. The first step involved assigning geometry that needed to be preserved. The green bodies illustrated in Figure 31 are the preserved geometries for this design study; the figure also shows the constraints on the pin mount, the force of gravity, and the force equally distributed to the footplate.

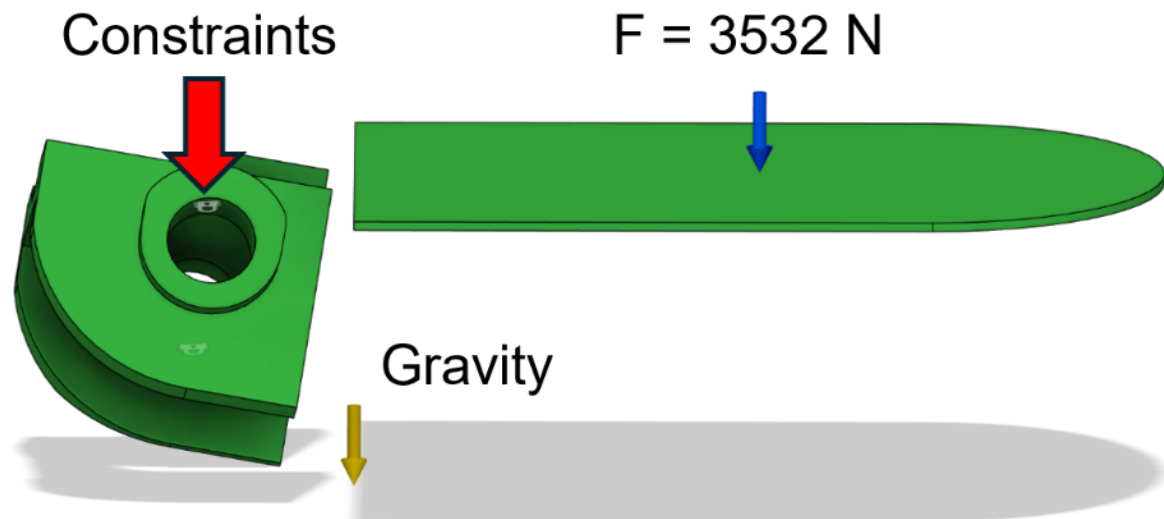


Figure 31: Preserved geometries, constraints, and forces.

Next, obstacle geometries were defined – regions where material *cannot* be added. The mounting points on the motorcycle, displayed in Figure 32 (Supermotodaz, 2024), were defined as obstacle geometries, along with the top of the footplate (the original teeth design would be added to this region).



Figure 32: Motorcycle foot peg mounting points (Supermotodaz, 2024).

The assigned obstacle geometries are the red regions in Figures 33 and 34.

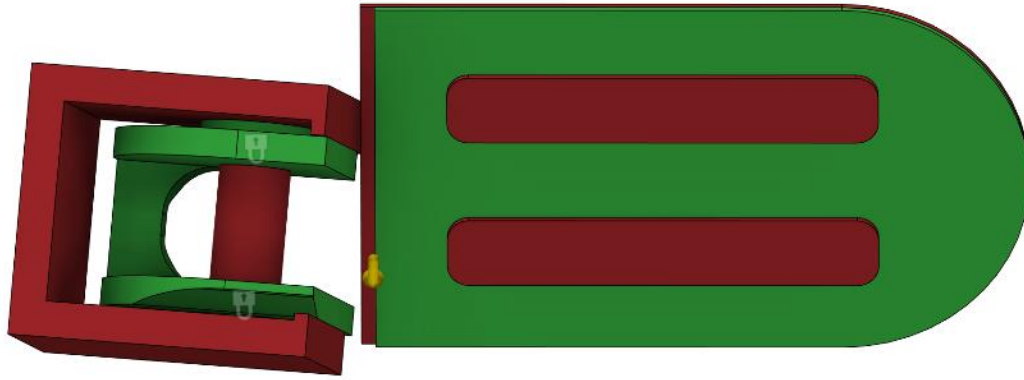


Figure 33: Obstacle geometries view 1.

