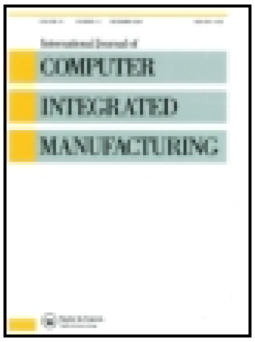

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International Journal of Computer Integrated Manufacturing

ISSN: 0951-192X (Print) 1362-3052 (Online) Journal homepage: http://www.tandfonline.com/loi/tcim20

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International Journal of Computer Integrated Manufacturing, 2015
http://dx.doi.org/10.1080/0951192X.2015.1067920

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Additive manufacturing–integrated hybrid manufacturing and subtractive processes: economic model and analysis

Guha Manogharan [a]*, Richard A Wysk [b] and Ola L.A. Harrysson [b]

[a]*Department of Mechanical and Industrial Engineering, Youngstown State University, Youngstown, OH, USA;* [b]*Department of Industrial and Systems Engineering, North Carolina State University, Raleigh, NC, USA*

(*Received 24 September 2014; accepted 31 May 2015*)

This article presents economic models for a new hybrid method where additive manufacturing (AM) and subtractive methods (SMs) are integrated through composite process planning. Although AM and SM offer several unique advantages, there are technological limitations such as tolerance and surface finish requirements; tooling and fixturing, etc. that cannot be met by a single type of manufacturing. The intent of this article is not to show a new manufacturing method, but rather to provide economic context to additive and subtractive methods as the best practice provides, and look at the corresponding economics of each of those methods as a function of production batch size, machinability, cost of the material, part geometry and tolerance requirements. Basic models of fixed and variable costs associated with additive, subtractive and hybrid methods to produce parts are also presented. An experimental design is used to study the influence of production volume, material and operating cost, batch size, machinability of the material and impact of reducing AM processing time. A composite response model for the unit cost is computed for the various levels associated with such engineering requirements. The developed models provide insight into how these variables affect the costs associated with engineering a mechanical product that will be produced using AM and SM methods. From the results, it appears that batch size, AM processing time and AM processing cost were the major cost factors. It was shown that the cost of producing 'near-net' shape through SM and AM was the decision criteria; which will be critical for tough-to-machine alloys and at multi-batch size.

Keywords: hybrid manufacturing; EBM; CNC-RP; AIMS; economic analysis and additive manufacturing

1. Introduction

Today, manufacturing industries struggle with long lead times and high costs for critical low volume highly customised parts. In some cases, like weapon system modernisation and rebuild, product renewal is required (also in the case of some custom commercial products such as biomedical implants), where the equipment is old and spare parts are not readily available. Traditional processes such as forming, shaping and machining have part-specific processing tool requirements such as moulds, dies, jigs and fixtures. Significant lead time and fixed costs are associated with such tooling and also, they need to be replaced for every individual part design. These problems are more prevalent for new product development in low volume industries where long lead-times and tooling costs significantly increase the unit cost. This need for customised tooling for manufacturing components associated with each individual product design (expensive dies, moulds and fixtures for each design) and qualification requirements for new processing methods is challenging. In this article, a hybrid methodology that integrates additive and subtractive methods called additive methods integrated with subtractive methods (AIMS) is presented. Production economic models for the additive-based hybrid process and the subtractive process are developed and analysed in this article.

Direct digital manufacturing is the process of making a physical product directly using a computer aided drafting (CAD) model. Direct digital manufacturing technologies have rapidly evolved over the past decade and are gaining applications in aerospace, functional components and biomedical implant manufacturing (Gibson, Rosen, and Stucker 2010; Frazier 2010). Some of the appealing features of direct digital manufacturing systems include; reduced part development time, lower or no process engineering time, lower material consumption and faster design-to-part production (Chiu and Yu 2008; Czajkiewicz 2008). The layer-by-layer principle of additive manufacturing has been employed for a variety of materials including plastics, ceramics and metals. Several studies have classified and compared different processes (Yan. and Gu. 1996; Pham and Gault 1998; Horn and Harrysson 2012). More recently, the ability to directly manufacture metal components with complex part geometries without tooling (e.g. moulds, dies or fixtures) has been a topic of great interest. The huge investment associated with tooling

*Corresponding author. Email: gpmanogharan@ysu.edu

typically necessitates the production of medium to large batch sizes to reduce the unit cost of components and hence, traditional manufacturing methods are preferred for mass production. A study has highlighted the advantage of additive methods for production volume of one, when compared to conventional methods (Petrick and Simpson 2013).

