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Original Article

Assessment of Aircraft Assembly Jig Fabrication by Use of Additive Manufacturing Technology

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Abstract *- The fabrication of jigs and fixtures in aerospace has seen a rise in usage as it is a more accessible approach that does not require as stringent certification as flying parts. AM provides opportunities for design optimisations to address the issue of heavy metallic tooling, which is cumbersome for the shop floor operator to handle. A careful design approach can also lead to lower tool maintenance. This research aims to investigate the redesign of an existing aerospace assembly jig through design optimisation to reduce weight and part count to increase worker ergonomics and reduce tool maintenance. All this is done whilst maintaining rigidity and the ability to adjust to meet the tight tolerance of the tool and exploring alternative materials. Design for Additive Manufacturing (DfAM) and Generative Design (GD) were studied to generate multiple design iterations, which were then filtered through the industrial requirements and analysed using Finite Element Analysis (FEA). The resulting design was 60% lighter, reducing the part count by 55%. The jig was fabricated using industrial-grade Filament Deposition Modelling (FDM) and validated onsite as per industrial practice.*

Keywords **-** *Additive manufacturing, 3D printing, Jigs and fixtures, Aerospace industry, Design optimization.*

1. Introduction

Aerospace industries are adopting Additive Manufacturing (AM) to improve efficiency and enable on-demand production. The automotive and aerospace sectors have begun creating AM for their parts [1]. When reviewing industry applications for additive manufacturing, it was discovered that the aerospace industry is estimated to account for USD 4.8 Billion [2] of the total USD 17.99 Billion [3] of the total AM market size in 2023, which is a quarter of the total market share. As additional uses in aerospace are identified, the demand for AM will grow. Similarly, as metal additive manufacturing advances and matures, its applications in aerospace will increase significantly. 3D printed jigs and fixtures are not merely a concept for the future but rather a reality in a constantly changing industry, providing a novel and environmentally conscious approach to contemporary manufacturing [4]. Using AM methods facilitates the fabrication of intricate geometries exhibiting enhanced accuracy and diminished lead times. This technology enables the fabrication of moulds precisely adapted to manufacturing specifications. Through AM, producers can conceptualise and fabricate jigs that possess intricate characteristics, internal frameworks, and integrated capabilities that were hitherto unattainable or impracticable using conventional manufacturing techniques. This technological progression amplifies the flexibility and adjustability of moulds, facilitating manufacturing processes with greater efficiency and efficacy [5].

1.1. Motivation

Implementing design optimisation and fabrication through AM on jigs was chosen due to its low-hanging fruit nature. Only entities qualified with Design Organisation Approval (DOA) can carry out design works and changes in aerospace. The DOA is a formal recognition by the aviation authorities [6] of a country or region, such as the American Federal Aviation Authority (FAA) or the European Union Aviation Safety Agency (EASA) and recognised by OEMs such as Airbus and Boeing, that the said entity is capable of carrying out design works [7] that is compliant to the aerospace requirements and regulations. Manufacturing companies that manufacture aerospace parts, on the other hand, require Production Organisation Approval (POA) [8], a recognition by the authorities mentioned above and recognised by the OEMs that the manufacturing entity is capable of carrying out the manufacturing processes [9] that is compliant with aerospace requirements and regulations. All aerospace manufacturing companies within the supply chain are POA holders but rarely DOA holders. The DOA applies mainly to the flying parts, but in some cases, it also applies to the design of jigs. Flying parts also require aerospace-certified materials for quality control systems during material manufacturing and properties. Jigs are fixtures, on the other hand, and are not subject to material certification and qualification. These approvals change the design and fabrication process of existing aerospace flying parts, which is a highly complicated process requiring a re-qualification. This involves a multi-party process involving the aircraft OEM and its suppliers, which are affected by it. This process is less tedious when it comes to jigs and fixtures, whereby the re-qualification process can readily be done provided the tolerances of the jigs are met. Boeing famously broke the world record in 2016 by producing a trim-and-drill jig measuring 5.33m long, 1.67m wide and 0.45m tall, weighing approximately 748kg in 30 hours using ABS thermoplastic [10]. They estimated that a conventionally made jig would have required 3 months of lead time. The use of AM to produce this trim and drill jig showed the aerospace industry that the AM provides the needed accuracy and reduces lead time.

The study serves as a pilot project in Spirit Aerosystems Malaysia and as a collaborating member of this study. It is hoped to enable other aerospace companies to relook at the practicality of designs and consider their optimisation. As AM enables new design spaces and simplification of the fabrication process, companies can optimise the designs of their current and new jigs. Furthermore, the motivation to reduce weight further and increase the ergonomics of jigs on an aerospace manufacturing shop floor is easing the operators' handling of the jigs. Repeated carrying of heavy weights over a long period can be an occupational hazard.

1.2. Objectives

The objectives of the study are as follows:

- Display the use of AM in the industry without the need for metal for non-loading, non-flying jigs
- Reduce part count to reduce the complexity during calibration and the annual tool cycle check process.
- Reduce weight to allow for single-user handling.

Objective 1 looks at proving the usability of polymer-based AM jigs, which can achieve required tolerances without any geometric post-processing post-printing. Objectives 2 and 3 consider making the jig more manageable for the shop floor technicians to use and operate practically. Beyond the main objectives, this study aims to compare and contrast the 2 design optimisation pathways available for the industry to implement. GD represents an automated form of optimisation that requires a low manual redesign effort by the design engineer. DfAM represents a manual design approach guided by a sound methodology and requires more engineering judgment to make the decision. Exploring both methods is crucial to ascertain their usefulness in redesigning an existing design. The use of design optimization in AM is not only a useful feature in order to save weight and for material reduction, but in some cases, it is required in order to explore untapped design spaces, which could, in some cases, be the path to AM’s viability when compared cost wise, to conventional manufacturing.

Further, this study aimed to ensure that any assembly jig designs converted from an original design to a design optimised for AM production still possess adjustability in their design, which is crucial for the calibration of the jig itself. It has been found that many reported uses of AM in jig fabrication have been for static, non-adjustable jigs. This is seen in examples such as the aforementioned large Boeing trim and drill jig, the Moog Aircraft Group [11], and studies by [12, 13]. One study presented the idea of shimming and adjustability as features of an AM produced jig. This was a study by [14] that presented two ideas similar to this study, which are design optimization and the AM jig having inbuilt adjustability. However, this study used metal AM to fabricate a welding jig. This unique design feature, however, has not been observed in polymer based AM as carried out in this study.

1.3. Scope

The scope of the study is as follows:

- Use of Fused Deposition Modelling (FDM) form of AM
- Use of polymer materials
- Redesign of an existing jig within Spirit AeroSystems Subang, which is non-load bearing.
- Assumption of isometric properties of a homogenous material, with solid construction with no considerations of lattice structures due to software limitations and complexity

2. Methods

The methodology for the whole exercise of this case study followed the process flow shown in Figure 1. This started with selecting the part used in this case study. Then, the phase was broken into two pathways, whereby the design was optimised separately using two distinct methods, namely Design for Additive Manufacturing (DfAM) [15-17] and Generative Design (GD). The resulting designs from both methods were verified using Finite Element Analysis (FEA) simulation [18-20], considering actual life loading and available printing materials.

The design is fabricated through additive manufacturing and assembled using industrial standard attachment components. Finally, the component is tested onsite on the manufacturing shopfloor to validate the fabricated part using standard industrial practice. This methodology section and this overall paper shall focus on the design optimisation processes employed and briefly overview the processes conducted in the remaining aspects of the case study process flow.

