Metal Additive Manufacturing: Cost Competitive Beyond Low Volumes

Additive manufacturing (AM) is increasingly of interest for commercial and military applications due to its potential to create novel geometries with increased performance. For additive manufacturing to find commercial application, it must be cost competitive against traditional processes such as forging. Forecasting the production costs of future products prior to large-scale investment is challenging due to the limits of traditional cost accounting’s ability to handle both the systemic process implications of new technologies and the cognitive biases in humans’ additive and systemic estimates. Leveraging a method uniquely suited to these challenges, we quantify the production and use economics of an additively manufactured versus a traditionally forged GE engine bracket of equivalent performance for commercial aviation. Our results show that, despite the simplicity of the engine bracket, when taking into account the part redesign for AM and the associated lifetime fuel savings of the additively designed bracket, the additively manufactured part and design is cheaper than the forged one for a wide range of scenarios, including at higher volumes of 2000–12,000 brackets per year. Opportunities to further reduce costs include accessing lower material prices without compromising quality, producing vertical builds with equivalent performance to horizontal builds, and increasing process control so as to enable reduced testing. Given the conservative nature of our assumptions as well as our choice of part, these results suggest that there may be broader economic viability for additively manufactured parts, especially when systemic factors and use costs are incorporated. [DOI: 10.1115/1.4035420]

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many of these parts, which can often be found in safety-critical applications [4].

For AM to be introduced into such applications, it must be cost competitive. Forecasting the production costs of future products prior to large-scale investment is challenging due to the limits of traditional cost accounting’s ability to handle both the systemic process implications of new technologies and cognitive biases in humans’ additive and systemic estimates. Here, we leverage a method uniquely suited to these challenges: process-based cost modeling (PBCM). We focus on the case of a GE engine bracket for civil aviation applications. This simple part allows us to create a conservative estimate of metal AM (MAM) cost-competitiveness without the likely additional benefits of parts consolidation. We quantify the production and use economics of an additively manufactured versus a traditionally forged bracket of equivalent performance for commercial aviation.

Our results show that, despite the simplicity of the engine bracket, when taking into account the part redesign for AM and the associated lifetime fuel savings of the additively designed bracket, the additively manufactured part and design is cheaper than the forged one for a wide range of scenarios, including at higher volumes of 2000–12,000 brackets per year. Opportunities to further reduce costs include reducing material prices without compromising quality, producing vertical builds with equivalent performance to horizontal builds, and increasing process control so as to enable reduced testing.

The rest of the paper is organized as follows: a discussion of our methods, background on the case study that we selected for analysis, additional details on our data collection and model development, a discussion of our results, and possible areas for future work.

Methods

Assessing the cost of new technologies prior to investment has been a long-standing challenge [5–8]. Most traditional costing methods, such as total cost of ownership or activity-based costing, rely on historical data and statistical or parametric methods to calculate costs based on similarities between current and past products or processes [16]. Generative methods base cost projections on the details of production requirements to achieve a desired output of good brackets. To transform this model of production for a new design to a model of cost, we simply multiply each of the inputs by its price (e.g., material prices, wages, electricity prices, machine prices, building prices, or land prices).

A PBCM consists of three main parts: decision rules, inputs, and model architecture. With the complete set of decision rules and inputs, the outcomes of any model can be reproduced. The architecture of the model has no consequence for outcomes; it is simply how the decision rules and input data are organized so as to maximize the model’s user-friendliness, user-transparency, and developer flexibility.

The decision rules, which can be described in their entirety by a set of mathematical equations, can be found in Appendix A, which is available under the “Supplemental Materials” tab for this paper on the ASME Digital Collection. These mathematical equations describe both the relationship between design decisions and their consequences for process and also the operating rules of the production facility. We base these rules on production methods we observe on the shop floor for existing designs as well as any methods specific to the emerging design or production process being modeled.