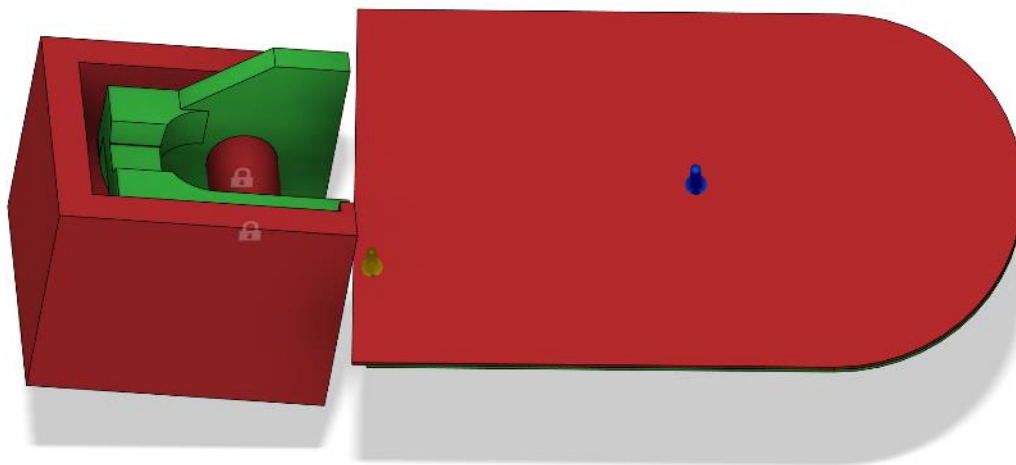


Figure 34: Obstacle geometries view 2.

Within Autodesk 360, users can select one of two objectives: minimise mass or maximise stiffness. This study aimed to minimise mass while achieving a minimum safety factor of two.

The final inputs were assigning the manufacturing process and materials. Additive manufacturing was chosen along with the PBF design rules discussed previously. The following materials were selected:

- Aluminium AlSi10Mg
- Inconel 718
- Stainless Steel 17-4 PH
- Titanium 6Al-4V

Upon setting up the inputs, the software generated multiple design iterations until convergence was achieved - the four design outcomes are illustrated in Figure 35.