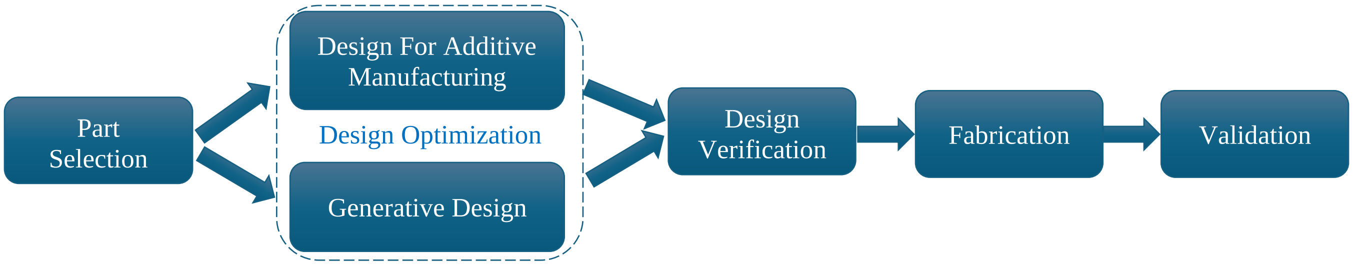

Fig. 1 Case study process flow

Table 1. Design constraints and conditions

Item	Types/Notes	Value
Loading (Directional or rotational in X, Y, and Z)	Force	Aircraft panel ~ 5N Sideways accidental collision ~50N
	Pressure	Negligible
	Moment	Negligible
	Bearing load	Negligible
Objective and limits	Minimise mass	Yes (~10kg)
	FOS	1.5
	Mass target	< 5kg
Structural constraints	Fixed	Yes
	Pin	No
	Frictionless – radial	No
	Frictionless – axial	No
	Frictionless – tangential	No
Displacement		5 thou or 0.127 mm

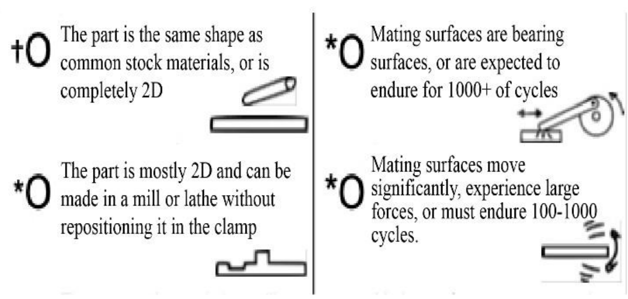

Fig. 2 Conditions to avoid in DfAM

2.1. Part Selection

It was decided that 2 main aspects would govern the part selection process: a suitability score test method and the overall part size (due to the printing envelope of the available printer). The secondary selection aspects are the number of part count and the weight of parts, supporting the objectives of part count and mass reduction. The suitability score tests will be conducted using the DfAM worksheet by Purdue Engineering [11]. On the top left-hand corner of the worksheet, 4 conditions marked with † and * of the original part are given, as shown in Figure 2. To ensure a successful, meaningful redesign was possible on the chosen jig, any parts that score in these 4 conditions are parts that should not be considered for the DfAM process. In short, shapes close to stock materials, such as standard metal blanks and simple 3D designs, can be milled in a single step. Parts exposed to a high fatigue and duty cycle during operation, such as hinges, cams, and gears, should also be avoided. Data was collected on all the possible loading the jig will be subjected to, and reference surfaces, design constraints and attachment points were captured. The parameters captured are as shown in Table 1. Initially, 4 parts were considered. as shown in Figure 3. The jigs on the left side of the photo are from a family of jigs that are used to locate hole positions for a drill and rivet process. The jigs shown in the two pictures on the right are from another family of jigs, locators for component placements during the assembly process. Both jigs are heavy and expensive in design.

Optimisation can produce more lightweight and cost-effective jigs. After careful consideration of the aspects mentioned, the jig shown in the far-right photo in Figure 3 was chosen. This jig shall be known as the IC jig for this paper. The IC jig scored 27 on the suitability score test, but it steered clear of the cyclic loading conditions to which the RP jigs are subjected. The IC jig originally weighed more than 10kg, which requires two technicians to carry it from its storage rack to its main assembly jig, whereby the IC jig is assembled during the assembly process of an aircraft wing component. The overall size of the part is less than 1m x 1m x 1m, which is the envelope of the giant polymer printer accessible by the research team. The IC jig has 9 parts and is made of aluminium 6061. These parts are joined by welding (for 4 non-movable parts) and bolt and nut assembly for 5 adjustable pieces (which are adjusted during the annual calibration process).

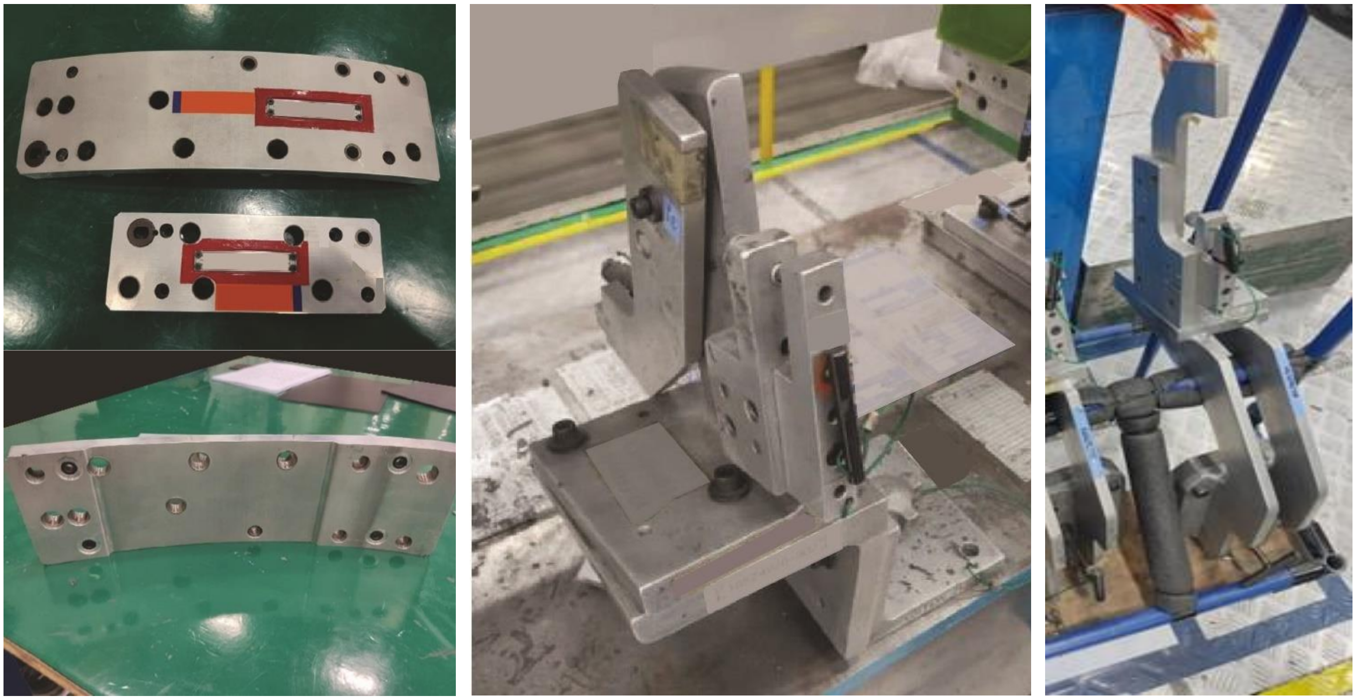

Fig. 3 RP jigs (left), IC jigs (right)

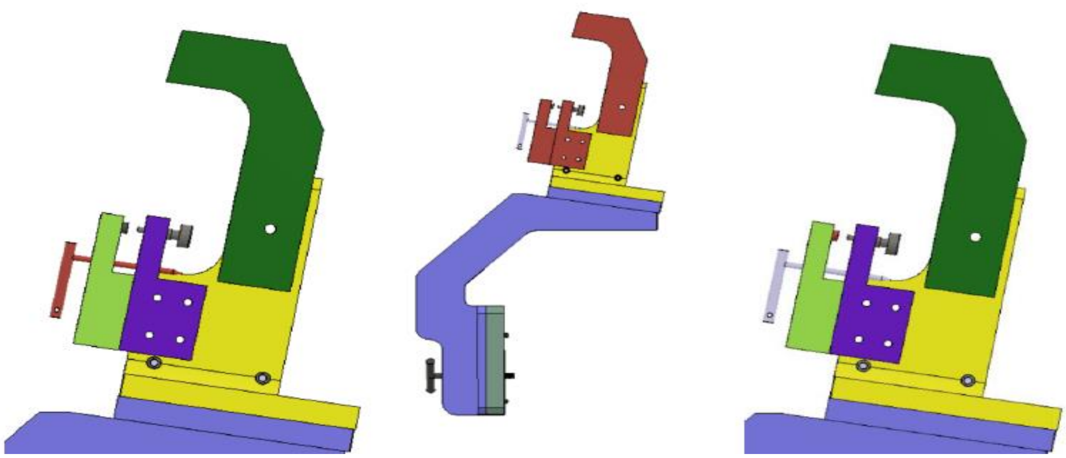

Fig. 4 IC jig positioning in reference surface, highlighted in red and sequenced from left to right x, y, z (of aircraft frame of reference)

This jig has 3 reference surfaces (x,y,z), as shown in Figure 4, which has a tolerance of 0.127 mm (5 thou). These are the 3 measurements must be met during the physical validation process.

