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Measuring the value of DfAM in metal powder bed fusion direct part production

Iñigo Flores Ituarte [1], Niklas Kretzschmar [2], Sergei Chekurov [2]

[1] *Department of Engineering Design and Production, School of Engineering, Aalborg University, Copenhagen Campus (Denmark)*
[2] *Department of Mechanical Engineering, School of Engineering, Aalto University, Espoo (Finland)*

ifi@mp.aau.dk

Abstract

Achievable unitary cost of production and delivery time often define the successful industrialization of additive manufacturing (AM). Integrating AM into a holistic manufacturing process must ponder cost-benefit and trade-offs between conventional manufacturing and AM. A systematic method to measure the success of any given AM business case requires the combination of both technological as well as operational aspects. In this research, we present an online decisions support system (DSS) to facilitate the comparison of AM and conventional manufacturing. The DSS tool allows evaluating productivity factors (i.e., manufacturing cost and manufacturing time) for any given geometry. Additionally, we show quantitatively how the competitiveness of part production using metal Powder Bed Fusion (PBF) benefits from Design for Additive Manufacturing (DfAM). We compare three DfAM cases that relate to: (i) re-design of a structural bracket including complexity in terms of cellular structures and topology optimization, (ii) new product design of a heat exchanger with shape complexity and functionally enhanced performance, and (iii) re-design by part consolidation of a clamping system for assembly and welding operation. Our research measures the value of DfAM for AM industrialization, and tests the advantages and limitation of the presented DSS, indicating future research activities that can promote AM adoption.

Additive manufacturing; DfAM; Value engineering Topology optimization; Lattice structures; Part-consolidation

1. Introduction

The role of design for additive manufacturing (DfAM) is crucial to successfully use additive manufacturing (AM) as an alternative production technology [1]. Often, the value of DfAM in direct part production relates to design freedom and complexity. Design opportunities at the part level include micro-scale complexity (e.g. lattice, trusses, and cellular materials) and macro-scale complexity (e.g. material choice, freeform geometry, and topology optimization (TO) for functional performance and cost savings through material savings). The value of DfAM is also linked to complexity at product level (e.g. part consolidation [2].

Metal powder bed fusion (PBF) is at the spotlight of industry. Today metal PBF is a strong niche competitor against conventional manufacturing, especially for manufacturing scenarios that require flexibility, small lot production, mass-customization applications, and functionally enhanced parts [3]. The competitiveness of metal PBF in manufacturing depends significantly on material cost savings [4] and reduced lead times [5]. Therefore, introducing macro, micro, and product level complexity enabled by DfAM can notably increase the technical and operational feasibility of AM designed parts and assemblies.

The value and cost in AM is often analysed by comparing the cost of AM part versus the cost of conventional manufacturing using a break-even point analysis [6]. AM cost include the price of used raw powder materials (including sacrificial support structures and non-recyclable powder) as a direct cost, machine cost allocated through setup, build and cooling down time, as an indirect cost, and labour as a separate fixed cost [7]. However, companies still have difficulties to think of AM as an alternative manufacturing solution due to the difficulty of: (i) *Integrating DfAM in part and product design* and (ii) *calculating the value of DfAM enhanced parts versus conventional alternatives.*

The existing body of knowledge helps to think *"additively"* in part and product design; however, transferring knowledge requires a systemic approach. Experts of DfAM understand the opportunities to engineer new products. For example, to re-design complex hydraulic manifolds with higher efficiency and decreased pressure drop [8], design optimized heat exchangers with maximized efficiency by decreasing the part volume [9], or conceive part consolidated products [10].

However, industrialization of AM with the integration of DfAM in a holistic design to manufacturing process must be guided by tools and methods that allow to ponder cost-benefit and trade-offs between conventional manufacturing and alternative AM business cases. A systematic method to measure the value of any given AM business case requires the combination of both technological as well as operational aspects [3].

To help in this process, we present the online version of a Decision Support System (DSS) that is used to measure AM competitiveness versus conventional manufacturing. The DSS tool allows evaluating productivity factors such as manufacturing cost and manufacturing time for any given geometry. Additionally, we test the DSS tool measuring the value of DfAM quantitatively to increase the competitiveness of metal PBF part production. We analyse three potential business cases that include macro, micro, and product level complexity enabled by DfAM.

In sum, the novelty of this work is twofold: first, we publish an online DSS system that allow users to compare AM versus conventional manufacturing. Second, we introduce a value analysis in terms of cost reduction, productivity, and functionality of three DfAM cases by testing the advantages and limitation of the presented DSS.

