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Stress concentrations and design for additive manufacturing: a design artefact approach to investigation

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Abstract

The accelerated rate of product development and design complexities offered by Additive Manufacturing (AM) has allowed for innovation in the space industry. However, the surface roughness of parts poses a challenge, as it impacts performance and is tied to design choices. Design tools for traditional manufacturing methods fall short in AM contexts, prompting the need for alternative design processes. This work proposes an experimental approach to design for AM investigation using design artefacts to explore a process-structure-property-performance relationship.

Keywords: additive manufacturing, design artefact, design for additive manufacturing, surface roughness, prototyping

1. Introduction

Additive Manufacturing (AM) is increasingly becoming an economically and commercially viable manufacturing method, typically involving fewer processes and resources than alternative subtractive manufacturing methods (Gibson *et al.*, 2020). The layer-by-layer process provides designers with unique shape, hierarchical, functional, and material complexity capabilities, enabling new opportunities for customisation and lowering manufacturing costs (Gibson *et al.*, 2020). AM's capabilities allow generative design (GD) methods to create low-weight metal parts in the space industry (Samal *et al.*, 2022). Applications of GD and AM have demonstrated that space product development times can be reduced ten-fold while also providing a three-fold improvement in structural performance (McClelland, 2022). With AM, designers can use topology optimisation (TopOp) techniques to design and manufacture lightweight brackets (Reiher and Koch, 2016). The University of Paderborn conducted a TopOp study for a biomimetic shape for a reaction wheel bracket and found the AM TopOp structure reduced waste by 98%, manufacturing time by 32%, and cost by 53% (Universität Paderborn, 2016). However, AM process factors bring design challenges and uncertainties that must be considered in the early phases of product development (Renjith *et al.*, 2020; Thompson *et al.*, 2016). These process factors affect design choices and impact material characteristics such as part buildability, fatigue properties, and overall performance (Gradl *et al.*, 2023). A challenge in designing AM space components is the inherent roughness of the as-built surface. This roughness is closely linked to a part's design due to the layered manufacturing process, which produces a staircase effect (Gradl *et al.*, 2023). This staircase effect, in turn, acts as micro notches for stress concentrations that impact fatigue performance (du Plessis and Beretta, 2020). Fatigue performance is critical for satellite brackets as they must withstand the high forces experienced during launch.

Structural sensitivity indexes derived from empirical testing, such as stress concentration factors (SCF) in traditional manufacturing, support designers in comprehending how geometric features influence performance (Pilkey and Pilkey, 2007). SCFs provide easily understandable and applicable knowledge that designers can apply when designing for subtractive manufacturing methods. When such knowledge is integrated with computer-aided design (CAD) software tools, it provides analytics supporting designers in assessing process–structure–property–performance relationships (PSPP). However, there are significant challenges in understanding the PSPP relationships in Design for AM (DfAM) due to the complexity and multitude of process parameters (Hashemi *et al*., 2022). Most CAD tools are not yet well adapted for the PSPP representation of AM-designed structures, nor have the embedded heuristics to suggest certain features (e.g., raft or chamfer) would be detrimental to performance (Nazir *et al.*, 2019). Consequently, designers require methods to acquire this design knowledge to help them understand AM process capability and effectively manage their limitations.

Parametric feasibility studies can be conducted to investigate and provide knowledge on design-property relationships (Jones *et al.*, 2021; Zhou *et al.*, 2021). However, in the early phases of product development, with many ideas proposed, extensive studies would be required to understand the feasibility and performance of different design concepts long before specifications are set. Prototyping can provide an understanding of design-performance relationships for AM components (Thompson *et al.*, 2016). Ulrich and Eppinger (2012) classify prototypes along two dimensions: physical and analytical. Physical prototypes are tangible representations of a design that can be tested and experimented with. In contrast, an analytical prototype represents the design mathematically or visually to analyse interesting aspects of the product, such as a Finite Element Analysis (FEA). Ulrich and Eppinger (2012) further describe that prototypes are used for four purposes: learning, communication, integration, and milestones. Lawrence (2003) suggests designers consider the 'right-rapid-rough' approach to prototyping to foster innovation when solving design problems. 'Right' implies designing a prototype to address a specific question, i.e., targeting the prototype to the 'right' question a designer wants answered rather than multiple. 'Rapid' means that a prototype should be quick to design, allowing a designer to simulate and test a design challenge quickly. Finally, 'rough' suggests that a prototype does not need to be pretty in describing the design uncertainty; it should be rough enough to provide knowledge while allowing the designer to focus on the main design solution (Lawrence, 2003).

