THE DEVELOPMENT OFA DESIGN CYCLE OF ADDITIVE MANUFACTURED PRISMATIC AND BIOMIMETIC AEROSPACE COMPONENTS

N. Britz[1*] & J.L. Serfontein[2]

[1] Department of Mechanical Engineering, North-West University Potchefstroom, Aerosud Aviation, Research and Development, South Africa, n.britz@aerosud.co.za

[2] Aerosud Aviation, Research and Development, South Africa jp.serfontein@aerosud.co.za

ABSTRACT

The hypothesis of the study is the design cycle process for prismatic and biomimetic aircraft components that will be manufactured, mainly focusing on Additive Manufacturing (AM). This design cycle will also be used for additional methods of manufacturing and not only limited to AM. Many factors have to be taken into account during the process; thus, the design cycle will be split into various phases. Each phase will be investigated individually, as well as the design cycle as a whole. This is done to ensure that the component complies with the OEM requirements and is fully optimised for the desired outcome.

[1] The author is enrolled for an M Eng. (Mechanical) degree in the Department of Mechanical Engineering, North West University
[2] The author is enrolled for a M Eng. (Industrial) degree in the Department of Industrial Engineering, University of Stellenbosch

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1. INTRODUCTION:

1.1 Background

The popularity of topology optimisation methods in structural design has increased in recent years, since the rapid development of Additive Manufacturing (AM) technology [1]. AM is making it possible to manufacture more biomimetic shapes generated by the topology optimisation process, as opposed to a prismatic perspective where specific parameters are required for Traditional Manufacturing (TM) techniques. Biomimetic refers to organic or natural shapes that occur in nature similar to bone or trees, the load path generated when topology optimisation is applied mimics the behaviour of the natural shapes. Prismatic shapes are also generated using topology optimisation, but it is necessary to set specific parameters, for example, the draw direction and symmetry planes.

Topology optimisation is rapidly developing and with the maturation of topology theory[1]. With the increased number of tools, it has become an active method in the design of components. Surface porosity, checkboard design, mesh dependency, radii, holes and chamber minimums, and other design and manufacturing aspects must be considered when a component is conceptualised. If not taken into consideration, it will lead to non-manufacturable topology that cannot be accepted in the traditional manufacturing processes, for example, machining [1]. The possibility to solve problems has imporved as AM has fewer limitations than traditional manufacturing methods. However, although AM significantly opens up the design freedom , it is not entirely a free-form manufacturing technique[2]. For example, to be able to evacuate the unmelted powder, enclosed voids in structures should be avoided in powder-based processes such as selective laser melting (SLM).

A significant factor of the design cycle includes the manufacturability of the component. Important factors that affect the manufacturing qualities of additive manufactured components are building accuracy, interlayer mechanical properties and surface finish. Support structures must be taken to into account because it has added advantages, for example, its keeps AM components from collapsing if the overhang angle becomes too high, it will also dissipate heat into the build platform to avoid local distortion of the component. Component cost and surface finish quality is compromised by manufacturing supports. Correct design and post-processing can reduce the effects of these issues[3]. Many factors and parameters still need to be considered when optimising a component even if it is manufactured using AM.

Although optimisation and manufacturability validation have significant roles in the design cycle process, there are many other contributing factors in developing aircraft components.

1.2 Problem statement and methodology

The purpose of the study is to investigate each of the proposed phases in the pursuit of developing a comprehensive design cycle process. In Figure 1 the proposed phases for the additve manufacturing design cycle for aerosspace components are:

- Computer-Aided Design (CAD)
- Optimisation
- Internal Features and Surfacing
- Manufacturability
- Qualification and Certification

The primary objective of the design cycle is to design a component that meets airworthiness requirements and customer specifications.

The design cycle is an iterative process; thus, the component may not conform to all the requirements in the first iteration. Each phase of the design cycle will be investigated individually. At the end of the study, a process manual of the design cycle will be created. The process manual will give design rules and methodology that will standardise AM design for aircraft components. the quilification part of the study is still underway and will be added to future publications.