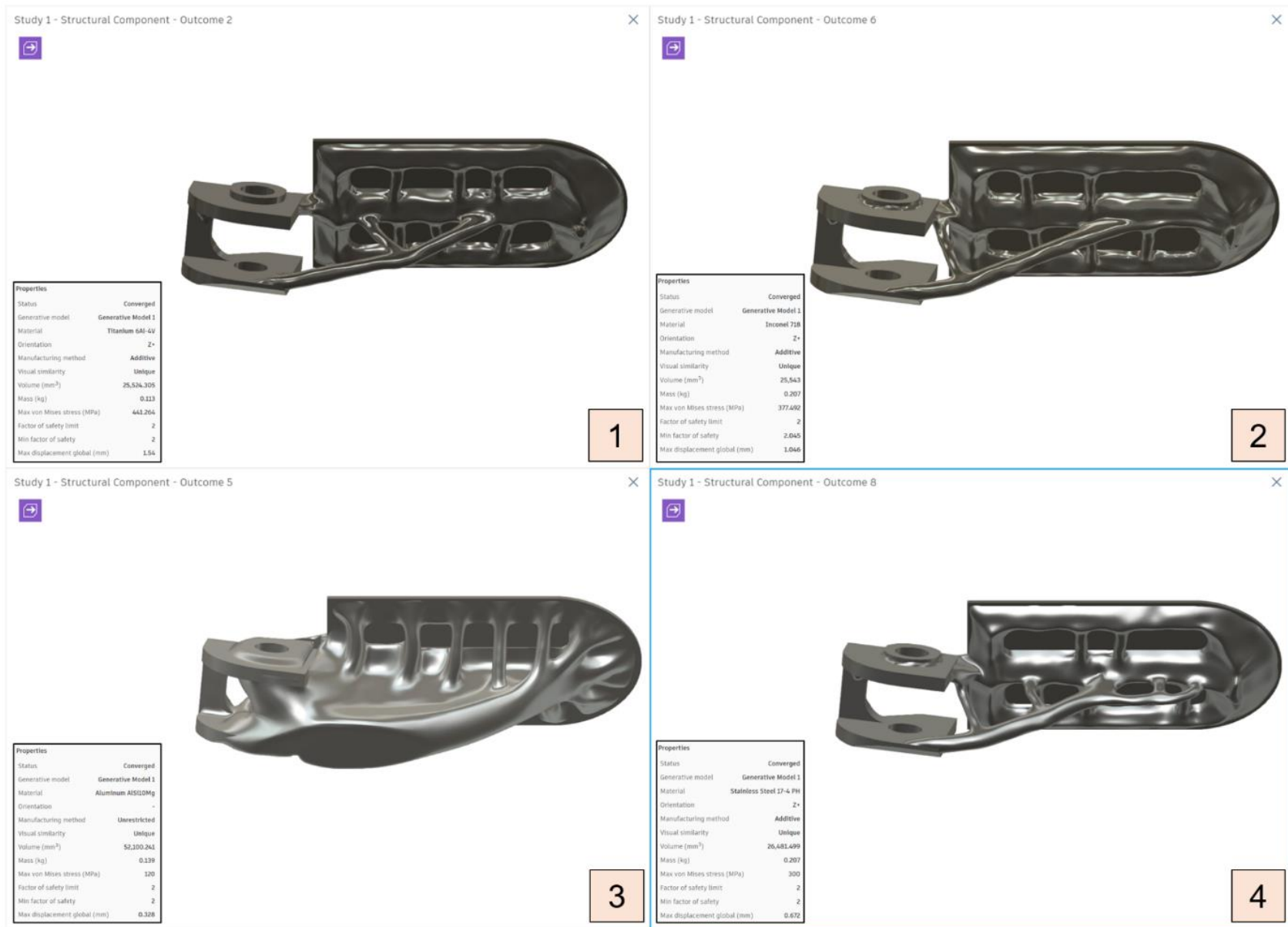


Figure 35: Generative Design (GD) outcomes.

Each design was scored against these key features:

- Weight: The target was to achieve less than 250 g.
- Manufacturing cost: The target is less than £200 per part.
- Factor of safety: The design must achieve a minimum of two.
- Max displacement: No greater than 1 mm under load.
- Service temperature: Must accommodate temperatures of -20°C to +50°C.
- Appearance: This is a subjective assessment between the stakeholders.

The cross-functional team assigned importance weightings to each feature and scored the processes based on their performance in each category. Table 21 contains the final results of the design selection process.

Table 21: Generative Design (GD) selection matrix.

Feature	Weighting (1 - 5)	Design Outcomes			
		1 - Titanium 6Al-4V	2 - Inconel 718	3 - Aluminium AlSi10Mg	4 - Stainless Steel 17-4 PH
Weight	5	25	15	20	15
Manufacturing cost	4	12	8	20	16
Factor of safety	5	25	25	25	25
Max displacement	4	8	12	20	16
Service temperature	3	15	15	15	15
Appearance	3	9	9	15	9
Total Weighted Ratings		94	84	115	96

Design outcome number three (aluminium) was chosen. Although some refinements would be required first, these included removing the material highlighted in Figure 36, removing sharp edges, adding fillets to improve the joining strength between layers, and adding the teeth.

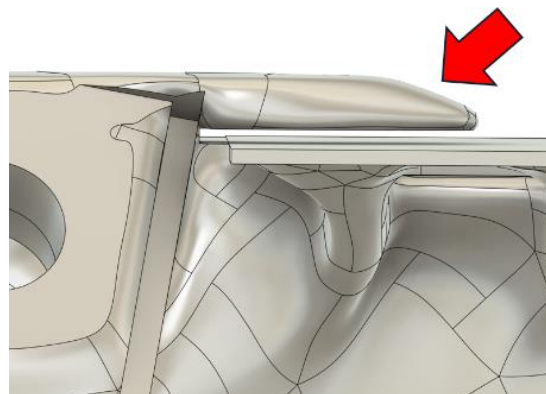


Figure 36: Excess material on Generative Design.

Figures 37–39 illustrate the final design solution. Note the support structure at the bottom, which resembles tree growth.