2.2. DfAM Design Optimisation

The original IC jig design was subjected to two different design optimisation methods: DfAM and GD. The DfAM process, while manual in its optimisation, was still In the context of CAD software, namely the Dassault Systemes Solidworks. The DfAM is a design guided by the worksheet mentioned above. The process is an iteration by the designer and engineer experience and testing to get the lowest score on the sheet, which can be laid out as a process flow, as shown in Figure 5. Starting with part reduction, AM can form complex shapes and take advantage of it by combining multiple parts into one, reducing the number of parts to be fabricated. After a part is consolidated, part optimisation is the next phase in line with the sheet, which includes removing cavities and overhangs. Optimisation involves weight reduction, streamlining the design to use the least amount of material, and increasing complexity, taking advantage of AM. The design and engineer's changes are iterated through Finite Element Analysis (FEA) simulation to ensure the design complies with the constraints and performance expectations and is checked with the worksheet. Designs with thicker walls and smoothing (reducing sharp corners and using chamfers or fillets) minimise stress points. The designer and engineer are responsible for moving it to the final design through the aid of the worksheet.

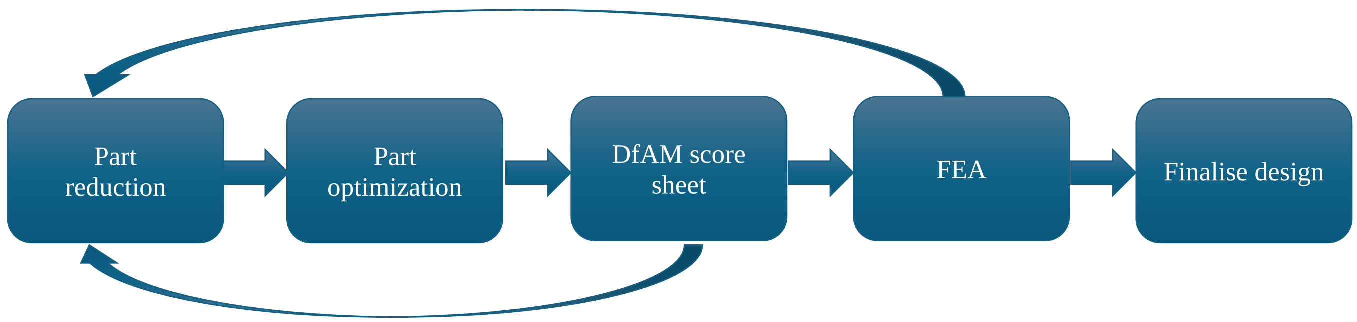

Fig. 5 DfAM process flow

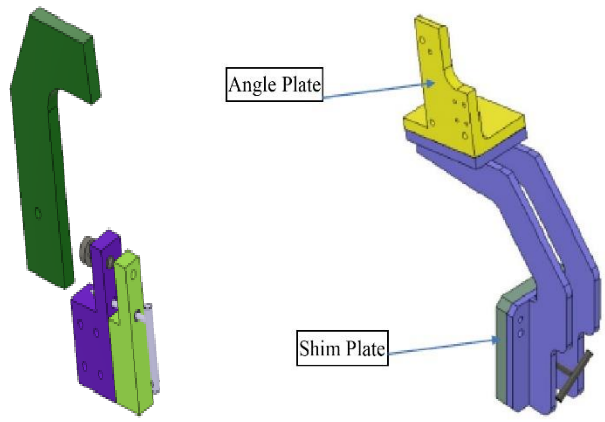

Fig. 6 The top portion (left) and bottom portion (right) of the IC jig

2.3. GD Optimisation

Before starting the GD process, the original design is studied, and the design engineer decides that the original design's top and bottom portions can be separated and optimised separately. Areas separated as top and bottom portions of the IC jig are shown in Figure 6. After an initial test, it was determined that the top portion was unsuitable for GD optimisation as GD tends to have an organic shape. This could lead to unsuitable designs, primarily when the top portion hosts all the reference surfaces, which must be flat. Therefore, only the bottom portion was subjected to GD. The top portion was optimised manually by the design engineer. The GD process utilised the AutoDesk Fusion CAD software with the Generative Design add-on. Based on the official training course by Autodesk on the Generative Design add-on, 40 required steps were observed in using the GD function from start to finish. For this paper, only 6 of the most essential steps are presented.

Step 1: Setup Preserve Geometry

This step allows the user to specify the exact geometry that needs to be preserved throughout all design permutations. Three regions were selected (Figure 7), namely the attachment plate (interface of jig and main assembly jig), the angle plate that holds the attachment points for the purple and yellow potion of the jig as seen in Figure 4, but modified, and lastly, a handle, which the design engineer creates to make the final design more ergonomic for handling.

Step 2: Specify Obstacle Geometry

The obstacle regions allow the user to indicate the areas where the optimised design cannot exist. This is useful for predicting where other components of the main jig and aircraft components exist in real space relative to the IC jig. The obstacle regions of the IC jig, including the main assembly jig, are shown in Figure 8.

Step 3: Setup Load Case

The original load cases, which mainly account for the aircraft component weight, are set on the preserve region, as shown in Figure 9. A secondary sideways load of 50N was later added to simulate any accidental collision on the shop floor.

Step 4: Select the Manufacturing Method

The software allows the user to specify the final manufacturing method for the optimised design to be fabricated. For this study, only AM is of interest; therefore, no other manufacturing methods were selected.

Step 5: Specify the Material

Fusion 360 has a limited number of polymers, which makes it suitable for AM. The eventual printing supplier and their material availability were unknown during this study phase. Therefore, variations of PA11 and PA12 nylons were used for this study.

Step 6: Setup of Optimisation Objectives and Limits

The objectives of the optimisation study were set for weight reduction. A safety factor of 1.5 was set as per typical aerospace industry requirements. A maximum allowable displacement in x,y, and z directions of 0.127mm was set.

2.4. Design Verification

When both designs were finalised, GD and DfAM parts were simulated with the loading conditions and tolerances in Table 1. The simulations are conducted as a solid (100% infill), treating the DfAM and GD designs as one solid piece with no cavity to simplify the process. Simulating a hollow part (due to infill density and wall thickness) and the anisotropic nature of FDM is complex [21, 22], hence the simplified process to speed up design iterations. The results are compared to determine the candidate suitable for the fabrication phase and validation. The validation considers the part that can perform within the specified parameters. FEA gives an idea of the expected behaviour from the material selected when printed. The finalisation process includes adding points used to fit the part with other components in the assembly through part allocation or embedding. The loading and mounting conditions were extracted from the original part specification and are used in the FEA. The IC jig has a single fixed point (green) and two loading points (red), as noted in Figure 10. The loading points are gravity-based on the two points with no external force other than the part's mass with a force of 5 N.