Figure 1: The design cycle for additive manufactured aerospace components

1.3 Computer aided design (CAD)

The primary use for Computer-Aided Design (CAD) in this design cycle is to conceptualise components and to designate the design space for the topology optimisation process. The design space is the area in which the topology optimisation is carried out.[4] In Figure 2, the design space is shown in blue and the fixed space as green.

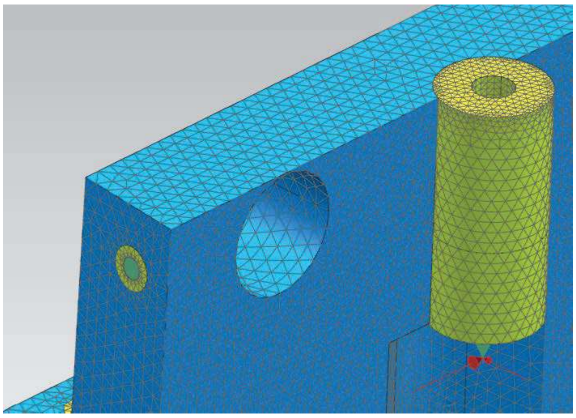

Figure 2: Design space

The CAD phase will be used in conjunction with several of the phases to perform changes to the geometry. In conceptualising components, it is key to generate the initial shape for the application, which entails defining interface planes and points. This will ensure that the maximum design space is used in the operation or working space of the component. In some cases, the topology optimisation software requires certain file types, which are exported from CAD. It is not necessary to export the data when using one platform. A platform refers to a software package that has more than one function. For example, Finite Element Method (FEM) with the capability to do topology optimisation and Finite Element Analysis (FEA). Any CAD software can be utilised for the exportation of the following file formats:

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- STEP
- IGES
- STL

In addition, existing components will be optimised requiring the geometry to be re-evaluated. This refers to removing features, such as fillets and chamfers, and consolidating components if possible. This process is defined as volumetric re-evaluation of the component in preparation for FEA.

1.4 Optimisation

1.4.1 Topology optimisation

Topology optimisation is one of the structural optimisation methods[4]. The distribution of the material is optimised based on a set of loading and boundary conditions while adhering to the structural requirements of the component. Topology optimisation techniques are conducted using a combination of engineering knowledge, CAD and FEA concepts, while taking the manufacturing technique into consideration. The volumetrically re-evaluated data will then be used in the FEA software to calculate the stress and displacement throughout the component. The primary objective in topology optimisation investigations is the removal of material not subjected to load, however, structural integrity must be maintained

Since Bendsoe and Kikuchi's study[5] has triggered renewed interest in topology optimisation, the popularity of using the methods in the design phase has increased rapidly. Topology optimisation has rapidly developed with an increase in the number of tools, and the evolution of the theory, it has become a notable addition to design methodology[1]. With reference to section 1.1, specifically prismatic and biomimetic structures, it is pertinent to note the limitations and requirements of the component for optimisation. This will determine the manufacturing constraints, design objectives and design constraints.

1.4.2 Prismatic structure

Prismatic refers to a parametric shape, geometrical features that are defined by parameters, and the manufacturing process. As mentioned in section 1.1, many stumbling blocks are caused by topology optimisation for TM methods. Complex geometries created are either manufactured at uneconomical rates or not manufacturable using TM. According to Chen et al. to conceptualise components that conform to the TM, efforts have been made to integrate manufacturing constraints into the optimisation process[6]. The following factors based on several studies are denoted as the main aspects that must be taken into consideration for effective outputs to be achieved from a topology optimisation process:

1. Minimum feature size and geometric symmetry as manufacturing constraints:

   Topology optimisation is a concept design method; thus, it is essential to keep in mind that there are limitations in the manufacturing process. Zuo et al. state that minimal hole size for machining tools are generally not taken into consideration in the topology optimisation process, but minimal hole size is seen as a characteristic that affects casting and the symmetry property of the function of a component [1]. The minimum feature size should thus be taken into consideration as a manufacturing constraint during the topology optimisation process to avoid non-manufacturable geometry. With the latest software, manufacturing constraints are now a general part of setting up the optimisation.