2. Measuring the value of DfAM

2.1. AM decision support system (DSS)

We measured the value of DfAM integration in laser PBF by a custom developed DSS for metal PBF. For a detail discussion of the underlying algorithm, methodology, and assumptions of the DSS calculations refer to [4]. The novelty in this research is linked to the development of the online version of the same tool that is accessible using this link (https://amdsp.org.aalto.fi). Figure 1 shows the user interface of the online DSS.

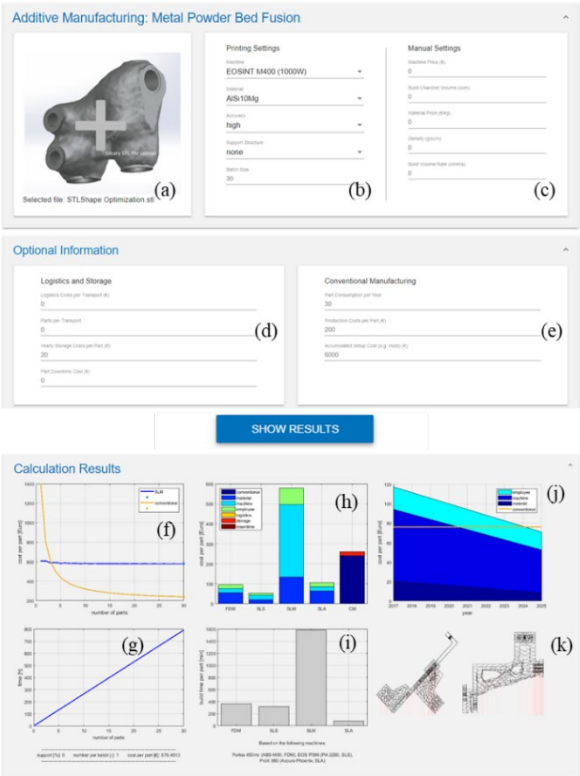

Figure 1. Graphical user interface of the DSS online tool for rapid dimensional, cost and lead time evaluations in metal-based PBF.

The user interface is divided as follows: In Figure 1(a), by clicking on the image, the user can upload a binary STL file of the design to analyse it from a technical (e.g. dimensional verification of the uploaded part) and economic viewpoint (e.g. cost structures and lead times). (b) Printing settings, where the user can select among nine different metal PBF machines, three material types and three accuracy levels that influence achievable maximum build rates in metal PBF. (c) Manual configurations. (d) Logistic and storage considerations. (e) Possibility to consider comparisons to conventionally produced parts including upfront cost of conventional manufacturing. After the user selects the options in the primary menu and clicks on the "show results" button. The calculation results are displayed in: (f) Cost per part and break-even point analysis. (g) Total time function and manufacturing time per part. (h) Stacked bar chart of cost structures (e.g. machine, material, labour, storage, logistics, etc.) and comparison for four AM processes and conventional manufacturing. (i) Build time per part using alternative AM technologies. (j) Future cost projections. (k) Orientation optimizer, part and support structure preview.

2.2. DfAM cases

We include three DfAM cases: (i) re-design of a structural bracket including complexity in terms of cellular structures and topology optimization. (ii) New product design of a heat exchanger with shape complexity and functionally enhanced performance, and (iii) re-design by part consolidation of a clamping system for assembly and welding operation. To simplify the DSS calculations, we select an EOS M400 system in high-accuracy mode for all three cases.

In the first case, we re-design for AM a structural mounting bracket of a Corvette 1988-1996 brake system (*Case 1*). We reverse engineered an obsolete spare part that is often manufactured on-demand due to the difficulty to find original spare part. Figure 2 shows the original bracket design and the DfAM alternative. The re-design introduces micro and macro complexity by lattice design and topology optimization [2]. To obtain the TO version we defined load and boundary conditions (i.e. two compressive forces 300N each at the outer edges of the part and two fixed constrains to the holes close to the centre of the part with the objective to minimize mass).

