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Design for Wire + Arc Additive Manufacture: Design Rules and Build Orientation Selection

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Abstract

Wire + Arc Additive Manufacture (WAAM) is an additive manufacturing technology that can produce near net-shape parts layer by layer in an automated manner using welding technology controlled by a robot or CNC machine. WAAM has been shown to produce parts with good structural integrity in a range of materials including titanium, steel and aluminium and has the potential to produce high value structural parts at lower cost with much less waste material and shorter lead times that conventional manufacturing processes.

This paper provides an initial set of design rules for WAAM and presents a methodology for build orientation selection for WAAM parts. The paper begins with a comparison between the design requirements and capabilities of WAAM and other additive manufacturing technologies, design guidelines for WAAM are then presented based on experimental work. A methodology to select the most appropriate build orientation for WAAM parts is then presented using a multi attribute decision matrix approach to compare different design alternatives. Two aerospace case study parts are provided to illustrate the methodology.

Keywords: additive manufacture, design for manufacture, aerospace engineering

Nomenclature

C_i	Decision Criteria i
M_+^{AM}	Mass of deposited material above the central plane of the substrate
M_-^{AM}	Mass of deposited material below the central plane of the substrate
M_i^{AM}	Mass of WAAM deposited material
M_f	Mass of final part
M_i^M	Mass of initial billet
M_s	Mass of the start substrate
M_{sf}	Mass of the substrate incorporated into the final part
N	Number of WAAM Build Operations
S_j	Score for Build Option j

1. Introduction

Additive Manufacture refers to manufacturing processes where parts are built up layer by layer directly from a 3D model. Wire + Arc Additive Manufacture is an additive manufacturing technology

that uses wire feedstock to produce parts by depositing material layer by layer onto a substrate plate, using welding technology controlled by a robot or CNC machine (Williams et al. 2015). The part may be mounted on a part-rotator so that the build direction can be changed during deposition (this is referred to as multi-axis deposition (Zhang and Liou 2013)) and regions of the substrate plate can be incorporated into the final part if required. The part may be machined to its final dimensions either during deposition or after deposition is complete, depending on the application (Williams et al. 2015).

WAAM has been shown to produce medium to large scale parts with good structural integrity in a range of materials, and has the potential to produce high value structural parts at lower cost, with shorter lead times, and greatly reduced waste material than conventional manufacturing processes. Typical deposition rates are up to approximately 1.5 kg per hour and layer height is typically 1 - 2 mm (Williams et al. 2015). WAAM does not allow unlimited design freedom and for successful WAAM manufacture it is necessary to consider the build orientation, build sequence and design constraints of the WAAM process. If post-machining is required, for example in structural applications where stress raising features are of concern or for mating faces, then machining constraints must also be considered. However, WAAM also opens a wide range of new design opportunities, for example through hybrid manufacture with other processes, functionally graded materials, and parts with internal features. These design constraints and opportunities are substantially different to those offered by powder additive manufacturing technologies and require a different approach to design.

A key objective of WAAM is to reduce waste material produced during manufacturing. In the Aerospace industry this waste material is referred to as the buy-to-fly (BTF) ratio, which is defined as the ratio of the mass of material purchased to manufacture the part to the mass of the finished part that is flown on the aircraft. Allen (2006) states that for aero engine components the buy-to-fly ratios can be as high as 25, highlighting the substantial material saving benefits of a near-net-shape process.

The aims of this paper are to firstly to illustrate the differences between designing for WAAM and other AM processes, secondly propose a set of design guidelines for WAAM, and thirdly provide a methodology for WAAM build orientation assessment that maximises the benefits of WAAM

production. The paper is structured into six parts. Section 2 provides a literature review of design for additive manufacturing methods, section 3 compares design for WAAM and other AM technologies and presents the general design requirements for WAAM. Section 4 proposes a methodology to select the most appropriate build orientation for WAAM parts, and the methodology is tested on two aerospace case study parts in section 5. The summary and conclusions are presented in section 6.

2. Literature Review

The concept of design for manufacture is defined by Kalpakjian and Schmid (2008) as "a comprehensive approach to the production of goods that integrates the product design process with selection of materials, consideration of manufacturing methods, process planning, assembly, testing, and quality assurance." Design for manufacture has been widely studied for many manufacturing processes such as machining, casting and moulding, which have well established design rules developed from many years industrial experience. Design for manufacture methods can be divided into three main approaches (Herrmann et al. 2004): (i) manufacturability guidelines based on experience (Bralla 1999; Beeley 2001; Clegg 1991) (ii) design assessment tools such as Design for Manufacture and Assembly (DFMA) (Boothroyd, Dewhurst, and Knight 2011) method that provide a quantitative basis for comparing design alternatives; (iii) simulation models that predict a product's performance, for example simulation of cooling rates in castings or thermal behaviour of welding processes. In engineering design there is a common tendency for designers to rely on their own knowledge of a limited range of manufacturing processes and designers may not consider unfamiliar manufacturing processes that may be more appropriate for their application (Herrmann et al. 2004). Design for Manufacture methods help designers compare different manufacturing processes and better understand the manufacturing impact of their design choices.

Design for Additive Manufacturing (DfAM) applies design for manufacture principles to additive manufacturing technologies. To date DfAM has mainly been focussed in two main areas – firstly, defining the design freedoms and customisation capabilities of AM (Hague, Mansour, and Saleh

2004; Gibson, Rosen, and Stucker 2010; Rosen 2014), and secondly investigating the optimal manufacturing strategy for additive manufactured parts (Ponche et al. 2014; Adam and Zimmer 2014; Kerbrat, Mognol, and Hascoët 2011). Laverne et al. (2015) classify these two DFAM research areas as "design making" and "design assessment", and further subdivide design making approaches into *opportunistic* DFAM methods which help designers explore creative shape complexity offered by AM, *restrictive* DFAM methods that take into account the limitations of AM and *dual* DFAM methods which combine the other two approaches. Their proposed early A-DFAM approach is mostly focused on the early design stages. Most previously published DfAM research has been applied to polymer 3D printing and metal powder AM technologies. Thompson et al. (2016) provide a comprehensive review of design for additive manufacture trends, opportunities and constraints for a wide range of AM technologies and conclude that design for AM is "still in its infancy" and there is insufficient understanding of "how and when to design for AM".

2.1. Design for Additive Manufacture Guidelines

Currently there no standard definition of DfAM principles. In 2004 Hague, Mansour, and Saleh (2004) stated that "the principal advantage of the additive manufacturing processes (including most, but not all, of the currently available RP techniques) is the ability to manufacture parts of virtually any complexity of geometry entirely without the need for tooling". More recently Gibson, Rosen, and Stucker (2010) defined DfAM as "maximis[ing] product performance through synthesis of shapes, sizes, hierarchical structures, and material compositions, subject to the capabilities of AM technologies" and identified four unique AM capabilities as shape complexity, hierarchical complexity, functional complexity and material complexity. Rosen (2014)further extended the set of DfAM principles to include customised geometries.

Atzeni and Salmi (2012) propose five general design for AM guidelines for Direct Metal Laser Sintering that emphasise the need for new design thinking, unconstrained by existing manufacturing process constraints. These can be summarised as (i) avoid conventional design principles, (ii) focus on integrated freeform design and reducing part count, (iii) minimise raw

material use, (iv) use freeform designs, undercuts and hollow structures if they are useful and (v) optimise the part shape according to functionality.

Several other researchers have presented more detailed design rules for AM. For example Adam and Zimmer (2014) propose a design rule catalogue for additive manufacture that subdivides the part to be manufactured into basic elements (shapes such as cylinders, blocks etc.), element transitions (joints) and aggregated structures (features that combine two or more basic elements and a transition) and then defines design rules for those elements. They created a design rule catalogue for Laser Sintering, Laser Melting and Fused Deposition Modelling and undertook experiments to assess the capabilities of three AM processes to produce these feature combinations with different thicknesses, then developed design rules based on these experiments. Kranz, Herzog, and Emmelmann (2015) present a detailed set of design guidelines for laser additive manufacturing of lightweight structures in titanium based on an extensive set of experiments. These guidelines provide pictorial and descriptive design guidelines for a wide range of design features, following a similar approach to design handbooks for conventional manufacturing processes.

The published design guidelines for additive manufacture either present general design guidelines that are applicable to a group of AM processes or detailed design guidelines for a specific technology. To date there has been a lack of clarity about the differences between the design requirements of different additive manufacturing processes and the DfAM guidelines published to date are only partially applicable to WAAM due to the differences between WAAM and other AM technologies. There is a need to better understand the similarities and differences between WAAM and other AM technologies. The only previously published WAAM design guidelines were produced by Kazanas et al. (2012) who published an initial an investigation into geometric feature deposition using WAAM, and Mehnen et al. (2014) who published a design study for WAAM containing some examples of design features and process capabilities; but there are no published methodological approaches to designing for WAAM.

