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Evaluating the cost competitiveness of metal additive manufacturing – A case study with metal material extrusion

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ABSTRACT

Metal additive manufacturing (MAM) is a rapidly advancing manufacturing process with the potential to replace or supplement existing conventional manufacturing processes. MAM is currently associated with a high investment cost and is mostly seen in centralized manufacturing configurations with low-volume and high-value products. This paper evaluates the cost competitiveness of MAM by investigating a novel low-cost MAM process – metal material extrusion (Metal MEX). Metal MEX, unlike other MAM processes such as powder bed fusion (PBF), has a lower investment cost, faster production rate, and simpler operations, which has opened new opportunities for distributed low-cost production through MAM. A cost model of the metal MEX process - Atomic Diffusion Additive Manufacturing (ADAM) that focused on the production costs was presented. The cost model was further used to evaluate the cost competitiveness of metal MEX through a case study. Three production scenarios were compared to CNC machining, where it was shown that metal MEX, under specific production conditions, has the capability to be cost-competitive with CNC machining. Based on the proposed cost model and case study, a conceptual cost framework is presented, giving key insight into how a MAM cost advantage can be generated by incorporating the benefits of MAM.

Introduction

Metal Additive Manufacturing (MAM) has emerged as an advanced manufacturing technology that is causing shifts in the scale and distribution of manufacturing [1]. MAM was first designed for prototyping and personalized small-volume production approximately three decades ago. Nowadays, it has evolved into a highly flexible manufacturing technology for final part production with the potential to revolutionize the global manufacturing and logistics landscape [2]. It particularly holds promise in the development of cost-effective mass customization because of its extreme flexibility and toolless production [3]. The rapid technological development through new materials, machines, and process innovations [4], more focus on sustainability implications [1], dropping costs [5], as well as the expiration of prior copyrights [6] have made MAM more reachable than ever, especially as a viable option to conventional manufacturing techniques.

One of the decisive questions toward more widespread adoption of MAM is whether it is cost competitive. MAM technologies refer to seven main categories as defined and categorized by ASTM [7], namely, powder bed fusion (PBF), material extrusion (MEX), sheet lamination, material jetting (MJ), binder jetting (BJ), directed energy deposition (DED), and VAT polymerization. It seems to be a common perception that all MAM technologies are expensive to use, especially compared with conventional manufacturing technologies. The high perceived costs of the MAM processes can be closely tied to the leading MAM process - PBF. PBF is currently the most widespread process due to its maturity and high accuracy [8]. According to the 2020 AM power management report, PBF generated 85% of the total revenue of the system suppliers and dominates the MAM market with installed and sold machines [9]. Industrial PBF solutions are also among the most expensive solutions. Typically purchased starting from 250,000 USD [10].

However, new technological advancements are dropping the barriers to entry and opening up new opportunities for low-cost production through MAM. One of these technological advancements is metal MEX solutions. Metal MEX has only recently gained the attention of researchers due to its similarities to fused deposition modeling (FDM) printing and its significantly lower investment costs as compared to many other MAM processes. Its increasing recognition is also due to its simplicity, increased safety, as well as less energy-intensive operations. For instance, neither lose metal powder nor high-powered laser or electron beam are used as opposed to other common MAM processes such as electron Beam Powder Bed Fusion (EB-PBF) or laser powder bed fusion (L-PBF) [11]. Metal MEX can also offer significantly faster production rates as compared to

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PBF systems. For instance, after a print is completed and removed with metal MEX, the printer is immediately ready to initiate a new build. In contrast, L-PBF or EB-PBF processes often require tedious cleaning and preparation of a chamber with inert gas or vacuum, respectively [12].

As more mechanical manufacturers are seeking competitive edges through low-cost, less capital intensive, flexible, safe and easy to apply, and environmentally sustainable production technologies, metal MEX seems to offer a great opportunity, especially for those small- and medium-sized enterprises (SMEs). However, despite the obvious cost advantages of metal MEX, its industrial application has not been followed up. One of the possible reasons is that SMEs do not have any applicable methods for cost assessment to support decision-making and trade-off analysis. This is argued by the fact that the proliferation of PBF is supported by well-defined cost models which provide clear pictures for economic consequence of this technological adoption. This research aims, therefore, to bridge this gap and provide.

- A cost model considering the entire production phase (production and post-processing) to estimate the production cost of metal MEX
- Evaluation of the cost competitiveness of metal MEX compared to CNC machining
- Knowledge on low-cost MAM suitable for distributed supply configurations opening up new opportunities, especially for small and medium-sized enterprises (SMEs).

The rest of this paper is organized as follows. Section 2 explores metal MEX technology and its advantages for companies in gaining cost competitiveness. Section 3 provides a literature study on existing MAM cost models followed by an analysis of the models' suitability in analyzing the metal MEX cost. In section 4, the authors propose a cost model for evaluating the production costs of metal MEX. Section 5 presents a case study where the production costs of a spare part are evaluated through metal MEX and compared with that of CNC machining. Section 6 details the results of the case study. Section 7 discusses the findings, and Section 8 concludes the paper and proposes further work.

Metal material extrusion

Metal MEX falls under the material extrusion (MEX) process, which has been one of the most widely used AM methods due to its accessibility and flexibility when printing polymers or plastics. In metal MEX, the feedstock is made with metal powder and a polymeric binder material. The feedstock is then extruded above the melting point of the polymer onto a build platform layer-wise, creating the 3D object. The following step often includes debinding to remove parts of the polymeric material, leaving just enough to maintain the structural integrity of the product. The final step includes sintering to fully densify the part by fusing the metal powders and burning of the remaining polymeric binder.

Metal MEX systems can take different forms. According to Chunun et al. [11], these can be classified into three types: screw-based MEX, which uses a screw to push granulated powder into the nozzle (e.g., AIM3D GmbH system [13]); plunger-based MEX, which uses a plunger to force granulated powder or bars through the nozzle (e.g., Desktop Metal Inc. systems that use bound metal deposition process (BMD) [14]); and filament-based MEX, which employs pre-made filaments fed into the nozzle and melted using a heating element (e.g., ADAM process like the Markforged Metal X system [15]).

One of the most notable advantages of metal MEX is the low investment costs as compared to other MAM processes. Additionally, there is no need for high energy consumption or complicated and expensive powder handling systems. The increased incentive for metal MEX systems are also argued by the fact that metal MEX can be operated in an open environment.

Metal additive manufacturing costs

In the context of MAM, there are mainly two motivational categories for examining the costs [16]. Both to examine whether MAM is cost-competitive or not. The first category compares MAM processes to other conventional processes, such as molding or machining. The second category identifies which resources are used in different steps of the MAM chain. In these contexts, several cost models have been developed. Newer models are considerately more accurate than older models due to a better understanding of the technology, as suggested by Costabile et al. [17]. The below section discusses the current state of research on cost model development for MAM, and the models' suitability for calculating metal MEX costs.

