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STRATEGIC APPLICATION OF DIGITAL TOOLS TO ENHANCE LIFECYCLE COST: PRODUCT DESIGN AND OPTIMIZATION IN METAL-BASED POWDER BED FUSION

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Abstract: Additive manufacturing (AM) has undergone different phases of technological changes from being a mere manufacturing method for consumer goods, prototyping, and tooling to industrial series production of functional end-use parts. The seven AM sub-categories allow the creation of unprecedented designs that are otherwise impossible using conventional manufacturing (CM) methods. The layer-by-layer approach to manufacturing enables the creation of metal components with hollows and overhangs, often requiring sacrificial support structures which are removed prior to or during the post-processing phase. Factors such as poor part quality, high investment cost, low material efficiency, and long manufacturing time hindered the widespread adoption of AM in the past. The adoption of laser-based powder bed fusion for metals was particularly hindered due to reasons such as the need for support structures, demand for post-processing, the numerous affecting processing parameters and the lack of understanding of the interaction between laser beam and material. Technological advances in AM have helped users reduce or omit some of the limitations to adoption, such as optimized support structures for better material efficiency. Simulation-driven tool is one means offering ways to time-efficient product development and more superior structural components amidst the raw material and cost reductions. This study elucidates how such benefits are feasible via using simulation tools. Simulation-driven optimization of the product design, process, and manufacturing is revealed to change the design, support structures and postprocessing required to bring parts to the required reliability. Virtual manufacturing planning also gives a prior understanding of how processing parameters such as laser scan velocity, laser power, scanning strategy, hatch distance and others can be controlled; to achieve optimal interaction between laser beam and material for the required part quality. Simulation-driven design for additive manufacturing (DfAM) allows for agile design optimizing with design parameters and rules, boosting resource efficiency and productivity. This research proposes a life cycle cost (LCC)-driven DfAM tool, which potentially improves service life and life cycle cost. The results provide insight into the simulation-driven DfAM of laser-based PBF and demonstrate the potential for LCC-based approaches to enhance the confidence in adopting PBF for metals.

1 INTRODUCTION

Advanced manufacturing technologies, such as additive manufacturing (AM) [1] and advanced machining [2,3], allow for producing discrete metal parts with unique, precisely and significant reduced mass that still satisfy structural and other functional requirements [4]. Manufacturing methods can either be additive, subtractive, joining or formative. Additive methods (a.k.a. 3D printing), create parts by adding material layer-by-layer in contrast to subtractive methods [5] such as cutting and grinding which produce parts by removing material from a workpiece. This study is limited to laser-based powder bed fusion (L-PBF), a sub-category of powder bed fusion (PBF). PBF is one of the seven main categories of AM. Some aspects of these manufacturing systems have not kept up with advancements in these methods and thereby fail to apply them for the needed benefits. Insufficient knowledge of available software and hardware [1,6] that provide adequate means of fully utilizing the advantages of design complexity may be limiting. The correct use of product design for AM and software solutions are primary steps to enable AM users to make "first time right" and durable parts capable of extending useful life. The activities of industrial engineering are, in practice, both business and engineering centered [7]. A design of components must consider whether using a specific manufacturing method will satisfy the intended requirements. The requirements may include better reliability, functionality, durability, aesthetics, customization, resource efficiency, cost efficiency, or a combination of these, depending on the use case [1,7]. An optimal design is often required to satisfy different functionalities such as reduction of mass, stresses and deformation [1]. AM offer a means to functionality-driven designs with no or negligible manufacturing difficulties [8]. Ensuring that the component will offer added value is one of the central aspects of business strategies that must be considered. This strategy will require well-informed decision-making regarding which comparable methods and digital tools (e.g., AM or computer numeric control machining (CNC-machining); SolidWorks or nTopology) give the needed advantage to thrive in ongoing competitive environments.

The flexibility and swiftness of product design and manufacturing with metal AM and digital tools (computational design and simulation) allow on-demand manufacturing to meet market needs, thereby replacing the conventional operational models of make-to-order (MTO) and make-to-stock (MTS). Such disruptions are facilitated through a single-seamless strand of data that stretches from the initial design to the finished part, referred to as the digital thread. The digital thread of AM enables the creation of optimized components capable of swift response to industrial value chains via design iterations, data management and inventory [4]. Value chain analyses (VCA) can help identify aspects of the supply chain needed to optimize either for cost or differentiation advantage [9].