The contribution of this paper is the proposition of an experimental methodology to investigate design uncertainties related to using GD for AM parts. The paper commences by providing a background on practices and guidance that assist designers in gaining knowledge on PSPP relationships, highlighting a design support process utilising design artefacts for knowledge generation (Section 2). Section 2 further delves into an AM use case in the space industry where PSPP knowledge is limited, and design uncertainties for buildability and the impact of roughness on stress concentration are identified. Subsequently, the research methodology (Section 3) through the design support process, including the design logic and the experimental design, is presented. Then, simulated results are given (Section 4). The paper concludes with a discussion on the considerations for PSPP relationship investigations when using design artefacts, followed by conclusions that outline future work (Sections 5 &6).

2. Background and related work

Guidelines for understanding PSPP relationships for AM are available through standards (ISO/ASTM, 2017, 2018). ISO/ASTM 52910 provides general design-performance support, whereas ISO/ASTM TC261 (2018) suggests test artefact designs for investigating the geometric capability of AM systems. Nevertheless, the standards and suggested artefacts fall short in providing support for complex geometries, prompting researchers to modify the designs of standard test specimens to better investigate design uncertainties. Benedetti et al. (2016) devised a test specimen design, slightly deviating from typical push-pull axial fatigue specimens, to investigate the effects of surface roughness on the fatigue limit of metal AM components. Their modification aimed to better capture the effects of roughness, which they found were inadequately revealed with standard hourglass specimens.

Others have developed more PSPP-focused artefacts to investigate design-related performance factors for AM. Zhou et al. (2021) found that fluid channels made through AM had higher friction factors than expected from classical theory. To better understand this, they manufactured a series of small fluid channels with varying diameters and build angles to characterise the fabrication quality and measure friction factors. From their findings, they developed design guidelines and a model for predicting the friction factors of AM-produced fluid channels that consider the fabrication quality. These activities can be time-intensive; hence, the investment may be more worthwhile during the later design stages when the specifications are further set.

Dordlofva and Törlind (2020) observed the use of product-specific AM design artefacts (AMDA) by engineers in the space industry to investigate and explore AM design uncertainties. Their observations revealed that design artefacts can be used to inspire designers' solutions for utilising AM potentials. Inspired by the prototyping design process of the IDEO design consultancy (Hartmann, 2009), the AMDA process, depicted in Figure 1 is a systematic approach to identify, explore, and reduce uncertainties in AM design when inspiring, evolving, and validating solutions for AM design. The learnings from design artefacts in the early phase can be used to drive design specifications, particularly during the concept phase. In contrast, the design of artefacts, when used later in the development process, when the product is more detailed, is driven by the product specification.

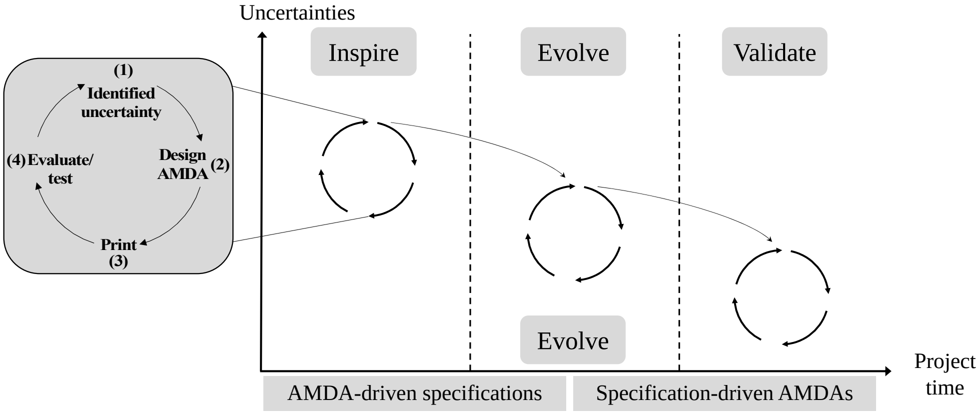


Figure 1. The design process with AMDAs (adapted from Dordlofva and Törlind (2020))

The AM of components by space industry companies has allowed for rapid cost-competitive innovation in an industry where product development cycles can be slow and low-weight part designs are beneficial (Sacco and Moon, 2019). AM production can hasten product development; however, the pace can be hindered by a designer's lack of DfAM understanding (Lindwall, 2023). Designers need to decide early in the product development process if AM is feasible for their product idea. Thus, it is important to understand PSPP relationships, such as buildability and surface roughness-induced stress concentrations in complex geometries, when considering taking advantage of AM design opportunities (Nicoletto *et al.*, 2020). A lack of understanding brings design uncertainties for engineers exploring AM design solutions.