2.2. Optimal Manufacturing Strategies for Additive Manufacture

The second DfAM approach relates to the development of optimal manufacturing strategy methods for AM parts. Build orientation selection is a key aspect of AM build strategy and is a trade-off between build time, surface finish and manufacturing cost. Several researchers have proposed methods to optimise the build orientation of rapid prototyped parts (Kulkarni, Marsan, and Dutta 2000; Byun and Lee 2006; Canellidis, Giannatsis, and Dedoussis 2009). Kulkarni, Marsan, and Dutta (2000) state that build orientation and support structure generation are key tasks to be performed in the model domain of process planning for layered manufacturing of polymer parts. They identify the key build orientation selection parameters as being the area of the part that needs to be supported by support structures and the build time (usually based on the part's height). Hu, Lee, and Hur (2002) present a build orientation determination method for hybrid rapid-prototyping (combined additive and subtractive manufacturing) based on five key factors: tool accessibility for machining features, build time for deposition and machining, number of bridges (machining supports) and number of support structures. The optimal build orientation is selected using a weighted score calculated from these five factors.

Ponche et al. (2014) developed a more extensive DfAM methodology for additive laser manufacturing that comprises three steps: part orientation, functional optimisation and manufacturing path optimisation. In their methodology the part orientation is optimised with the objective of minimising support volume, minimising cost and maximising quality. They propose using topological optimisation to functionally optimise the part and optimise the manufacturing path to (i) minimise the number of path ends, (ii) maximise the curvature radius and (ii) minimise the number of points of discontinuity. Kerbrat, Mognol, and Hascoët (2011) propose a design for manufacture assessment tool combining laser powder additive manufacturing and high speed machining. The manufacturability of the design is assessed using indices for additive and subtractive manufacture based on design parameters such as geometry, dimensions and material information. The approaches presented by Hu, Lee, and Hur (2002)and Kerbrat, Mognol, and Hascoët (2011) have some similarities to design for WAAM due to the combination of additive and subtractive manufacturing.

However, due to the different constraints and abilities of WAAM these methods are not directly applicable to WAAM. The literature review has shown that DfAM is a relatively new but rapidly growing field that is being addressed through two main viewpoints: firstly defining design rules and guidelines for additive manufacturing, and secondly developing design methods to optimise the manufacturing process of AM parts. WAAM does not conform to many of the previously published general principles of DfAM, and therefore needs its own specific design rules and methods. In the following section the Design for WAAM (DfWAAM) capabilities and constraints will be compared and contrasted with those for AM other processes, and an initial a set of design rules for WAAM will be presented.

3. Design for Wire + Arc Additive Manufacture Capabilities and Constraints

3.1. General WAAM Design Guidelines and Capabilities

DfWAAM requires a different design approach to other additive manufacturing processes because, as discussed above WAAM introduces different manufacturing constraints, as well as some unique manufacturing capabilities that are not possible using other AM technologies. Examples of WAAM capabilities include the ability to build overhanging structures without supports and use of coordinate motion to change the build orientation during deposition by mounting the part onto a part-rotator. In Figure 1, three example WAAM parts are presented showing (a) a structural part in which the substrate will form a central web of the part, and (b) a part with overhanging regions that have been built without supports (c) a section cut through a part with an internal passageway.



(a) (b) (c)

Figure 1. Example WAAM Parts Built at Cranfield University, (a) Landing Gear Rib (b) Unsupported Overhanging Regions (c) Part with Internal Passageway

Table 1 provides a comparison between the DfAM guidelines proposed by Gibson, Rosen, and Stucker (2010) and the capabilities of WAAM. Based on the summary in Table 1 it can be seen that the benefits and capabilities of WAAM are somewhat different to other AM technologies. WAAM does not aim to compete in the realm of highly complex structures, but aims to reduce the manufacturing cost and lead time for high value engineered parts. We therefore propose a new set of general design capabilities for WAAM based on minimising cost and environmental impact, hybrid manufacturing opportunities, material properties optimisation, functional and shape optimisation. The WAAM design capabilities are presented in Table 2.

Table 1. Comparison of General DfAM and DfWAAM Guidelines

DfAM Design Guideline (Gibson, Rosen, and Stucker 2010)	**Description (Gibson, Rosen, and Stucker 2010)**	**Application to DfWAAM**
Complex Geometry	"AM enables the use of complex geometry in achieving design goals without incurring time or cost penalties compared with simple geometry"	WAAM is not suitable for the production of parts with complex geometries due to relatively large minimum feature size (typically 2 mm)
Customised Geometry	"AM enables customised geometry and parts by direct production from 3D data"	WAAM enables customised geometry and parts by direct production from 3D data
Integrated Assemblies	"With AM it is often possible to consolidate parts, integrating features into more complex parts and avoiding assembly issues"	With WAAM it is often possible to consolidate parts by integrating features and avoiding assembly issues
AM Unique Capabilities	"AM allows designers to ignore all constraints imposed by conventional manufacturing processes (although AM-specific constraints might be imposed)"	WAAM offers unique capabilities in hybrid manufacturing, functionally graded materials and producing parts with integrated functionality. Conventional machining constraints must be considered if the part is to be post-machined

Table 2. WAAM Design Capabilities

WAAM Design Capabilities	
Minimising Cost, Environmental Impact and Lead Time	WAAM reduces the cost and environmental impact of manufacturing by substantially reducing the amount of waste material during manufacture compared to machining from billets or forgings. WAAM can also reduce manufacturing lead time compared to forging and machining.
Hybrid Manufacturing	WAAM can be integrated with conventional manufacturing processes to open up new design opportunities and further reduce manufacturing cost. By using WAAM to deposit features onto pre-formed parts produced by machining, forging or sheet metal, it is possible to produce hybrid parts with lower cost and manufacturing

	time. The substrate is commonly designed to be incorporated into the final part to minimise the amount of deposition and minimise cost.
Material Properties Optimisation	WAAM parts can be produced using mixed or functionally graded materials to tailor the material properties of the part. This is achieved by using multiple wires of different materials; the chemical composition can be tailored locally by controlling the wire feed speeds.
Functional Optimisation	Parts can be manufactured with internal features and passageways or embedded systems including fibre optics and fluidic tubing to incorporate functional behaviour into the component.
Shape Optimisation	WAAM can produce parts with shape optimised forms, benefitting from the ability to deposit overhanging features without support structures either by using multi-axis deposition or by depositing in positions other than downwards. However, care must be taken to ensure access for post machining if required.

3.2. Design for WAAM Guidelines

An initial set of DfWAAM guidelines has been established based on experimental research by Sequeira Almeida 2012, Kazanas et al. 2012, Wang et al. 2013, Lin 2015 and Williams et al. 2015. The design guidelines are presented in the following sections and are collated into a simple graphical table for easy reference in Appendix A. The table follows the layout used by Adam and Zimmer (2014)

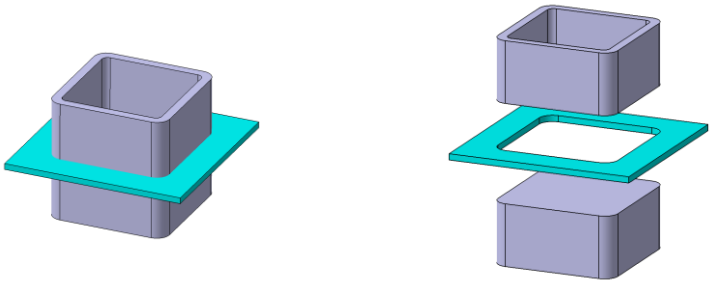
3.2.1. Part Dimensions

Unlike most other AM technologies, WAAM is not constrained by an enclosed working chamber, therefore for materials such as aluminium and steel which do not have stringent requirements for gas shielding the maximum part size is determined by the reach capability of the manipulator. For materials such as titanium which require shielding, a bespoke shielding device has been developed also allowing unlimited build volumes by avoiding the need for the chamber (Ding et al. 2015). Parts have been built successfully up to 6 metres in length in a two robot cell that could produce parts up to 10m in length. The minimum wall thickness for deposition is 2mm, and thinner walls can be achieved by post machining.

3.2.2. Symmetry

Due to the significant heat input in metal AM processes, components can be subject to distortion due to the thermal stresses from heating and cooling (Bralla 1999). The residual stresses are associated with shrinkage during cooling and are largest along the direction of deposition. Parts can be built using a symmetrical deposition strategy where the substrate is positioned at a plane of symmetry on

the part and layers are deposited alternately on each side of the plate by rotating the part between layers. This balances the build-up of the residual stresses avoiding distortion during the manufacturing process (Williams et al. 2015). For parts without a suitable plane of symmetry it may be possible to build two parts "back to back" to achieve a symmetrical build as shown in Figure 2. In this case the parts must be heat treated to relax the residual stress before they are separated.



(a) (b)

Figure 2. Schematic of Back-to-Back Build of WAAM Parts (a) During Build (b) After Separation from Substrate)

3.2.3. Enclosed Features

WAAM parts can have enclosed features such as passageways which cannot be produced using conventional subtractive manufacturing. Enclosed features can be produced by using multi-axis build techniques or carefully designed deposition paths that allow unsupported regions to be deposited without any support structures. High aspect ratio holes can be produced by drilling holes after each deposited layer. Care should be taken when designing parts with enclosed features because they cannot be easily inspected or post machined. Figure 3 shows an example of a part containing a fully enclosed passageway in the final part (Lijuan Sun 2015).