Metal AM refers to a layer-by-layer manufacturing of three-dimensional physical components from a digital file using metal material. Some benefits of the metal AM are functionally-graded designs, design consolidation, design complexity, better-optimized products, reduced time to market, localized manufacturing and resource effectiveness [4,10,11]. Product design in the case of AM considers the selection of the right design, suitable material, hardware, software solutions, quality assurance, etc [12,13].

Metal AM has inherent limitations that need conscious design and planning to offer benefits along with the design, manufacturing and use phases. This study aimed to identify the hotspot in metal-based AM that can be targeted to improve costs via lifecycle thinking (LC). LC thinking summarizes tools and actions to achieve these goals with a life cycle approach, including the supply chain steps of products/services, from the cradle to the grave. Life cycle costs (LCC) in the case of AM consider all the expenses from design, manufacture, use and end-of-life phases of products.

The success of the adoption of metal AM may not advance solely on the speculative benefits of the process. There is the need to gain a prior understanding of the distinct capabilities of AM among different players for effective and broader adoption. Many adopters of AM do so with a set of conventional product designs without prior knowledge of AM design aspects [14]. The efficient and effective use of computational software and the readiness to implement good supportive strategies at the management level is equally essential to ensure that metal AM offers the anticipated advantages. Digital tools are useful in AM as the entire process chain can be controlled and managed using data from geometry preparation, design optimization, validation, and reworking, build preparation, pre-/actual- post-build simulation, and quality assurance/documentation. Simulation-driven design for additive manufacturing (DfAM) is one working method revolutionizing industrial AM product design. This method combines the abilities of digital tools to design optimized parts in conformity to AM-specific design considerations to ensure their printability [15]. The right digital tools and their proper use with DfAM could yield in-time efficiency, swift product development and produce superior structural components. These benefits amidst the introduction of new raw material and multi-laser L-PBF machine systems are promising to cost reductions in metal L-PBF.

2 METAL ADDITIVE MANUFACTURING

Additive manufacturing (AM) is the *process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies*. ISO/ASTM 52900:2021 [16] categories AM into seven main groups, namely, powder bed fusion (PBF), binder jetting (BJ), material jetting (MJT), directed energy deposition (DED), material extrusion (MEX), sheet lamination (SHL) and vat photopolymerisation (VPP).

1) PBF: is *an AM process in which thermal energy selectively fuses regions of a powder bed.*
2) BJT: *is an AM process in which a liquid bonding agent is selectively deposited to join powder materials*
3) MJT: is *an AM process in which droplets of build material are selectively deposited*
4) DED: is *an AM process in which focused thermal energy is used to fuse materials by melting as they are being deposited*
5) MEX: is *an AM process in which material is selectively dispensed through a nozzle or orifice*
6) SHL: is *an AM process in which sheets of material are bonded to form a part*
7) VPP: is *an AM process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization* [16].

The different AM categories can manufacture any shape with a vast range of single or multi-materials, including polymers, metals, ceramics, composites and paper [4,10,17]. Metal products are possible via PBF, BJT, DED, MJT, and SHL. L-PBF, one of the sub-categories of

PBF, is the most matured and widely used for industrial application [11] and is suitable for several metals, including aluminum alloys, stainless steel, and titanium alloys, nickel alloys, metal-ceramic composites [18]. Some of the key advantages for the use of L-PBF are high resolution, dimensional accuracy, design flexibility, customization, better-optimized products and lightweight [10,11,19]. L-PBF also offers advantages such as the flexibility to throughput [20] by controlling the build volume [21] and build rate with multi-laser systems [22]. The more efficiently the platform space is used for combined built, the better the lead time [4]. L-PBF, via the use of DfAM (including software, tools, and training), can help create components that offer lifetime cost-effectiveness. Studies [1,11] have shown that DfAM can reduce total manufacturing cost example by 54% via the reduction of feedstock, pre, build and postprocessing time [19]. The cost of well-sophisticated digital tools that give the possibility to vast design, the limited number of materials and the lack of suitable standards continue to hinder the wide spread of AM [14,23]. The continuous development of suitable low-cost software, machine systems, new materials and standards such as ISO/ASTM 52911-1 and ASME Y14.46-2022 are promising to democratize and streamline metal AM for a wider adoption [14,24,25].