MAM cost model development

In 2014 Gilbert and Douglas [5] summarized cost studies on AM categorized by the manufacturing process and the corresponding materials. At this point, the only identified cost models for MAM were aimed toward PBF. Later, to accommodate for the rapid development of the AM industry and the continuous development of new costing models and tools, Kadir et al. [18] provided a comprehensive classification review of AM cost models used in the AM development phase. Within their review, they provide an overview of existing cost models. Their review does not explicitly target MAM, but rather AM as a whole and no other studies summarizing MAM cost models were identified. For this reason, we have summarized existing cost models that target MAM in Table 1. This list is not necessarily complete but provides an overview of the current development of cost models for MAM.

It is observed that the cost model development on MAM have a definite emphasizes towards PBF [19–22–25–28–31–34,35,36] with only a few other cost models identified for DED [37–39], and two recent cost model for metal MEX [40][41]. The most representative cost components transferable across all MAM processes and almost all cost models are the material, machine, labor, and post processing costs followed by additional cost components such as pre-processing and overhead. A significant portion of the cost models focus on energy costs [19,23,27–30,32] and gas costs [21–23,25,28], which can be tied to the high power consumption associated to the PBF process as well as gas needed for creating the inert atmosphere for the powder fusion. While most studies focus solely on production costs, there are a select few that expand beyond to consider elements such as DFAM [20,30], and logistics, life cycle, transportation, and inventory related costs (denoted system costs) [21,29–32,34].

For metal MEX, its operation differs from both PBF and DED, and its cost components also differ accordingly. For instance, metal MEX, specifically filament-based MEX, uses powder infused in a filament wire, and there is no need to consider additional material cost elements such as material recycling. Another significant difference is the energy source. Both PBF and DED use powerful lasers or electron beams to fuse the material together, which is reflected by several cost models that consider energy costs and gas costs. Post-processing occupies a considerable role in MAM to enhance the part quality, which to a certain extent, is reflected in available cost studies. In the existing cost models, post-processing mainly covers build removal, support removal, and machining operations. However, for metal MEX, the post-processing expands beyond the typical steps needed to finalize production and includes additional steps such debinding, drying, and sintering which can only be seen in the study by Deboer et al. [40].

Table 1
Overview of existing cost model development for MAM. c_m: material costs, C_{mach}: machine costs, C_l: labor costs, C_{pre}: pre-processing costs, C_{post}: post-processing costs, C_{over}: overhead costs, C_{energy}: energy costs, C_{gas}: gas costs, C_{DFAM}, Design for additive manufacturing related costs, C_{system}: System costs such as lifecycle, transportation inventory, supply chain costs.

Process	C_m	C_{mach}	C_l	C_{pre}	C_{post}	C_{over}	C_{energy}	C_{gas}	C_{DFAM}	C_{system}	Papers
PBF	x	x	x			x	x				[19]
	x	x	x		x				x		[20]
	x	x	x	x	x	x		x		x	[21]
	x	x	x	x	x			x			[22]
	x	x	x			x	x	x			[23]
	x	x	x	x	x						[24]
	x	x	x	x	x			x			[25]
	x	x	x			x					[26]
	x	x	x	x		x	x				[27]
	x	x	x	x	x		x	x			[28]
	x	x	x	x	x	x	x			x	[29]
	x	x	x			x	x		x	x	[30]
	x	x	x	x	x	x				x	[31]
	x	x	x	x			x			x	[32]
	x	x	x			x					[33]
	x									x	[34]
	x	x	x	x	x						[35]
	x	x		x	x		x	x			[36]
WAAM	x	x	x	x	x						[37]
	x		x	x	x						[38]
	x	x	x		x	x	x	x			[39]
MEX	x	x	x		x	x					[40]
	x	x	x				x				[41]

Today, there is an inadequate amount of work on the cost competitiveness of metal MEX. Only two work have previously investigated the cost of metal MEX.

Deboer et al. [40] developed a cost calculator to determine the economic feasibility of bound powder extrusion (BPE) methods, which is a filament-based metal MEX process. The cost model in this work specified the cost in three categories, namely material, machine, and post-processing. While this model presents a good overview of cost, its limitations are also apparent. This cost model considers the sintering cost as a cost per volume of part instead of considering the total gas consumption used in the sintering process. To remedy these deficiencies, we consider the total gas consumption in the sintering process to demonstrate the total production costs better. Moreover, their main focus was on the development of a cost model, which was further used to develop a cost calculator tool, and they do not provide any insight into the competitiveness of the metal MEX as compared to more mainstream conventional manufacturing techniques.

Quarto and Giardini [41] also developed a cost model for metal MEX. In their cost model, they compare the cost of metal MEX to metal injection molding (MIM), which, similarly to metal MEX, requires the produced part to undergo a de-binding and sintering stage. In their model, they considered fixed costs, including machine depreciation, maintenance, and operator costs, and variable costs including materials, consumables, and energy consumption. Metal MEX and MIM both have a similar debinding and sintering stage, and they did not consider any post-processing steps as they assume the same materials and the same external company performs the treatment, and the cost will be the same. Their cost model provides a good comparison between the metal MEX and MIM costs. However, as they did not include all the process stages, the model is limited in its scope to comparisons with MIM, and the general cost competitiveness of metal MEX remains undisclosed.

To establish the cost competitiveness of metal MEX it is necessary to consider the entire production stage, including post-processing. No work has provided an accurate representation of the post-processing costs and its relationship to the processing costs. Nor is there any work that evaluates the cost competitiveness of metal MEX and compares the cost to conventional manufacturing by considering the entire production phase.

Proposed cost model for metal MEX

The foundation for any cost model is the definition of the model's scope. In this section, we present a cost model for the filament-based metal extrusion process, specifically, the ADAM/FFF process. The aim of the proposed model is to accurately describe the production costs of metal MEX, but also demonstrate the cost breakdown of the different cost components. In this study, we solely focus on the direct costs associated with the metal MEX process to provide a more accurate and consistent estimate of the cost per part. Indirect costs or overhead costs such as sales and administrative expenses and general utilities, are not directly related to the metal MEX process and can vary significantly depending on the specific circumstances of a given company or organization. We choose this approach as the aim was to accurately determine the cost per part of the metal MEX process. However, it is important to mention that the indirect costs such as general utilizes, and sales and administrative costs can have a significant impact on the overall cost of production and should not be ignored in a comprehensive cost analysis. Especially, when considering the overall profitability of an organization or a firm.