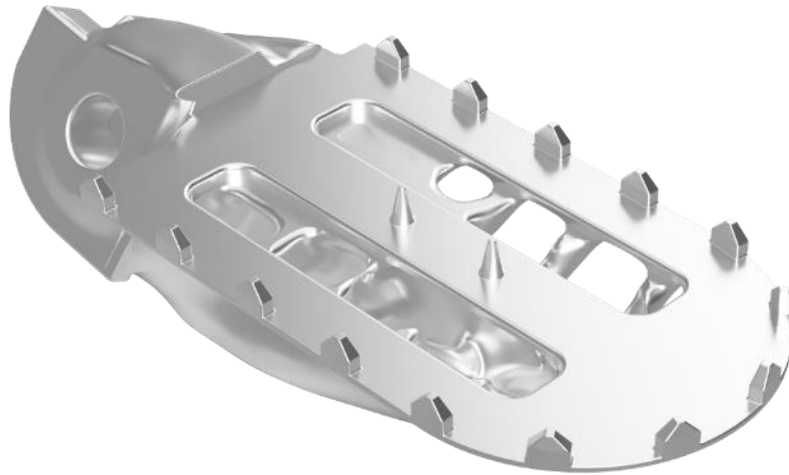


Figure 37: Isometric view of final foot peg design.

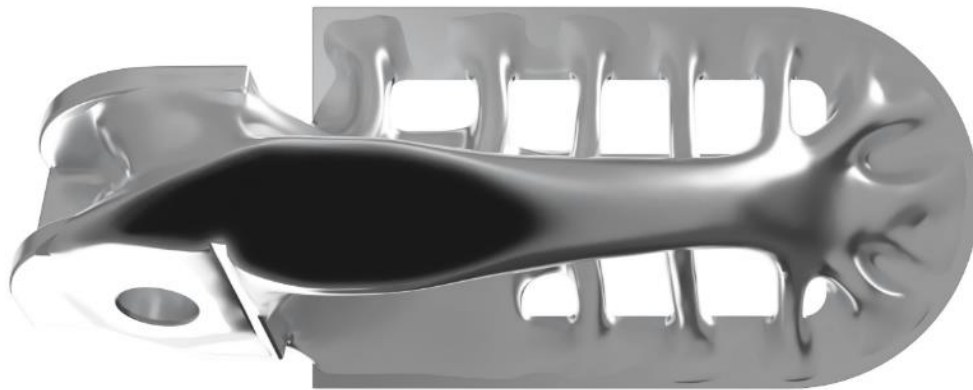


Figure 38: Bottom view of final foot peg design.



Figure 39: Side/bottom view of final foot peg design.

Finite Element Analysis (new design)

An additional FEA was conducted to ensure the design alterations didn't negatively impact the safety factor. Figure 40 confirms that the safety factor was still above the minimum requirement of two.

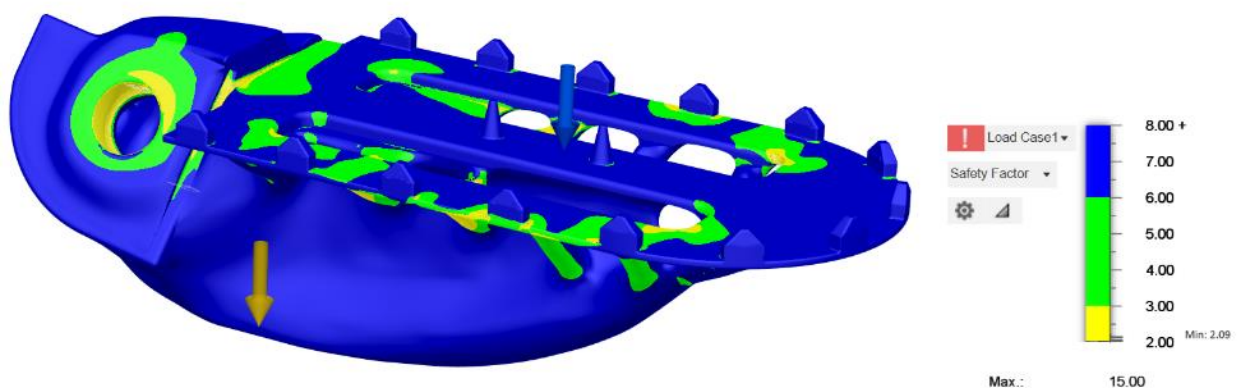


Figure 40: FEA of new foot peg design.

From CAD to 3D Print: The Conversion Process

A CAD file contains extensive information about the form, dimensions, and parameters of the 3D model, which is used for traditional manufacturing processes. However, most AM processes require the CAD model to be converted into an STL (Standard Tessellation Language) file - a geometric approximation of the surface of a 3D model comprising a triangle-based mesh structure (like in FEA) – as illustrated in Figure 41 (3D Printer Academy, 2023).