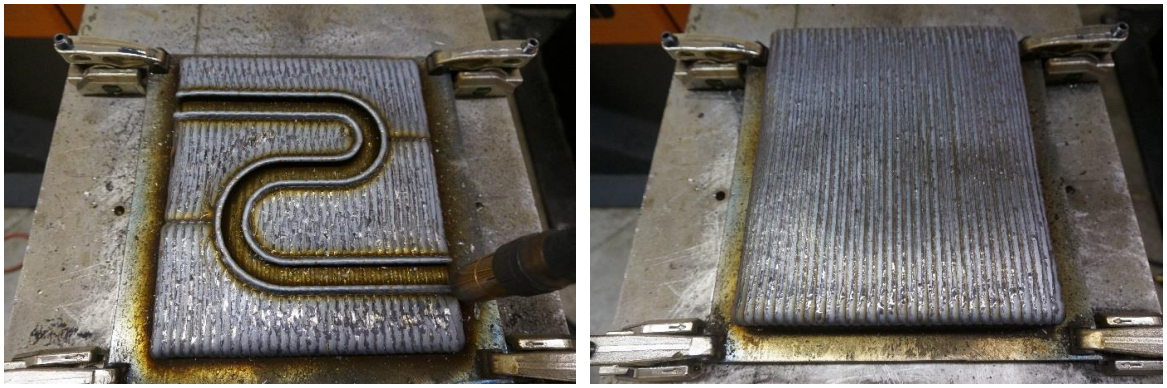


Figure 3. Example WAAM Part with Enclosed Passageway (Lijuan Sun 2015)

3.2.4. Unfinished Faces

For many applications it is not necessary to post-machine some or all of the deposited faces. However, there may be stress raising features on unfinished faces, so care must be taken in stressed and particularly fatigue driven parts. The surface finish can also be improved without post-machining by using techniques such as shot peening or vibratory grinding (Bralla 1999).

3.2.5. Machining Considerations

In common with other near-net shape manufacturing technologies such as casting and forging, many WAAM parts are post-machined after deposition, particularly for precision engineering applications. Where post machining is required, standard design for machining guidelines should be followed and consideration must be given to the work holding during post machining. Suitable location points must be provided on the WAAM part for machining setup (Campbell 2004). If an integrated WAAM deposition and machining system is used to the part may be machined after every layer, or periodically during the manufacturing process. In this case careful consideration must be given to the sequence and accessibility for deposition and machining. A machining allowance must be added to to allow for the material removed by the machining process, this is typically 1mm added to all machined faces (Williams et al. 2015).

3.2.6. Undesirable Features

The WAAM process is not suited to the manufacture of some complex features utilised in other additive manufacturing processes. The production of complex 3D lattices is not desirable for WAAM

and long thin unsupported members may be difficult to deposit and post machine. Hence, topological optimisation should be undertaken with due consideration of the WAAM constraints.

3.2.7. Corners

It is preferable to deposit WAAM parts with internal and external radii at corners to allow for continuous deposition around the corner and avoid introducing stress raising features as shown in Figure 4. WAAM can produce parts with sharp external corners but they are more difficult to manufacture due to additional stop-starts in the deposition process. For parts that will be post-machined, internal corners must be designed with generous radii to allow for the tool radius during post machining as well as to avoid stress concentrations.

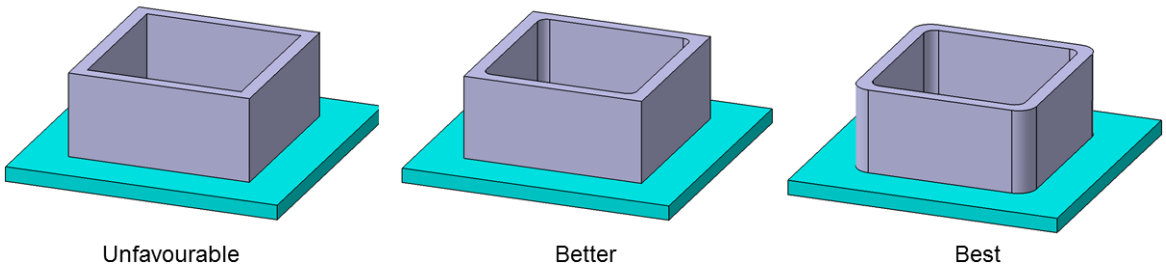


Figure 4. WAAM Design Guidelines for Corner Radii

4. WAAM Build Orientation Selection Methodology

A WAAM build orientation selection methodology has been developed to help designers investigate the best WAAM build strategy for a part. The methodology provides a structured process to identify the best build orientation for based on substrate waste material mass, deposited material mass, number of build operations, build complexity and symmetry.

4.1. Pre-Assessment

The first stage in the design assessment process checks whether the part meets the general manufacturing criteria for WAAM. Four criteria are used to assess a part's suitability for WAAM: part mass, maximum and minimum bounding box dimension and buy-to-fly ratio. The bounding box

is defined as the minimum enclosing cuboid for the part as shown in Figure 5 and provides a rough estimate of the buy-to-fly ratio for the part if machined from a rectangular billet. Note that this approach slightly underestimates the actual buy-to-fly ratio of the part because a machining envelope of 5 – 10 mm around the finished part is usually assumed for machined parts (Allen 2006) in addition to the material required for work holding.

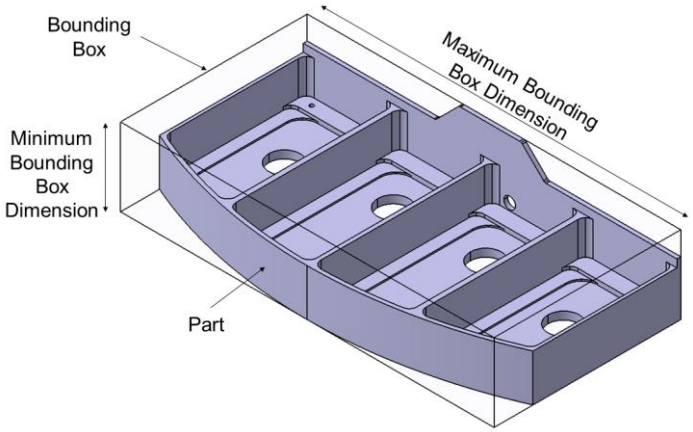


Figure 5. Illustration of Minimum Bounding Box

The initial selection criteria have been developed based on previous WAAM experience and are subject to change as the technology continues to develop and are summarised in Table 3.

Table 3. Initial Assessment Criteria for WAAM Manufacture

Design Criteria	**Preliminary Assessment Criteria**	**Comment**
Minimum part mass	0.5 kg	Parts with a mass of less than 0.5kg are unlikely to be cost effective for WAAM production
Minimum bounding box dimension	20 mm	Parts with one or more bounding box dimension of less than 20mm are unlikely to be cost effective for WAAM production because they could be produced more cost effectively from plate material by machining or other methods
Maximum bounding box dimension	10 m	The maximum part size is limited by the size of the WAAM cell. Currently the largest WAAM cell available is 10m in length
Initial Buy-to-fly estimate	4	Parts with a lower buy-to-fly ratio are likely to be more cost effective to machine from billet. (Martina and Williams 2015) Minimum buy-to-fly ratio is also material dependent

4.2. Build Orientation Selection Process

The first step in the build orientation selection process identifies a wide range of possible build orientations and substrate positions that could be used to build the part. These design alternatives are then compared using a multiple attribute decision matrix and ranked based on the results. The part design should then be reviewed and if necessary adjusted to take best advantage of the selected build option. This structured design process helps the designer to consider manufacturing requirements at the design stage and achieve the best design and manufacturing solution for the part. The process flow for the design methodology is presented in Figure 6.

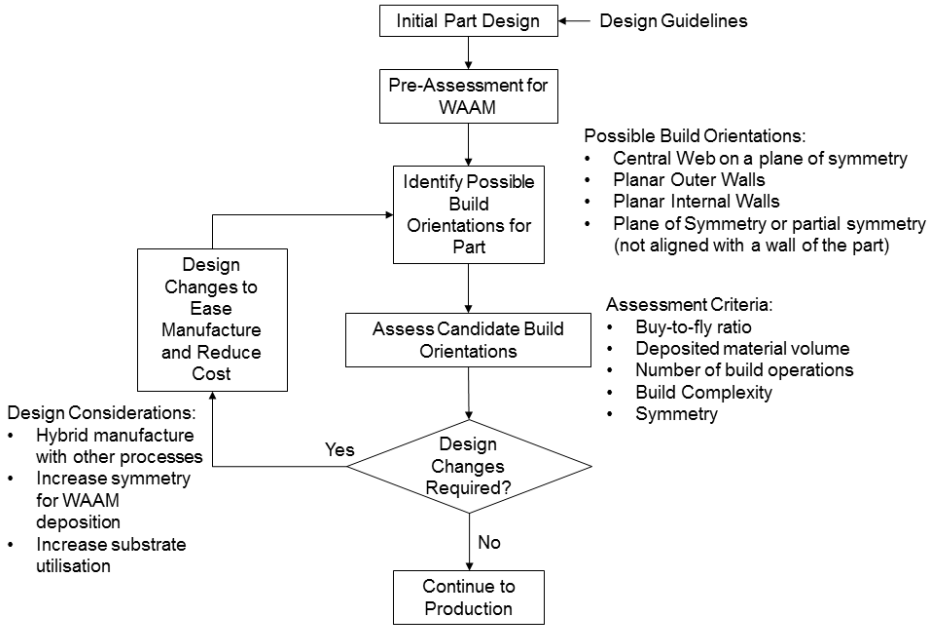
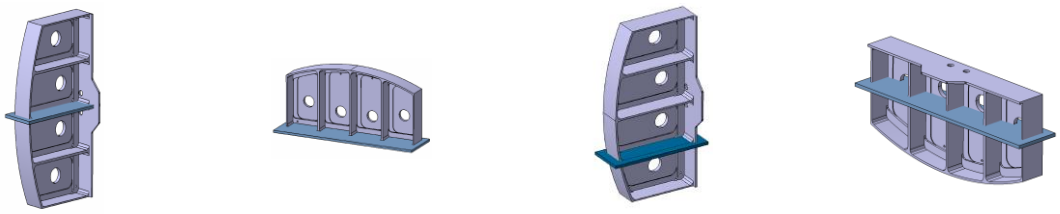