2.1. Directed Energy Deposition in the space industry

The AM process of Directed Energy Deposition (DED) melts material, either in powder or wire form, using a heat source as it is deposited (Gibson *et al.*, 2020). DED processes provide high material usage efficiency in comparison to subtractive manufacturing methods, enabling the manufacture of metal component designs with reduced weight, reduced part numbers and quicker production times (Thompson *et al.*, 2015). The rocket manufacturer Relativity Space used wire-DED to manufacture the fuselage of their Terran 1 rocket, which was launched in 2023. They found that the DED process readily allowed for incremental design changes, enabling them to reduce part numbers and optimise material usage faster than traditional manufacturing processes (Relativity Space, 2023). DED processes often require finish machining due to relatively poor part accuracy and higher surface roughness than other AM processes in the as-built state (Gibson *et al.*, 2020), which increases the cost and the time for production (Ding *et al.*, 2015). In an optimal manufacturing scenario, a part could be used in its as-built state. For instance, despite the as-built rough surfaces of the Terran rocket tank accounting for roughly 5-10% of the mass, Relativity Space does not remove the surface roughness as it causes no aerodynamic problems (Veritasium, 2021).

Another AM process used in the space industry is Laser Powder Bed Fusion (LPBF), which uses a laser as a heat source and powdered metal material to create parts. LPBF is used for manufacturing high-strength-to-weight satellite brackets (Samal *et al.*, 2022). However, considering the increased rate of satellite launches and the associated demand for satellite bracket manufacturing, the higher deposition rates offered by DED could be beneficial. Additionally, space manufacturers advertise using AM for a more sustainable manufacturing process and product (Orbex, 2023). LPBF has a high environmental impact due to the energy demand and argon usage, while the DED process, in contrast, can offer superior production efficiency and reduced environmental impact per part, particularly in brackets manufacturing (Min *et al.*, 2019). Further, wire-DED offers better control for deposition efficiency than powder-DED (Gibson *et al.*, 2020; Thompson *et al.*, 2015). The surface condition and geometrical accuracy of DED parts tend to be worse than those from powder bed processes, and despite the potential benefits of designing as-built DED, there is limited support available for designers regarding wire-DED DfAM (Ding *et al.*, 2015).

2.2. Stress concentration and DED design uncertainty

DfAM support is particularly useful when using GD techniques, as they can produce designs with considerable geometrical changes, leading to several areas of high-stress concentrations (Benedetti *et al.*, 2021). Stress concentrations refer to localised areas of a structure that experience higher stress levels than the average stress distribution across the body (Pilkey and Pilkey, 2007). Design tools like Peterson's elastic stress concentration factor (SCF) charts have supported designers for several years (Pilkey and Pilkey, 2007). However, time-consuming FEA models are needed as parts get more complicated, and a more accurate understanding of SCF is required (Shanmukha Prasad *et al.*, 2020). Stress concentration analysis for AM is particularly challenging due to the staircase effect creating further stress concentration sites and points for crack initiation, impacting fatigue performance (Ding *et al.*, 2015; ISO/ASTM, 2017). Geometries like sharp radii have high stress concentrations. If designers wish to lessen the concentrations, they could increase the radius size (Axsom, 2022). However, due to the material deposition method of wire-DED, increasing the radius leads to a more significant staircase effect, creating a rougher surface and impacting fatigue performance.

Additionally, as support structure is not used for DED components, there is uncertainty about the quality and buildability of the unsupported radius. Hence, multiple design uncertainties exist regarding the buildability of radii, the degree of roughness due to radius variation and the possible influence of roughness on performance. Further, these design uncertainties are challenging to model using software tools due to the uncertainty of the SCFs' accuracy for AM applications. In the early phases of product ideation, when there is no fully defined specification for a product, design artefacts could allow for a quick and rough investigation into these identified design uncertainties.