2. Cost of manufacturing in the optimisation process:

   According to Chang et al. in the automotive and aerospace industries, engineers are challenged to create and design parts that take certain load cases that are strong enough to sustain substantial impact. The geometry of said load-bearing components are usually complicated due to efficiency requirements, efficiency referring mainly to strength and weight. These requirements usually come at a high price because the more complex a component, the more time it takes to manufacture, and this increases the cost of the component[7].

1.4.3 Biomimetic structure

Since the development of the additive manufacturing industry, the ability to design components with a certain sense of manufacturing freedom has made topology optimisation a lot more relevant. The general meaning of biomimicry is "innovation inspired by nature", in other words, to use nature as the inspiration for any natural or organic shape in the design[8]. Structural biomimetic components are a result of the geometry generated by the topology optimisation that eliminates the material that is not situated on the load path. The shapes generated, emulates the growth of tree branches, but this is only inherent to the path based on the loading and boundary conditions. In an ideal world, AM would be able to satisfy any design, but the current state of the technology still has limitations, for instance:

1. Surface quality

   For excellent surface finish, post-processing is generally required, and these processes will come at a high cost. Surface finish will influence the fatigue life of a component as the poor surface condition most likely will induce cracks due to defects such as porosity[9].

2. Overhang angle

   Overhang angle is a well know constraint in the AM industry. The typical overhang angle for metal AM is 45 degrees and lower. If this angle is exceeded, support structures are required, and as mentioned in the previous section, support structure are not ideal for surface finish[9].

1.5 Internal features and surfacing

1.5.1 Internal features

This section will focus on features that affect the internal structure of an AM component and the surface clean-up of the topology optimisation facet geometry.

1. Lattice structures:
The basic description for "Lattice" is described as a framework or structure of crossed woods or metal strips and can be implemented to a geometrical arrangement of points or objects over a designated design space[10].

For this study, a peripheral view of lattice structures will be investigated for additively manufactured aerospace components. There is yet a way to qualify and certify the components as flight airworthy due to the variability of the lattice beams and the multitude of load paths that would exist within a lattice. The Siemens NX lattice structure capability was investigated. It was found that the software has an extensive list of lattice options and will be beneficial to future studies in the lattice field.

Hussein et al. completed a study investigating new steps for the design and manufacture of a more effective support structure using a lattice structure with minimum volume[11]. Support structures will only be investigated in the manufacturability phase of the design cycle.

2. Bamboo Structures:
This is still a very new concept as there is little to no literature where it has been used for Additive Manufacturing in tube-like structures. In Figure 3, is an example of the bamboo structure generated by Kranz et al. [12].

Figure 3: Bamboo structure to save weight[12]

1.5.2 Surfacing

Surfacing or in better terms refers to surface clean-up of the faceted geometry created by the optimisation process, an example of this can be seen in Figure 4. The shapes generated from the topology optimisation process is facet geometry, alternatively termed a "dumb solid". Facet geometry is not directly compatible with subsequent CAD tools. Non-uniform rational B-spline (NURBS) are preferred in this conversion method because they represent the geometry more efficiently and accurately. However, converting third-order meshes to NURBS is difficult and time-consuming.

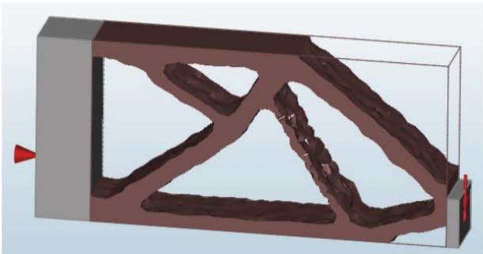

Figure 4: Facet geometry created from the TOP process[13],[14].