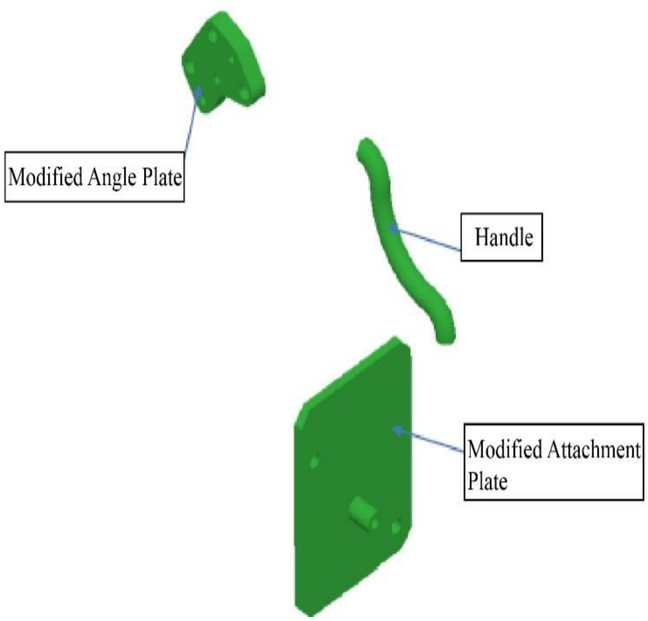

Fig. 7 Specified preserved region

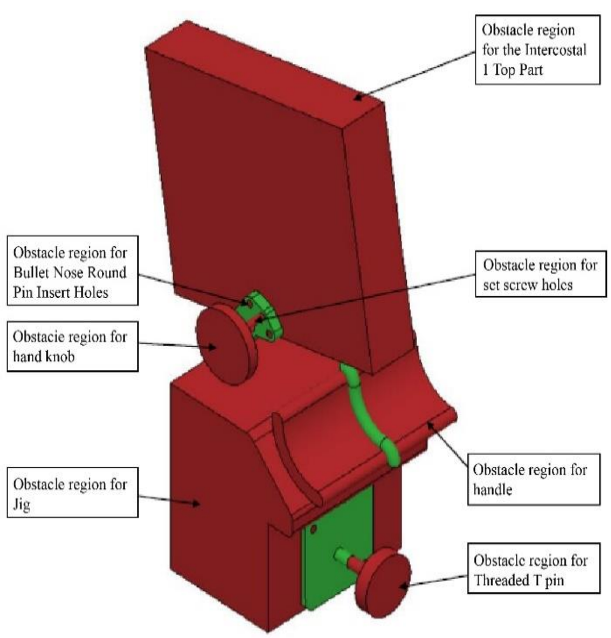

Fig. 8 Assigned obstacle region (in red)

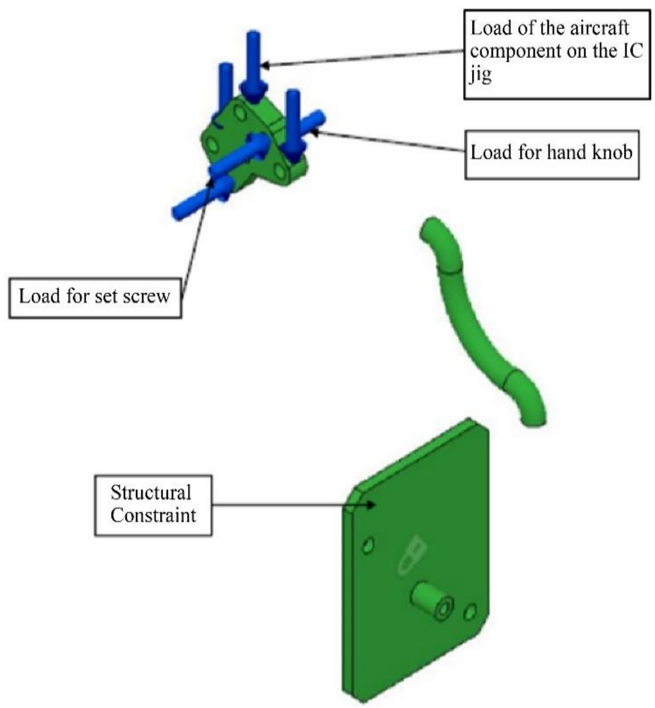

Fig. 9 Loading areas

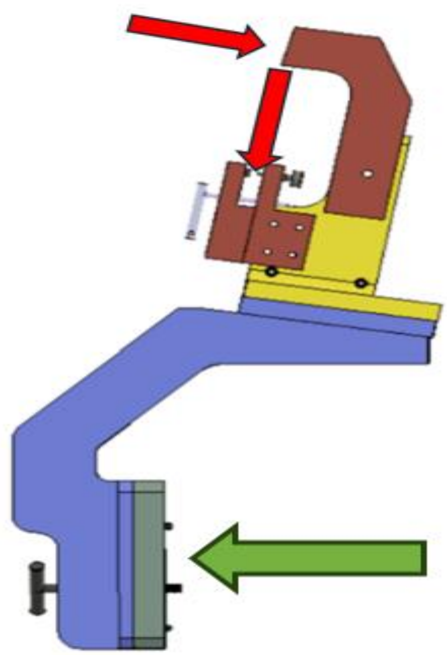

Fig. 10 IC jig loading and fixture points

2.5. Design Finalisation, Jig Fabrication and Assembly

Upon selection of the final design, the design was then improved to consider all the attachment points to assemble the 4 final pieces of the jig. This improvement was guided by the industrial partner's input on attachment points, ensuring annual tool calibration can be quickly done with existing industry tools.

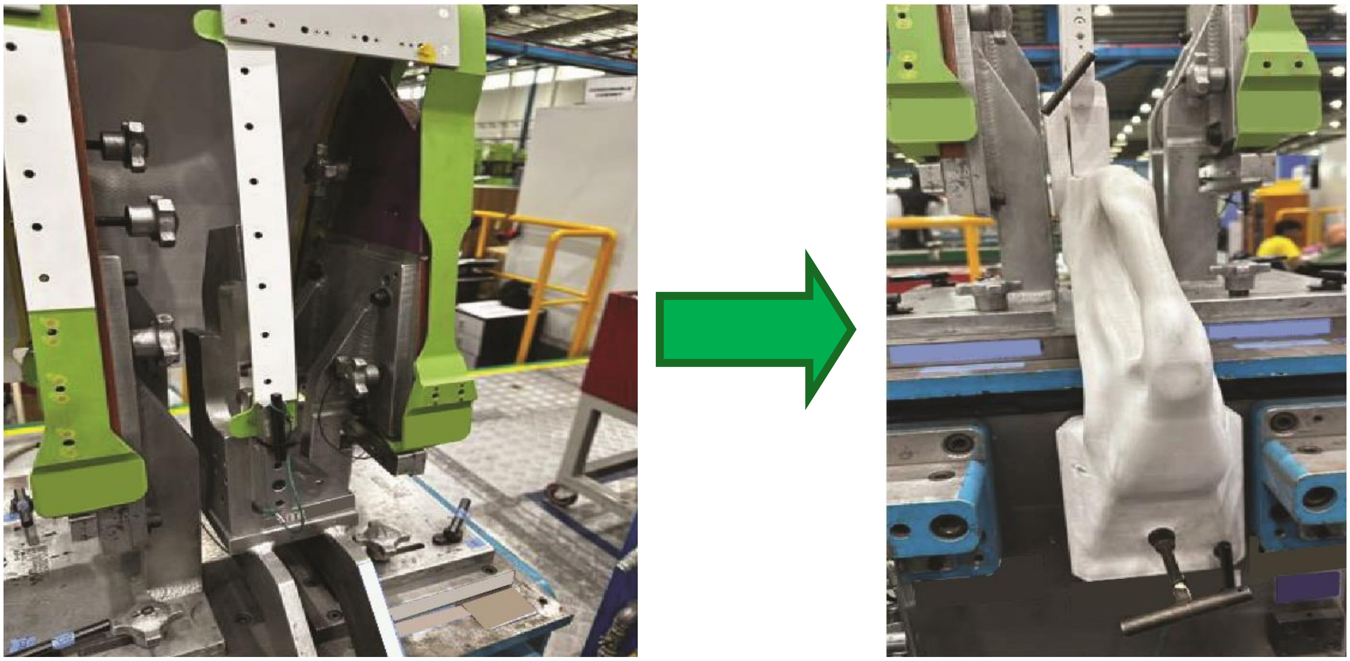

Fig. 11 Assembly of the IC jig into the main assembly jig (left) the original aluminium jig holding the aerospace component during the assembly process (right) the AM jig

Industrial AM machines can now achieve a printing accuracy of 0.1mm (100 microns) [23]. Most aerospace applications require a typical tolerance that can range from 50 microns to 150 microns. The resulting design was fabricated in an industrial grade Fused Deposition Modelling (FDM) printer. This is due to FDM's access to materials ranging from plastics to composite mix of metal and the relative abundance of FDM printers compared to other forms of AM. More importantly, large-format FDM printers are much more accessible compared to other forms of AM, whereby large-scale printers can be prohibitively expensive to purchase and use, causing them to be less available. 5 materials were used in the FEA simulation, namely, PA6, PC-ABS, PETG, ASA, PA12-CF of which each material varies in performance and cost. A performance vs cost analysis was done, so the ASA material was chosen to fabricate the final design. The design was oriented to ensure the main direction of loading was aligned to the main x-y printing plane to ensure maximum strength. The secondary loading direction is aligned to the perpendicular plane of the x-y plane. All design components are printed with 100% infill, translating to a solid part with no infill lattice within its structure. After printing, the support material was removed. The printed part did not require any structural post-processing to strengthen it further. Geometric post-processing was also unnecessary as the dimensions during the design stage already considered all the printing tolerances through dimensional compensation. Some minor surface finish post-processing was conducted to smoothen parts where the supports have been removed. As this jig is only for testing and not long-term, no further surface finish post-processing is required. Lastly, the printed jig was assembled using industrial standard metal attachments.