3. Design artefact process

GD and the possibility for light weighting and lower costs were identified as potential benefits from as-built DED brackets. However, before time and effort are spent on generating designs, the design uncertainties described have been identified regarding this idea. Dordlofva and Törlind (2020) presented how engineers in the space industry used product-specific design artefacts to investigate design uncertainties. Without appropriate simulation means for these uncertainties, design artefacts are proposed as a low-investment option to generate rough design knowledge and investigate these uncertainties. The following section describes the proposed artefact design and experimental methodology to investigate and learn about the design uncertainties.

3.1. Artefact design

The first step of the AMDA process is identifying uncertainties. In this case, it is the capability of the machine to manufacture the radii, how geometrically accurate the radii are, and the degree of surface roughness and impact on fatigue performance. The second step is designing the artefact, where key considerations are on which uncertainties will be represented and how. In this case, the artefact is designed to enable all described uncertainties to be sequentially investigated due to the knock-on effect of the design variation. A designer must consider their initial specifications as constraints when designing an artefact to ensure a feasible investigation. Constraints in the ideation stage include the AM machine, i.e. build volume and available materials. Additionally, the design is constrained by the desired equipment as the artefact size and dimensions should consider the fixtures and mounting options of the test equipment. Similarly, if measurements are required, i.e. radius and surface roughness measurements, the measurement equipment further constrains the artefact design. For this investigation, the artefact's design is based on similar research using design artefacts to investigate a PSPP relationship by Obilanade et al. (2022). In that work, a design artefact and experiment were proposed by engineers investigating the performance of a specific radius related to a design uncertainty of an AM rocket engine turbine manifold. The variations to that artefact design are based on the constraint considerations described. A diagram of the artefact is presented in Figure 2, and the dimensions are provided in Table 1. The artefact is designed with an open internal lozenge shape design to allow for the investigation into the impact of varying an unsupported radius (R1) to reduce stress concentrations. The internal radius of the lozenge shape (R2) will be constant for all artefacts, and the angle between the radii is 65° as specified by the design guidelines of the AM machine.

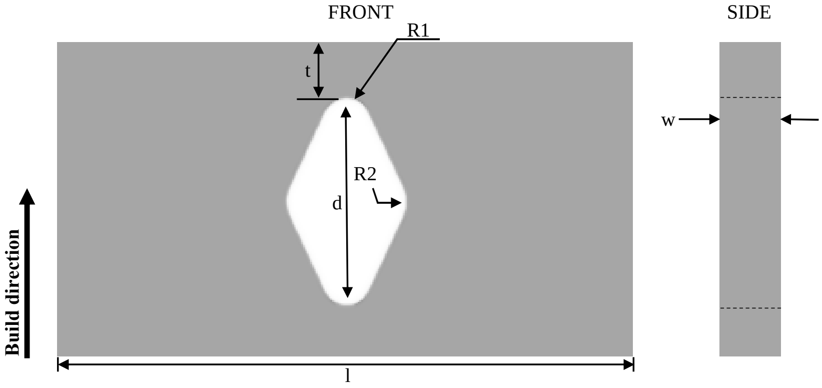


Figure 2. Example diagram of the artefact design

Table 1. Artefact geometries (angles between radius base and roof are 65°)

Artefact type ID	Diagonal width d, [mm]	Artefact width w, (mm)	Thickness t, (mm)	Length l, (mm)	R1 (mm)	R2 (mm)
A	45	6	8	120	1	4
B	45	6	8	120	3	4
C	45	6	8	120	5	4
D	45	6	8	120	7	4
E	45	6	8	120	9	4

The artefact is designed to investigate the surface roughness and mechanical performance at five radii: 1 mm, 3 mm, 5 mm, 7 mm, and 9 mm. All artefacts will be built with 5 mm additional height as a support structure at the base to allow for cutting from the base plate and the stack. Five of each artefact geometry shall be manufactured: one for maximum tensile testing, three for cyclic fatigue loading and an additional as a spare.