In 2016, SolidThinking addressed this problem by developing a solution called PolyNURBS[13]. According to SolidThinking, this new modelling method allows the user to easily trace over the facet results from the topology optimisation process to create a smoother, watertight NURBS version of the facet geometry. An example out of the help file can be seen in Figure 5. This PolyNURB model can be exported to other CAD systems and prepared for the next phases of the design cycle.

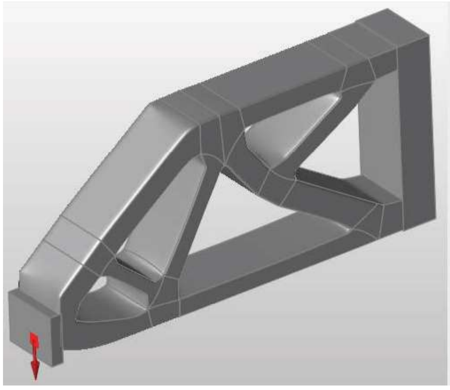

Figure 5: PolyNURB geometry[13],[14]

1.6 Manufacturability

The AM industry has made a lot more free-form designing possible. However, as with any manufacturing process, limitations or constraints must be taken into consideration. There are several processes for manufacturing metals using AM. The technology used in this study is Powder Bed Fusion (PBF), and the process is Selective laser melting (SLM). Many parameters affect the build. Some of the parameters are listed below[15]:

- Beam width
- Laser power
- Laser velocity
- Hatching strategy
- Material type
- Layer thickness
- Powder size and morphology;

Bugatti et al. refers to the manufacturability phase as "Process optimisation". The process relies on the results of expensive experimental campaigns. This approach is advantageous as it is the most accurate solution as the results come directly from the machine. However, this is an iterative process that is very time consuming and can be overly expensive because it relies on quality measurements of the components[15]. Due to the high cost of this process, utilising a new process that is driven by simulation and minimal experiments will lower the cost tremendously. This will invoke the thought process of "first time right", by identifying or making supervision during the simulation for any problems with the build.

The residual distortion of a component is a significant technical challenge when using PBF[16]. Excessive distortion can lead to build failure, cracks and loss in structural integrity. Due to the inherent heating and cooling of the AM process, residual stresses can rarely be avoided[16]. By using simulation software to do accurate distortion prediction, it is an effective way of ensuring manufacturability and build quality. Simufact Engineering has developed Simufact Additive software for the simulating of metal additive manufacturing. This software simulates all the critical process steps in the AM process. These process steps are:

- A component build
- Heat treatment
- Cutting from the build plate
- Removal of support structures
- Hot isostatic pressing (HIP)

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Simufact Additive predicts the final distortion and residual stresses of the metal parts. The inherent strains are determined through several iterative calculations using an experimental calibration process. The inherent strains, associated to the calibrated machine, are then used in simulating a component. The software can then accurately determine where the distortion and stress will accrue during the build after it has been cut from the bed, and all the support structures have been removed.

2. CASE STUDY

The case study is defined as the Continues Fiber Reinforced Thermo Plastic (CFRTP) Rudder AM component. The brackets of the rudder are designed by means of the proposed AM design cycle. The goal of this study is to achieve an AM manufactured part that conforms with all the airworthiness requirements and can sustain the desired loading. In Figure 6, the component is shown in the assembly of the rudder and where all the interface planes and points are defined. The loading conditions for this bracket are specified as ultimate loads. When the ultimate loads are applied, the rules are as follows:

- No buckling
- Von Mises is smaller or equal to the ultimate tensile stress of the material