2.6. Jig Validation

Validation was conducted to ensure that the design and printing of the optimised IC jig met the required criteria and the capabilities of the original tool. As the printed jig was based on an active tool in Spirit Aerosystems, the original jig was substituted with the printed model to compare and directly determine its functionality and capabilities. On the factory floor, the fully assembled printed jig was fixed into position at the main jig, which is the main assembly jig of the aircraft part. The substitution can be seen in Figure 11.

The jig was then aligned and validated using a laser tracker on the shopfloor as per industrial practice to ensure all 3 reference surfaces (x,y,z) tolerance requirements of the jig were met. The accepted tolerance for this part is 0.127mm (127 microns) (listed as displacement in Table 1).

This process starts with preparing the validation dataset, which was prepared from the original CATIA CAD file. More comprehensive details of the laser tracking process are given in Figure 12.

2.7. Case Study Analysis

The nature of the project involves achieving and proving the process concerning the objectives. The empirical data from the design and FEA is the part mass and the simulation results regarding displacement and stress. The DfAM part mass is compared to the original design but requires the part to pass the FEA deflection tolerance dictated by Table 1. Additionally, to validate the DfAM FEA printed part, the part undergoes jig validation to confirm its compliance with the original part position specifications.

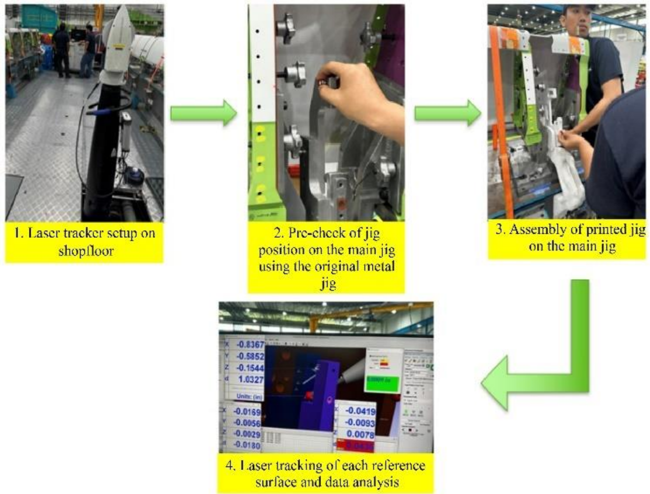

Fig. 12 Process flow of the laser tracking validation on the shop floor

3. Results

3.1. Design for Additive Manufacturing

There were 3 designs proposed by the DfAM method, as shown in the first 3 designs from the left of Figure 13. Design 1 follows a consolidation approach whereby the 2 metal legs are redesigned to be joined at the top. Design 2 follows a simplification approach whereby a simplified bottom part is designed, and integrating the bottom part with the top part employs a hinged top part. Design 3 consists of a further optimisation of Design 2. The engineering idea was to produce various iterations of the DfAM of the IC jig. Design 1 retained most of the original design; the two arms were retained, but the bottom portion was merged. Turning 3 parts into one but keeping the original 3 contact piece. This design scored 18, a significant decrease from the original design. The original design consisted of many overhangs, and this design was more streamlined, reducing the scoring on overhangs. As for Design 2, further material reduction and combination were made to Design 1, removing the identities of the original design and only retaining the required contact and attachment points. Design 2 scored 17 points, a slight improvement from Design 1, which improved by 1 point due to the further reduction of overhangs. Design 3 was aimed to reduce the material usage further and take full advantage of the DfAM abilities. However, Design 3 scored 23 due to the thin features and overhangs, which negatively impacted the performance of the part. The FEA and DfAM sheet rules favoured Design 2. Adjusted to include a more robust assembly mechanism and points to install fittings that were not considered during the original design iteration. This was then used as the final DfAM design.

3.2. Generative Design

The GD optimisation process of Fusion360 runs within cloud computing. The GD run of the lower portion of the IC jig initially yielded 147 solutions, filtered across 7 materials with mass ranging up to 12kg. Aluminium, which was included in the initial pool to monitor how AM would influence the GD results, was removed. One of the objectives was to reduce the weight of the IC jig by 50%, which is approximately 5kg, and this 5kg includes the top portion. Therefore, the weight of the lower portion was limited to 3kg. All results obtained after said filtration had a range of min factor of safety between 1.5 (the set value) and 100. Results were filtered to bring the maximum safety factor down to 60. The following filter removes failed studies. Due to the iterative nature of the GD process, some results displayed are failed studies that cannot be used, but they are listed to show a potential option. Sometimes, the study can be re-run to attempt design convergence, and these failed studies may yield viable results. The max displacement, even though set to 0.127mm, was only used by Fusion360 as a guide. The filtered results gave global displacements/ deflection variations beyond the set tolerance. This was then filtered down to a displacement of 0.2mm (the lowest value Fusion360 allowed to set during filtration).

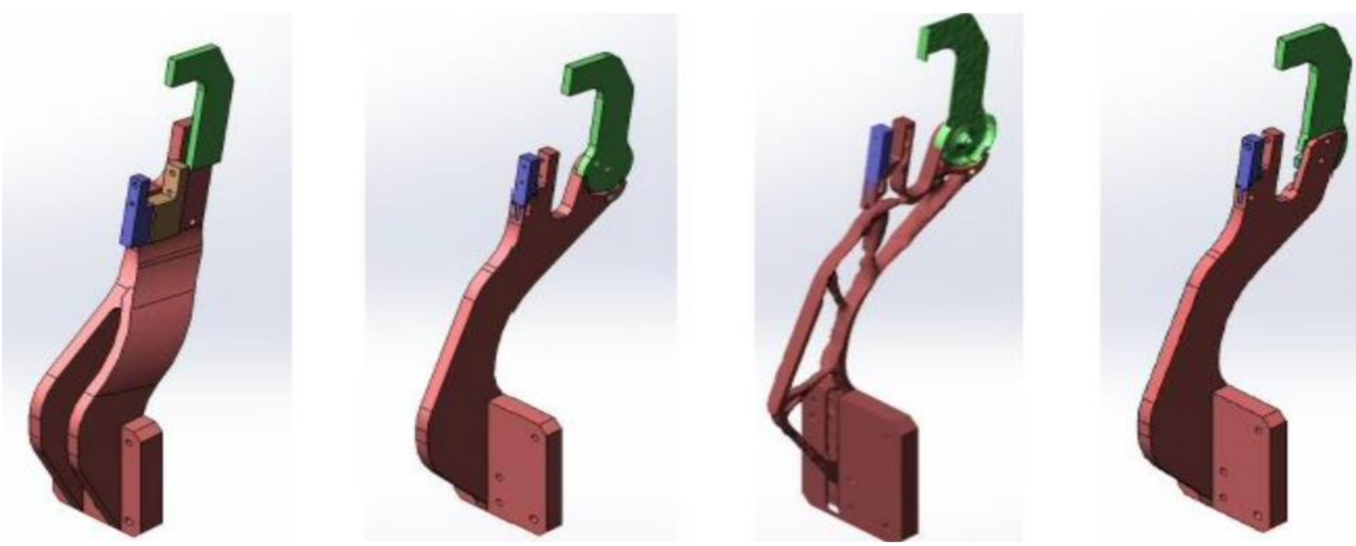

Fig. 13 From left, design 1, design 2, design 3, and finalized DfAM design

Table 2. Part mass analysis

Material	DfAM			Generative Design	
	Design 1(kg)	Design 3 (kg)	Final Design (kg)	Outcome 98 (kg)	Outcome 132 (kg)
ASA	2.05	1.34	2.01	3.14	3.60

