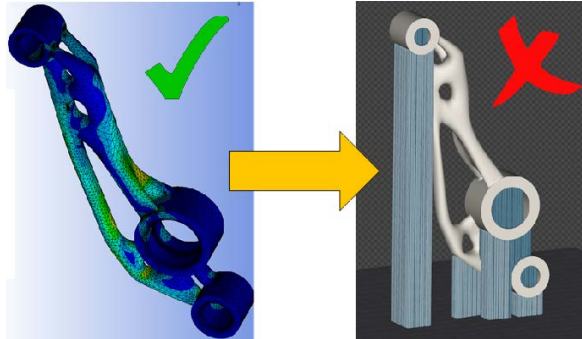


# Design for metal AM - a beginner's guide

Additive manufacturing (AM) gives us tremendous freedom to create components with free-form and intricate features, direct from CAD and without the need for expensive tooling. These complex designs would be impractical, if not impossible, to produce conventionally. Additive components are often lighter, more efficient and better adapted to their application.

This flexibility does not, however, give us total freedom to design any shape that we can think of. At least, not if we want to manufacture it at a sensible cost.

Like any manufacturing process, AM technologies have their capabilities and their limitations. For instance, laser powder-bed fusion parts that are designed with overhanging features – i.e. where we are building on top of un-fused powder – may require sacrificial supports to enable them to build successfully. These supports increase build time, consume extra materials and require additional post-processing for their removal.



Functionally optimised parts that have not been designed for AM may require a lot of supports, making them inefficient to manufacture.

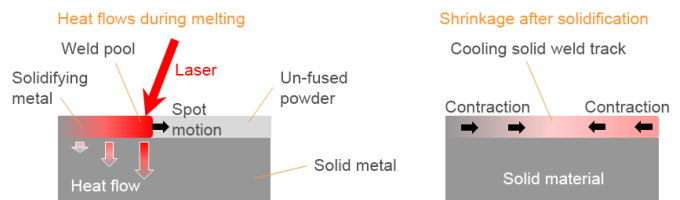
Design for AM (DfAM) is, therefore, critical if we are to produce parts that combine exceptional performance with practical, cost-effective additive manufacture. The intimate relationship between functional optimisation and design for process in the article [Is topological optimisation really optimal?](#)

This article considers the key factors that drive the success rate and productivity of AM builds, and explains some of the critical guidelines that designers should follow to create efficient production components.

## Factor #1 - residual stress

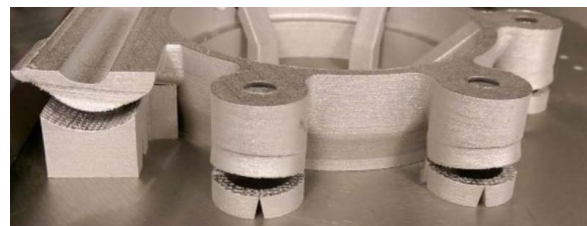
Residual stress is a natural result of the rapid heating and cooling that is inherent to the laser powder bed fusion process. Each new layer is created by moving the focused laser across the bed, melting the top layer of powder and fusing it to the layer below. Heat flows from the hot weld pool down into the solid metal below, and so the molten metal cools and solidifies. This all happens very rapidly; in a matter of micro-seconds.

As a new layer of metal solidifies and cools on top of the layer below, it contracts. The new metal is constrained by the solid structure below and so its contraction sets up shear forces between the layers.



Laser melting of a new weld track on top of a solid substrate (left). As the laser moves along the scan vector, it melts the powder, which then cools mostly through conduction of heat into the solid metal below. Once it solidifies, the cooling metal contracts (right), setting up shear forces between it and the layer below.

Residual stress can be destructive. As we add layers on top of one another, the stresses build up and can result in distortion of the part, leading it to curl up at the edges and pull away from its supports:



In more extreme cases, the stress may exceed the strength of the part, leading catastrophic cracking of the component, or distortion of the build plate:



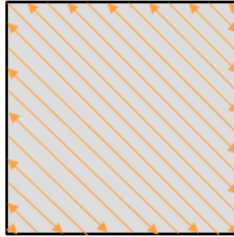
These effects are most pronounced in parts with large cross-sections, as these tend to have longer weld tracks and there is more distance over which the shear forces can act.