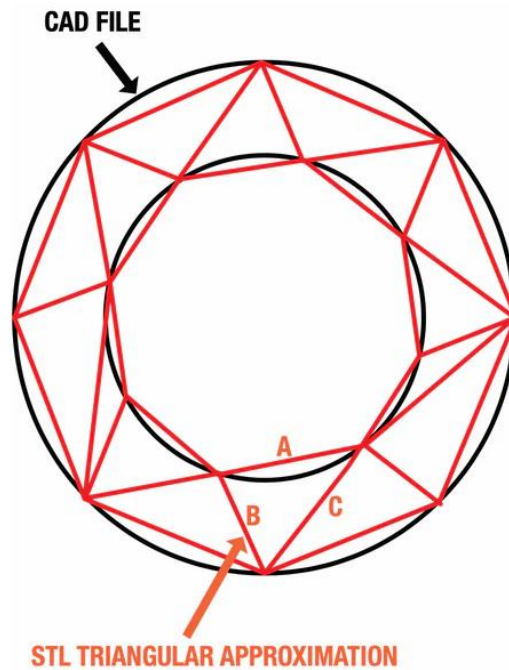


Figure 41: Comparison of CAD and STL file geometry (3D Printer Academy, 2023).

Higher resolution meshes better represent the original 3D model; however, this comes at the expense of file size, meaning longer processing times (additional cost). The resolution of the STL file should never exceed the manufacturing equipment's capabilities. An equilibrium should be aimed between a quality resolution that satisfies the functional requirements and a file size that can be efficiently processed (Mark Forged, 2024). Figure 42 depicts a tessellation of the new footpeg design.

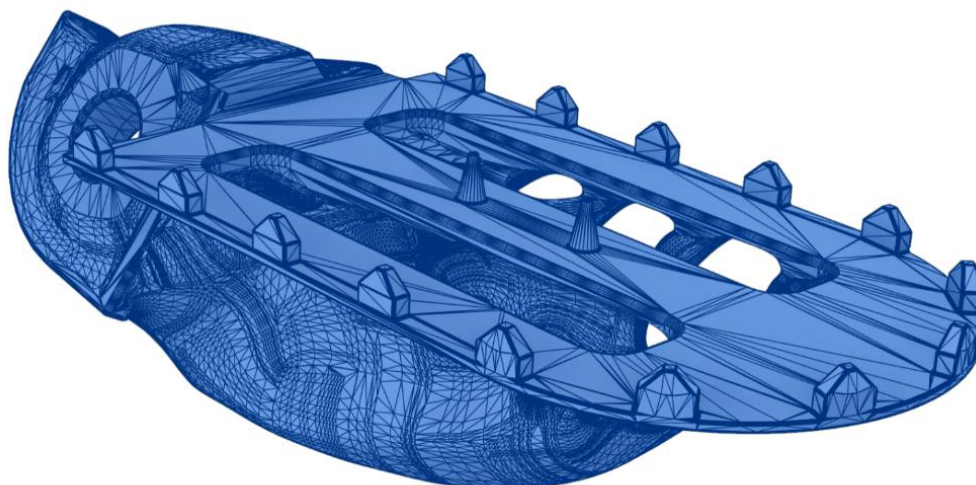


Figure 42: STL mesh of new footpeg.

The final element was converting the STL file to a programming language that could be understood by the manufacturing equipment. The predominant language is G-code. Like computer numerical code (CNC), G-code files contain lines of command instructions for the 3D printer.

Before file conversion, the printing extrusion parameters must be entered:

- Layer height
- Material type
- Wall/perimeter thickness
- Infill density: The footpeg was printed with 100% infill to replicate the FEA.
- Infill pattern
- Support structures: Overhangs exceeding 50° required support, as Figures 43 and 44 represent.