The cost model relies on a cost breakdown driven by the three phases of metal MEX, which include production (3D printing), debinding, and sintering. Furthermore, calculations based on hourly machine rates, material costs, labor costs, and consumables are applied to determine the production cost on a per-part basis. A detailed view of the manufacturing cost components is shown in Fig. 1. The total production costs can then be expressed as:

$$C_{tot} = C_m + C_{mach} + C_l + C_c + C_w + C_s, \quad (1)$$

where, C_{tot} is the total production costs, C_m is the cost of materials, C_{mach} is the machine costs, C_l is the cost of labor, C_c is the consumables costs, C_w is the washing costs and C_s is the sintering costs. The following subsections describe these costs in detail.

Material costs

The metal MEX printers are supplied material in filament rolls where the material costs are expressed as

$$C_m = N \cdot v_m \cdot c_m \quad (2)$$

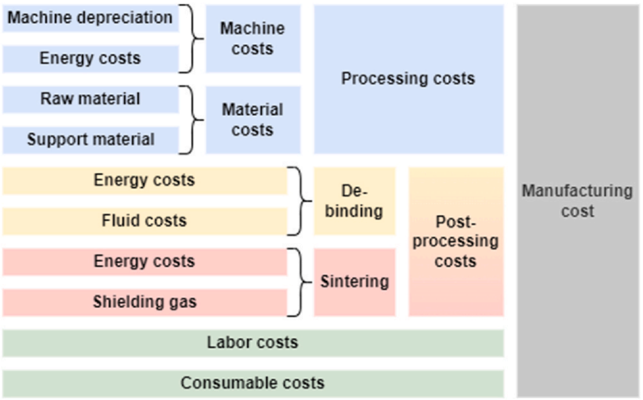

Fig. 1. Cost components for metal MEX.
Adapted from Wiese et al. [42].

where N is the number of parts, $v_m(cm^3)$ is the volume of the material used for printing the parts, and $c_m(USD/cm^3)$ is the cost of the material per unit volume. In the metal MEX process, the support material is supplied as a separate filament roll, and the formula (2) can be expanded to

$$C_m = N(v_m \cdot c_m) + N(v_s \cdot c_s) \tag{3}$$

where $c_s(USD/cm^3)$ is the cost of the support material per unit volume, and $v_s(cm^3)$ is the volume of the support.

Machine costs

To calculate the machine costs, there are three cost components: machine depreciation, energy consumption, and maintenance costs. These are influenced by the printing time per part and the machine's hourly operating costs. The total machine cost per part, denoted as C_{mach}, is given by:

$$C_{mach} = C_{dep} + C_{maintenance} + C_{energy} \tag{4}$$

Here, C_{dep} (USD/part) represents the machine depreciation cost per part, $C_{maintenance}$ (USD/part) is the maintenance cost per part, and C_{energy} (USD/part) is the direct energy consumption cost per part To calculate the machine depreciation cost per part, we first determine the hourly depreciation cost, $C_{dep\ \mathrm{p},h}$. The relationship between the machine depreciation cost per part (C_{dep}) and the hourly depreciation cost ($C_{dep\ \mathrm{p},h}$) can be expressed as:

$$C_{dep} = C_{dep,h} \cdot T_p \tag{5}$$

where T_p (hours) represents the printing time per part. The hourly depreciation cost is given by

$$C_{dep,h} = \frac{C_{dep,a}}{U_{machine}} \tag{6}$$

where $C_{dep\ \mathrm{p},a}$ (USD/year) is the annual depreciation costs, and U is the machine uptime expressed as a decimal between 0 and 1, representing the proportion of time the machine is in operation. Furthermore, the annual depreciation cost is given by:

$$C_{dep,a} = \frac{PP}{Y} \tag{7}$$

where PP (USD) is the machine costs and Y (years) is the machine's lifetime. Furthermore, The energy consumption cost, which estimates the direct cost associated with the energy required to produce one component, is calculated as:

$$C_{energy} = T_p \cdot P_p \cdot c_0 \tag{8}$$

where T_p (hours) is the printing time, P_p (kWh) is the power consumption rate of the machine, and c_o (USD/kWh) is the energy costs.

Lastly, the maintenance costs per part can be calculated using the hourly maintenance costs and printing time per part. The maintenance cost per part is given by:

$$C_{maintenance} = \frac{PP \cdot MC_{\%}}{Effective\ Operating\ Hours} \cdot T_p \tag{9}$$

where PP (USD) is the machine purchase price, $MC_{\%}$ is the maintenance cost percentage, and T_p (hours) is the printing time per part. The effective operating hours per year, which is the amount of time the machine is expected to operate per year, is the product of the total hours per year and machine uptime U:

$$Effective\ Operating\ Hours = Total\ Hours\ Per\ Year \cdot U \tag{10}$$

Labor costs

The direct personnel costs for the production process are based on the time spent in the production of one part multiplied by the hourly labor rate. The printing process is automated and the operator does not have to attend to the machine during printing. However, the operator has to set up the machine, sporadically observe the print, remove fabricated parts, clean the parts, clean the machine, get the machine ready for the next build, and conduct the necessary post-processing steps. Thus, the labor costs can be expressed as

$$C_l = \sum\nolimits_j T_j \cdot c_j \tag{11}$$

where (j) is the elements of the different production steps, described as

$$j = \{setup,\ changeover,\ wash,\ sinter,\ machining\}$$

$T_j(hrs)$ is the duration the operator spent on the jth element of production stages, and $c_j(USD/hrs)$ is the labor rate associated to the jth production stages.

Consumables

The consumables are the materials (not including the raw materials) used in the production and include everything from the printer start pack to various filters for the printers, furnace, and wash. The cost of the consumables is calculated according to their unit price and the amount used which can be estimated as

$$C_c = \sum\nolimits_i c_i \cdot N_i \tag{12}$$

Where (i) are the consumable elements used throughout the production process, $c_i(USD)$ is the unit cost of the ith element of consumable, and N_i is the number of units for the ith consumable.

Post processing costs

The two main steps for the metal MEX post-processing are sintering and washing.

Debinding

The debinding process removes the primary binding material, leaving the part semi-porous so the remaining binder can easily be burnt off in the sintering process. The fluid has to be changed after a set number of hours. The cost of the debinding operation can be given as

$$C_w = V_w \cdot c_w + P_w \cdot T_w \cdot c_0, \tag{13}$$

where, $V_w(liters)$ is the volume of washing fluid, $c_w(USD/liters)$ is the fluid costs per liter, $P(kW)$ is the power consumed during the wash, $T_w(hrs)$ is the total washing time, and $c_o(USD/kWh)$ is the price of power supplied by the electrical provider.