2.1 Digital tools for product design in metal AM

Natural patterns and shapes are poised with beauty, complexity, lightweight and aesthetically pleasing though, mostly non-prismatic [10,26]. Examples of such include honeycomb, lattice, web-like and form-like. Shapes can broadly be classified either as organic or geometric [27]. Organic shapes originate from nature and thus have no defined reading for the shapes making them more flexible but less accurate. Geometric shapes are formed based on defined readings making them more accurate but less inflexible. The modern-day industrial era requires a combination of both shape characteristics to satisfy the requirements. Designing and engineering are constantly finding new ways to maximize time, resource efficiency, performance, and overall cost. However, the conventional manufacturing (CM) methods do not allow such benefits to be fully tapped as only the permissible designs based on available tools, fixtures and materials are possible. CM methods often require considering possible machine constraints and may need redesigning or multi-manufacturing steps to make organic-geometric designs, if possible. AM gives the freedom to tap the full potential of nature-mimicked designs (see Figure 1) to maximize functionality.

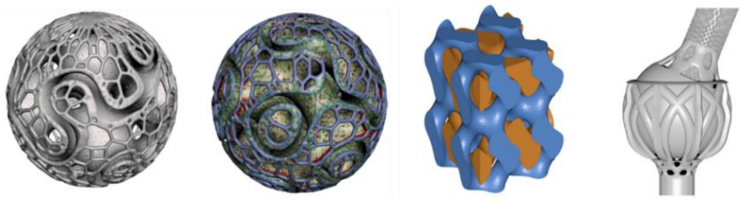


Figure 1: Simulation-driven designs that are feasible with AM, color variation indicates multi-materials. Reproduced from [26]. Pending permission from The American Society of Mechanical Engineers.

As Figure 1 shows, AM can feasibly manufacture unique parts geometry with multi-transitional features (shape, multi-material) of low to high degrees of complexities [26]. Digital tools allow such designs to be generated [11] and manufactured correctly on the first run. The concept of "first time right" in advanced manufacturing systems is key to reducing the amount of downtime, faulty products, and extra costs while maintaining functions or meeting requirements. This concept is mostly achieved using digital tools for designing, validating, manufacturing, monitoring, and testing. Computer and numerical-based interaction software have helped reduce workload and product design time. Product design in AM significantly benefits from the ability of digital tools and DfAM to create successful products. The product design in metal AM consists of rules and guidelines limiting allowable and successful features for AM. Product design in AM considers the selection of materials, processing parameters, postprocessing, quality assurance, software, and hardware.

Digital tools help achieve optimal control and optimum designs [7]. Optimal control systems offer a means to increase throughput with automated system controls. Optimum designs offer means to optimize objective function to create better elements of components to increase throughput [7]. Some machine systems are equipped with monitoring systems that observe a manufacturing process via different sensors or cameras and halt the process in case of any identified output fluctuations [7,28,29]. Some of the existing AM machine systems are equipped with feedback controllers that offer closed-loop system to produce the desired output with adaptive processing parameters controls [29]. Examples of such systems integrated in AM machines areVELO3D intelligent fusion and Interlayer Realtime Imaging & Sensing System (IRISS®). AM machine systems equipped with such systems automatically adjust parameters to correct fluctuating condition and optimize performance. These ensure continuous manufacturing without the need to halt the build process in the event of any [30,31]. Creating optimized designs via generative design or topology optimization software eases the workload and offers better time efficiency for creating organic and geometrically complex shapes. These advanced simulation-driven design tools are promising to achieve features which are otherwise not possible with parametric modeling [27].

The Aim and purpose of this study were to elucidate the role of simulation driven-software in PBF and to evaluate their potential to create optimized designs to reduce weight and increase stiffness without comprising the performance of metal components.