Figure 6. WAAM Build Orientation Assessment Methodology Process Flow

The build orientations and substrate positions are selected using the following guidelines and illustrated in Figure 7:

1. A central web on a part plane of symmetry
2. Planar outer part walls
3. Planar part internal walls
4. Plane of symmetry or partial symmetry (not aligned with a wall of the part)



(a) Central Web on Plane of Symmetry

(b) Planar Outer Wall

(c) Planar Internal Wall

(d) Plane of Symmetry or Partial Symmetry (Not Aligned with a Wall)

Figure 7. Guidelines for Substrate Positions

Each build option is then assessed using a multiple attribute decision matrix with five assessment criteria: substrate waste, deposited material, number of deposition operations, build complexity and symmetry. Each criterion is assessed on a normalised scale between 0 and 1 and in each case the best option is the maximum value of 1. In order to perform the assessment a 3D CAD model of the designed part and substrate is required to calculate the required material masses. The amount of waste material from WAAM deposition is assumed to be small compared to the substrate waste and is therefore not included in the assessment; the additional material required for machining allowance and work holding is also not considered.

The evaluation criteria used in the assessment are defined as follows (the objective is to maximise all criteria when scoring a design):

- **Substrate Waste (C_1)** is the ratio of substrate waste material mass (M_{sf}) to the initial billet mass for the machined part (M_i^M). The complement of the score is used to provide a maximum score for minimum waste material.

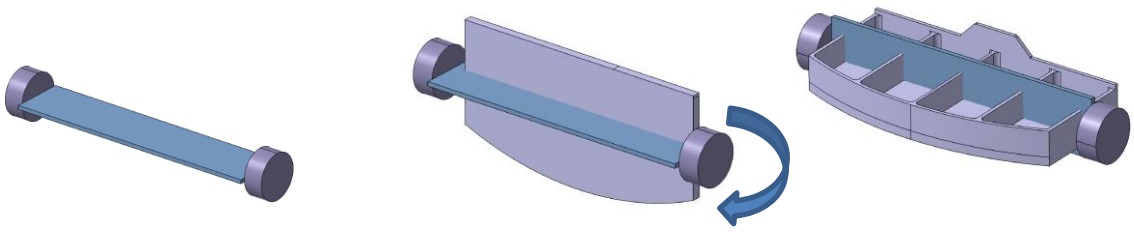
$$C_1 = 1 - \frac{M_{sf}}{M_i^M} \quad (1)$$

- **Deposited Material (C_2)** is the ratio of the deposited material mass (M_i^{AM}) to the final part mass(M_f). The complement of the score is used to provide a maximum score for minimum deposited material.

$$C_2 = 1 - \frac{M_i^{AM}}{M_f} \quad (2)$$

- **Number of Build Operations (C_3)** is the reciprocal of the number of WAAM build operations (N) required to build the part. When assessing the number of build operations it is assumed that the part is mounted on a part-rotator so that the deposition direction can be changed between operations to build features in different orientations as shown in Figure 8. Each change of position is considered to be a build operation. Double sided build operations where the part is rotated between each layer are considered as two build operations.

$$C_3 = \frac{1}{N} \quad (3)$$



(a) (b) (c)

Figure 8. Example Assessment of Number of Build Operations for a Simple Part (a) Substrate Mounted on a Part Rotator (b) First (Double Sided) Build Operation to Build Base of Part (c) Part Rotated before second (Single Sided) Build Operation to Build Side-Walls of Part

- **Build Complexity (C_4)** is a qualitative assessment of the build process complexity scored between 0 and 1. The complexity is assessed based on the number of features in the part, number of intersections, variation in wall thickness and build angle/ curvature. A part with a single constant thickness feature where all walls are built vertically will score 1, whereas a part with many features and intersections, varying wall thickness/ angle will score 0.
- **Symmetry (C_5)** is the ratio of the deposited material mass above the substrate centre-plane (M_+^{AM}) to the deposited material mass below the substrate centre-plane (M_-^{AM}). The absolute value of the ratio is used to avoid negative values.

$$C_5 = 1 - abs(\frac{M_+^{AM}}{M_-^{AM}}) \quad (4)$$

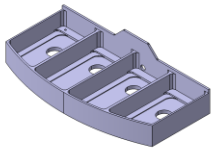
A weighting factor *w* can be applied to each criteria C_i based on the experience of the designer if required. The sum of the five weighting factors must be 100. The score for each build option *j* is calculated as the weighted sum of the five decision criteria. In the case studies presented in this paper all of the criteria are weighted equally.

$$S_j = \sum_1^5 w_i C_i \quad (5)$$

4.2.1. Demonstration of the Build Orientation Selection Process

The build orientation selection process will be explained using a simple part selected from the STEP tools part database (http://www.steptools.com/support/stdev_docs/stpfiles/ap203/Boeing.step). The first step in the process is to assess whether the part meets the criteria for WAAM manufacture. As shown in Table 4, it can be seen that the part meets the initial assessment criteria for WAAM manufacture with a buy-to-fly ratio of 6.6, minimum bounding box dimension of 20mm and weight of 9.6 kg.

Table 4. Simple Stiffened Part Initial Assessment.

Part	**Bounding box mass (kg)**	**Machining Buy-to-fly estimate**	**Bounding Box X (mm)**	**Bounding Box Y (mm)**	**Bounding Box Z (mm)**	**Part Mass (kg)**	**Suitable for WAAM ?**
WAAM Criteria		>4	>20mm	>20mm	>20mm	>0.5kg	
	63.95	6.6	610	305	127	9.64kg	YES

The second step is to define the possible build orientations for the part. Five possible substrate positions have been identified for this part. The substrate has been assumed to be rectangular and to extend by 25mm in all directions from the base of the part, and the substrate is assumed to be 10 mm thick in all cases. The details of the build options and the build orientation assessment results are shown in Tables 5 and 6

Table 5. Simple Stiffened Part Build Option Details

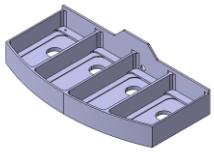
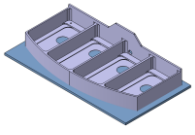
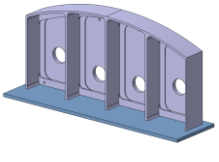
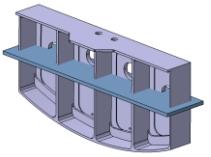
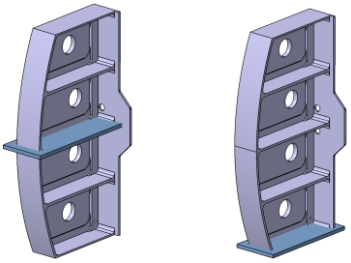
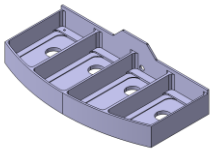
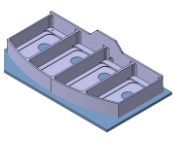
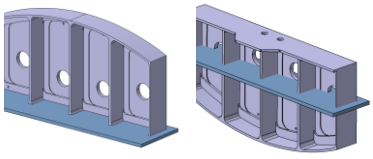
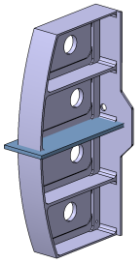
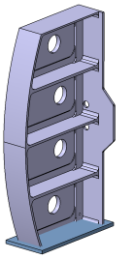
	Build Option 1	Build Option 2	Build Option 3	Build Option 4	Build Option 5
					
Buy to Fly WAAM	1.2	1.2	1.2	1.1	1.1
Substrate Mass (kg)	6.3	3.2	2.5	1.2	1.0
Deposited Material Mass (kg)	5.2	8.5	9.4	9.2	9.3
Waste Material from Substrate (kg)	1.9	2.0	2.2	1.0	0.7
Number of Build Operations	1	2	2	2	2
No. of Double Sided Build Operations	0	0	1	1	0
Total Build Operations	1	2	3	3	2
Mass Above Substrate (kg)	9.6	9.6	4.4	4.8	9.6
Mass Below Substrate (kg)	0.0	0.0	5.4	4.8	0.0

Table 6. Stiffened Part Multiple Attribute Decision Matrix

		Build Option 1		Build Option 2		Build Option 3		Build Option 4		Build Option 5	
											
Criteria	**Weighting (%)**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**
Substrate Waste	20	0.97	19.42	0.97	19.38	0.96	19.30	0.98	19.69	0.99	19.79
Deposited Material Factor	20	0.5	9.3	0.1	2.5	0.0	0.5	0.0	1.0	0.0	0.7

Number of Build Operations	20	1.0	20.0	0.5	10.0	0.3	6.7	0.3	6.7	0.5	10.0
Build Complexity	20	0.8	16.0	0.5	10.0	0.2	4.0	0.2	4.0	0.5	10.0
Symmetry	20	0.0	0.0	0.0	0.0	0.9	17.8	1.0	20.0	0.0	0.0
Total	100		65		42		48		51		40

The results identify Build Option 1 with a score of 65 as the best option for this part. Build Option 1 allows for simple, one sided deposition with low deposited material mass and effective utilisation of the substrate in the final part. Build Option 4 achieves the second highest score of 51 with a symmetrical double-sided build and relatively simple build strategy, but requiring more build operations. Option 3 achieves the third highest score with partially symmetric deposition and a relatively simple build strategy.