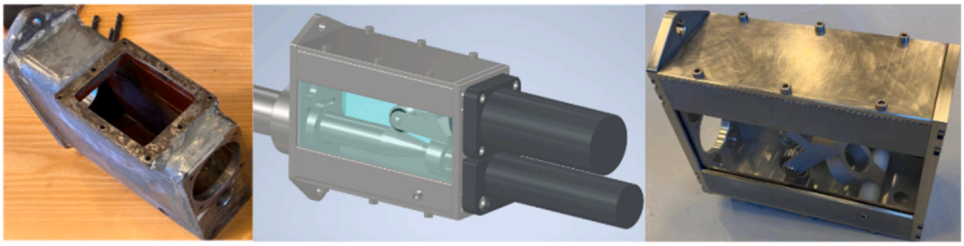

Fig. 2. Intake valve housing. From left to right: the original design, the optimized redesign for 3D-printed trigger assembly, and the final product showcasing the manufactured housing.

Sintering

The sintering for metal MEX has to be done in a controlled atmosphere to densify the parts in a similar fashion to metal injection molding (MIM) processes. Two types of furnaces can typically be used. Batch furnaces or continuous sintering furnaces. Batch furnaces are most widely used and are carried out in a protective atmosphere or a vacuum, while for high volumes applications, continuous debinding and sintering furnaces enable economical mass production of metal MEX parts. For this study batch furnaces are investigated. Estimating the sintering costs can be challenging and depends on the energy costs and the shielding gas consumption, but also how effectively the space within the furnace is used and the placements of the parts in the furnace. Moreover, several products can be fit within the same sintering furnace and the total sintering costs including energy costs, and shielding gas costs can be expressed as

$$C_s = \frac{(V_a \cdot c_a) + (P_s \cdot T_s \cdot c_0)}{N_s}, \tag{14}$$

$V_a(liters)$ is the volume of the gas consumed, $c_a(USD/liters)$ is the cost of the gas per unit volume, $P_s(kW)$ is the power consumed during the sintering process, $T_s(hrs)$ is the sintering time, and C_o (USD/kWh) is the price supplied by the electrical provider. The total sintering cost can then be divided by the number of parts in the sintering furnace denoted N_s.

Assumptions

The proposed cost model and presented case study rely on some assumptions.

- Overhead costs, such as sales, marketing, and administration, are not included in our analysis, as they are often difficult to estimate and can vary greatly depending on the specific company of production process. We focus on direct costs for a more straightforward and easily applicable cost model.
- We assume that the machine installation cost and warranty are included in the purchase price or package.
- Markforged has not set a life expectancy for the metal X system. We set the life expectancy of the metal X system at five years, based on the longest warranty offered by Markforged and considering the general advancement of the MAM industry.
- We assume a machine utilization rate of 70%, which is similar to what FDM service bureaus use, due to the difficulty of obtaining robust data.
- In our cost model, we do not have specific maintenance cost information for the machine. As a general guideline, we assume a maintenance cost percentage of 5% of the machine purchase price per year.
- For the debinding operation, we estimate that 2 kg of debinding fluid is used in 6 batches, resulting in 0.33 kg of Opteon SF79 fluid used per batch.

Case study

The aim of this case study was to evaluate the competitiveness and feasibility of metal MEX using the cost model developed in Section 4. Specifically, we wanted to compare the cost of metal MEX to that of CNC machining, in order to determine whether MEX could compete with conventional manufacturing processes. The case study was designed to provide a practical application of the cost model and to validate its effectiveness in predicting the cost and production time of MAM. To achieve this, we printed and produced a part using metal MEX, which provided us with the necessary data and parameters to evaluate the feasibility and competitiveness of metal MEX.

A housing for an intake valve was redesigned for 3D printing using the Metal X system produced by Markforged [15]. The large dimensions and simple geometry of the housing made it unsuitable for 3D printing. The trigger, a key component controlling the compressing force for horizontal hydraulic cylinders within the housing, was identified as a viable candidate for 3D printing due to its size and shape.

Fig. 2 shows the transition from the initial product to the redesigned housing, and finally, the finished manufactured. Similarly, Fig. 3 illustrates the journey of the trigger from the initial product, through simulation, to the final 3D-printed component. The redesign

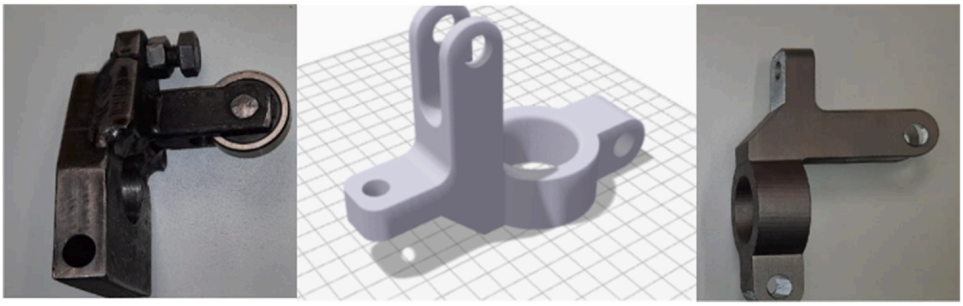

Fig. 3. Initial trigger (0.86 kg), simulated and printed product(0.34 kg).

aimed to reduce weight and volume for storage and transport, and shorten production lead time. Through this redesign and hybrid manufacturing process, significant benefits were demonstrated, including cost and material savings, improved assembly, and streamlined production.

The trigger, which was the focus of our cost evaluation, was printed in 17–4 PH Stainless Steel (SS 17–4PH). It had printed dimensions of 44 mm x 111 mm x 78 mm. In the debinding operation, the trigger was submerged in the Opteon SF-79 washing fluid and later sintered using two types of gases, argon gas, and 3,0 mol-% Hydrogen gas. As this part can typically be manufactured with the help of CNC machining a cost estimation for CNC machined costs was acquired by forwarding the design to several 3rd parts manufacturing service providers. Although the obtained quotations varied slightly - An approximation of 380 USD was used in the cost comparison.

To collect the necessary data for our case study, we utilized the Metal X system, which comprises the Metal X printer, the Wash-1 for debinding, and the Sinter-1 for sintering. The system uses the Atomic Diffusion Additive Manufacturing (ADAM) technique, a filament-based metal MEX process. We used Eiger, a slicer software for the Metal X printer, to simulate and print the trigger part, and documented the material usage, production times (printing, debinding, and sintering), labor times, and gas consumption throughout the production process. Some values, such as the amount of consumables required for each print and estimated debinder consumption, were based on prior experience and measurements and documented beforehand. Additionally, we collected external data, including energy prices, labor rates, and machine and material prices, to ensure our calculations were accurate. The values used in the cost calculations can be found in Annex A: Data Table. We then used this data to calculate the production cost, as described in section 4.

The gas consumption was measured by recording the gas amount before and after the sintering process.

Production layout and process optimization for sintering

To ensure optimal productivity in our production environment, we considered an optimized production layout for sintering in order to minimize variable cost components, such as energy consumption and gas costs. Specifically, we utilized the Sinter-1, an electrical sinter that falls under batch-type furnaces. To prevent tube contamination, inert gases must continuously flow through the system.