3.2. Experimental design

The artefacts will be manufactured using a Meltio M450 wire-DED machine, and the material used will be stainless steel with a wrought tensile strength of 550 MPa (Meltio, 2024). Stainless steel is investigated as it is favourable for making satellite brackets (Samal *et al.*, 2022). Several process-dependent factors, such as the wire diameter, tool path, feed rate, laser power, infill pattern and feed orientation, can bring uncertainties for the performance of the geometry and mechanical properties of wire-DED parts (Ding *et al.*, 2015; Rismalia *et al.*, 2019). Design artefact investigations are conducted as a controlled study to focus on specific elements of design uncertainty by limiting the parameter space. In this investigation, the uncertainty is radii variation and its knock-on impact on buildability, surface roughness and performance. Hence, only one design variable, an overhanging radius, shall be varied, allowing for a focused investigation into DED build capability, geometric accuracy, and performance through evaluation and testing. Upon building completion, all artefact radii will be measured to investigate the geometric accuracy of the radius geometry. The material thickness between the radius and the top of the artefact will also be measured. Ensuring that the *t* value is similar for all artefacts is important for a fair performance assessment. The loading experiment will investigate for the PSPP relationship. Two tests are proposed to gain insight into how the performance of the artefact is affected by the design variation. Both tests will be conducted on a 25kN Instron 8872 tensile testing machine, and the artefacts will be gripped by 12.5 mm wide hydraulic jaws and loaded as shown in Figure 3, fixed at one end and the load applied at the other. A cut shall be performed at the opposite radius to the radius under investigation to focus on the R1 radius and to allow flexion for the cyclic fatigue loading.

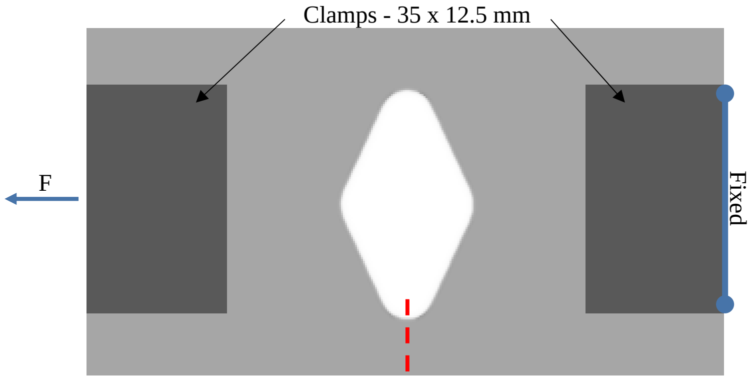


Figure 3. Diagram of artefact and rationale for testing (red line indicating cut point)

The tests will focus on a fracture failure mode implemented by a stopping condition on the Instron when the separation of the upper and lower jaws reaches an F_{max}= 4kN. A tensile test shall be conducted to investigate the maximum tensile load each artefact can hold before fracture. This test will be performed for each artefact variation to inform if 4 kN seems appropriate for the investigation and will provide a simple control against which the artefacts can be compared. The artefact and investigation design are purposely simplistic to quickly obtain design and process knowledge.

The second test aims to gauge the effect of varying radii and resulting surface roughness upon the artefacts' fatigue fracture resistance. The test will follow the procedure of the ASTM standard E466 for "Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials" due to its widespread use and repeatability (ASTM, 2002). An FEA tensile test was run using Abaqus for each artefact variation. Once all tests are completed, plots of the maximum load against the simulated maximum load from the FEA analysis shall be created. A second plot will be created, plotting the average number of cycles for the cyclic fatigue loading at the various radii.

Table 2. ASTM E466 load-controlled fatigue test standard characteristics

Test method	Load controlled fatigue
Test temperature	Room Temperature
Test environment	Air
Waveform	Sinusoidal
Frequency	10 Hz
Rσ-ratio (ratio of maximum: minimum loading)	0.1
Load range, run-out	500-50,000 cycles
Failure criterion	Fracture

4. FEA simulation results

The FEA modelling used Young's modulus of 200 GPa and Poisson's ratio of 0.27. A visualisation of an FEA result is presented in Figure 4, and the analysis results for the Max. Mises stress are presented and plotted in Figure 5. The model had fixed constraints on one end, matching the shape as in Figure 3, and a surface traction load on the opposite end of 2.285 MPa, resulting in a 4kN load across the entire surface. The investigation anticipates an increase in surface roughness with the radius of the artefacts, affecting the mechanical properties. The evaluation will involve comparing the maximum tensile load of the artefacts at the various radii for similarity with the FEA's maximum von Mises stress plot.