The methodology provides a structured approach to selecting the WAAM build orientation. It can be seen that the process ensures that the designer considers the build strategy for the part at the design stage before the design is finalised. It is recommended that the part design is reviewed after the build option has been selected to consider possible design changes that can maximise the benefits of WAAM.

The methodology has been tested on two structural aerospace components and the results are presented in Section 5. Redesign opportunities have been considered for the second case study and compared to the original design.

5. Case Studies

Two case studies are presented in this section to test the build orientation selection process. The case studies were selected as being representative of the type of aerospace components that could benefit from WAAM production. The first case study (the wing rib) includes only the build orientation

selection process, whereas the second case study (the flap track) considers design changes that could further reduce the cost of WAAM.

5.1. Wing Rib Component

The first case study is an aluminium light wing rib (John 2013) shown in Figure 9. The part is 1.4 m long, with a mass of 2.9 kg and a buy-to-fly ratio of 26.4 for the machined part. The first step in the process is to assess whether the wing rib meets the initial criteria for WAAM, and the results show that the part meets the general requirement with suitable dimensions and a high buy-to-fly ratio for the machined part (Table 7).

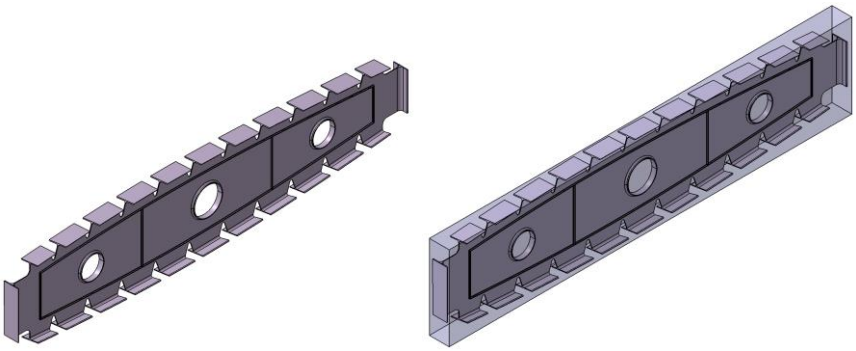
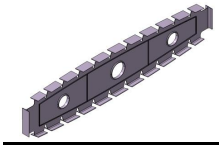


Figure 9. Rib Component and Minimum Bounding Box

Table 7. Rib Component Initial assessment

Part	Bounding box mass (kg)	Machining Buy-to-fly estimate	Bounding Box X (mm)	Bounding Box Y (mm)	Bounding Box Z (mm)	Part Mass (kg)	Suitable for WAAM?
WAAM Criteria		>4	>20mm	>20mm	>20mm	>0.5kg	
	76.6	26.4	1401	69	292	2.9kg	YES

The second step is to identify possible build orientations for the part. Four substrate positions have been identified for this part, three on planes of symmetry and one aligned with a planar end face. The build orientations are then assessed against the five assessment criteria and the results are shown in Tables 8 and 9. The substrate is assumed to be rectangular and extend by 25mm in all directions from the base of the part, and the substrate is assumed to be 10 mm thick in all cases.

Table 8. Rib Component Build Orientation Options

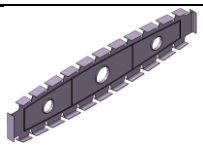
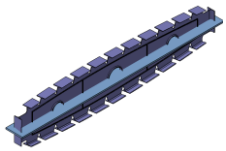
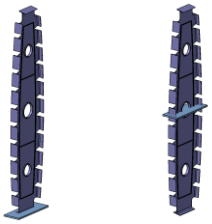
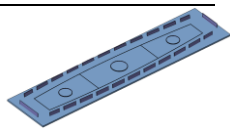
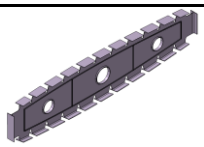
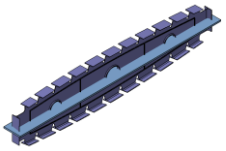
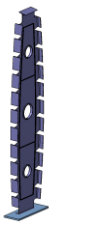
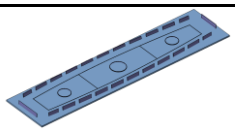
	Build Option 1	Build Option 2	Build Option 3	Build Option 4
				
Buy to Fly Ratio WAAM	2.6	1.3	1.4	4.8
Substrate Mass (kg)	4.7	1.1	1.1	13.0
Deposited Material (kg)	2.8	2.8	2.9	0.8
Waste Material from Substrate (kg)	4.6	1.0	1.1	10.9
Number of Build Operations	2	2	2	1
No. of Double Sided Operations	2	1	2	1
Total Build operations	4	3	4	2
Mass above Substrate (kg)	1.4	2.9	1.4	1.4
Mass below Substrate (kg)	1.5	0.0	1.5	1.5

Table 9 Rib component Multiple Attribute Decision Matrix

		Build Option 1		Build Option 2		Build Option 3		Build Option 4	
									
Criteria	**Weighting (%)**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**
Substrate Waste	20	0.94	18.80	0.99	19.74	0.99	19.73	0.86	17.16
Deposited Material	20	0.0	0.6	0.0	0.6	0.0	0.1	0.7	14.8
Number of Build Operations	20	0.3	5.0	0.3	6.7	0.3	5.0	0.5	10.0
Build Complexity	20	0.2	4.0	0.2	4.0	0.2	4.0	0.8	16.0
Symmetry	20	1.0	19.5	0.0	0.0	1.0	19.5	1.0	19.7
Total	100		48		31		48		78

Based on the above assessment Build Option 4 is the preferred candidate with the highest score of 78. This build option allows for straightforward symmetrical deposition with the lowest mass of deposited material, but has the highest substrate waste material. By contrast Build Options 1 – 3 all have a much higher mass of deposited material and require more build operations. Build Options 1 and 3 are preferable to Option 2 due to their symmetrical build. The total mass of raw material for each build option is shown in Figure 10. It can be seen that Build Option 4 gives a waste material saving of 63 kg per rib, whereas Build Option 3 gives a greater saving of 73 kg per rib. However, Option 3 requires a much higher mass of WAAM deposition and due to the high machining rate of Aluminium it is likely to be more cost effective to manufacture Build Option 4 using WAAM.

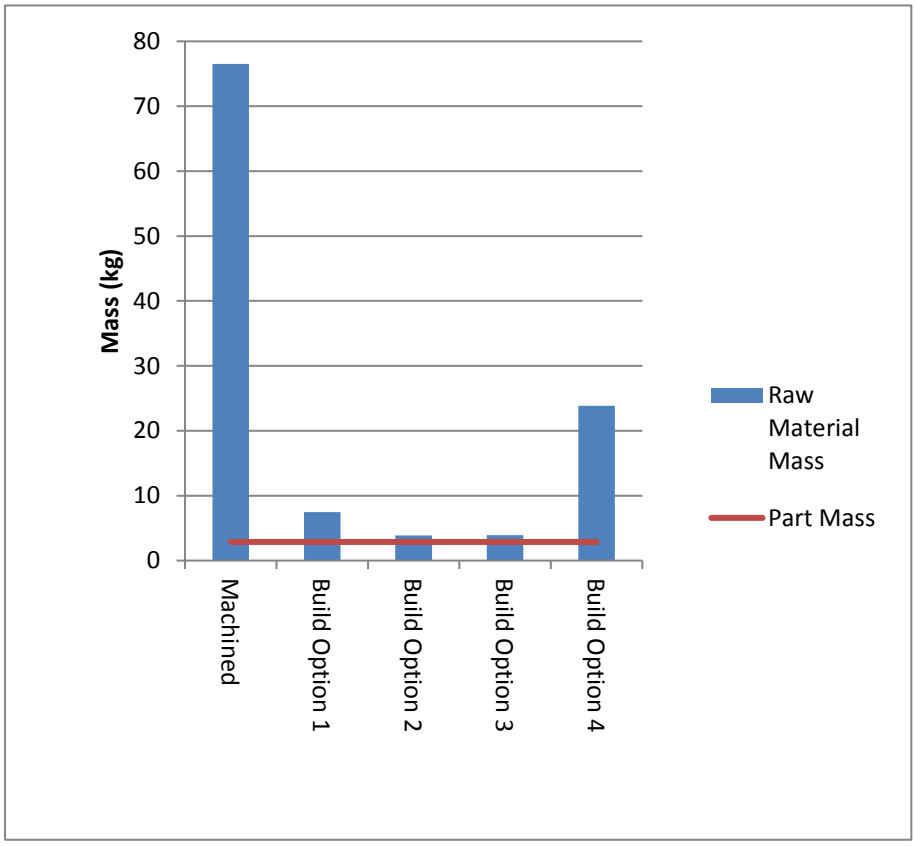


Figure 10 Rib Comparison of Raw Material Mass for Machining and WAAM Build Options

5.2. Flap Track Component

The second case study part is a flap track component which is to be produced in Ti-6Al-4V by machining from billet (Osa-Uwagboe 2010). The part is 1.2 m long with a mass of 16.2 kg and has a buy-to-fly ratio for the machined part of 5.1. A picture of the component is shown in Figure 11.