The Sinter-1 has a maximum sintering volume of 4760 cm^3, a sintering capacity of 141 mm ID x 305 mm L, and a surface area of 114 mm x 304 mm. The trigger before sintering had part dimensions of 44 mm x 111 mm x 78 mm. Only identical copies of the trigger were considered, as different parts or materials may require different sintering parameters and treatments. This allowed us to effectively fit four parts into the sintering area, as shown in Fig. 4.

Since we only consider one relatively large part and not multiple parts with different geometries and sizes, it is reasonable to assume that they can be arranged in the sintering area in a straightforward manner, without the need for an advanced search method. However, if the production layout were to become more complex, with multiple different geometries and sizes, or if there were more constraints and variables to consider, then advanced search methods, such as optimization algorithms, might be necessary to optimize the production layout and capacity of the sintering area.

It is important to note that the cost model estimates the production costs of metal MEX for a single part. In our cost minimization approach, we assume that the sintering operates at optimal capacity. The goal is to estimate the production cost per part, so we aimed to optimize the available equipment despite producing only one part instead of four. Producing multiple parts can significantly reduce gas costs, as continuous gas flow would otherwise be wasted without filling up the sintering area.

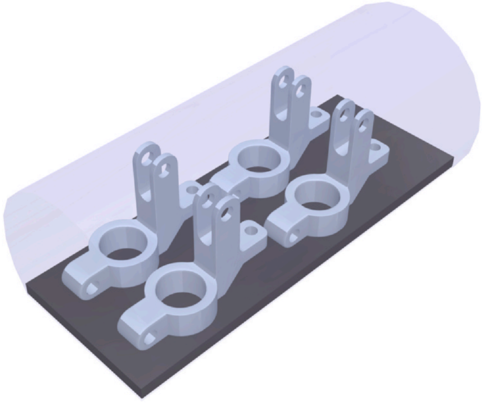

Fig. 4. Sintering build area and distribution of components.

Results

In this section, we present the results of our study, which aims to address the need for an applicable cost assessment method to support decision-making and trade-off analysis in metal MEX, particularly for SMEs. To achieve this, we developed a cost model that considers the entire production phase, evaluated the cost competitiveness of metal MEX compared to CNC machining, and sought to provide knowledge on low-cost MAM. We present our findings based on a case study and a comparison of three different scenarios, highlighting the impact of various factors on the overall cost of MAM production. These three scenarios showcase a near-optimal production execution, as well as typical mistakes or limitations among companies or operators when using MAM. All the following results and costs are referred to for one single part with the three scenarios presented below.

- Metal MEX production costs with triangular infill and narrower wall thickness according to the Eiger slicer software, and sintering oven operating at maximum capacity
- Metal MEX production costs with triangular infill and narrower wall thickness according to the Eiger slicer software with only one part produced and treated in the wash and sintering furnace.
- Metal MEX production where the trigger was solid and the sintering oven operating at maximum capacity

Scenario 1: optimal production execution

In this scenario, we aimed to determine a near-optimal production execution of metal MEX by varying two parameters that are easily edited in the process: infill and wall thickness. We chose triangular infill as it generally offers great strength and design flexibility while reducing wall thickness and material consumption. Additionally, the parts were oriented to minimize support structure. Furthermore, the sintering operation was operated at maximum capacity, with as many parts as possible filled in the chambers to maximize production efficiency. By implementing these optimal conditions, scenario 1 illustrates the most cost-effective production method using metal MEX. Fig. 5 illustrate the cost breakdown of scenario 1. The post-processing associated with metal MEX remains a major expense and time-consuming process step. The debinding, drying. sintering, and machining, even for the near-optimized version, accounts for 76% of the total production time and nearly 50% of the total costs, including the wash, sintering, and labor costs associated with the post-processing operations.

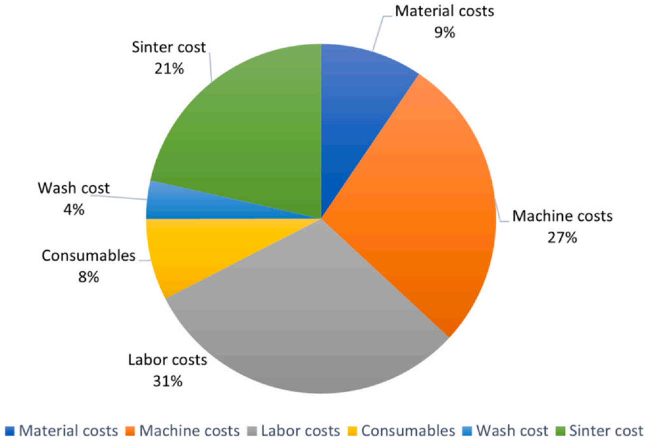

Fig. 5. Metal MEX production cost with infill, narrower wall thickness and sintering capacity maxed.

Scenario 2

Scenario 2 illustrates the importance of maximizing the efficiency of production equipment, a common challenge faced by MAM operators. Specifically, we focused on the sintering process, which is often a significant cost bottleneck for the entire production process. We used a sintering furnace with a temperature setting of 1300°C. The sintering furnace also operates with a constant gas flow regardless of its capacity utilization, meaning that even if the furnace is used at a low capacity, the same amount of gas would be consumed as if it were operated at a high capacity. Therefore, scenario 2 demonstrates the importance of the sintering process where insignificant actions are taken towards using the equipment to the best use. Although we did not go into specific details such as temperature and dwell time, scenario 2 emphasizes the importance of using the production equipment at maximum capacity, which is critical for achieving cost-efficient MAM production.

Scenario 2 (Fig. 6) had the highest production costs. Scenario 2 was printed with narrower wall thickness and infill similar to scenario 1 but was treated alone in the sintering. Consequently, all the production costs excluding the sintering were identical to scenario 1. As the sintering costs are divided by the number of parts, the sintering costs are four times the initial scenario. The labor cost remains constant, as the manual operation stays the same despite the increased production times. While the consumables can vary slightly, the cost of consumables remains constant as these are based on the number of operations, and not the time of operation.

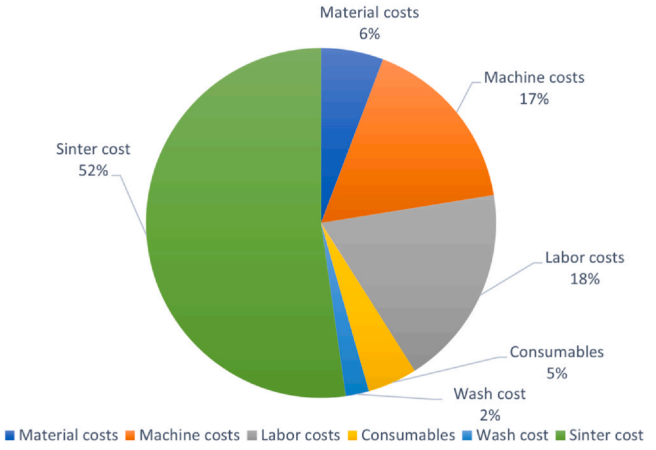

Fig. 6. Metal MEX production costs with infill, narrower wall thickness, and sintering capacity not optimized.