### Minimising residual stress

One way to tackle this is by varying our scanning strategy, choosing a method that is best suited to the part geometry. When we are filling in the centre of our part, an activity known as 'hatching', we typically move the laser back and forth. The pattern that we choose affects the length of the scan vectors and hence the level of stress that we are likely to build up in the component. Strategies with shorter scan vectors will generate less residual stress:

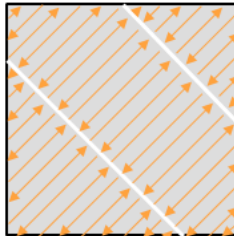
#### Meander Hatching Pattern

- 67° rotation after each layer
- Higher build rate
- Increases the residual stresses
- Suitable for small and thin features



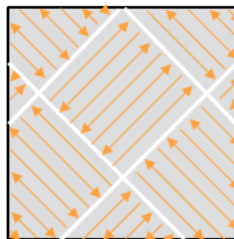
#### Stripe Hatching Pattern

- Homogenous distribution of residual stresses
- Suitable for large parts
- Higher build rate than Chessboard



#### Chessboard Hatching Pattern

- Each layer divided to 5 by 5 mm islands
- 67° rotation of whole pattern and each island after each layer
- Homogenous distribution of residual stresses
- Suitable for large parts



*Images above - scanning strategies and their suitability for different part types. The two most common strategies are 'meander' for thin walled parts (also known as rastering), and 'stripes' for parts with thicker sections. 'Chessboard' or 'island' strategies can also be effective. Stripe and chessboard scanning keeps the lengths of individual scan lines shorter, reducing the build-up of residual stress.*

We can also rotate the orientation of our scan vectors from one layer to the next so that stresses are not all aligned in the same plane. A rotation of 67 degrees is typically used between each layer to ensure that it is many layers before the scanning direction is exactly repeated.

Heating of the build plate is another technique used to reduce residual stresses, whilst post-process heat treatments can also relieve the stresses that have built up.

### Residual stress design tips

Design out residual stresses where possible:

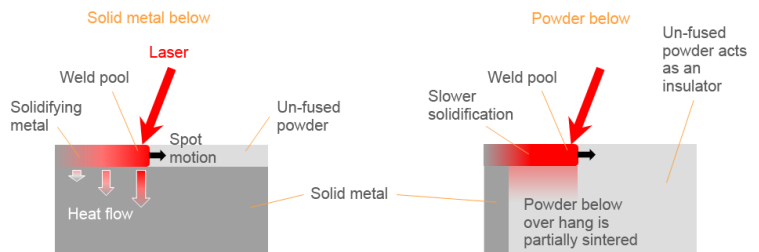
- Avoid **large areas of uninterrupted melt**
- Be careful about **changes in cross-sections**
- **Hybrid builds** incorporate thicker base-plate into an AM part
- Use **thicker build plates** where stress is likely to be high
- Select an **appropriate scan strategy**

### Factor #2 - orientation

With any additive layer process, the build direction is always defined as being in the Z axis - i.e. vertically from the build plate. Note that the build orientation is not always the general use orientation. It should be chosen to produce the most stable build with minimal or no support material.

### Overhangs and the melting process

In powder-bed processes, where shapes are built up layer by layer, the way these layers relate to each other is important. As each layer is melted, it relies on the layer below to provide both physical support and a path to conduct away heat.



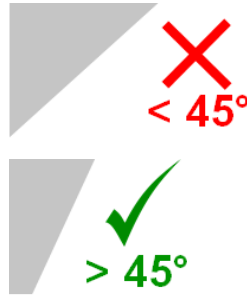
*Melting above solid metal enables rapid cooling (left). Where melting occurs in an overhanging region above un-fused powder, then cooling takes much longer and unwanted additional material may become attached to the bottom surface of the component.*

When the laser is melting powder in an area where the layer below is solid metal, then heat flows from the weld pool down into the structure below, partially re-melting it and creating a strong weld. The weld pool will also solidify quickly once the laser source is removed as the heat is conducted away effectively.

Where component features overhang those below, then at least part of the zone below the weld pool will consist of un-melted powder. This powder is far less thermally conductive than solid metal, and so heat from the melt pool is retained for longer, resulting in more sintering of surrounding powder. The result can be additional material attached to the bottom surface of the overhanging region, meaning that overhangs can exhibit both misshapen surfaces and a rough finish.

### Orientation options

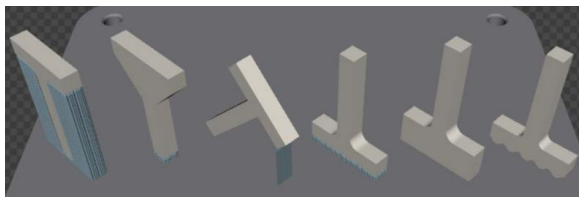
Generally speaking, overhangs of less than 45 degrees to the build plate require support.