The inputs for the model are based on empirical design and production data we collect with engineers in laboratories (in some cases for the emerging technology) and on-site at firms. To collect this data, we conduct interviews with experts to identify typical values for such inputs and how such inputs may change with production ramp-up and with broader contextual or environmental changes over time. We collected input data for 13 facility-wide variables as well as 13–21 variables for each process step. These variables for which we collected input data can be found in Tables 5A–5C, which are available under the “Supplemental Materials” tab for this paper on the ASME Digital Collection.

We then run sensitivity analyses and what-if scenarios across the full range of decision rules and production inputs expected by developers and observed across the firms, as well as potential future values expressed by engineers and firm respondents. This sensitivity analysis examines input ranges of several variables, including build orientation, material price, machine price, cycle times, and destructive testing to determine the effect of variation of each input on total unit cost.

Lightweighting Benefit Analysis. To evaluate the lightweighting benefits of the additively manufactured parts, we calculate the net present value (NPV) of potential fuel savings achieved by using the lighter weight AM bracket. Using jet fuel price data from the last 15 yr (Fig. 1), we assess the jet fuel cost savings per kilogram per year for the highest, lowest, and average prices found across that 15 yr period [30].

To calculate the fuel savings of the additively manufactured bracket over the traditional bracket, we estimate the lifetime fuel consumption of an aircraft per unit weight. Fuel use depends not only on the equipment using the fuel, but also on many other factors such as maintenance practices, airport traffic, and pilot skills. We assume that a 1% reduction in an aircraft’s operating empty weight would approximately translate into a 1% reduction in the fuel needed (Table 1). We obtain the operating empty weight of several aircraft of the Boeing family (727–777) from Boeing’s airplane characteristics for airport planning [31] and round them to two significant digits, as shown in Table 2.
We then do a first-order estimation of fuel savings based on a method used by Boeing that provides the average fuel savings per year associated with a 1% reduction in fuel [32]. We compute the equivalent annual fuel savings per unit mass (Table 3), and multiply them by the weight savings of the modeled additive manufacturing bracket (1.66 kg). We use the average value of the savings across the different models as our reference. Assuming a constant fuel price, we compute the net present value (NPV) of those annual savings over 10 yr using a 7% discount rate via the following equation:

$$\text{NPV} = p_{fuel} \times S \times \sum_{i=1}^{N} \left( \frac{1}{1 + r} \right)^i$$  \hspace{1cm} (1)

where $N$ is the number of years, $r$ is the discount rate, $S$ is the average annual fuel savings, and $p_{fuel}$ is the jet fuel prices. Plugging our best and worst fuel values found in Table 1 into Eq. (1), we obtain the ranges for the net present value of the fuel savings (see Table 4). The two last columns in Table 2 contain the estimated interval for the annual fuel savings from the reference document.

### Case Selection

To assess the cost of a MAM design versus a traditional one, we chose a simple one-to-one part redesign for which performance equivalency with the traditional part had been tested. This simple part allows us to create a conservative estimate of MAM cost-competitiveness without the likely additional benefits of parts consolidation. We sought a publicly available part design for which full data could be shared in a publication, and where both the traditional and MAM redesigned parts serve the same functional purpose. The case we chose, the “TJ2” aerospace engine bracket, which won second place in the GE Engine Bracket Challenge, provides an ideal case study. The engine bracket has public designs for both additive and conventional manufacturing, and while the two designs serve the same function, the additive design boasts a >80% weight reduction over the conventional design (while retaining all required mechanical properties for industrial use) [33]. As can be seen in Fig. 2(b), the additive design would be extremely difficult or impossible to produce via traditional manufacturing. The material for both the conventional and the additively manufactured bracket is the titanium alloy Ti-6Al-4V (Ti64), an industry standard for high-temperature applications, known for being light weight, high strength, and corrosion resistant. In 2015, GE sold over 3300 engines [34]. If this engine bracket were installed at four brackets per engine in all of those sales, then this would total an annual production volume of approximately 13,500.