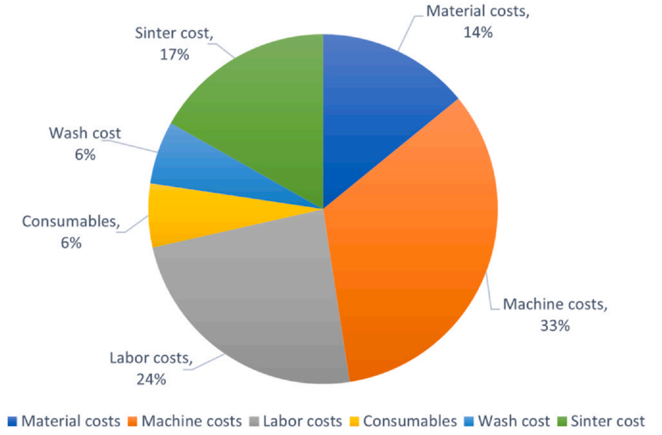

Fig. 7. Scenario 3 Metal MEX production costs with sintering capacity maxed and solid part.

Scenario 3

In contrast to scenario 1, we chose solid infill for scenario 3 to evaluate the impact of design choices on the production process and the cost of additive manufacturing using metal MEX without considering design optimization. This approach resulted in longer production times and higher costs. In some cases, the importance of Design for Additive Manufacturing (DFAM) practices may not be fully recognized by users of MAM, leading to missed opportunities for cost reductions and efficiency improvements. For instance, reducing the part size and incorporating lattice structures can significantly reduce material consumption and production time [43]. By not implementing DFAM practices, the production costs of the component in scenario 3 were increased, highlighting the importance of considering DFAM during the design process.

Herein. scenario 3 (Fig. 7) was printed solid and identical to the CNC machined version. This version has significantly higher production time which directly affects the machine costs. Resulting in substantially higher machine costs. Moreover, the material cost is also increased, directly tied to the increased material consumption. While the sintering remains unaffected, the wash costs significantly increase cost and production time due to the higher mass density of the part.

Comparison of scenarios and CNC machining

To compare the cost-effectiveness of the three scenarios presented in the previous sections with CNC machining, we have plotted the production costs of a single part for each method (see Fig. 8). The costs are also summarized in Table 2. Furthermore, the

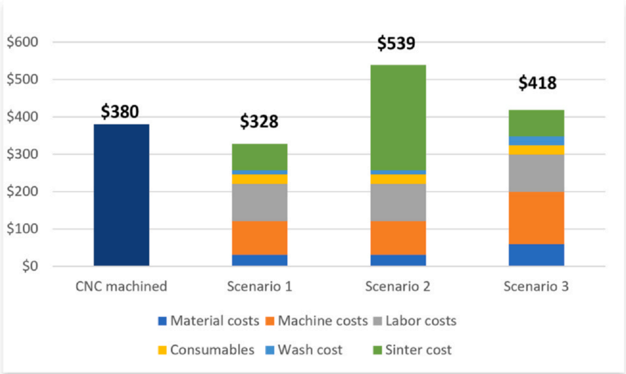

Fig. 8. Comparison of production costs of MAM and CNC machining.

Table 2
Cost values for scenario 1, 2, and 3.

Cost drivers ($)	Scenario 1	Scenario 2	Scenario 3
Material costs	31	31	59
Machine costs	89.9	89.9	139.9
Labor costs	100	100	100
Consumable costs	24.6	24.6	24.6
Washing costs	11.6	11.6	24.4
Sintering costs	70.4	281.4	70.4
Total costs	327.5	538.5	418.3

Table 3
Production Time Comparison.

	Scenario 1	Scenario 2	Scenario 3
Printing	13.92 h	13.92 h	21.67 h
Washing and Dry	19 h	19 h	102.5 h
Sinter	25.50 h	25.50 h	26.50 h
Labor	1 h	1 h	1 h
Total Time	59.42 h	59.42 h	151.67 h

associated production time for the three scenarios and its distribution among the various process stages are shown in Table 3.

As can be seen, only scenario 1, where we optimized the production process by using triangular infill and ensuring the production equipment was operating at near-optimal capacity, resulted in metal MEX being able to compete with CNC machining in terms of cost. The sintering process in this scenario operates at maximum capacity, leading to significant cost reduction. In contrast, scenario 2, where we did not optimize for sintering, resulted in the highest production costs. Since the sintering requires a constant gas flow running through the furnace chamber the cost-effectiveness of metal MEX becomes heavily influenced by the number of parts that can be sintered at once. Hence, smaller parts are not only more feasible for production through most MAM processes but also for metal MEX due to the necessary post-processing, particularly the sintering process, which alone occupies 52% of the total production costs. Increasing the number of parts that can fit into the sintering furnace can have a significant impact on the cost-effectiveness of the metal MEX process. However, with further research and improvement in post-processing operations, such as the development of new and improved furnaces that can better facilitate 3D printed parts or furnaces with higher capacities, the cost-effectiveness of metal MEX can be drastically improved.

Furthermore, scenario 3, where we did not optimize for design choices and produced the same part with no infill specification (solid), resulted in higher production costs compared to scenario 1, and slightly higher than the CNC machining baseline. This highlights the importance of considering DFAM practices during the design process to reduce costs. The extra costs are mostly due to increased material usage and longer production time, which drive up overall costs.

Discussion

Cost-effectiveness of metal MEX

One of the fundamental decisions concerning the adoption of MAM is costs and whether MAM is cost-effective or not. Metal MEX has opened up new opportunities for low-cost MAM being an affordable MAM method in terms of investment. Especially compared to other processes such as PBF that occupy a significantly higher investment cost [11]. The main aim of this work was to develop a model that allows for the comparison of metal MEX and CNC machining costs under different scenarios. The model's results showed that metal MEX could be a promising alternative production technology for low-volume production, particularly when the part design is optimized for additive manufacturing.

From the case study, the breakdown of production costs revealed the potential of metal MEX as a cost-effective solution. Our comparative analysis reveals that by adopting best practices in design and production, MAM can in some circumstances be a competitive alternative to CNC machining. The findings underscore the importance of optimizing production parameters such as infill, wall thickness, and equipment utilization, as well as leveraging DFAM practices. Implementing these strategies can significantly reduce material consumption, production times, and post-processing requirements, ultimately lowering the overall cost of MAM production. This insight has important implications for the adoption of MAM technologies in industries where cost efficiency is a critical factor. Furthermore, as MAM technology continues to advance and post-processing operations improve, we expect that the cost-effectiveness of MAM will further increase, making it an even more attractive option for a wider range of applications.