Overhanging surfaces are known as down-skins. They will generally exhibit rougher surface finish than vertical walls and upward facing surfaces. This effect is driven by the partial sintering of powder below the overhang, resulting from the slower cooling of the weld pool.

Parts can often be built in multiple orientations. Our choice of orientation should ideally self-support so that we minimise build costs and post-processing.

## “Consideration of the build orientation at the design stage is one of the fundamental principles of DfAM”



*A component can often be built in many orientations, the choice of which has a major impact on the amount of wasted support material and post-processing that will be required.*

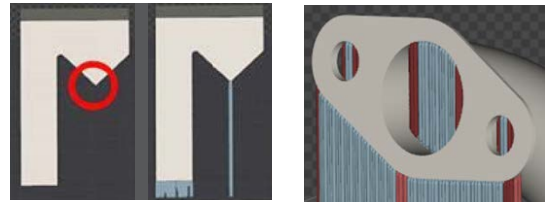
From the left:

- Large overhangs requiring extensive support material (shown in blue)
- Modified design with additional tapered material to reduce supports, increasing the part mass and possibly requiring post-process machining / wire erosion
- Angled at 45 degrees - mostly self-supporting except for one local minimum (see below for more details). Down-skins and up-skins will exhibit different surface roughness
- Inverted with short supports under the bottom face - shorter build time, but post-process finishing of the supported face will be needed
- Solid attachment to the bed with a stock allowance for EDM removal - residual stress could be a concern here
- A similar approach, but with smaller attachment regions to reduce stress build-up - this is likely to be the most efficient design from a manufacturing standpoint
- A final alternative (not shown) is to lay the part flat on the plate. This reduces the build height, but also limits the number of parts that can be nested on the build plate, and will be prone to greater residual stress.

It is a good idea to evaluate a range of build orientations using build preparation software early in the component design process to establish which is most promising. Once this decision has been reached, detail design can proceed on this basis.

### Local minima

Local minima are any areas of the part that are not connected to the layer below. These require support to anchor them during the build. If we start building without a support structure below, then the first built layer is likely to be displaced by the wiper as it doses the next layer, leading to a failed build.

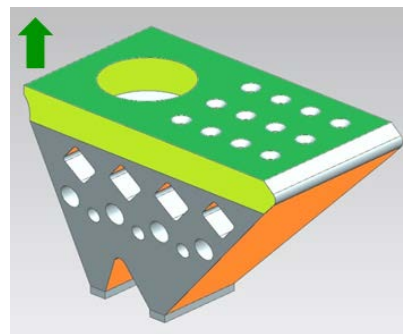


Local minima can be obvious such as the example shown above. They can also appear at the top of lateral and angled holes where they intersect the edge of the part (shown above).

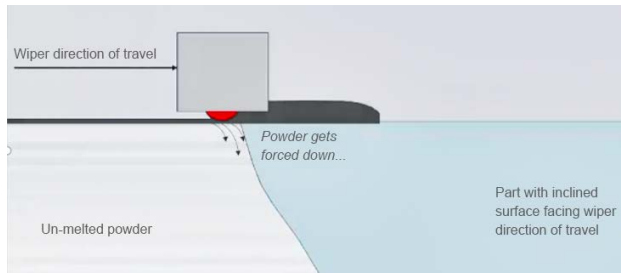
Our goal should be to design out local minima where possible to minimise supports.

### Orientation of features

As we have already discussed, down-skins tend to have inferior surface finish. If we want to produce detail features with the best accuracy, then it is best to orientate these on the top surface of the part, also known as the up-skin. Detail features that are inset into down-skins are likely to suffer from a loss of definition.



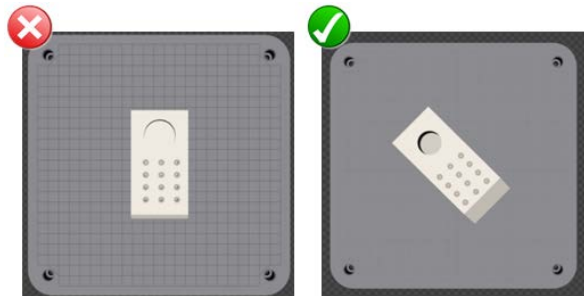
Another consideration is the orientation of the component relative to the dosing wiper. As a new layer of powder is applied and the wiper pushes it across the bed, the powder is progressively squeezed under the wiper to create the new densely-packed layer. This creates a pressure wave in the powder bed as the material is pressed down. This can interact with component surfaces that are inclined towards the wiper, forcing powder down and pushing the front edge of the component upwards. This can cause the part to catch on the wiper, which may lead to a failed build. Note that a flexible wiper reduces this effect.