### Process Data Collection and Model Development

To collect information on the process steps and commercial production operations requirements, we worked with 14 companies, including metal additive manufacturing product producers, material, and equipment suppliers, as well as one of the three university laboratories in the country with commercial-grade direct metal laser sintering (DMLS) and electron beam melting (EBM) machines. The specific commercial-grade machines at the university laboratory are from Arcam (S12 model) and EOS (M290 model).

### Process Flow and Process Step Inputs

The process flow for each of the four systems is shown in Fig. 3. A comprehensive list of inputs can be found in Appendix B, Tables 6A–6C, which are available under the “Supplemental Materials” tab for this paper on the ASME Digital Collection. The facility-wide inputs, which are the same for all four systems, are shown in Table 11. The sources of the data collected can be found in Appendix B, Tables 7A–7C, which are available under the “Supplemental Materials” tab for this paper on the ASME Digital Collection.
For the MAM process flow, we assume that a user has already optimized the part design, converted it to a stereolithography (STL) file, and oriented the part for the AM build, and that the machine has already been set up for this specific build. Our model then begins at the build step. We collected data on three MAM machine suppliers. Two of these are equipment suppliers of DMLS technology and one of these is EBM technology. For the build step, we worked with each supplier and the academic lab to obtain build times for the particular build orientations, batch sizes, and production parameters required for the engine bracket. The base case build time for each system is estimated by each equipment’s build simulation tool.

We also collected data on seven pre and postprocessing steps for both forging and AM. Given the bracket design and the DMLS and EBM suppliers in the final analysis, only four of the postprocessing steps on which we collected data were in the end necessary for the AM analysis. The postprocessing required between EBM and DMLS systems are slightly different: EBM does not require a heat treatment step for stress relief, but DMLS does. In our process flow for the bracket design, the remaining postprocessing steps (wire electrical discharge machining (EDM), hot isostatic press (HIP), and shot peening) are the same for the three equipment platforms. Finally, given AM’s nascent role in aerospace production, destructive testing must be performed to ensure quality and repeatability.

To ensure uniform comparison between forging and AM, we constructed a PBCM of a hammer forging process, which would be the most likely production method for the traditionally designed GE engine bracket (Fig. 2(a)). Our data was primarily obtained from the Forging Industry Association. The forging process includes induction heating, forging, heat treatment, grinding, multi-axis milling, and wire EDM. In contrast to MAM, testing for forging is nondestructive, as is standard for forged aerospace parts, as forging is a well-documented process with high consistency and repeatability.

**Machine Dedication.** In all scenarios (best, base or worst), we classified the forging machine as nondedicated. Since production of the target annual production volume of brackets would take such a small amount of time (approximately 25 days), it is likely to be fully utilized in a production environment for other products the remainder of the year. The Forging Industry Association respondent confirmed that given how low the engine bracket volumes were and how fast the entire year’s throughput would be completed, the forging machine would not sit for 11 months of the year without any other work put on it. Thus, we assume that the forged machine is producing other parts when not making the engine bracket.

In the MAM case, if the machine is not fully utilized, it cannot be used for other parts because of current Federal Aviation Administration (FAA) safety regulations. Specifically, a FAA Production Certificate certifies that the applicant has established a robust quality system and supplier control to ensure the replicability of the properties, which appear in the type certificate (TC) [37]. Once production approval is granted, the manufacturing process is “frozen” under configuration control, meaning that any change made to the process must be approved by FAA [37]. For MAM, this implies that a manufacturer with a machine certified to produce a certain part would not be allowed to produce a different part, whether FAA certified or not, without recertifying that machine for both the previous part and the new part [38]. This lack of flexibility affects the economic viability of MAM for the
production of parts at low volumes, precisely where MAM might be more competitive against traditional manufacturing techniques.