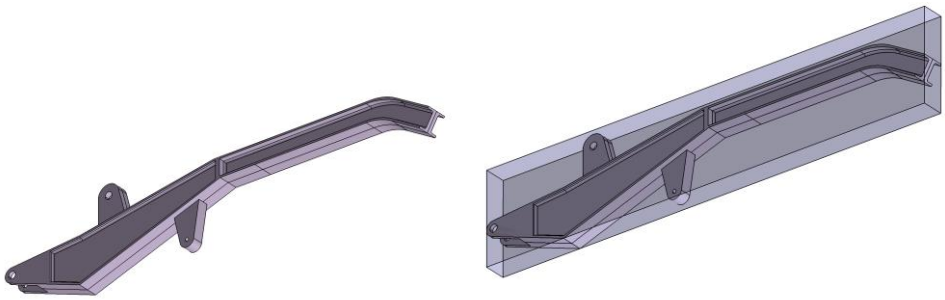
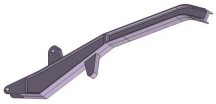


Figure 11. Flap Track Component and bounding box

The flap track component meets the initial selection criteria for WAAM production as shown by the results in Table 10. The buy-to-fly ratio is moderate at 5.1, but due to the high material cost of titanium there is still an opportunity to save manufacturing cost using WAAM.

Table 10. Flap Track Initial Assessment

Part	**Bounding box mass (kg)**	**Machining Buy-to-fly estimate**	**Bounding Box X (mm)**	**Bounding Box Y (mm)**	**Bounding Box Z (mm)**	**Part Mass (kg)**	**Suitable for WAAM?**
WAAM Criteria		>4	>20mm	>20mm	>20mm	>0.5kg	
	81.8 kg	5.05	1236	60	247	16.2kg	Yes

Five substrate positions are been considered for the flap track at planes of symmetry and planar faces on the part. The build orientations are then assessed against the five assessment criteria: substrate buy-to-fly, deposited material factor, deposition complexity, number of deposition operations and symmetry. The substrate is assumed to be rectangular and extend by 50 mm in all directions from the base of the part at its intersection with the substrate; and the substrate is assumed to be 10 mm thick in all cases. The results of the evaluation are shown in Table 11 and 12.

Table 11. Flap Track Build Strategies

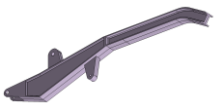
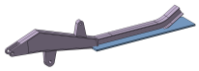
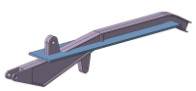
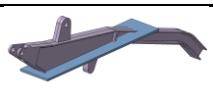
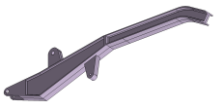
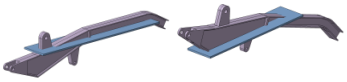
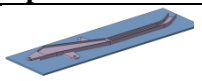
	Build Option 1	Build Option 2	Build Option 3	Build Option 4	Build Option 5
					
Buy to Fly Ratio WAAM	1.2	1.3	1.2	2.0	1.1
Substrate Mass (kg)	5.0	6.5	5.0	20.7	1.1
Deposited Material Mass (kg)	15.1	14.7	15.0	11.8	16.0
Waste Material from Substrate (kg)	4.0	5.0	3.8	16.4	1.0
Number of Build Operations	5	3	4	2	4
No. of Double Sided Operations	1	1	1	1	2
Total Build Operations	6	4	5	3	6
Mass Above Substrate (kg)	15.9	4.1	11.2	8.1	11.9
Mass Below Substrate (kg)	0.1	9.4	5.0	8.1	4.3

Table 12. Flap Track Multiple Attribute Decision Matrix

		Build Option 1		Build Option 2		Build Option 3		Build Option 4		Build Option 5	
											
Criteria	**Weight (%)**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**
Substrate Waste	20	1.0	19.0	0.9	18.8	1.0	19.1	0.8	16.0	1.0	19.8
Deposited Material	20	0.1	1.4	0.1	1.9	0.1	1.5	0.3	5.4	0.0	0.2

Number of Build Operations	20	0.2	3.3	0.3	5.0	0.2	4.0	0.3	6.7	0.2	3.3
Build Complexity	20	0.5	10.0	0.7	14.0	0.7	14.0	0.9	18.0	0.5	10.0
Symmetry	20	0.0	0.5	0.7	13.4	0.6	12.4	1.0	20.0	0.5	10.6
Total	100		34		53		51		66		44

Based on the assessment, Build Option 4 has the best score of 66 due to the symmetrical build with low deposited material mass and low build complexity. However, this option also has the highest substrate waste material mass. Build Option 2 is the second best option with good substrate utilisation and moderate deposition symmetry. For series production, the buy-to-fly ratio of Build Option 4 could be improved by nesting several parts on to the substrate plate, but the waste material is still relatively high, and Build Option 2 could be used as a good starting point for a lower waste design. This opportunity may not be obvious from initial inspection of the part, but is highlighted by the assessment method. The comparison of total raw material usage for each build option is shown in Figure 12. Once again it can be seen that while the best option does not have the lowest material utilisation it still saves 49 kg of titanium material waste per component compared to machining from billet. Build Option 3 can save a further 12 kg per component.

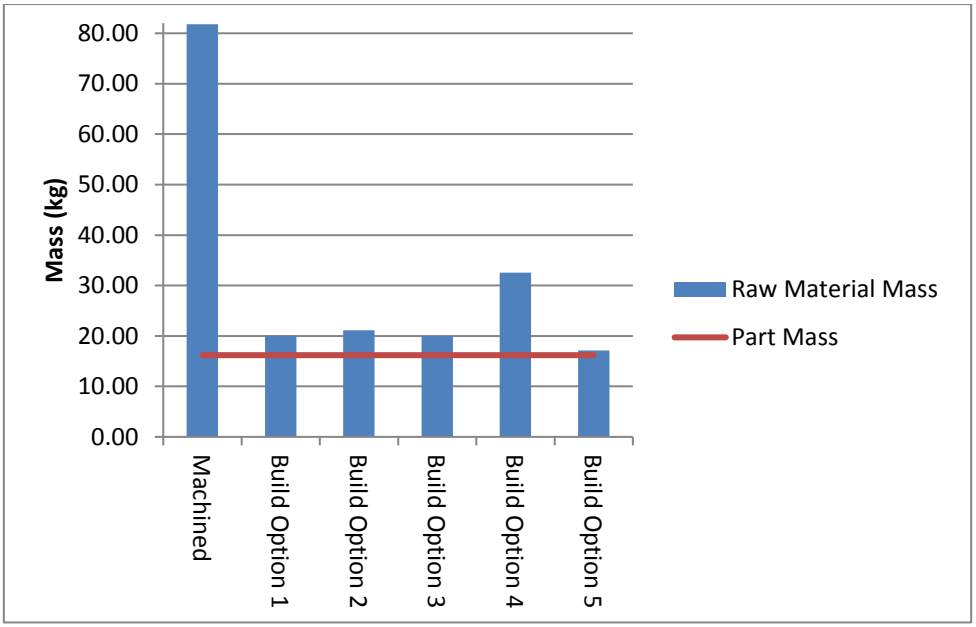
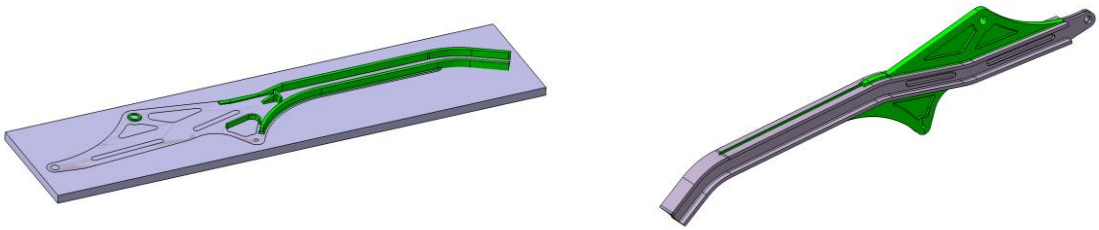


Figure 12. Flap Track Comparison of Raw Material Mass for Machining and WAAM Build Options

A design study was performed to investigate whether the flap track could be redesigned to allow for more efficient WAAM production and reduced part mass. The design study proposed redesigning the flap track using a hybrid manufacture strategy to maximise the use of the substrate in the part and reduce the volume of deposited material, the redesigned parts are shown in Figure 13. The first redesign (Figure 13 (a)) is composed of a thicker substrate plate with the track flanges built up using simple two sided WAAM deposition (shown in green). The substrate waste material assessment has been performed assuming that 12 parts would be nested together onto a substrate plate measuring 2.6 x 1.3 x .022 m. The DfWAAM design guidelines presented in appendix A were used during the redesign process, and the new design has a symmetrical build and generous internal and external fillets on all corners. Unfinished faces are not considered due to the fatigue requirements for this part. The second redesign option (Figure 13 (b)) uses a formed extrusion as the base part with WAAM deposition to produce the attachment features. This approach greatly reduces the amount of waste material but increases the cost and lead time for manufacturing by introducing an additional manufacturing process. The DfWAAM design guidelines presented in appendix A were used during the redesign, and the new design uses of hybrid manufacture. It is not possible to achieve a

symmetrical build for this design, but the stiff I-section extrusion should minimise the risk of distortion after deposition. A static finite element analysis was performed for both designs to ensure that they met the structural requirements of the original design.