3 COST STRUCTURE IN METAL AM

The costs in metal AM significantly differ from CM methods and other material-based AM. Again, the discrepancies in costs also exist for the different metal AM methods. A comparison of common metal AM may differ by example, part resolution, part size, type and form of feedstock. The various AM methods can be used to manufacture components based on the desired resolution, complexity and size of the component. The quality of the constituent, part size and flexibility to manufacture intricate designs can affect the cost for the different metal AM sub-categories. The different AM sub-categories can make components of varying complexities, resolutions, and sizes [17,32]. While BJ or PBF may be a good option for high complexity and resolution, parts size limits their application to only about 1 cm to 10 cm components. DED, on the contrary, is capable of making parts up to 1 m but often with lower resolution and may not be suitable for high complex designs. Factors such as machine systems, software solutions, feedstock, support structures, and quality assurance also contribute to cost differences. To avoid operational surprises, adopters of AM need to critically understand how such factors can affect the overall cost of their product before investing in the process. The contributory elements to the cost of metal AM can sometimes remain hidden until encountered in the product design. Such costs in metal PBF include qualification testing, overhead costs such as support staff, monitoring, consumable costs (for example, gases), build plate removal, lighting and cleaning [33].

Some major contributing factors to the costs of metal AM products are design costs, build time, machine costs, and feedstock costs, pre-and postprocessing costs [1,20,23,24,34,35]. Efficient use of feedstock reduces the part cost, and this can be achieved with reduced production runs, parts weights and support structures. The build time, which depends on the part height and build volume, is closely tied to machine cost [20,23]. In PBF the build rate directly contributes to manufacturing cost. The longer it takes to build a part, the more the total cost of manufacturing. Likewise, the less quality feedstock the more there will be repeated production run due to part defects. The use of high quality feedstock and multiple lasers (high power) offer a means to increase the build rate though at a much higher cost [20,36]. A consideration of the potential lifetime usage of more expensive feedstock and L-PBF machine amount to high-cost savings due to its ability to increase build rate [20].

The manufacturing phase of metal AM can maintain a constant cost structure while increasing complexity [8,36] compared with comparable manufacturing methods such as CM. AM is characterized by the notion that “complexity is for free”. Manufacturing products with intricate designs are often labor intensive and may require more tooling and lead time when using CM methods [4]. The manufacturing cost structure for AM and CM based on complexity and batch size are compared in Figure 2.

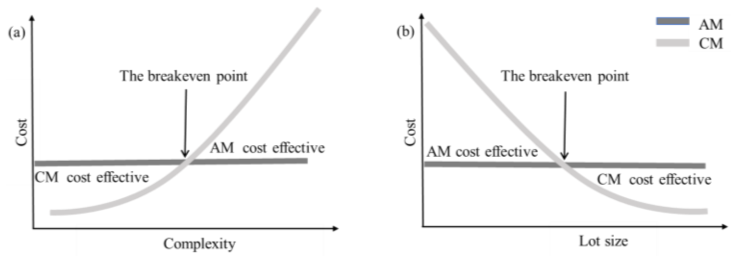


Figure 2: Illustration of influence of (a) complexity and (b) lot size on the cost structure of AM and CM. Adapted [8].

As it can be seen from Figure 2, the cost of manufacturing with AM remains constant regardless of the increased complexity. This stability implies that component designs that may be difficult to manufacture conventionally [11] may be considered for AM e.g. lattice [13] and scaffolds-like designs [12]. CM, however, may be a cost-effective option for making components requiring minimal intricacy. The breakeven point (BEP) marks the border at which total revenues equal total expenses [37]. BEP analysis can be used to select the best points at which comparable methods are most cost-effective as shown in a comparable study of high-pressure die-casting (HPDC) and AM [38]. Nearly all new technologies, including AM, incurs losses during the early stages. Cost comparison in manufacturing is most effective only after the maturity stage [39]. The investment cost of AM is often criticized as high and often deter admirers from entering. These investments are mostly unavoidable before profits, regardless of know-how [40].

3.1 Case example

A simple equation to estimate the part costs based on the four main cost factors has been presented in this study [23]. However, it does not include a practical evaluation of costs. A simple case of a stainless steel 316L was performed in this study to compare how software can benefit the design process in AM. Two computer-based software was utilized, namely, SolidWorks and nTopology. The design optimization was done with two different software (1) topology (SolidWorks) and (2) lattice (nTopology) due to the limitation of the former to generate lattice structures. Industrial software packages may, however maybe more equipped to create all types of designs. The basic plate and the two optimized designs will be referred to as Part A, Part B and Part C, respectively, hereafter.

This case study briefly introduces topology, lattice design optimization, static stress, and displacement. A basic one-body model referred to hereafter as Part A is a simple rectangular plate with dimensions 100 mm by 50 mm by 5 mm for length, height, and width respectively. The goal of the design was to reduce mass as possible (50% minimum) and increase stiffness for the final parts without compromising on the ability to withstand the used force. The effect of build orientation and build platform utilization on manufacturing time was also evaluated. The stepwise approach to design optimization and virtual manufacturing is shown in Figure 3.