Process Input Uncertainty and Ranges for Sensitivity Analysis. For all four approaches (DMLS 1, DMLS 2, EBM, and forging), where possible, we requested ranges of best and worst possible scenarios to help capture uncertainty in the process inputs. These best, base, and worst case inputs for key cost drivers, based on our data collection, are shown in Tables 8A and 8B, which are available under the “Supplemental Materials” tab for this paper on the ASME Digital Collection. Given limited time with any singular informant, we focused on getting the most detailed information for inputs we expected to be the most impactful on cost or time [39]. In addition, we were able to engage in a variety of informal conversations with MAM producers, industry experts, and equipment suppliers not represented in the final analysis. We use these informal conversations, combined with knowledge of past production in other areas, to bind our best and worst case scenarios for each process input. For MAM, inputs for which we collected best and worst case inputs were the main AM machine price, batch size (and thus build time), Ti64 powder price, reject and scrap rates, postprocessing machine price, postprocessing cycle time, and destructive testing (Table 8A, which is available under the “Supplemental Materials” tab for this paper on the ASME Digital Collection). For forging, inputs for which we were able to collect best and worst case inputs were Ti64 price, forging scrap rate, and forging reject rate (Table 8B, which is available under the “Supplemental Materials” tab for this paper on the ASME Digital Collection).

Decision Rules. The decision rules, or equations, that turn the facility-wide inputs and inputs for each process step into the final output can be found in Appendix A, which is available under the “Supplemental Materials” tab for this paper on the ASME Digital Collection, along with explanations thereof. Two decision rules specific to our modeling of MAM are important to note in the main text. First, our model accounts for the increased production volume required to account for destructive testing as a separate input on top of per-process-step reject rate. The yield hit from destructive testing is accounted for in the final step. We assume that 1.8 destructive testing to ensure performance is being maintained. AM manufacturers are currently producing parts for aerospace applications with sufficient reliability to have 1.8 destructive testing, and some are currently moving to destructively testing 1 in 100 parts. We therefore believe this to be a reasonable, if not conservative, starting assumption. In contrast, we assume nondestructive testing for forging. Thus, AM must make more parts per process step to have the same number of “good parts” as forging, and this is reflected in the production costs. Additionally, it is important to note that for the AM build step, cycle time includes warm up and cool down time in addition to the actual time the machine spends building the part.

Results and Discussion

Figures 4 and 5 show the production costs of a good engine bracket for the two DMLS platforms and the EBM platform (for the MAM engine bracket design) and for the forging platform (for the traditional bracket design) at varying production volumes. The intermittent spikes in production cost represent the model needing to add an additional piece of equipment (whether build or postprocessing) to achieve a certain number of good parts per year.

Our results suggest that for additive-design engine bracket production, there is a significant cost overlap across the two dominant production platforms, DMLS and EBM, given uncertainties (Fig. 4). Of course, each platform has different part advantages—EBM has a faster build rate but less precision and poorer surface finish compared to DMLS. As expected, the traditional hammer forging process is the cheapest option for producing the engine bracket (Fig. 4). Importantly, the additively manufactured design offers an approximately 80% weight savings over the traditional forged design. There are also slight cost differences between different suppliers within the same MAM technology, as seen in Fig. 5.

As can be seen in Fig. 4, the forging cost curve is flatter than the AM cost curve, the latter of which rises steeply below 2000 good engine brackets per year. That the AM process has less of a cost advantage over forging at these extremely low volumes might at first seem counterintuitive. This difference is due to the forging process being nondedicated, while the AM process is dedicated: FAA regulations allow multiple different parts to be run on the forging equipment, keeping it fully utilized, while FAA regulations allow only one part to be run per machine on the additively manufactured process. This dedication is what causes the additive design to rise in cost at low volumes, with an increasing portion of the equipment charged to each part that is made, while the forged equipment does not rise in costs at lower volume, since other parts can be (and are) made on the machine without hurting part integrity when the forging machine is not making the bracket. This effect may be seen in Fig. 6(b), where at a volume of 1000 brackets, not only is the unit cost of the additively manufactured part significantly higher than the forged part (approximately $3200 versus $400), but also the proportion of cost made up of equipment is significantly higher than what was observed at high volumes, as seen in Fig. 6(a).