(a) (b)

Figure 13. Alternative Design Solutions for Flap Track (a) WAAM Deposition on Thick Plate (b) WAAM Deposition on Formed Extrusion (WAAM Deposition Shown in Green)

The two alternative designs have been compared with the best two build options for the original design and the results are shown in Tables 13 and 14. It can be seen from the results that the second design option based achieves the highest score with very little waste material from the extrusion and very simple WAAM deposition. The thick plate also scores highly, but the waste material from the substrate is high, even with several parts nested close together on the substrate.

Table 13. Redesigned Flap Track Build Strategies

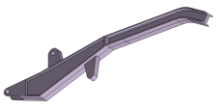
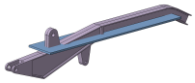
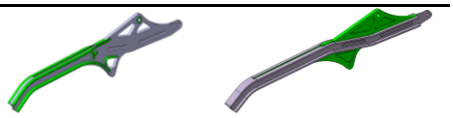
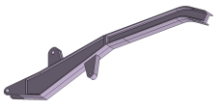
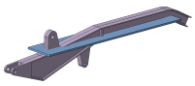
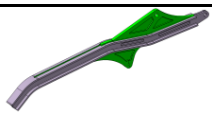
	Build Option 2	Build Option 4	Redesign 1: Thick Plate	Redesign 1: Extrusion
				
Part Mass	16.2	16.2	11.6	11.2
Buy to Fly Ratio WAAM	1.3	2.0	2.5	1.3
Substrate Mass (kg)	6.5	20.7	26.6	10.4
Deposited Material Mass (kg)	14.7	11.8	2.1	3.8
Waste material from substrate (kg)	5.0	16.4	17.0	0.7
Number of Build Operations	3	2	1	2
No. of Double Sided Operations	1	1	1	0
Total Build Operations	4	3	2	2
Mass Above Substrate (kg)	4.1	8.1	1.0	2.5
Mass Below Substrate (kg)	9.4	8.1	1.0	1.3

Table 14. Redesigned Flap Track Multiple Attribute Decision Matrix

		Build Option 2		Build Option 4		Redesign 1: Thick Plate		Redesign 2: Extrusion	
									
Criteria	Weight (%)	Score	Weighted Score	Score	Weighted Score			Score	Weighted Score
Substrate Waste	20.0	0.9	18.8	0.8	16.0	0.8	15.8	1.0	19.8
Deposited Material	20.0	0.1	1.9	0.3	5.4	0.9	17.4	0.8	15.3
Number of Build Operations	20.0	0.3	5.0	0.3	6.7	0.5	10.0	0.5	10.0

Build Complexity	20.0	0.7	14.0	0.9	18.0	1.0	20.0	0.9	18.0
Symmetry	20.0	0.7	13.4	1.0	20.0	1.0	20.0	0.9	18.6
Total	100		53		66		83		82

Based on the results in Table 14 it can be seen that the redesigned parts achieve the highest scores of 83 and 82. Redesign 2, based on an extrusion has minimum waste material and simple deposition whereas Redesign 1, has higher waste material, but a very simple manufacturing process. One limitation of the build assessment method is that the higher cost and lead time of the additional manufacturing process for the bent extrusion are not considered.

6. Summary and Conclusions

This paper has presented an initial investigation into designing for WAAM. The literature review identified that most existing Design for Additive Manufacture methods are developed for powder bed additive manufacturing processes and cannot be applied to WAAM, due to the very different manufacturing constraints and opportunities of these technologies. An initial set of design guidelines for WAAM have been developed based on experimental work undertaken at Cranfield University that can be used to help designers to take into account the capabilities and constraints of WAAM.

The paper also provides a build orientation assessment method for WAAM production that can help designers to consider a wide range of WAAM manufacturing strategies for a part and then tailor the design where possible for WAAM manufacture. This structured approach ensures that the design is adapted to WAAM production from an early in the design process. The assessment criteria for WAAM are defined as substrate waste, deposited material mass, number of build operations, build complexity and symmetry. These are different criteria to those used in other AM build orientation assessments, for example the method developed by Ponche et al. (2014) which minimises support volume, minimises cost and maximises quality.

The use of a multiple attribute decision matrix provides a quantitative method to compare different build options. This approach helps the designer to consider a wide range of options to minimise the volume of waste material and manufacturing complexity, however engineering judgement is still required in order to ensure a practical solution. The method has been tested on two engineering case studies and the results reviewed by WAAM manufacturing experts at Cranfield University. The methodology has been shown to select appropriate build strategies for WAAM parts and helps the designer to consider potential design changes that could prove the manufacturability of WAAM parts.

One potential weakness of the multiple attribute decision matrix methodology is that poor performance in one criterion can be compensated by good performance in another, meaning that the best ranked solution could have a poor score in one attribute.

Future work will include testing the methodology on a wider range of industrial parts and assessing its suitability to assist non-specialist designer engineers when designing for this new manufacturing process.

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References

Adam, Guido A O, and Detmar Zimmer. 2014. “Design for Additive Manufacturing-Element Transitions and Aggregated Structures.” *CIRP Journal of Manufacturing Science and Technology* 7 (1). CIRP: 20–28. doi:10.1016/j.cirpj.2013.10.001.

Allen, J. 2006. “An Investigation into the Comparative Costs of Additive Manufacturing vs. Machine from Solid for Aero Engine Parts.” In *“Cost Effective Manufacturing via Net-Shape*

Processing", Proc. Meet. RTO-MP-AVT-139,. Neuilly-sur-Seine: NATO.

Atzeni, Eleonora, and Alessandro Salmi. 2012. "Economics of Additive Manufacturing for End-Usable Metal Parts." *The International Journal of Advanced Manufacturing Technology* 62 (9–12). Springer-Verlag: 1147–55. doi:10.1007/s00170-011-3878-1.

Beeley, Peter R. 2001. *Foundry Technology*. Butterworth Heinemann.

Boothroyd, G. (Geoffrey), Peter. Dewhurst, and W. A. (Winston Anthony) Knight. 2011. *Product Design for Manufacture and Assembly*. CRC Press.

Bralla, James G. 1999. *Design for Manufacturability Handbook*. McGraw-Hill.

Byun, Hong S., and Kwan H. Lee. 2006. "Determination of Optimal Build Direction in Rapid Prototyping with Variable Slicing." *The International Journal of Advanced Manufacturing Technology* 28 (3–4). Springer-Verlag: 307–13. doi:10.1007/s00170-004-2355-5.

Campbell, John. 2004. *Castings Practice : The 10 Rules of Castings*. Elsevier/Butterworth-Heinemann.

Canellidis, V., J. Giannatsis, and V. Dedoussis. 2009. "Genetic-Algorithm-Based Multi-Objective Optimization of the Build Orientation in Stereolithography." *The International Journal of Advanced Manufacturing Technology* 45 (7–8). Springer-Verlag: 714–30. doi:10.1007/s00170-009-2006-y.

Clegg, A. J. (Allen J.). 1991. *Precision Casting Processes*. Pergamon Press.

Ding, J., P. Colegrove, F. Martina, S. Williams, R. Wiktorowicz, and M.R. Palt. 2015. "Development of a Laminar Flow Local Shielding Device for Wire+arc Additive Manufacture." *Journal of Materials Processing Technology* 226: 99–105. doi:10.1016/j.jmatprotec.2015.07.005.

Gibson, I., D. W. Rosen, and B. Stucker. 2010. *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing*. *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing*. doi:10.1007/978-1-4419-1120-9.

Hague, R, S Mansour, and N Saleh. 2004. “Material and Design Considerations for Rapid Manufacturing.” *International Journal of Production Research* 42 (22): 4691–4708.

Herrmann, Jeffrey W., Joyce S. Cooper, Satyandra K. Gupta, Caroline C. Hayes, Kosuke Ishii, David Kazmer, Peter A. Sandborn, and William H. Wood. 2004. “New Directions in Design for Manufacturing.” In *2004 ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference*.