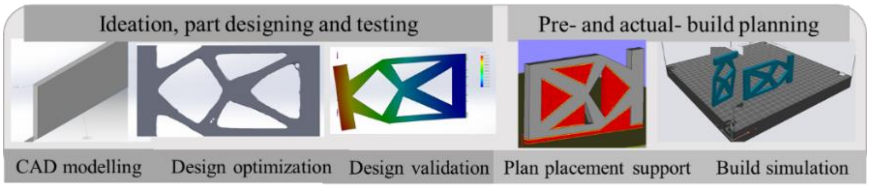


Figure 3: Illustration of simulation-driven DfAM workflow for design case.

As Figure 3 shows, the start-up CAD model (100 mm x 50 mm x5 mm), part optimization, validation of the optimized design, pre-build, and actual build planning can virtually be organized and accomplished. Digital tools allow defining material properties (e.g., stainless steel 316L) in this case. Design constraints (e.g., plate was fixed from one of the short edges) and structural loading (e.g., 100 N force along the edge of the plate) can be defined to run static or dynamic studies. System interoperability of digital software allows for the exchange of files for further studies or optimizing (e.g., SolidWorks CAD model to nTop for lattice optimization). Pre-selection and testing of build orientations and processing parameters virtually offer means to optimize manufacturing and reduce /omit faulty build cycles.

The build time and cost for L-PBF parts can be estimated using equations 1 and 2, respectively [23].

$$Build\ time = \frac{\frac{(Part\ Volume)}{(Build\ Rate*80\%)} + \frac{(Max\ Part\ Height)}{(Layer\ Height)}*(Recoat\ Time)}{3600} \quad (1)$$

$$Total\ AM\ Part\ Cost\ (€) = \frac{(Build\ Time)x(Machine\ Operating\ Cost) + Material\ cost}{(1 - Pre-(or\ post-)Processing\ Cost\%)} \quad (2)$$

The material properties of SS 316L and processing parameters used are shown in Table 1.

TABLE 1: Material properties and process parameters (* Horizontal / **Vertical) orientations)

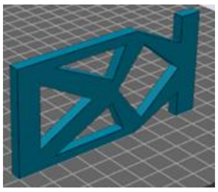
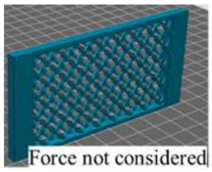
Density (kg/m^3)	7900	System manufacturer and user-defined inputs Supports structures not considered due to lack of license
Modulus of elasticity (GPa)	210	
Poisson's ratio	0.3	
Build Rate (mm^3/s)	3.0	
Layer Height (mm)	0.04	
Recoat Time (s)	10	
Maximum Part Height (mm)	50* / 100**	
Part Volume m/*p* (mm^3)	Part A, 25000; Part B, 15075; Part C, 9860	

As Table 1 shows, the virtual planning of the build considers two different build orientations for the different parts varying the maximum build height as 50 mm and 100 mm, respectively, for horizontal and vertical orientations. For equal comparison, other parameters were kept the same for this case. A practical case might, however, increase the build rate and layer height to optimize the build time. The values used also bring the estimated and software values a par.

3.1.1 Results

Optimally complex and o8optimized designs via the democratization of software that feature intricate geometries can be manufactured with AM. The resultant of the design optimizations in Part B and Part C and build time are shown in Table 2.

Table 2: The main result of the case study for the base, topology, and lattice plates.

*denotes horizontal orientations ** denotes vertical orientations			
Mass (g)	198	119	77.9
Mass saving (%)	-	39.8	60.7
Von misses stress (Mpa)	6.04	8.77	27.0
Virtual build time (h)	5.40* / 9.10**	4.51 / 8.21**	4.28* / 7.58**
Estimated build time (h)	6.37* / 9.85**	4.79* / 8.69**	4.61* / 8.09**
Virtual combined build time (h)	25.3* / 29.1**	17.1* / 20.6**	13.3* / 13.3**
Estimated combined build time (h)	32.4* / 36**	20.9* / 24.4**	14.9* / 18.4**
Estimated cost 1part with * (€)	276	228	214