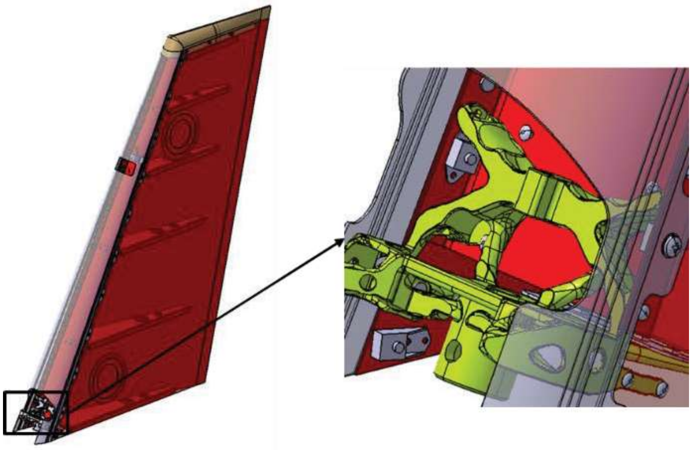

Figure 6: The Rudder assembly for the bottom bracket [17]**.**

3. RESULTS

Figure 7 is the summary of all the results achieved by each of the phases for the AM design cycle based on the case study. Each of the sections to follow will give an explanation on what particulars have been achieve for that specific phase of the design cycle.

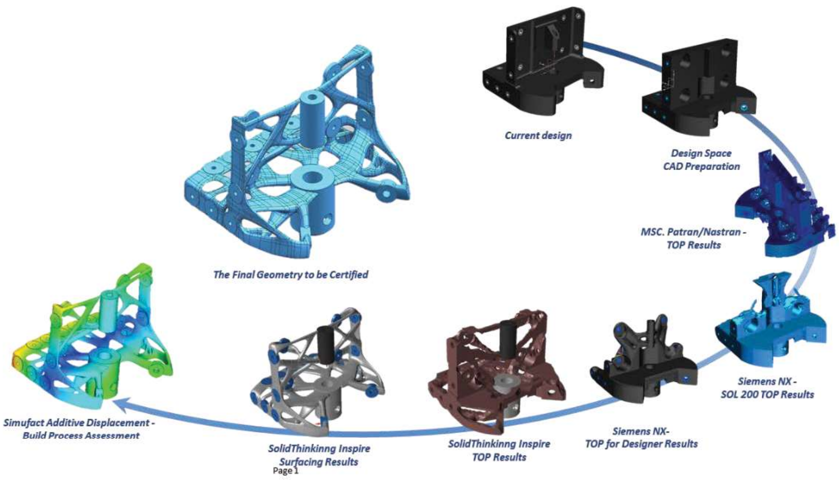

Figure 7: The results of the AM design cycle

3.1 CAD

In the first phase, the component is altered by means of the re-evaluation process. The difference between the current geometry and the re-evaluated geometry can be seen in Figure 7. The re-evaluated geometry encapsulates the complete design space the component can utilise. The designated design space is used to allow the most efficient load path to be defined by the topology opposition simulation without limiting or forcing a defined path.

3.2 Optimisation

For the optimisation phase, the investigation spreads across a variety of software packages as the results obtained from the optimisation process were inadequate, due to the lack of development of the software and lack of knowledge. The following software packages were used:

- Patran/Nastran, 2014.1 and 2018 (MSC. Software Corporation)
- NX, 12(Siemens)
  - Topology Optimization for Designers
  - Sol 200 NX Nastran Topology Optimization
- Inspire, 2018.2 and 2019 (Altair Solid Thinking)

In Figure 7, the various results from the topology optimisation can be seen. The desired outputs were not achieved from the MSC.Patran/Nastran and the Siemens NX software packages. This outcome is due to insufficient time to develop the skills required to effectively use these software packages for topology optimisation. The Solidthinking Inspire software package yielded the best results from the topology optimisation investigation.

3.3 Internal Features and Surfacing

Inspires PolyNURB functions have been used to clean up the geometry from the optimisation process. This improves the aesthetics of the part and converts the CAE data to usable CAD data. In Figure 7, the results for both designs can be seen.

3.4 Manufacturability

Simufact Additive was used to determine if the component that is generated in the topology optimisation phase can be manufactured without the risk of build failure or significant distortion. To do this evaluation with an accurate output, a calibration experiment was conducted. The calibration procedure is necessary to capture all the build parameters that have been used to print the cantilever test sample. The samples are cut at a defined height, and the deflection in the z-direction is measured. These values are captured by the software and used to determine the inherent strain values. A machine profile is now defined and will be used for all component manufactured on the specific machine using the defined parameters

3.4.1 Calibration Results

In Figure 8, calibration samples have been distributed across the build plate to ensure the whole build plates inherent stain is calculated. Simufact interpolates from the four data points for the inherent strain value at any given point in the print space. The calibrations samples where manufacture using a Concept laser M2, the material used for this build was Ti-6Al-4V grade 23.