Fig. 5 DMLS systems show significant cost overlap given uncertainty of best and worst case scenarios noted in Table 8A, which is available under the “Supplemental Materials” tab for this paper on the ASME Digital Collection. Forging remains cheaper by small margin.
An integral part of moving AM toward cost parity with traditional manufacturing is discovering and understanding major cost drivers. Given their respective build rates, reject rates, scrap rates, material prices, and machine prices, DMLS and EBM have a different set of cost drivers per good part. Main machine cost and material cost are the major cost drivers for the DMLS system, whereas main machine cost is the overwhelming driver of the EBM system (Fig. 6). As can be seen in Table 6A, which is available under the “Supplemental Materials” tab for this paper on the ASME Digital Collection, the DMLS systems require finer powder particles than the EBM system, and have powder prices two to three times that of EBM. One of the two DMLS systems does have lower material scrap rates, but this does not outweigh the higher material price in the base case comparison (e.g., DMLS still has higher material costs than EBM). Currently, the equipment system suppliers sell the powder and their equipment warranty is only valid if their powder is used [40]. Interestingly, if—as represented by the best case scenario—the necessary quality powders can be sourced more cheaply, as is being claimed by material vendors outside the AM equipment system suppliers, then the contribution of material to overall cost of the DMLS parts would drop considerably. In contrast, despite having faster base case build rates and slightly better base case yields than DMLS, the EBM’s machine price is nearly twice that of DMLS (Table 6A, which is available under the “Supplemental Materials” tab for this paper on the ASME Digital Collection). Overall, the faster build and slightly better yields do not outweigh this higher price in the comparison (e.g., EBM still has higher main machine costs than DMLS), assuming that equivalent parts can be produced by both the DMLS and EBM systems. Overall, the EBM base case is, at 10,000 brackets per year, cheaper than the DMLS systems; however, given the range of input uncertainties, no conclusive distinction should be made.

**Top Cost Drivers.** To further assess the sensitivity of unit production costs to process inputs, we examined which individual inputs (given their expected best and worst case scenarios) had the largest impact on cost (Fig. 7). Here, we found that the Ti64 powder price, given uncertainties, has the most significant impact on production costs, along with batch size. Further work will be necessary to better understand the trade-offs between powder size and source (powders offered by machine suppliers versus those offered directly by the powder producers), in addition to the effect of powder size on production yields and final part properties and thus performance. Likewise, batch size for this part is tied to build orientation; to increase the batch size, one must stand the parts up vertically. However, the effect of varied build orientation on material properties is still an ongoing research topic.

**Cost Impact of Destructive Testing.** Another possible area of cost reduction is that of testing. Currently, due to challenges...
presented by part geometries, cost, and porosity for other testing mechanisms, destructive testing is necessary to characterize the mechanical properties of AM parts. For example, in the case of GE’s fuel nozzle, initially one in every eight parts was lost to destructive testing. To better understand the cost-consequences of this type of destructive testing, and the opportunities to reduce cost by reducing destructive testing (through, for example, improved understanding of the relationship between process decisions and material characteristics), we incorporated into our model these additional losses of good parts due to destructive testing. Our analysis shows that reducing the number of destructive tests from 1:8 to 1:100 could reduce costs of our DMLS best case by approximately $150 per bracket at the annual production volume of 10,000 brackets per year, after which there were diminishing returns (Fig. 8). If this reduction in destructive tests can be combined with increasing the batch size (and thus changing the build orientation), costs per usable part can be driven down even further by approximately $260. This leads to a total cost reduction of approximately $410 by reducing destructive testing and building vertically.

Cost Impact of Part Orientation. Being able to produce a part of equivalent functional performance with a vertical build (thus enabling larger batch sizes) provides arguably the greatest opportunity for cost savings (Fig. 9). EBM shows significant cost savings with a vertical build, even given uncertainty. DMLS shows the possibility for cost savings, though there is some overlap in the cost of vertically built versus horizontally built brackets given the uncertainty. Given these potential cost savings, it is worthwhile to work toward understanding and mitigating microstructural anomalies associated with a vertical build. Many studies have discussed the effects of part orientation and location on the build plate on the mechanical properties of the AM parts. For instance, previous studies by Simonelli et al. [41] and Hrabe et al. [42] have shown that the effect of build orientation on tensile...
properties is significant in both selective laser and electron beam melting of Ti64. Simonelli et al. [41] have reported that vertical builds have 30% lower elongation when compared to horizontal builds. Similarly Hrabě et al. [42] detail the effect of build orientation on ductility for Ti64 parts built using DMLS processes and identify edge build as the direction for highest elongation at fracture. Both future research and technological advancements in MAM (such as increased speed, reliability, quality, and expanded range of materials) will deepen understanding of the limits of build orientation and thus batch size.