As Table 2 shows, the results of comparable weights, stress, and displacement for the different plates highlight how topology or lattices improves resource efficiency and performance. The result of this study is validated by the software-generated build time and the calculated build time for both horizontal and vertical orientations. The orientation and part volume can be optimized to control the build time with comparable process parameters, as shown in Table 2. The reduced weight and the ability to manufacture parts of increased complexity can reduce the build volume, thus the time and costs in agreement with studies [8,36]. The optimized components potentially also offer use-phase reduced cost and energy use as lightweight components consume less amount of energy. The differences in stresses for the optimized parts require empirical testing to validate their ability to withstand operational forces against that of the base plate. Using such a virtual design optimization case study highlights digital tools' potential for cost benefits in PBF without committing to physical manufacturing trial and error. Such may be used to guide decision-making and help strategic planning to facilitate the acceptance of metal PBF.

3.2 Strategic adoption to metal PBF

The LC benefits of AM adoption may be enhanced through optimized designing, expert-led technology transfer of information to accelerate lead time, learning and implementation [4]. Value chain analyses (VCA) and strengths, weaknesses, opportunities, and threats (SWOT) models of metal AM prior to adoption could potentially identify the best entering level and opportunities that may be used to improve the value and create long-term cost benefits. Applying simulation-driven DfAM software with AM does not necessarily translate to increased efficiency. Management needs to monitor process efficiency (right things) and process effectiveness (results). Efficiency is the right use of the right resources, such as the right usage of available resources (machines, equipment, materials, software, workforce, time, and so on). Efficiency involves resource consumption improvement alongside a decrease in waste. Effectiveness at the managerial level ensures there are right things and demonstrates how well a procedure satisfies a request. Managers in manufacturing industries must ensure that the skills of personnel are appropriately used with tangible and intangible resources to satisfy the objectives of the company as well the desires of customers. Different strategies such as communication, research support, training to increase workforce skills, and adequate digital software are needed to control resource efficiency and cost-efficacy and promote the wellbeing and inclusiveness of all personnel. Good communication among the value changers (management, engineering, production, etc.) within the work chain could guarantee successful implementation and working strategies for benchmarking the process a broader adoption [14]. Effective measures will swiftly be taken to yield the expected results with documented and available information. Figure 4 is a schematic of how the required efforts may be used to subdue or propagate the realization of the benefits of metal PBF adoption.

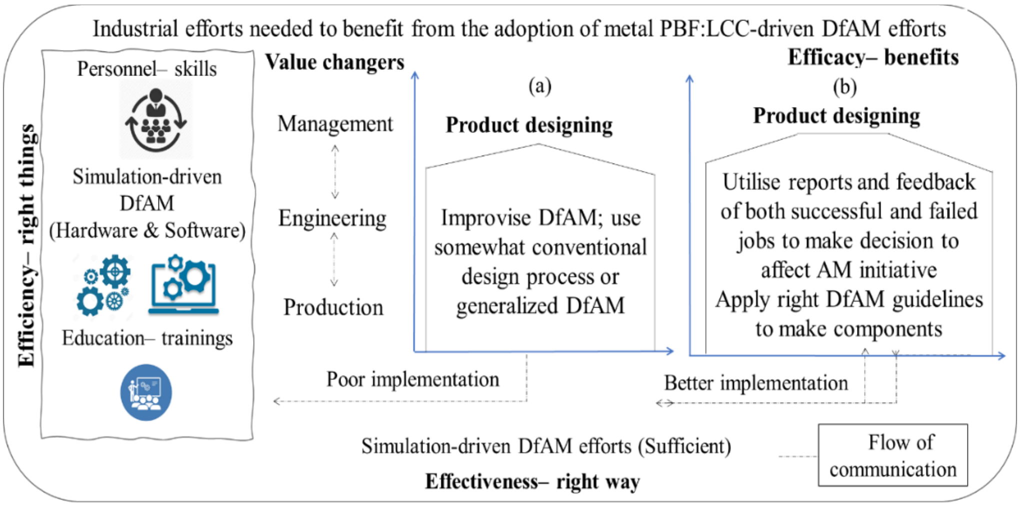


Figure 4: Representation of (a) one-way and (b) two-way information flow to the adoption of metal L-PBF.