Hu, Zhu, Kunwoo Lee, and Junghoon Hur. 2002. “Determination of Optimal Build Orientation for Hybrid Rapid-Prototyping.” *Journal of Materials Processing Technology* 130–131: 378–83. doi:10.1016/S0924-0136(02)00727-6.

John, Michael. 2013. “Inner Wing (Metallic) Design for SL-12 Reusable Orbiter.” Cranfield University.

Kalpakjian, Serope, and Steven R. Schmid. 2008. *Manufacturing Processes for Engineering Materials*. Pearson Education.

Kazanas, P., P. Deherkar, P. Almeida, H. Lockett, and S. Williams. 2012. “Fabrication of Geometrical Features Using Wire and Arc Additive Manufacture.” *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*. doi:10.1177/0954405412437126.

Kerbrat, Olivier, Pascal Mognol, and Jean Yves Hascoët. 2011. “A New DFM Approach to Combine Machining and Additive Manufacturing.” *Computers in Industry* 62 (7): 684–92. doi:10.1016/j.compind.2011.04.003.

Kranz, J., D. Herzog, and C. Emmelmann. 2015. “Design Guidelines for Laser Additive Manufacturing of Lightweight Structures in TiAl6V4.” *Journal of Laser Applications* 27 (S1). Laser Institute of America: S14001. doi:10.2351/1.4885235.

Kulkarni, Prashant, Anne Marsan, and Debasish Dutta. 2000. “A Review of Process Planning

Techniques in Layered Manufacturing." *Rapid Prototyping Journal* 6 (1): 18–35. doi:10.1108/13552540010309859.

Laverne, Floriane, Frédéric Segonds, Nabil Anwer, and Marc Le Coq. 2015. "Assembly Based Methods to Support Product Innovation in Design for Additive Manufacturing: An Exploratory Case Study." *Journal of Mechanical Design* 137 (12): 121701. doi:10.1115/1.4031589.

Lijuan Sun. 2015. "Manufacturing Internal Features in Metallic Structures Using WAAM Process." Cranfield University.

Lin, Nan. 2015. "Design for Wire and Arc Additive Manufacturing: Development of Design Guidelines and an Automation Design Tool." Cranfield University.

Martina, Filomeno, and Stewart Williams. 2015. "Wire+arc Additive Manufacturing vs. Traditional Machining from Solid: A Cost Comparison."

Mehnen, J., J. Ding, H. Lockett, and P. Kazanas. 2011. "Design Forwire and Arc Additive Layermanufacture." In *Global Product Development - Proceedings of the 20th CIRP Design Conference*. doi:10.1007/978-3-642-15973-2-73.

Mehnen, Jörn, Jialuo Ding, Helen Lockett, and Panos Kazanas. 2014. "Design Study for Wire and Arc Additive Manufacture." *International Journal of Product Development*. doi:10.1504/IJPD.2014.060028.

Osa-Uwagboe, N. 2010. "A-9 Dragon Fly Medium Range Airliner Metallic Flap Design." Cranfield University.

Ponche, Remi, Olivier Kerbrat, Pascal Mognol, and Jean Yves Hascoet. 2014. "A Novel Methodology of Design for Additive Manufacturing Applied to Additive Laser Manufacturing Process." *Robotics and Computer-Integrated Manufacturing* 30 (4). Elsevier: 389–98. doi:10.1016/j.rcim.2013.12.001.

Rosen, David W. 2014. "Research Supporting Principles for Design for Additive Manufacturing."

Virtual and Physical Prototyping 9 (4): 225–32. doi:10.1080/17452759.2014.951530.

Sequeira Almeida, P. M. 2012. “Process Control and Development in Wire and Arc Additive Manufacturing.” Cranfield University.

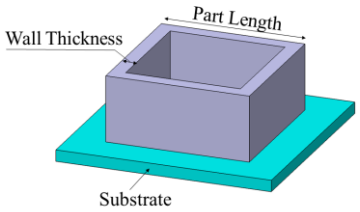
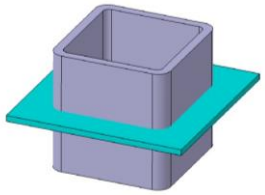
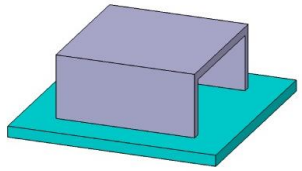
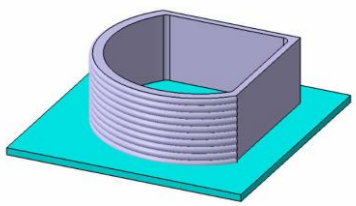
Thompson, Mary Kathryn, Giovanni Moroni, Tom Vaneker, Georges Fadel, R. Ian Campbell, Ian Gibson, Alain Bernard, et al. 2016. “Design for Additive Manufacturing: Trends, Opportunities, Considerations, and Constraints.” *CIRP Annals - Manufacturing Technology* 65 (2): 737–60. doi:10.1016/j.cirp.2016.05.004.

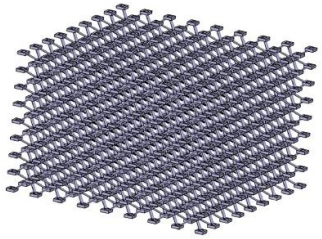
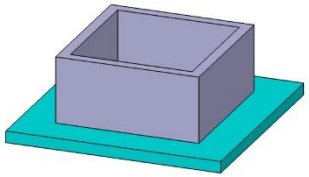
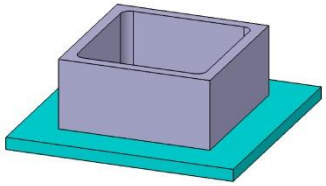
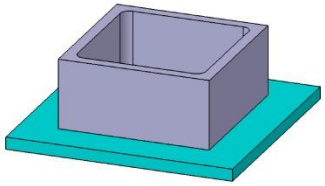
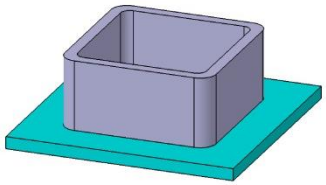
Wang, Fude, Stewart Williams, Paul Colegrove, and Alphons A. Antonysamy. 2013. “Microstructure and Mechanical Properties of Wire and Arc Additive Manufactured Ti-6Al-4V.” *Metallurgical and Materials Transactions A* 44 (2). Springer US: 968–77. doi:10.1007/s11661-012-1444-6.

Williams, S W, Filomeno Martina, A C Addison, J Ding, G Pardal, and P Colegrove. 2015. “Wire + Arc Additive Manufacturing.” *Materials Science and Technology* 836 (March): 1743284715Y.000. doi:10.1179/1743284715Y.0000000073.

Zhang, Jun, and Frank Liou. 2013. “Multi-Axis Planinng of a Hybrid Material Deposition and Removal Combined Process.” *Journal of Machinery Manufacturing and Automation* 2 (3). World Academic Publishing: 46–57.

Appendix A. DfWAAM Guidelines

Wire + Arc Additive Manufacture – Design Guidelines					
Feature				**Example**	**Description**
Manufacturing Process – Wire and Arc Additive Manufacture	**General geometry/ part form**	**General part size**	**Part dimensions**		There is no theoretical limit on maximum part length and wall thickness for WAAM manufacture. The minimum practical part length is typically 50mm, and the minimum deposited wall thickness is 2mm. Thinner walls can be achieved by post-machining and are limited only by the machining capabilities.
			Symmetry		Parts should be designed where possible so that the part can be built symmetrically on both sides of the substrate in order to avoid buckling distortion and for ease of tooling. Alternatively parts may designed to allow them to be built back-to-back on the same substrate to achieve a symmetrical build and then separated after deposition
			Enclosed		Enclosed features can be produced using WAAM but may be difficult to inspect or post-machine
			Unfinished		Further cost savings can be achieved by leaving faces unfinished in unstressed regions. Care must be taken not to introduce stress concentrations on unfinished faces. Fatigue and damage tolerance should also be considered.

Manufacturing Process – Wire and Arc Additive Manufacture	**General geometry/ part form**	**Part**	**Machining**	• Ensure that all design features can be accessed for post machining • Avoid very thin walls that may distort during manufacture • Avoid high aspect ratio features and undercuts • Apply fillet radii on all internal corners (Bralla, 1998)	For parts that must be post-machined standard design for machining guidelines should be followed WAAM parts. Alternatively, using an integrated system, parts may be machined in-process after each layer is deposited. Consider whether some faces can be left unfinished to further save cost. The manufacturing process should be carefully planned to achieve the ease of tooling and work holding during machining.
			Undesirable Features		**Complex 3D Lattice Structures** are not appropriate for WAAM deposition and are costly/ inaccessible for post- machining. Avoid these design features for WAAM. **Unsupported thin members** may be difficult to deposit and costly to machine.
		Wall	**Internal corners**	**Unfavourable**  **Better** 	Internal corners should be designed with a generous radius to allow for post machining and avoid stress raisers.
			External corners	**Unfavourable**  **Best** 	External corners are recommended be designed with a generous radius where possible for ease of manufacture. This will reduce the number of stop/ starts during deposition and reduces material waste. Parts with sharp external corners can be produced but are more difficult to manufacture due to residual stresses in the corners.

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Design for wire + arc additive manufacture: design rules and build orientation selection

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