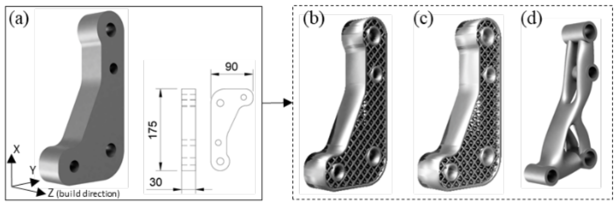

Figure 2. Re-design of a mounting bracket. (a) Original design, (b) and (c) micro complexity by lattice structures, and (d) macro complexity by topology optimization

The second case is a new design by AM of a counter-flow heat exchanger *(Case 2)* [9]. Figure 3 shows the new design of a counter-flow heat exchanger. Ignoring the limitations of conventional manufacturing methods, the new geometry consists of 144 conformally designed narrow square channels placed next to each other, alternating between hot (red) and cold (blue). The reason for using pipes with a small hydraulic diameter is to increase the overall internal surface area of the heat exchanger. Similar performance could be achievable with standard components with increased size of the heat exchanger, but very challenging or nearly impossible for the size of the newly designed heat exchanger. Small channels convergence conformally into a central section that maximizes the heat transfer between hot and cold fluid. Its central functional element is composed of a tightly packed checkerboard with a minimum distance of 1 mm between channels in the centre.

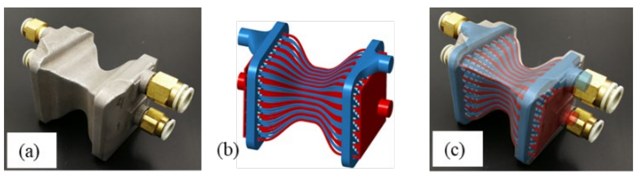

Figure 3. New design of a counter-flow heat exchanger. (a) Detail of the manufactured part made of AlSi10Mg with fitted adapters for hose connections, (b) detail of internal complexity, and, (c) detail of channels superimposed onto the manufactured heat exchanger

The third case is related to a re-design of a clamping system for assembly and welding operations, which is part consolidated introducing complexity at product level *(Case 3)*. Figure 4(a) shows the original design of the clamping system composed of three structural elements, and (b) shows the consolidated design space, loads (i.e. 300 N in the direction indicated in the arrows), constraints (fixed constraints to the base), and the TO version displaying the criticality of the load path. The optimization setting is set to maximize stiffness with a target mass ≤ 50%. In this case, the DfAM process for the clamping system combines both product level complexity by part consolidation and macro level complexity by shape optimization.

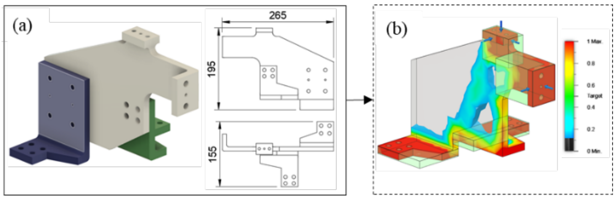

Figure 4. Re-design by part consolidation of a clamping system. (a) Original assembly design, and (b) product complexity by part consolidation including macro complexity by topology optimization

3. Results

Figure 5 shows the value analysis for cost reduction, manufacturing time reduction, and functionality by weight reduction for Case 1. The DSS was used to assess all four-design alternatives: (i) solid original design, (ii) micro complexity by integrating periodical octet truss lattice design with two volume fractions (VF) (i.e., 0.15 and 0.3), which is defined as the ratio between lattice structure volume divided by the bounding box volume , and (iii) macro complexity by TO design. It also displays three common alternative materials described as AlSi10Mg (Al), tool steel SS 1.4404 (St), and Titanium Ti6Al4V (Ti).