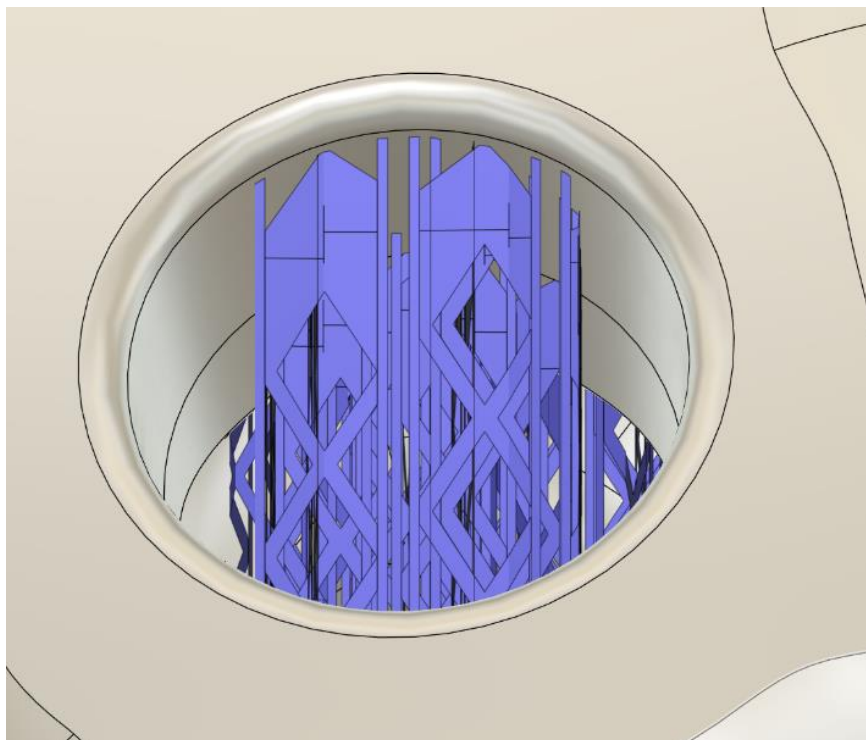


Figure 43: Pin location support structures.

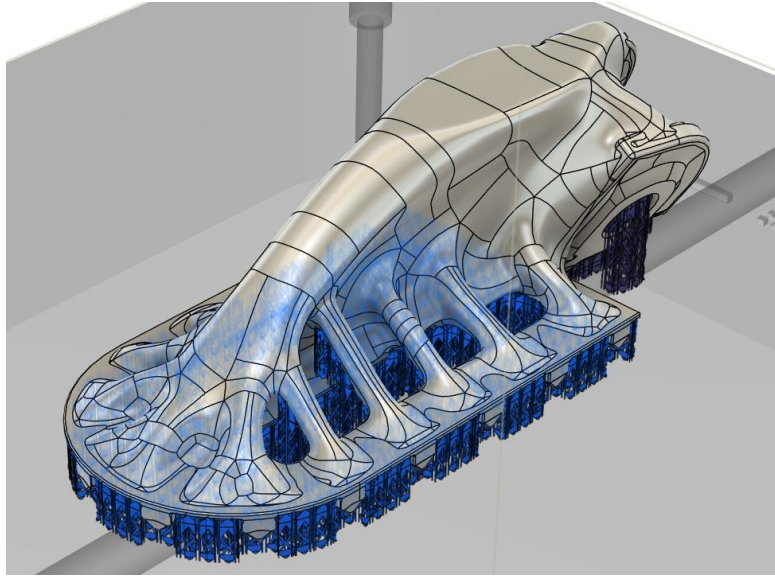


Figure 44: Support structures.

The 3D model is converted into a stack of vertical layers, including key command instructions, such as:

- Print head movement speeds
- Material temperature
- X, Y and Z axis coordinate points

Figure 45 depicts a sectional view of the footpeg. Based on a layer height of 25 μm , 1694 layers were created, marking the completion of the design stage.

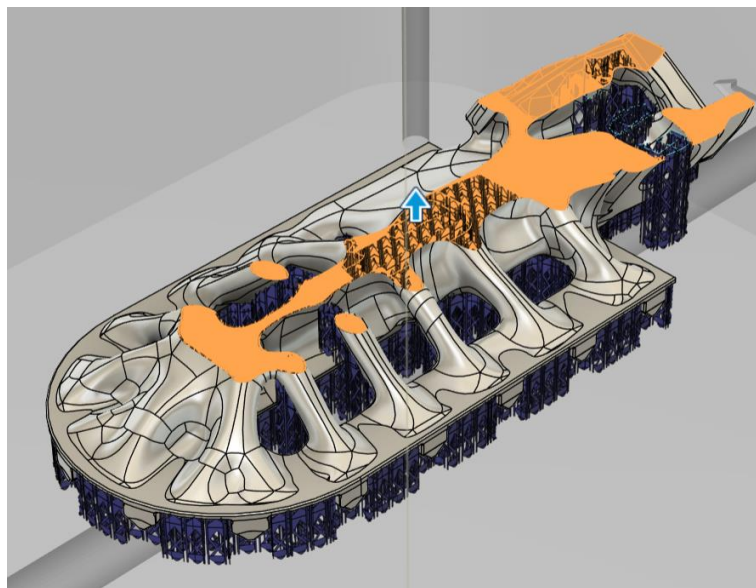


Figure 45: Section view of sliced footpeg file.