Table 3. Simulated 5N load on the designs

Material	DfAM			GD		
	Stress (N/m^2)		Displacement (mm)	Stress (N/m^2)		Displacement (mm)
	Min	Max	Max	Min	Max	Max
PA6	0.005	746500.000	0.102	0.078	6334000.000	0.882
PC-ABS	0.005	746500.000	0.131	0.060	6253000.000	0.968
PETG	0.003	883900.000	0.131	0.087	6589000.000	0.994
ASA	0.002	787500.000	0.113	0.068	6428000.000	0.941
PA12-CF	0.023	791000.000	0.079	0.169	5660000.000	0.671

Table 4. Simulated 50N load on the designs

Material	DfAM			GD		
	Stress (N/m^2)		Displacement (mm)	Stress (N/m^2)		Displacement (mm)
	Min	Max	Max	Min	Max	Max
PA6	0.353	2451000.000	8.129	0.036	7055000.000	0.534
PC-ABS	0.353	2451000.000	8.822	0.066	6967000.000	0.587
PETG	0.241	3044000.000	10.390	0.018	7434000.000	0.636
ASA	0.345	2472000.000	8.953	0.037	7157000.000	0.575
PA12-CF	0.585	2416000.000	6.356	0.296	6186000.000	0.435

Two results, Outcome 98 and Outcome 132, were chosen based on their global deflection value, which was 0.134mm for the former and 0.189 for the latter, as shown in Figure 14. These deflection values are based on the FEA of PA12 material. Outcome 98 had the lowest displacement, whilst Outcome 98 had the lowest mass of 2.598kg. Their complete comparison is shown in Table 2. Even though the global displacement of GD 98 was slightly higher than the maximum tolerance requirement, its displacement was still within tolerance. Therefore, it is a viable design. This design was then improved to account for ease of setup and calibration. Like the original jig design, the design team wanted to ensure the updated design could be adjusted/shimmed. This was done by splitting the total parts into 4. As shown in Figure 15, the final design consists of the main body (lower portion), an improved design of the top portion, a shim plate (which allows for adjustment in directions) and a standalone rest button plate, which allows for adjustment of the rest button surface. The strategic placement of set screws allows for small shimming to occur.

3.3. Comparison

3.3.1. Part mass

The 3 DfAM designs (Design 2 represented by the final chosen design) and the 2 GD designs (including the manually designed top portion) are simulated for ASA material, and the results are in Table 2. As for the final printed part, which includes metal attachments, the final weight is 4kg. This is a 60% reduction from the original IC design jig, which is 10kg.

3.3.2. Finite Element Analysis

Two designs were chosen to represent DfAM and GD, respectively. The final designs of DfAM and Outcome 98 were subjected to an FEA study, which simulates the part loading on the jig, as specified in Table 1. The designs were subjected to two loads. The first load of 5N simulates the placement of the aircraft panel on the IC jig, the first two columns in Figure 16 (top: GD, bottom: DfAM). The results are given in Table 3.

The secondary load is the potential side collision on the shop floor, the third column in Figure 16, which is taken to be a value of 50N and the results are given in Table 4. The FEA study assumed an isotropic behaviour of industrial-grade materials for the FDM process, printed in solid form with no internal lattices. The simulation materials used are based on the information the AM fabricator PebbleReka provided is based on actual filament material characteristics. Tables 3 and 4 show the best and least performing materials, PA12-CF and PETG. The PA12-CF on the 5N loading displaced by 0.079 mm for DfAM and 0.671 mm for the GD. The 50N loading for the DfAM had a large deflection of 6.356 mm, but the GD had a low deflection of 0.435 mm. The least-performing material PETG on both methods and loading had a deflection greater than 0.5 mm; Figure 17 is a sample from the GD and DfAM deformation simulation results. Both parts in FEA performed within the tolerance and requirements of the part for the 5N, but DfAM was out of tolerance for the 50N loading. The GD part fulfilled all the requirements and was chosen as the candidate for the final design.

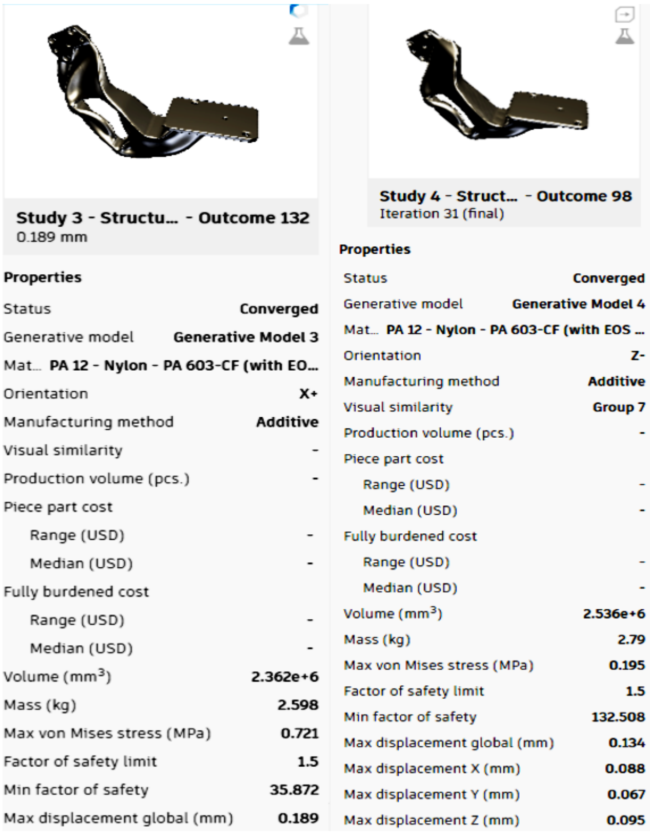

Fig. 14 Comparison of outcome 98 and outcome 132

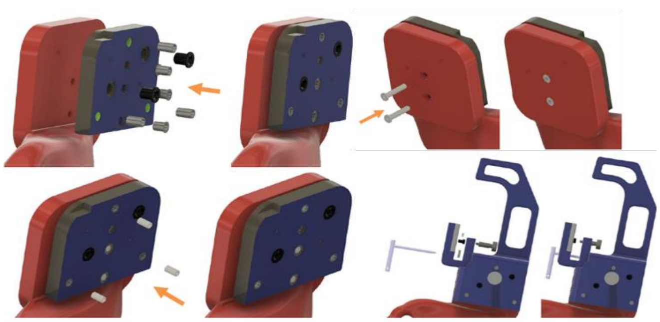

Fig. 15 The improved top portion, the GD bottom portion (main body), the middle shim plate, the rest button plate and all the attachments