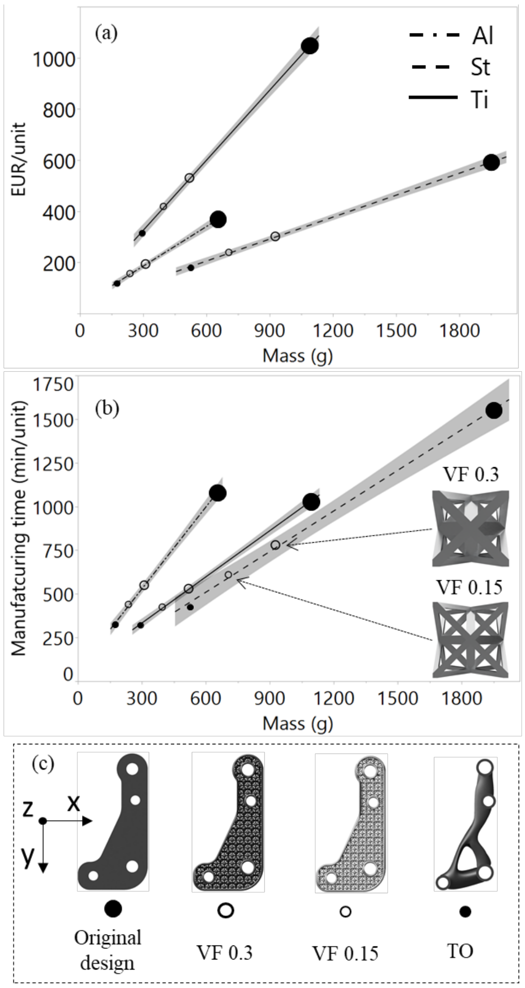

Figure 5. DSS results for Case 1. Weight reduction in grams as a function of (a) unitary cost of production and (b) manufacturing time. (c) Original design and re-design by DfAM including micro and macro complexity

Figure 6 shows the DSS results of the analysis of Case 2. The main diagram displays the unitary cost of production as a function of the production volume using AlSi10Mg (Al) as the preferred alternative. Additionally, the staked bar chart shows the cost distribution in manufacturing including labour, material, and machine cost for a production volume of 100 units. The figure also displays the preview extracted from the DSS as well as the build orientation.

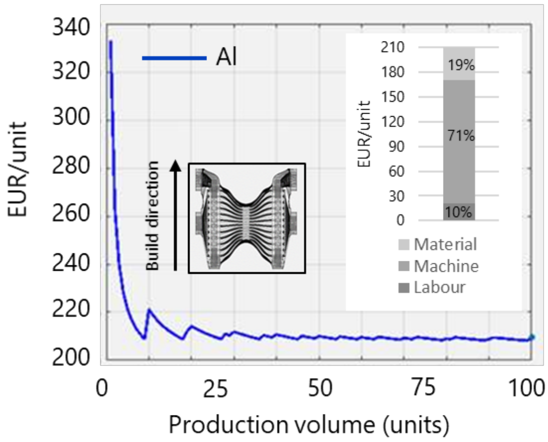

Figure 6. DSS results for Case 2 “new design by DfAM”. Unitary cost of production, stacked chart (machine, materials, and labour cost), and suggested build orientation

Figure 7 shows the assessment of Case 3. Figure 7(a) presents the break-even point analysis of the re-designed clamping system for assembly and welding operations. The figure compares the cost of producing the DfAM version of the part versus a conventional alternative. Figure 7(b) shows the value of DfAM by integrating a combined product and macro level complexity. Therefore, mass and volume is reduced in a two-step DFAM process. First, the initial original assembly made of steel (St) is part consolidated to define the design space. Second, the design space is shape optimized.

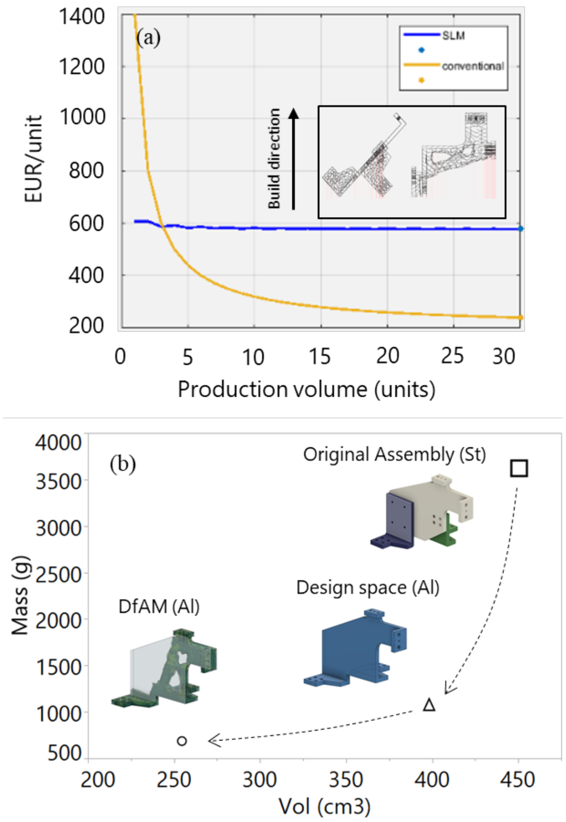

Figure 7. DSS results for Case 3. (a) Break-even point analysis and (b) effect of product level complexity by part consolidation for volume and mass reduction

4. Discussion

The integration of AM into holistic manufacturing processes requires to assess cost-benefit and trade-offs between conventional manufacturing and AM. As an answer to this, we published a freely accessible online DSS that allows users to compare AM versus conventional manufacturing. Additionally, the objective of this research was to measure the value of DfAM in terms of potential cost reductions and productivity increases.