Influence of design optimization

It is worth noting that the product in the case study was not fully optimized for MAM, and additional cost reductions are possible through DFAM approaches. The importance of (DFAM, including topology optimization and lattice structures on the economics and productivity, is well recognized in the literature and corroborated by several studies such as Atzeni et al. [20], and Flores et al. [43].

This study highlights the importance of considering these factors, as well as production time when evaluating the cost competitiveness of metal MEX compared to conventional manufacturing methods like CNC machining. Minor changes in the product design and/or operations can affect the cost drastically. For instance: .

- Despite the relatively low cost of the metal MEX machines as compared to PBF, the machine costs still occupy a considerable portion of the total production cost. In consequence, changes to product design that results in increased production time drastically increase the machine costs.
- A one-to-one copy of the product design from CNC machining had a significant impact on production time, increasing it from 58.4 h in Scenario 1–150.67 h in Scenario 3, which corresponds to a 158% increase in production time. This increase in production time results in a 27% cost increase (from $328 in Scenario 1 to $418 in Scenario 3) compared to the scenario with infill and narrower wall thickness.

Furthermore, among the cost components, the high labor cost is perhaps the most surprising. This is mainly due to the amount of post-processing needed. The printing itself is mostly automated and requires, in general, only minor manual labor. However, 80% of the labor cost comes from post-processing operations, including wash preparation, sinter preparation, as well as machining and deburring.

In terms of sintering, this study presented a different approach to estimating sintering cost than Deboer et al. [40]. By considering the total sintering cost and dividing it by the number of parts in the sintering oven, this study provides a more accurate representation of true sintering costs, which may vary depending on part design, size, and placement in the sinter.

Impact of production time

Production time is another crucial factor when evaluating the introduction of new technologies. From the results, Table 3 summarizes the production time for each of the three scenarios. In the optimal scenario, scenario 1, the production time is 59.4 h, with printing taking 13 h and 55 min, washing and drying taking 19 h, sintering taking 25 h and 30 min, and labor taking 1 h, of which 0.8 h are related to post-processing and 0.2 h are related to printing. Scenario 3 has the longest overall production time, primarily due to the significantly longer washing and drying time. As technology advances, two-stage metal MEX processes that avoid debinding could become more common, further reducing production time and costs. For instance, Desktop Metals has developed new metal MEX systems that eliminate the debinding process and directly proceed to sintering [14].

Taking into account conventional methods like CNC machining, the initial estimate for machining time provided by SolidWorks was approximately 9 h and 37 min. However, this might not accurately reflect real-world complexities. Machine operators suggest a more pragmatic estimate of about 2.5 h for machining the main part under optimal conditions. This estimate assumes a single-operation process, but complex features could necessitate additional operations or complex programming, potentially adding an extra hour to the machining time. It is vital to remember that these estimates mainly concern the actual machining process. When we consider the full production cycle - including programming, setup, and post-processing - particularly in scenarios where unique, complex parts are being produced in small batches, the total production time could extend to 15–20 h.

By addressing the production time aspect, companies can make more informed decisions about adopting metal MEX technology, weighing its advantages and disadvantages against conventional manufacturing methods such as CNC machining. While it is clear that CNC machining currently offers a faster production time, the benefits of metal MEX lie in other areas, such as the potential for cost reduction, material efficiency, and lightweighting.

Conceptual cost framework

To further evaluate metal MEX's cost competitiveness, a conceptual cost framework was developed. Fig. 9 depicts the conceptual cost framework, which shows the expected relationship between the costs of MAM and conventional manufacturing. The first part of the framework shows that MAM often has a higher production cost than conventional manufacturing methods. This is because MAM is still a relatively new and emerging technology, and it requires specialized equipment, materials, and processes that are more expensive than those used in conventional manufacturing. However, a cost advantage is attainable by accounting for total costs deriving from product optimization or optimizing life cycle and supply chain cost. Achieving this cost advantage through MAM can be considered through two paths. The first is to identify ways of reducing production costs to improve the competitiveness and feasibility of MAM. Secondly, is to offset the production cost by incorporating the strategic benefits of MAM.

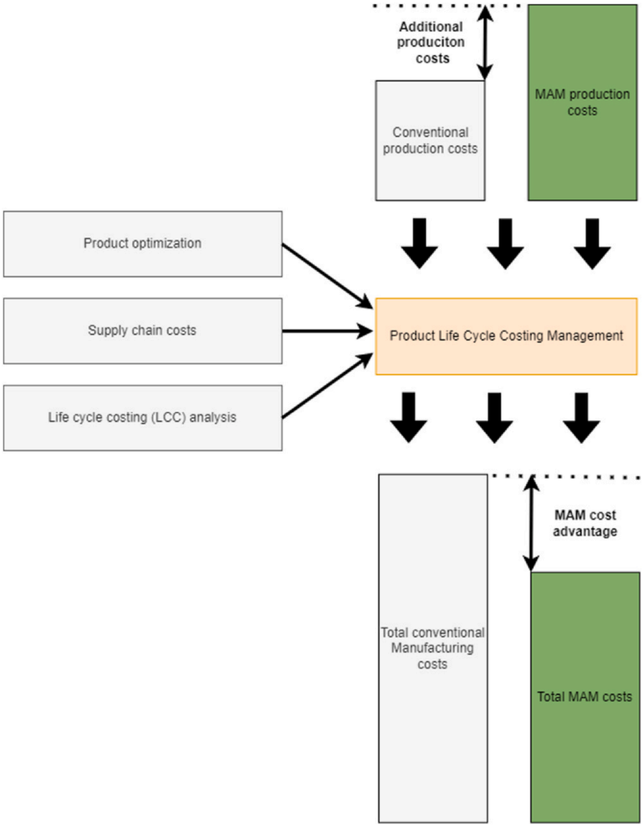

Fig. 9. Conceptual cost framework describing the relationship between the cost of MAM and conventional manufacturing.

Reducing production costs: The first path to achieving cost advantage through MAM is identifying ways to reduce production costs to improve the competitiveness and feasibility of the technology. For instance, by improving and optimizing the design by accounting for factors such as topology optimization, part consolidation, and shape complexity [44]. An optimized geometry not only reduces material waste by using only the material needed for the functional parts of the product but also minimizes the support structure required [45]. Furthermore, such optimization can potentially improve performance and profitability by reducing development times and associated costs [16]. As an example, GE Aviation redesigned a fuel nozzle for their LEAP aircraft engine using additive manufacturing, which consolidated 20 parts into a single component, resulting in a 25% weight reduction [46]. These improvements can indirectly contribute to cost reductions in manufacturing, assembly, fuel consumption, and maintenance. Other ways of reducing costs include accessing lower material prices without compromising quality [29] or re-evaluating the equipment or process choices for metal MEX technology, such as wash and sintering ovens, or even consumables, such as gas and debinding fluid.