Final Design Summary

The revised footpeg design satisfied all the PDS requirements. When comparing the two designs—as illustrated in Figure 46—the new design appears greater in mass, although this is not the case due to the use of aluminium AISi10Mg, a lighter-density material.

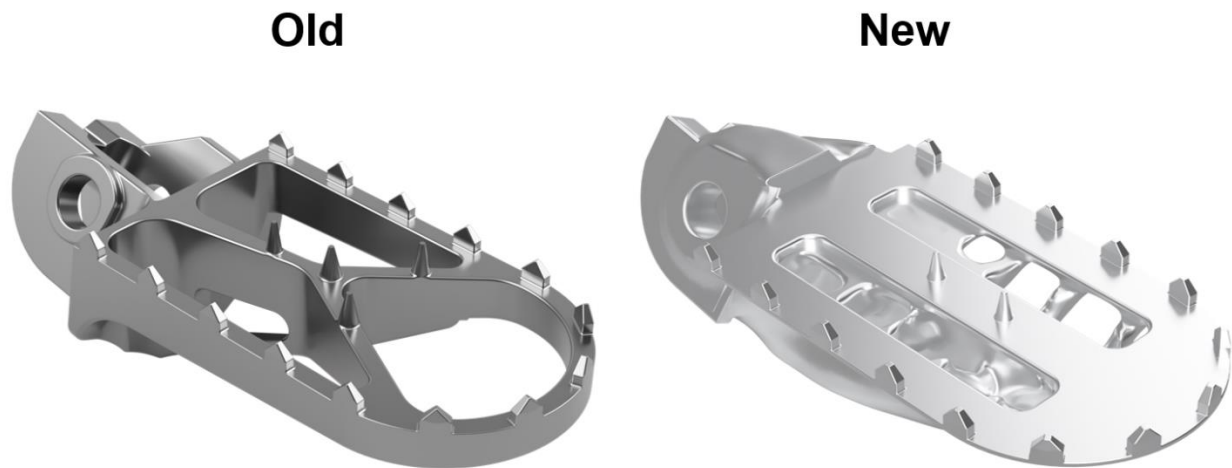


Figure 46: Isometric design comparison of old and new footpeg designs.

A list of the key design metrics is presented in Table 22.

Table 22: Key metrics comparison of old and new footpeg design.

Metric Description	Original Design	New Design	Improvement
Weight (g)	243	135	56%
Rated load (N)	1766	3532	50%
Max displacement (mm)	0.63	0.38	61%

Conclusion

The evolution of Additive Manufacturing (AM) since its inception in the mid-1980s has been remarkable, with consistent annual technological advancements. This trend aligns with HP Racing's initiative to enhance their off-road motorcycle's performance through AM, particularly focusing on redesigning the footpegs to create strong, lightweight structures.

Leveraging Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) tools, HP Racing conducted a detailed analysis of the original footpeg design. Finite Element Analysis (FEA) and Generative Design (GD) principles were instrumental in optimising the weight efficiency and robustness, essential for the harsh conditions of hard enduro racing events. The original footpeg underwent rigorous FEA to evaluate its strength under the increased dynamic loads, revealing areas for improvement.

The team selected Powder Bed Fusion (PBF) for the AM process based on its ability to meet the stringent design and production requirements. Subsequent generative design iterations led to the selection of an aluminium AlSi10Mg design, further refined to ensure structural integrity and manufacturability.

The final redesigned footpeg met the minimum safety factor of two and significantly reduced weight, enhancing the bike's overall performance. This project exemplifies the potential of AM and GD in revolutionising product design and manufacturing, offering substantial benefits in terms of strength, weight, and production efficiency. As AM technologies continue to advance, their application in competitive racing and beyond promises even greater innovations and improvements.

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