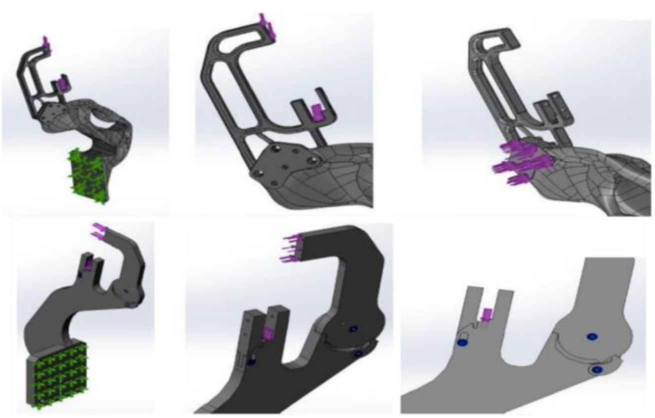

Fig. 16 Part loading and fixture for simulation (top) GD (bottom) DfAM

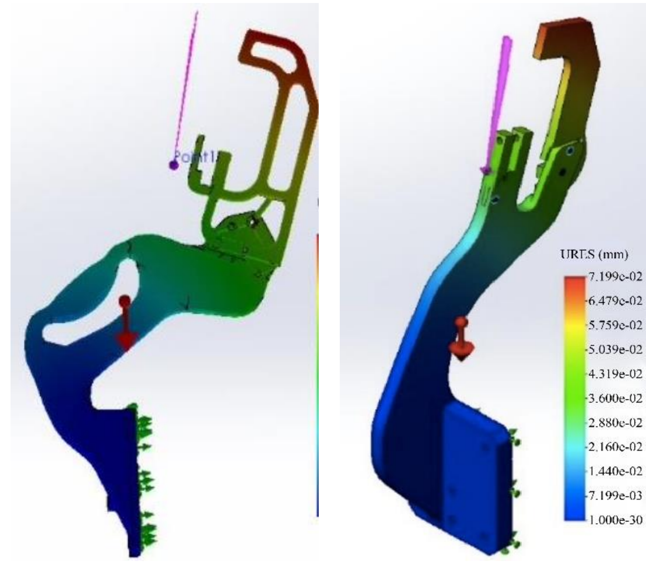

Fig. 17 Deformation simulation in FEA (left) GD design (right) DfAM design

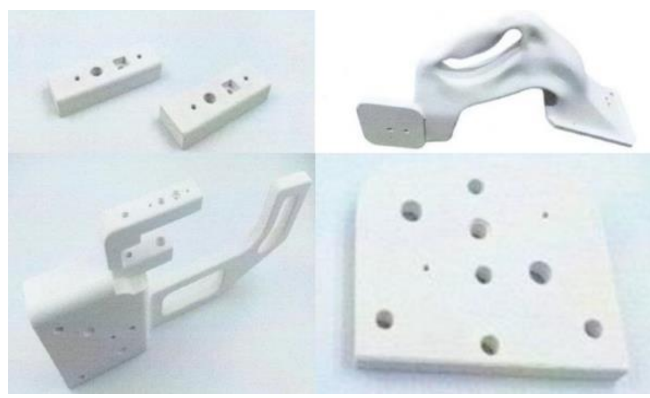

Fig. 18 Final printed parts in ASA

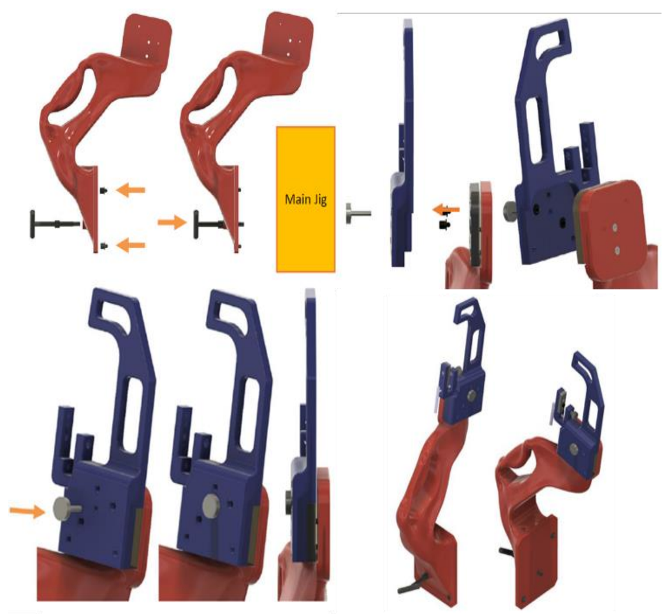

Fig. 19 Attachment sequence of the parts

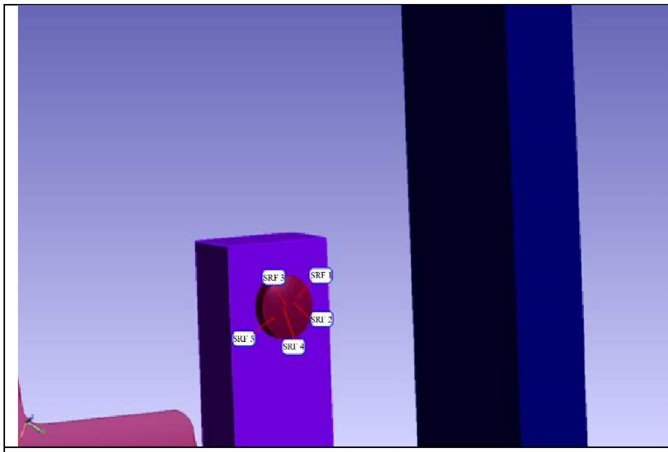

Fig. 20 Z-direction (rest button) measurement points

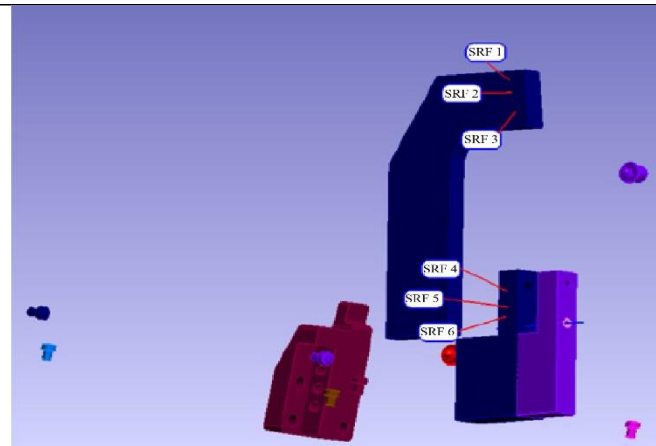

Fig. 21 Y-axis reference plane measurement points.

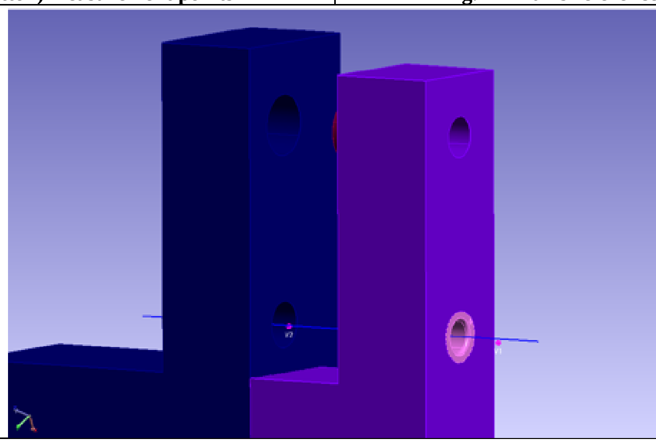

Fig. 22 X-direction (L-pin) measurement points

Table 5. Y-axis reference surface validation measurements

Points to Objects Relationship LOCATOR SURFACE 3D (Reported in FAJ163Z0001-901_J::WORLD)										
Name	Object			Point			Delta			
	X1 (in)	Y1 (in)	Z1 (in)	X2 (in)	Y2 (in)	Z2 (in)	dX (in)	dY (in)	dZ (in)	Mag (in)
SRF 1	1266.4371	-768.3771	249.8444	1266.4346	-768.3735	249.8439	-0.0025	0.0036	-0.0005	0.0044
SRF 2	1266.7305	-768.1949	249.6994	1266.7287	-768.1923	249.6991	-0.0018	0.0026	-0.0004	0.0032
SRF 3	1267.1818	-767.9177	249.4554	1267.1827	-767.9190	249.4555	0.0009	-0.0013	0.0002	-0.0016
SRF 4	1271.7433	-764.9237	248.3558	1271.7451	-764.9264	248.3562	0.0018	-0.0027	0.0004	-0.0033
SRF 5	1272.1496	-764.6643	248.2066	1272.1541	-764.6708	248.2076	0.0045	-0.0066	0.0009	-0.0080
SRF 6	1272.3848	-764.5041	248.1909	1272.3881	-764.5089	248.1916	0.0033	-0.0048	0.0007	0.0059

Table 6. Z-axis reference surface validation measurements

Points to Objects Relationship INDEX PIN 3D (Reported in FAJ163Z0001-901_J::WORLD)										
Name	Object			Point			Delta			
	X1 (in)	Y1 (in)	Z1 (in)	X2 (in)	Y2 (in)	Z2 (in)	dX (in)	dY (in)	dZ (in)	Mag (in)
SRF 1	1271.6919	-765.4728	247.8486	1271.6919	-765.4729	247.8484	-0.0000	-0.0000	-0.0002	-0.0002
SRF 2	1271.7174	-765.4861	247.8492	1271.7175	-765.4859	247.8504	0.0001	0.0002	0.0012	0.0012
SRF 3	1271.7570	-765.5135	247.8484	1271.7581	-765.5126	247.8553	0.0011	0.0010	0.0069	0.0071
SRF 4	1271.7703	-765.5220	247.8472	1271.7692	-765.5228	247.8414	0.0011	-0.0008	-0.0059	-0.0060
SRF 5	1271.8334	-765.5469	247.8346	1271.8328	-765.5471	247.8323	-0.0007	-0.0002	-0.0023	-0.0024

Table 7. X-axis reference surface validation measurements

Points to Objects Relationship LINE 3D (Reported in FAJ163Z0001-901_J::WORLD)										
Name	Object			Point			Delta			
	X1 (in)	Y1 (in)	Z1 (in)	X2 (in)	Y2 (in)	Z2 (in)	dX (in)	dY (in)	dZ (in)	Mag (in)
V1	1272.5890	-765.0528	246.5512	1272.6510	-765.0892	246.5513	0.0620	-0.0364	0.0001	0.0719
V2	1272.7787	-764.7239	247.9568	1272.7937	-764.7352	247.9574	0.0150	-0.0113	0.0006	0.0188

This design was edited to consider attachment points between the 4 parts, which also allows for yearly industrial maintenance and calibration adjustments on the shop floor.