**Lifetime Cost Savings Due to Weight Reduction.** Finally, as noted earlier, the additive design in our research boasts an approximately 80% weight reduction over the conventional design. This lighter design provides significant savings to the part end user. Our analysis estimates that the cost of additional fuel required by the forged bracket (over the additively manufactured one) would be approximately $1300 over 10 yr in the base case, with additional fuel costs as high as $3000 possible given the probable future fuel price increases (Fig. 10). While the AM manufacturers may not realize these savings, airlines may be willing to pay a premium for lightweight AM parts up front to reduce aircraft weight [43]. An investigation of these kinds of benefits, combined with other areas for cost reduction, such as further equipment and process standardization, will be important areas for ongoing research in understanding how the design benefits of AM can be brought to market to be cost competitive with traditional manufacturing methods.

**Future Work**

Going forward, given the cost competitiveness of MAM versus forging for such a simple part and the opportunities to further reduce the cost of MAM through reduced material pricing or shifted build orientation, particularly interesting future work would include building out the relationships between design geometry, process step requirements (including build rate and postprocessing requirements), and material properties (including mechanical properties), so as to be able to better understand these cost-benefit trade-offs with this simple example and also with a wider range of parts and geometries. For example, the latest EBM machine model, Q20, has room in the chamber to build 48 engine brackets if brackets are stacked on top of each other; however, it is unclear if the material microstructure of these engine brackets would be such that they would all be of sufficient quality.

Today, identical components built via MAM can vary in mechanical properties both within a single build and across multiple builds [44]. Also, particular energy scan patterns, build orientations, and powder qualities may result in sup-optimal final part properties [44]. It would be interesting to conduct techno-economic modeling analyses of strategies for addressing these challenges, including making real-time changes in the additive process itself (adjusting build rate, layer thickness, and beam overlap midprocess), and adding additional postprocessing steps on a part-by-part basis after real-time evaluation.

Finally, our model currently only accounts for the part loss associated with destructive testing methods, and not the time or capital equipment associated with the testing process itself. As such, it offers a conservative estimate of the benefits of reducing destructive testing, but a nonconservative estimate of the cost of having to do more destructive testing in MAM. Future work should model the costs versus potential added value of a range of testing interventions from destructive to nondestructive testing (with different impacts on end-part reliability).

**Conclusions**

Given the conservative nature of our assumptions as well as our choice of part, these results suggest that there may be broader economic viability in additively manufactured parts for commercial aviation, especially when systemic factors and use costs are incorporated. Indeed, we find that even in a simple engine bracket design without part consolidation, the cost per good bracket can be cheaper than forging once lifetime weight savings are taken into account, when using relatively conservative assumptions with respect to processing capability. Interestingly, the additively manufactured parts are particularly competitive against forging at higher volumes of 2000–12,000 brackets per year. The MAM systems we compared had similar unit costs given uncertainties despite significant difference between the processing methods of DMLS and EBM. High-impact opportunities to further reduce the cost of MAM versus forging include reducing material price without foregoing reliability and part quality, and increasing the number of parts that can fit per chamber (through vertical builds) without compromising quality or reliability.

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**Nomenclature**

\[ N = \text{number of periods (yr)} \]
\[ \text{NPV} = \text{net present value} \]
\[ p_{\text{fuel}} = \text{jet fuel prices (~$/gal)} \]
\[ r = \text{discount rate} \]
\[ S = \text{average annual fuel savings per bracket} \]

**References**