In Case 1, the re-design of the bracket is necessary to make metal PBF a cost-alternative to conventional methods. The value of DfAM in this case is obtained by (i) reducing weight and increasing strength-to-mass ratio, (iii) reducing manufacturing cost, and (ii) reducing manufacturing time. If we take a VF of 0.3 made of Al as a reference, the weight of the bracket design is reduced by 52.5%, from 654 g to 310 g. On average, the integration of lattices reduce the cost of metal PBF manufacturing by 53.7%. Similarly, the TO approach to re-design reduces the unitary cost of production by 59.8% on average. Simultaneously, manufacturing time decreases by 69.9%, 72.6%, and 68.9% for Al, St, and Ti materials, respectively.

In Case 2, the objective was to create new functionality and increased performance by implementing shape complexity, thus manufacturing cost is of minor importance. The DSS assessment shows that the unitary cost of the counter flow heat exchanger in AlSi10Mg (Al) is approximately 210€ and manufacturing time is approximately 10 hours. The new enhanced design cannot be manufactured by conventional methods; and therefore, establishing a break-even point analysis is not useful.

In Case 3, the original clamping system was composed of three parts made of steel S355JR. The re-designed clamping system by part consolidation and TO can be manufactured out of ALSi10Mg. However, this re-design is also manufacturable by conventional methods combining laser cutting, bending, welding, and machining operations. To this end, Figure 7(a) presents the break-even point of 3 units assuming initial set up cost, yearly storage of tools, and material cost for conventional manufacturing. Integrating complexity by DfAM in Case 3 allowed to reduce the number of parts to a single component and reduced the weight of the initial design assembly by 81%; from 3640g made out of St to 687g made out of Al. The unitary cost of production of the re-designed clamping system is 580€ and manufacturing time is estimated to be 20 hours.

Based on the two *re-design for AM* cases (i.e., Case 1 and Case 3), DfAM increases the technical performance by weight-reduction and high-strength/low-mass ratios. Operational performance in metal PBF is obtained by reducing manufacturing cost, delivery time as well as by reducing the need for assembly and handling multiple parts. In both re-design cases, metal PBF becomes an alternative when production volumes are low, there is product variability, and parts need to be delivered fast. In relation to Case 2, the *new design for AM* case, the value of parts with high complexity only manufacturable by AM is limited to gains in technical performance versus existing alternatives. We refer to [9] for a detailed discussion regarding the technical findings on the new design of the heat exchanger enabled by AM.

In summary, integration of complexity by DfAM enhances the operational performance of metal PBF by reducing significantly unitary cost of production and manufacturing time. The design engineering process should make use of DfAM to re-design or create new products with embedded micro, macro, or product complexity and obtain reduced part volumes that fulfil the mechanical and geometrical requirements of the intended application. This allows to increase the feasibility of direct part production using metal PBF and make AM an alternative to conventional manufacturing methods.

5. Conclusions and future work

The cost-effectiveness of metal PBF as a production alternative is dominated by the high cost of metallic powder materials when machine utilization rate is high. This research demonstrates how the competitiveness of metal PBF direct part production is increased when DfAM is integrated in engineering design phases and manufacturing. This is obtained by embedding functionality through shape complexity, weight and material reduction by means of topology optimization, lattice structures, and part consolidation.

The usefulness of the DSS is demonstrated by the ability to screen rapidly production cost, manufacturing time, and break-even point of potential AM business cases versus conventional manufacturing. However, it is better suited to part re-design cases that are mostly linked to the replacement of legacy systems and spare-part applications. As a limitation for further study, the DSS does not consider the cost of additional post-processing steps, such as heat treatments for stress relief and machining operations for increased dimensional accuracy. In addition, this research does not present an in depth study of the technical performance of DfAM re-design cases. Such analysis was out of the scope.

There are several directions for future research. Overall, a systemic approach to DfAM is fundamental to industrialize metal PBF and AM in general. Simultaneously, it is required to develop tailored methods to assess the technological and operational feasibility of the technology. In this context the DSS is currently in expansion to enable automated screening of inventories from CAD, PLM, and ERP data, to extract part information, such as size, material type, expected production volumes, storage information, and supply chain factors. These modifications will allow the automated screening of companies' part libraries to identify the most suitable candidates for AM.

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