Interaction between the dosing wiper and the inclined edge of a component.

Supports and inclined edges should therefore be orientated away from the wiper direction where possible. By rotating the part, the pressure wave now strikes the part at an oblique angle, reducing the likelihood of distortion.

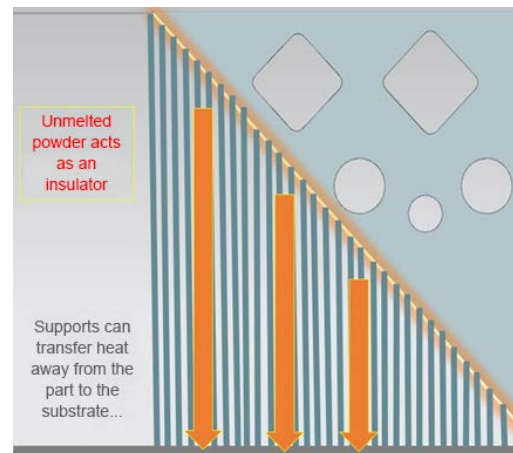
If the rotary alignment cannot be changed, or if the part is rotationally symmetric, then supports may be needed, possibly followed by post-process machining of the affected face.



### Orientation design tips

- Build orientation of a part **designed** for AM should be **obvious**
- Designers should aim to create **self-supporting** designs
- **Build success** is the primary consideration
- **Residual stress** and **surface finish** are also key factors affected by orientation
- Orientation affects **build time and costs**
- **Complex geometries may not be easy to orientate** - there is often a trade-off between surface quality, details, build time/cost and support structures
- Designers must assess competing factors to define orientation

### Factor #3 - supports



As we have already discussed, it is bad engineering practice to rely on supports to overcome an orientation issue. Whilst we may be able to tolerate the extra build time and post-processing if we are making a prototype, such waste is unacceptable for production AM parts. Excessive reliance on supports is an indicator of a 'marginal' part geometry, with potential manufacturing yield implications.

#### Support purposes

Whilst we should minimise supports by design, it may not always be possible to eliminate them altogether. Supports have three main functions:

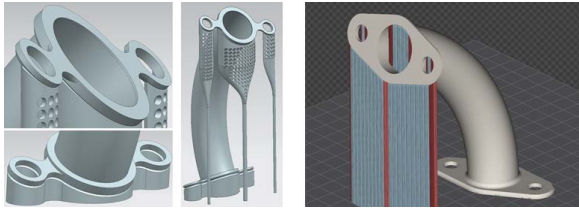
**Isolated material** – supports are used to 'anchor' material that is not connected to previous layers (i.e. the overhang is less than 45° with respect to the build plate, or the feature is a local minimum). Integrating support structures into the component design is preferred.

**Residual stress** – we should design to mitigate residual stress in the build, avoiding sharp edges and large areas of material built directly onto the build plate. Where this cannot be achieved, then supports may be applied to oppose stresses in the part to stop material peeling off the build plate. This is not recommended for production builds.

**Heat sink** – un-melted powder is an insulator. Supports transfer some heat away from down-skin areas to avoid burning, over-melt, distortion and discoloration, especially on down-skins that face the wiper direction. Minimise these effects by rotating the part relative to the wiper.

#### Primary and secondary supports

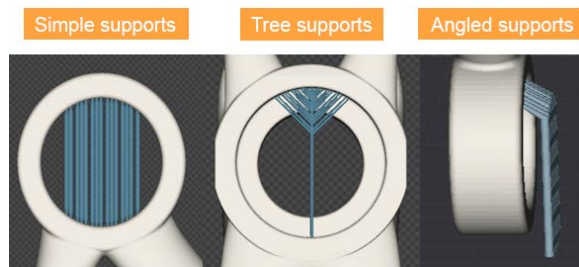
Primary supports are those that are developed in the CAD environment along with the component and designed as sacrificial structures that will be removed once the build is finished. Secondary supports are those that are generated in build preparation software.



Primary supports, developed in CAD (left) and secondary supports, developed in build preparation software (right).