Offsetting production costs: The second path to achieving cost advantage through MAM is utilizing the benefits of MAM to offset the higher production costs. Even though MAM might have a higher product cost compared to conventional methods, it can still offer strategic advantages if positioned correctly [47]. Thus, if there are limited ways of directly reducing production costs, then the costs can be evaluated from a broader perspective and not only from a manufacturing point of view. Since strategic decision-making typically occurs at the management level, it is natural to evaluate costs from this perspective. From a management perspective, Kadir et al. [18] suggested that costs can be classified into two categories: process-based and system-based costs. Process-based costs include the pre-processing, processing, and post-processing associated with the manufacturing process. System-based costs, on the contrary, provide a more holistic view of the total costs by incorporating supply chain, product life cycle, and service-related costs. By considering the total cost from a management perspective, the benefits of MAM can be incorporated while evaluating the costs. Such benefits can include increased flexibility and performance in the manufacturing process, changes and improvements in the supply chain [48], and a reduction in the environmental impact [49].

To fully realize the benefits of MAM, one approach can be through incorporating product life cycle cost management. Lindeman et al. [21] state that lifecycle analysis of MAM parts is needed to understand the cost drivers, which provides a focus for future cost reduction activities using MAM and helps compare the cost of MAM to conventional manufacturing. This involves considering the entire life cycle of a product, from design and development to manufacturing, distribution, use, and disposal. By designing products that are easy to manufacture, maintain, and dispose of, companies can reduce supply chain and service-related costs, and improve customer satisfaction.

Decentralized production using MAM can also enhance supply chain performance and reliability. By producing closer to the point of use, companies can reduce transportation costs and storage costs, as well as offer faster response time [50]. This can improve supply chain flexibility and responsiveness, making it easier to overcome demand unpredictability [51] and enhance the robustness against supply chain disruptions [52]. Additionally, MAM can contribute to sustainability improvements as the technology becomes more energy-efficient and reduces the need for inventory management and logistics information systems [52].

In conclusion, while the conceptual cost framework may appear general, it serves to contextualize the empirical evidence provided through the cost model and case study presented in this paper. It highlights the potential advantages of MAM when considering total costs and strategic benefits and contributes to validating the theoretical research in the field. Furthermore, the framework emphasizes the need for more empirical investigation in the MAM literature and suggests directions for future research, particularly in exploring the “hidden” benefits of MAM, such as production optimization, location, and supply chain optimization.

Conclusion

In this paper, the cost of MAM is assessed and compared with CNC machining to explore how MAM would fare as a replacement or addition to conventional manufacturing processes. Metal MEX is recognized as a promising MAM process due to its low investment and operation costs, as well as its simple and safe operation. We developed a cost model for metal MEX and validated it through a case study with an industrial company, providing valuable insight into the economic competitiveness of MAM. Our results show that achieving a cost advantage with metal MEX is challenging but achievable under certain production circumstances. The comparative cost analysis provided significant insights into the economic viability of metal MEX. The results indicate that metal MEX can compete with CNC machining when design and production parameters, such as triangular infill and narrower wall thickness, are optimized, and the sintering oven is operated at maximum capacity. Under these conditions, metal MEX production achieves a cost reduction of approximately $52 or 13.68% compared to CNC machining. However, the post-processing steps, including debinding, sintering, and machining, remain a significant cost driver, accounting for almost $162 or 49% of the total production cost (including labor) and taking up approximately 44.4 h, which constitutes 76% of the total production time in the optimal scenario. Furthermore, the failure to optimize the production equipment (sintering furnace) and improper parameter settings and design choices significantly increase production costs by $211 in scenarios 2 and $90 in scenario 3. These results demonstrate the importance of careful consideration and optimization of production parameters and equipment in achieving cost-effective metal MEX production.

The cost model, insight from the industrial case study, and literature provide valuable insight into MAM’s economic competitiveness. Herein, a conceptual cost framework is provided to better describe the relationships between the MAM and conventional manufacturing costs. The conceptual cost framework offers insight into how a strategic advantage can be generated by incorporating the benefits of MAM.

Further work

- Future work should consider the extension of the cost model to include different MAM machines and elementary data to improve the accuracy of the cost analysis. The inclusion of additional machines and data will help to broaden the scope of the cost model and provide more comprehensive insights into the economic implications of MAM. Future studies can also investigate the potential cost advantages and disadvantages of different MAM machines and processes and their respective cost structures.
- Research on cost optimization for the post-processing operations of metal MEX is currently lacking in the literature, suggesting there is room for additional cost savings.
- It is of relevance to evaluate the total costs, such as the supply chain costs, and quantify the cost of metal MEX in a decentralized supply chain configuration to fully understand the cost competitiveness as indicated in the conceptual cost framework in Fig. 9.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Appendix

Table A.1.

Table A.1
Data Table.

Variable	Description	Value	Units	Source
N	Number of parts	1	-	-
v_m	Material volume	47.53	cm^3	Eiger software
v_s	Support volume	0.28	cm^3	Eiger software
c_m	Cost of material per unit volume	0.65	USD	Markforged
c_s	Cost of support per unit volume	0.495	USD	Markforged
T_l	Labor time	1.0	hrs	Internal numbers
c_l	Labor rate	1000	USD/hrs	Internal numbers
T_p	print time	13.9167	hrs	Eiger software
T_w	wash time	17	hrs	Eiger software
T_s	sinter time	25.5	hrs	Eiger software
c_o	Cost of power from provider	0.08	USD/kWh	Local electricity prices (SSBss)
P_p	Power consumption (printing)	2400	kW	Markforged datasheet
P_w	Power consumption (wash)	1320	kW	Markforged datasheet
P_s	Power consumption (sintering)	6000	kW	Markforged datasheet
PP	Investment costs	150 999	USD	Markforged purchase
U	Printer utilization	70	%	See assumptions (sec: 4.6)
Y	Printer life expectancy	5	years	Markforged warranty
$MC_{\%}$	Maintenance cost	5	%	See assumptions (sec: 4.6)
V_a	Volume of argon gas (sintering)	22.78	liters	Eiger software
c_a	Cost of argon gas per unit volume	0.06	USD/liters	Purchase agreement
V_{a2}	Volume of gas (3.0 mol-% Hydrogen)	10.12	liters	Eiger software
c_{a2}	Cost of gas (3,0 mol-% Hydrogen)	12.06	USD/ liter	Purchase agreement
N_S	Number of parts sintered	4	-	-
V_w	Volume of OpteinSF79 washing fluid	0.33	kg	Manual measure
c_w	Cost of Optein SF79 washing fluid	26.4	USD/ kg	Purchase agreement

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