The models in Figure 4 depict how communication flow may be ineffectively or effectively used to control costs or increase efficacy benefits. The proper or improper implementation of metal PBF can affect productivity within the value chain. The implementation with Figure 4(a) shows a one-way flow of information and the lack of needed DfAM efforts. This strategy may improvise traditional design for manufacturing and assembly (DFMA) for DfAM effort or, at best, use generalized DfAM rules for metal PBF without considering the process-specific considerations. Top management may not understand the need for simulation-driven DfAM. This lack of understanding may negatively affect the decision-making in such instances based on successful or failed build rates without considering the root causes. The adoption plan in Figure 4(b) shows a reciprocal two-way communication between the different operational levels and adequate DfAM efforts. The strategy involves all levels of personnel to understand specific metal PBF constraints and make decisions considering both successful and failed components. Decision-makers can efficiently and effectively integrate digital tools along the value chain to enhance value, time, energy and material efficiency. This model could potentially yield material efficiency and create components of a higher value that can offset the much-publicized high energy consumption in metal PBF.

3.3 Discussion

Metal AM continues to emerge as a technological disrupter for different sectors that benefits from the numerous flexibilities, customization, and lightweight, functionally graded designs it offers. These capabilities help high-end manufacturing industries such as medicine, aviation, energy, and automotive create intricate internal designs, conformal channels, organic-geometric transitional shapes with process-dependent properties, and heterogeneous material properties for better performance, resource, operational and cost-effectiveness. There is limited knowledge regarding how the enormous benefits of adopting metal AM can be realized. Design for additive manufacturing (DfAM) is an emerging field in design engineering fostering the uptake of these unique capabilities of AM. The use of digital tools along the value chain of AM and the right DfAM guideline eases workloads and reduces developmental time, manufacturing steps and costs whilst giving the freedom to generate complex gradient designs and to manufacture inseparable pre-assembled elements objects by simply specifying design performance. The benefits of simulation-driven DfAM offers to the LC of AM products include increased quality, resource efficiency, mass customization, and on-demand and localized manufacturing. The components' energy consumption and the number of replacements that will be needed during their service life can be controlled during the design phase. Creating more resource-efficient parts with better durability is an example of how such goals could be attained during the use phase. Most L-PBF existing systems require closed-loop controlling systems to complete the already possibility of halting the build process to maximize resource and cost-effectiveness. There is a need for continuous development of advanced software and a better understanding of DfAM guidelines. Efficient and high-fidelity simulation algorithms will be required in order to analyze and synthesize complex shapes, constraints and specifications [1,41]. AM allows mass customization and serial production at a low volume. Increasing the number of components can reduce the production costs of AM until the breakeven point (SEE Figure 3). The cost increment after the breakeven may be attributed to part size and build platform limitations. Utilizing such an analysis will allow companies to compare competing methods and identify the most economically viable option. There is a need to understand the cost structure and related factors that can influence economic choices. Simulation-driven DfAM must be used to create optimized designs that will allow cost reductions via seamless collaborations between co-design creation, quality assurance and data management of the final components while creating superior products for the use phase.

4 CONCLUSIONS

- Digital tools (computational design and simulation software) allow a quick iteration of product design and system interoperability to achieve new designs that are aesthetically pleasing, lightweight, resource-efficient, cost-effective, and structurally sound. These benefits safely equate to savings in workload, time and costs, as Table 2 illustrates.
- Digital tools give Engineers the power to create designs that are beyond human ability and the keys to fine-tune the generative designs to suit the process-specific guideline.
- Digital tools help simplify the whole value chain of products by way of the auto generating ready to or almost ready-to-build part and processing parameters (see Figure 3). These tools also automate supporting reports for documentation, marketing, or communicating with other working teams and stakeholders.
- Simulation-driven DfAM improves working and resource efficiency and overall manufacturing cost with the right planning.
- Optimized and better functioning components offer use-phase energy and cost efficiencies.
- Inefficient use of digital tools can prolong the design and manufacturing phase time and even result in unsatisfactory part designs.
- Ineffective communication between administration and design engineers during the adoption of simulation-driven DfAM can cause delay or failure. Both ways must share information to reach the optimal set goals (see Figure 4).

Recommendations for further studies could include an LCC study for selecting design/process alternatives based on the created LCC-driven DfAM model with empirical data. Experimental validation with a practical industrial case study. Further development of LCC-driven DfAM.

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