3.3.3. Fabrication and Assembly

The final printed pieces of the 4 components are shown in Figure 18. They are then assembled using the standard metal attachments, as shown in Figures 15 and 19.

3.3.4. Part Count

The final part count of the printed GD design, not including the metal attachments, is 4 pieces. This is a 55% reduction from the original 9 aluminium pieces of the original design.

3.3.5. Jig Validation

The laser tracker measurement points are shown in Figure 20 and 22. The measurement of the reference surfaces for the Y and Z axes passed for all 6 measurement points, as shown in Table 5 and 6. However, the X-axis (L-pin) did not pass the 2 measurement points as shown in Table 7. The results of the X-axis validation testing show that there exists a significant difference between the measured and original tool reference values. For both values being tested, the tolerance exceeds the tolerance limit of 0.127mm. Therefore, the tolerance for the hole position is not reached, and the validation of the reference point in the X direction has failed. This shows that further reworking is necessary for the 3D-printed model before it can fully replace the original IC jig design.

4. Discussions

The coupling of design optimisation with AM enables exploring new design possibilities. In this case, the original jig was heavy, and its design was cumbersome. This project employed two design optimisation methods to compare and contrast their benefits and drawbacks. GD, whilst more straightforward to implement, is an additional investment for the user. Any investment into GD also needs to consider the CAD software already used by the company's users. A compatible GD suite with the pre-installed CAD software would be highly beneficial as amendments to the original design can be achieved more easily with seamless software integration. DfAM, on the other hand, uses the score sheet to provide a clear goal-based methodology that guides the design engineers on the best design practices, as noted in [15-20]. However, DfAM requires FEA as a validation step, whilst GD considers the load cases in its optimisation routine and makes FEA somewhat optional for non-critical components. In this study, both methods showed promising results, and with careful material selection and design iterations (for DfAM design), the final designs from both methods were usable. Despite the lighter DfAM part, obtaining the part depended on the engineering knowledge of the process and iterative design using FEA to achieve the desired performance, as noted in [18]. The GD part was heavier, but the process was automated, and the engineer's knowledge was not critical. The engineer obtained an optimised part quickly and only required the part tolerances and requirements [25]. Hence, GD is recommended for a fast initial design, and DfAM is a complementary process. Providing granular control over the design, allowing clean-ups and fitting to the final part conformation before manufacturing the part. When using the GD method, design engineers must not wholly rely on the software to address the complete design requirements as it still requires the user to refine the component as in [26]. As shown in this study, only the lower portion of the jig was suitable for GD optimisation, and the top portions were all optimised manually. Further, the industrial requirement for easy assembly and calibration of the jig was considered with a manual design change. The resulting design allows for an easy adjustment and calibration process.

This study modelled the AM designs as solid, monolithic, and isotropic during the FEA stage. A more advanced FEA could consider internal lattices and print orientations for lighter designs, but this approach would be more resource-intensive and costly, as noted in [21]. The fabrication process selection amongst the 7 AM process categories can be carefully studied in an ideal case. However, due to the limited availability of large-format printers, FDM was selected. The adoption of the industrial laser tracking procedure, which is the standard validation practice of the IC jig for the validation of the updated design, provides a much higher sense of confidence for both the research team and the industrial partner that the rigour applied during all the steps is a useable methodology and the materials and shimming method is also usable. The failure of the X-axis validation test shows that minor improvements to the 3D printed model or design are required before the 3D printed model can comfortably replace the original aluminium tool. It can be pointed out that the variation in tolerance magnitude is considerable between the readings for the X-direction. This could point towards two conceivable possibilities: potentially, the L-Pin is loose within the hole, or that dimension is difficult to measure due to its placement. For the former, a simple fix of either tightening the set screw using a temporary thread lock sealant before the test can be applied. However, the passing of the Y and Z axis tolerance points that the right AM technology and printer (to ensure tight tolerances) and a careful design to ensure adjustability/calibration, the need for the metal tool to achieve tight tolerances, particularly in low load-bearing conditions, is less relevant. Keeping the jig into 4 pieces, and not completely consolidating the 9 original parts together ensures the end user can replace only damaged components as and when required. This increases the serviceability of the jig throughout its lifespan. The choice to use polymer also means that the printing of a single replacement part can be much lower than the repair or replacement of their metal counterpart, especially if it is printed in house by the end user.

The use of AM for jigs and fixtures is pointed out as a future trend by [27] as an enabler for shorter lead times and flexible manufacturing setups, with the latter enabled by exploring previously unexplored design spaces, which are not feasible with conventional manufacturing. [28] pointed out that AM could only have achieved complex fixture designs and clamping methods previously. The use of AM for jigs is on the rise [29]. A market survey showed that as of 2021, 57% of the companies surveyed had employed AM for use on jigs and fixtures. Within the automotive industry, BMW has equipped most of its plants with 3D printers to produce jigs and fixtures [30]. In one reported example from BMW, the production of a handtool was reduced from 18 days to 1.5 days, a 92% lead time reduction with a 58% cost reduction, achieved by converting an originally aluminium design made by CNC to an Acrylonitrile Butadiene Styrene (ABS) made by FDM form of AM [31]. In another example mentioned in the same report, they managed to cut down the tool's weight by 72% by employing internal lattice structures.

5. Conclusion

This exercise has shown that the use of polymer-based AM jigs is feasible. The ability to achieve the required tolerances and withstand the load requirements of the original jig allows for a rethinking and reduction in dependency on metal tooling. AM’s ability to fabricate complex designs and a design optimisation exercise further improve the feasibility and business case for a polymer-based jig employing weight reduction and part consolidation. The weight reduction of 60% allows technicians to handle the jig more ergonomically. Part consolidation (from 9 parts, mainly welded and bolted together) to only 4 parts allows for a reduction of maintenance and calibration during use and during the annual required maintenance regime. Metal fittings are still needed to ensure ease of adjustment and to attach new AM jigs to current metal jigs.

5.1. Recommendation

More work is needed to ascertain the longevity of polymer-based AM compared to aluminium or metal-based tools for non-load-bearing, non-cyclic loading tools. This includes studies to understand the possible causes for the tool's deformation over time. A test to determine the tool's wear similar to that conducted by [32] would be helpful, especially when converting a jig from metal to polymer material.

6. Future Work

This study demonstrates the potential of polymer-based AM for creating precision jigs and tools that do not experience cyclic loading. However, producing an AM jig costs 2.5 times more than a conventional CNC-made tool. To maximise the benefits of AM, its application should focus on jigs with complex designs that typically require multiple machining steps and assembly. AM can produce these jigs in a single step, optimising the design process and cost-efficiency. Internal adoption is crucial to scale up the use of AM for shopfloor jigs. This involves several key strategies:

- In-house Design Capability: Designing jigs specifically for AM from scratch, rather than modifying existing designs, enables better optimisation. This approach also allows for multiple iterations using inexpensive materials before final production.
- Lightweighting through Lattice Structures: Exploring lattice designs and conducting FEA (finite element analysis) can reduce weight and cost further.
- Cost Efficiency of In-house Printing: Producing parts in-house is generally more economical than outsourcing fabrication.

Another area for AM expansion is in polymer jigs for inspection purposes. This includes two scenarios:

- Multiple-Part Variations: Producing inspection jigs for parts with slight dimensional differences or multiple part numbers is faster and potentially cheaper with AM than CNC, which requires various adjustments.
- Low-Volume Parts: AM is particularly feasible for inspection jigs for low-production parts. Polymers are lighter than metals, making them easier to handle and store when not in use.

Finally, one of the most promising directions for future work is using polymer AM to fabricate robotic end-effectors. As automation on the shop floor increases, the demand for end-effectors also grows. The precision and strength achievable with FDM make this a viable option. End-effectors can be seen as dynamic jigs integrated with automation. The design principles for adjustability, alignment, and calibration explored in this project can directly translate to developing optimised robotic end-effectors.

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