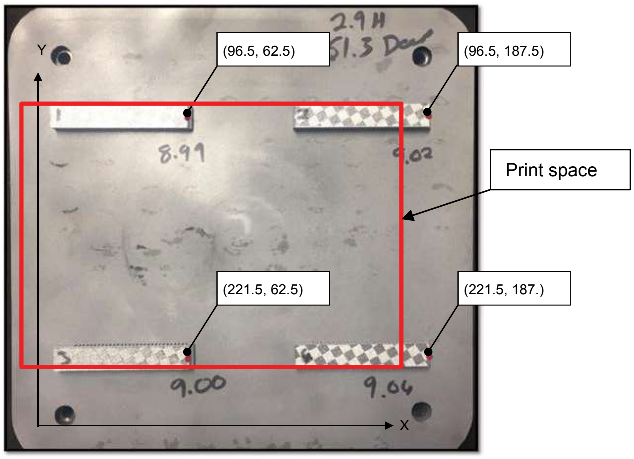

Figure 8: Distributed Samples across the build plate

In Figure 9, the displacements of the cantilever samples are shown after the samples have been cut at a certain height. The displacement in the Z-direction was measured with a calibrated depth gauge.

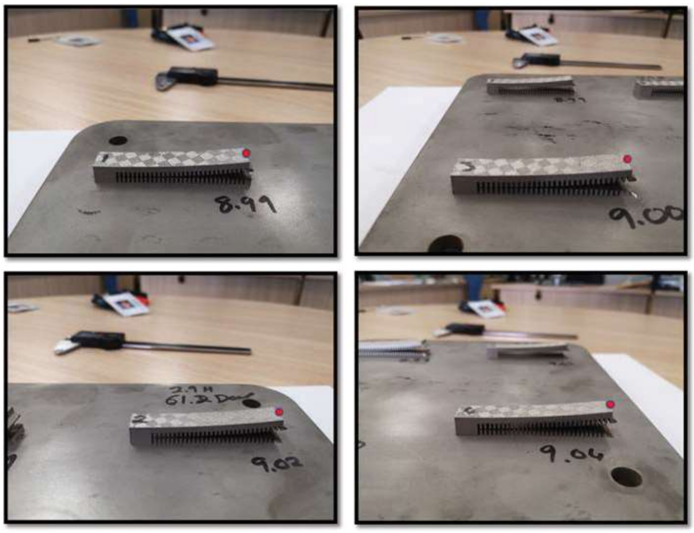

Figure 9: Cantilever samples after Cutting

Table 1 presents the experimental data that was measured compared to the convergent values simulated by the software. In Figure 10, the maximum deviation is seen for part 2, with a deviation of 2.94766%. This implies that the simulation outcome of the calibration is accurate to the maximum percentage achieved

Table 1: Output data from Simufact

Part	Δz_max target [mm]	Δz_max sim [mm]	Δz_max [mm]	Δz_max [%]
1	3.91	3.895	-0.015	0.383632
2	3.63	3.737	0.107	2.94766
3	3.78	3.811	0.031	0.820106
4	3.91	3.903	-0.001	0.179028