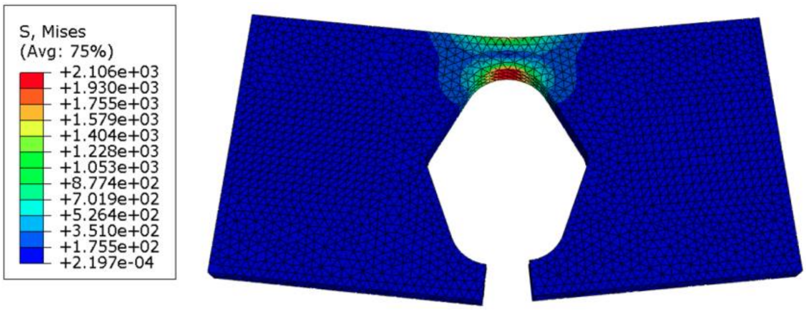
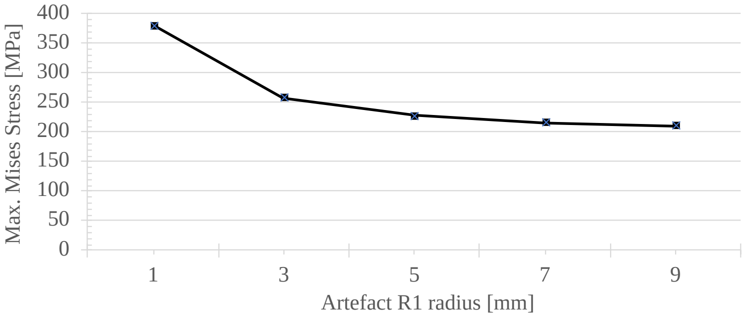


Figure 4. Visualisation of FEA results for artefact E (R1 = 9 mm) (stress is given in MPa)



Radius size [mm]	Max. Mises stress [MPa]
1	380.1
3	258.6
5	228
7	216.5
9	210.6

Figure 5. FEA results for Max. von Mises stress of the varying radii

Figure 5 indicates decreasing stresses with increasing radius, suggesting improved mechanical performance. A saturation in the stress values can be seen in Figure 5. SCF graphs derived from empirical testing of subtractive parts show that SCFs do not increase linearly with size (Pilkey and Pilkey, 2007). It can be assumed that the SCF of the radius also does not increase linearly as the radius decreases. The results of the artefact testing are expected to reveal higher stresses for a given tensile load than FEA predicts, as the FEA does not account for surface roughness. This expectation will be investigated by comparing the FEA-calculated stresses to the stress-strain curve produced during tensile testing. Hence, testing through design artefacts will provide a designer insight into this influence, if it impacts as expected, and, if so, how design variation may affect performance.

5. Discussion

This work proposes an experimental methodology for investigating design uncertainty in DED for GD AM components using a series of design artefacts. The proposed artefact design and experiment aim to provide an understanding of the DED process capability and the possible impact of as-built surface roughness on fatigue performance. They are addressing potential uncertainties related to the effect of increasing the radius for stress concentration reduction and improved mechanical performance. A satellite bracket designer anticipates forces during operation; however, uncertainties arise in as-built AM structure behaviour at complex geometries due to unknown surface conditions. Variations in radius geometry can be implemented to improve performance and would impact performance in non-AM parts, however, traditional design supports like SCFs and CAD programs are available to help analyse these impacts, as demonstrated with the FEA analysis. With the many other variables in AM processes, such as residual stresses and material composition due to process parameter choice, modelling becomes computationally intensive and time-consuming in the early phase. Additionally, SCF tables are not directly applicable to AM parts. If any build parameters are changed, an SCF table produced for an AM process would be difficult to generalise or inapplicable. Necessitating the need for design support processes like the AMDA process to investigate PSPP relationships. Post-processing via processes like milling can be done to improve the surface condition. However, the additional cost of milling, reduction in product development speed, and overall performance improvement are also unknown to the designer in the early phase. These types of artefacts could provide an understanding of the post-processing necessity for the selected AM process, i.e., the feasibility of a design to meet requirements without post-processing.