Solid primary supports give us greater control. They can be imported into the build preparation software (as STLs) or designed with the main body of the part. They can be derived parametrically with full revision control. Finite element stress analysis can also be performed. Plus, we can design and simulate primary supports that conduct away heat in a controlled manner.

Secondary supports created within the build preparation software can also be managed via parameters, but lack traceability and repeatability. They may need to be recreated if the part design is changed.



Types of secondary support, generated in build preparation software. Supports should be selected to minimise build time and post-processing costs.

Hybrid support design takes advantage of both CAD design and the build preparation software to achieve an optimal solution.

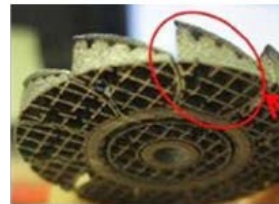
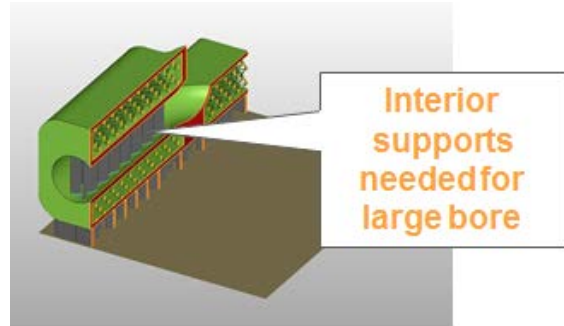
**Fillets and chamfers**

Whilst a horizontal overhang of 0.3 – 1 mm can self-support, this is not recommended. Meanwhile, overhangs of more than 1 mm will definitely need re-design or support. Fillets and chamfers can be added to components to eliminate overhangs (shown right).



**Support removal challenges**

Supports inside holes and tubes can be difficult to remove and may require subsequent machining. Similarly, supports that are too small can cause difficulties. If the part geometry is weaker than the support, there is a high risk of part damage during post-processing.



Part is too small and fragile to clamp whilst removing the support material

Supports can be difficult to remove without damaging the part.

**Example of orientation to minimise supports**

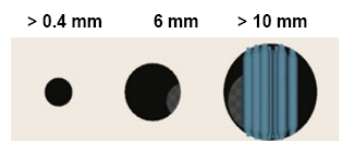
**✓** Vertical orientation builds directly onto the build plate with additional machining stock. Hole more likely to be circular. Minimum supports and high success rate.

**!** Angled orientation can reduce volume of supports needed and avoids trapped material. May produce an elliptical hole.

**✗** Horizontal orientation takes up more space and requires the most supports. Supports inside the hole will be difficult to remove. Hole likely to be non-circular.

**Horizontal details - support or re-design**

Lateral holes that emerge on the side faces of parts may also require supports. The minimum size of hole that it is sensible to build on most laser powder-bed machines is 0.4 mm.

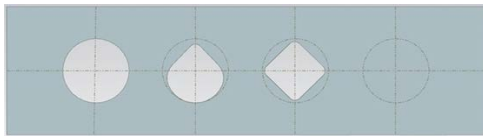


Distortion in a large lateral hole

Holes and tubes larger than 10 mm in diameter will require supports in their centre and should be considered for re-design. Holes between these sizes may be produced without supports but are likely to suffer from some distortion on their down-skin surfaces due to slow cooling of the weld pool above the overhang.

Since horizontal holes are unlikely to be perfectly round, it often makes sense to change their shape so that they are self-supporting. In some cases, a teardrop or diamond shape may be acceptable for the finished feature. Both profiles can be used for fluid channels and offer similar hydraulic performance, although a diamond shape provides significantly better resistance to pressure stress.

In other cases, where a precision, round hole is essential, then post-process machining will be needed. Diamonds provide a symmetrical pilot hole for milling and are better than teardrops in this respect. In many cases, filling in the hole and machining it from solid can make the most sense.



Options for lateral holes: build to size and accept some distortion, produce self-supporting teardrop or diamond shapes with some stock allowance for machining, or machine the feature from solid.