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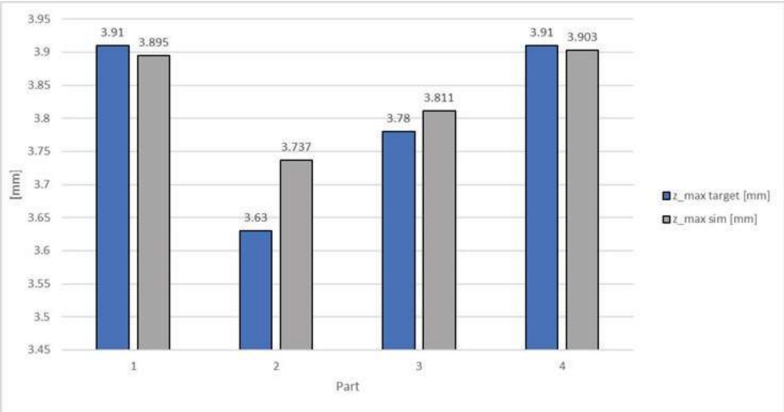

Figure 10: Bar graph of the Comparison between measured and simulated data

3.4.2 Component Assessment Results

The manufacturing assessment was conducted using the calibrated Simufact machine profile card. If there is any deviation in the build parameters, the simulated data will be inaccurate, thus it is recommended to redo the calibration process if the parameters are altered. There is also a function in Simufact to optimise the build orientation to minimise the volume of support. However, this may not give you the best residual; distortion result. In Figure 11, the component is fixed to the build plate, the component was cut from the build plate, and all the support structures were removed this can be seen in Figure 7. The legend on the side of the part indicates the displacement for the contour plot. The displacement increases when the component is cut from the build plate, and the supports are removed. The displacement represents the residual distortion that occurs due to the internal stress caused by the AM process.

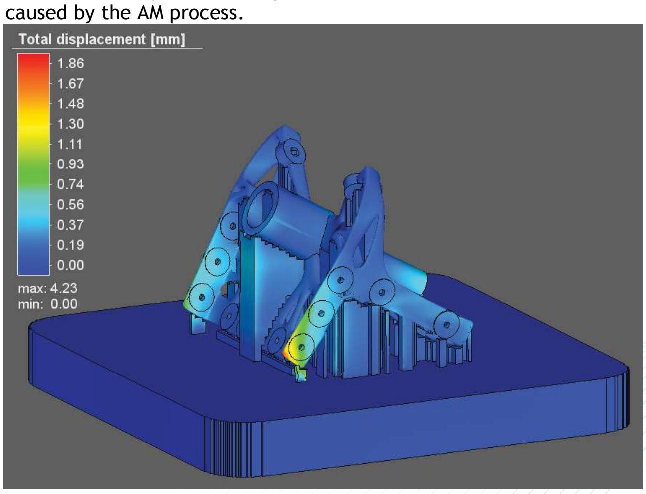

Figure 11: Manufacturability Results - Optimal Build Orientation

4. CONCLUSION

The literature has shown that there is minimal emphasis on the design cycle process when creating components for AM. This design cycle will make it possible to achieve components that conform to the airworthiness requirement and achieve the optimal design for the application. The aim of this study is to develop a design cycle that will be implemented by means of process manuals.

In this sense, the software used for the optimisation phase was briefly investigated, and with little to no exposure, the best result was achieved for each in the set time frame. It is important to note that MSC and Siemens software, using Nastran as a solver requires a vast amount of exposure and knowledge to generate topology from any given geometry. Inspire is a well-developed topology optimisation software package and has all the necessary tools to generate the desired geometry with ease. Thus it is evident that the other two counterparts require further development due to the fact that they are not easy to use without a fast amount of experience in FAE. Inspire also catered for the clean-up phase of the design cycle with the PolyNURB wrap function that "wraps" the facet geometry. PolyNURBS can be manipulated to a large degree. Thus we can generate both prismatic and biomimetic components.

The design cycle ensures that the component adheres to the manufacturing constraints and is manufacturable using the specific AM process. This reduces the cost of the build as the software emphasizes where the component might cause the build to fail. It also gives insight into the residual distortion and how to rectify this issue using the inverse of the displacement vector as a solution. The qualification phase investigation of the design cycle is still currently underway. This concludes the current iteration of the design cycle, and with minor alterations, in the orientation, the part can successfully be manufactured. The design cycle will make it possible to achieve optimised components that meet the manufacturability requirements of the build process as well as the requirements for the component to be airworthy.

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