Using design artefacts could help explore the design options beyond the information available in standard guides, published design rules and CAD systems while allowing designers to understand the functional impact of a creative decision. Using the AMDA process in the early phase prompts designers to detail considerations for AM usage. When a design uncertainty is identified, the designer must consider the influencing factors to that uncertainty in case further uncertainties can be identified. In this case, using GD and as-built DED brings uncertainties related to the machine's capability to produce geometries and the surface roughness on the fatigue performance. During artefact design, designers articulate initial assumptions to define uncertainty representation, considering practical constraints. Early decisions on build parameters are considered, and an understanding of the likelihood of build success is revealed during the print stage. Finally, in the evaluate/test activity, as discussed by Dordlofva and Törlind (2020), the early specifications are considered, and design knowledge output. Figure 6, illustrates a model of the artefact design process, describing the presented work, future work, and key considerations during the stages of the prescribed AMDA process.

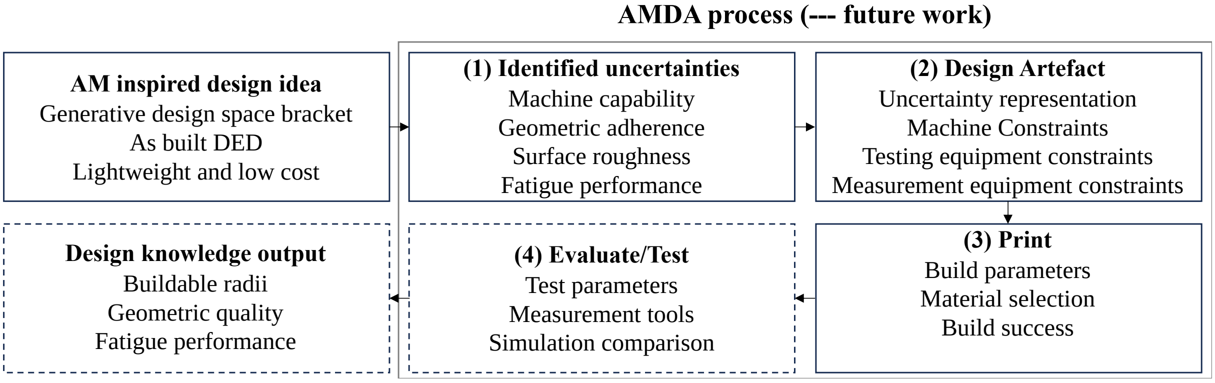


Figure 6. Model of the described design process

Considering the right-rapid-rough approach to prototyping, the choice of testing procedure can be adapted to allow for a rough understanding of PSPP relationships rather than following a standard or guide if it does not have information regarding the variations due to the chosen process.

The experiment proposed will investigate the possible benefit of design artefacts to generate general design knowledge faster than more specific parametric feasibility studies. In AM, many factors need consideration for their impact on the mechanical properties of a component. The design of this experiment purposefully focuses on the potential impact of as-built surface condition through comparison to a non-AM process FEA simulation. Using artefacts like the design in this work and varying process factors like tool path, infill pattern, and feed orientation instead of the radius could allow for investigations into other types of uncertainties. The results of this type of prototyping method may not directly apply to the eventual design solution, as the 'roughness' of the representation of the uncertainty in the artefact design and the experimental setup limits the result's applicability. However, with the lack of standardised PSPP support, focused rough prototyping provides a method of considering design uncertainties and building knowledge in the early phase.

6. Conclusions

In proposing the use of DED for a GD AM component and the use of and design of a design artefact for design investigation, the following considerations and points have been discussed in this paper:

- There are challenges in understanding PSPP relationships in DfAM due to the complexity of AM processes. E.g., unknown surface conditions in complex geometries create uncertainties in the behaviour of as-built AM structures, making traditional design supports less directly applicable.

- The process of creating design artefacts may be used to explore and consider design uncertainties in the early phases of product development due to considering the known constraints of the machine, testing capability and measurement tools.
- AM modelling complexities, e.g., residual stresses, are computationally intensive; hence, artefacts as an adaptive prototyping approach may be beneficial for design investigations.
- Rough prototyping may provide practical utility and offer useful early-phase insights, but representation constraints limit their direct application to the final design.

An analysis of the variety of ways designers investigate PSPP uncertainties during the AM product development process should be conducted to provide a comparison against the use of design artefacts. Future work will focus on printing and testing the artefacts following the procedure presented in this paper. Further, microstructural analysis of the artefacts could also be conducted to investigate other properties affecting performance.

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