### Supports design tips

- **Remodel holes over 10 mm** to self-supporting diamond shape
- Use chamfer radius to **avoid tall supports**
- **Remove areas overhanging less than 45°** to build plate
- Rotate downskins **away from wiper direction**
- **Machine small features** after build
- **Build directly to build plate** with additional machining stock
- Remove areas **horizontal downskin**

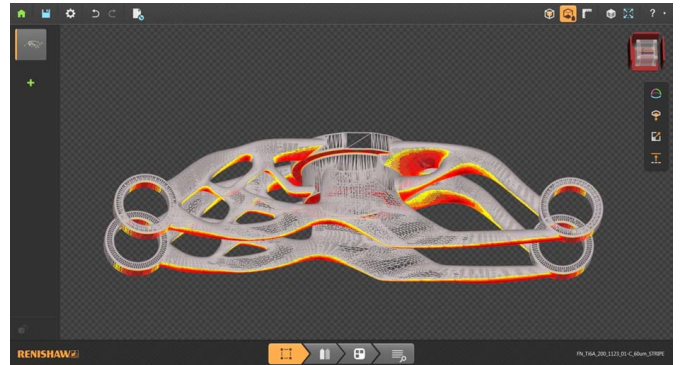
### Factor #4 - optimisation

Topological optimisation and generative design are increasingly being used to design efficient parts. Lattices can also bring weight-saving benefits. AM's capability to produce complex shapes makes it the ideal way to realise such designs.

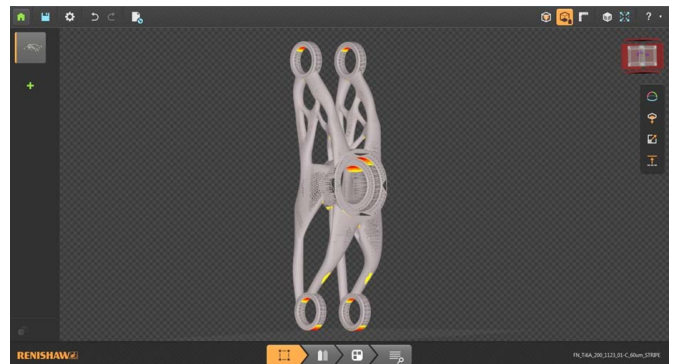


The main aim of these optimisation techniques is to retain structural strength and rigidity whilst removing unnecessary material. Often the optimised parts take on a more complex, organic appearance. It is important to note that a functionally optimised part may not be well suited to AM – especially in terms of build orientation.

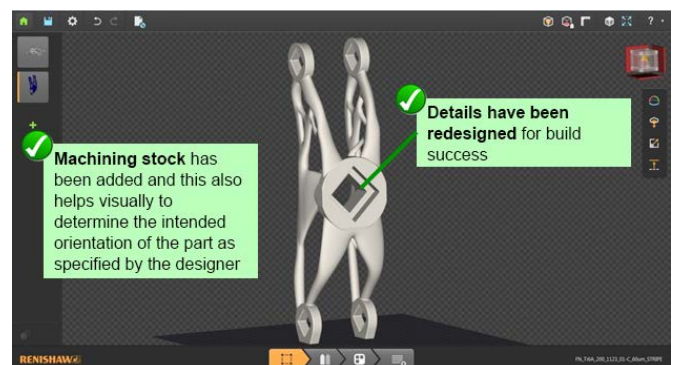
For instance, it is obvious that building this part in the horizontal orientation would result in a lot of supports being required in the overhanging regions highlighted in red.



Re-orientating the part vertically leads to fewer areas that need support. Details, such as the circular holes, will require support or re-design. Care also needs to be taken in the angles of the optimised struts and the fillet radii where they meet.



Re-evaluation of the part at the design stage has taken into account the build orientation so that it is clear that there is only one orientation for this part. Details such as lateral holes are now re-designed for subsequent machining:



### Optimisation design tips

- Apply minimum wall thickness guidelines
- Identify critical surfaces for machining
- Consider support positioning and removal or re-design to remove the need for supports
- Design for an orientation and modify details accordingly
- Establish if required surface finish can be achieved

Designers may need to combine various techniques – topological optimisation, hollow parts, lattices (where applicable) – to achieve an efficient design. Orientation should be the key driver after fit, form and function.

### Summary

AM offers great design freedom to produce efficient, high-performance parts. But accommodating AM process characteristics is essential to building production parts with minimum cost and waste.

Integrating DfAM thinking into the design process maximises build success and improves AM process economics. By necessity, designers are going to have to be smarter and more knowledgeable about the additive manufacturing process in use if they are to be competitive.

### About the author

**Marc Saunders, Director of AM Applications**

Marc Saunders has over 25 years' experience in high tech manufacturing. In previous positions at Renishaw, he played a key role in developing the company award-winning RAMTIC automated machining platform, and has also delivered turnkey metrology solutions to customers in the aerospace sector.

Marc manages Renishaw's global network of Additive Manufacturing Solutions Centres, enabling customers who are considering deploying AM as a production process to gain hands-on experience with the technology before committing to a new facility.

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