In additive manufacturing, a stereolithography (STL) file of the desired part is used to identify the layered 2-D geometry required during processing. This includes identifying and generating support structures for overhanging surfaces. By eliminating the need for part-dependent tooling, additive manufacturing can facilitate economical production of batch sizes as low as a single unit. This coincides with the increased interest in custom design and shorter lead times (Silveira, Borenstein, and Fogliatto 2001). In addition, metal-based additive processes provide an alternative approach to conventional processes for the growing demand to process special-purpose alloys such as Inconel and titanium alloys which are tough to process through traditional methods. However, the current additive processes are only capable of producing components that are near net shape and typically require secondary operations to achieve the desired accuracy and surface finish.

1.1. Subtractive processes

Conventional subtractive manufacturing methods such as milling are capable of achieving relatively higher precision tolerances and surface finish, but frequently require significant investment for custom fixturing. A recent development in subtractive rapid prototyping is the subtractive process of computer numeric control (CNC)-rapid prototyping (CNC-RP). Like additive processes, the part is fabricated in layers, however, rather than adding materials, CNC-RP removes materials layer by layer using island milling and automatic tool path planning of a CAD/computer aided manufacturing (CAM) system (Frank, Wysk, and Joshi 2004). Tool paths are automatically generated from an STL file and the part is machined from a symmetrical bar stock supported between the centres of a rotary indexer. Sacrificial fixtures are added to the part design in the CNC-RP software, so that the part can be supported within the cylindrical stock throughout the process of machining and access to the face features can be obtained. The CNC-RP process eliminates any manual refixturing of the stock since the rotary indexer is used for automatic repositioning (Frank, Wysk, and Joshi 2004; Yang et al. 2009; Petrzelka and Frank 2010). Unfortunately, both traditional CNC milling and CNC-RP machining can result in poor material utilisation due to excess material loss through chips and scrap. This also presents a challenge to economic manufacturing of parts without expensive fixturing and planning, especially, for growing applications in aerospace and biomedical engineering, many of which are for very small batch sizes. With growing demand for superalloys which are often difficult to machine, this results in expensive tooling and poor material utilisation.

1.2. Hybrid processes

The success and widespread implementation of any manufacturing process are based on its technical viability and economic feasibility. According to a recent Wohler's report, the market for AM including all products and services grew by 26% (compounded annual growth rate) to a total of $ 2.204 billion globally (Wohler's Report 2013). In particular, revenues associated with metal AM grew by 38.3% to a total of $ 24.9 million which indicates tremendous interest and potential for further improving end-metal AM products. The secondary market associated with AM (tooling produced from AM products) grew by 10% to $1.19 billion in 2012 (Wohler's Report 2013). This secondary market will further benefit from shorter lead times for part post-processing through modular finishing operation.

The project, cost analysis for additive manufacturing during product lifestyle (CoA2MPLy) is focused on estimating the benefits of metal AM through a life-cycle-based approach (Lindemann et al. 2012, 2013). It was noted that material cost is one of the two largest contributors to the total cost of the part along with operation cost. In metal-AM operation, the build time (speed) and personnel cost were identified as the major factors in the high cost, particularly, in the case of parts with shorter product lifecycle. One of the conclusions of this article was that part design optimisation should be verified to lower part renewal. The final cost driver noted by the project was that of data-preparation due to higher labour costs since skilled and experienced engineers are required to 'prepare' building plans, particularly, in the case of a higher volume of smaller parts (Lindemann et al. 2013). A recent study analysed the AM supply chain in the production of spare parts and concluded that lower machine cost and a distributed production system with decentralised production locations will lead to a more economical rapid manufacturing system (Khajavi, Partanen, and Holmstrom 2014) which shows the potential of AM post-processing centres near end-users. This study focused on spare parts supply chains and noted that such supply chains for capital-intensive technologies like AM will result in lower overall operation costs, down time and higher flexibility.

Prior studies have compared the cost of producing parts through traditional methods to AM, and it was consistently noted that AM is suited for small batch production. The cost is also impacted by AM machine and labour costs (Atzeni and Salmi 2012; Hopkinson and Dickens 2003). The significant impact of AM machine cost was shown with respect to production volume (e.g. injection moulding) and the cost of computational tools required in metal AM was detailed (Hopkinson and Dickens 2003). In the case of powder-bed processes, studies have shown that part size and packing ratio are two critical factors in lowering unit cost (Ruffo, Tuck, and Hague 2006; Ruffo and Hague 2007), particularly, when simultaneously producing different part designs (Ruffo, Tuck, and Hague 2007), and in some cases up to a 41% reduction has been realised (Rickenbacher, Spierings, and Wegener 2013). The existing economic models assume a fixed amount of time for 'post-processing' which varies from manual removal of support-structures to heat-treatment (annealing) in laser powder-bed processes. The current literature lacks an economic model which takes into account the post-process planning, machining time, etc. based on the part geometry, machining allowance, machinability, etc. Such an economic model will better reflect the impact of 'batch' metal AM-production or mixed component production in powder-bed processes on overall unit cost.

Recently published work has reviewed hybrid processes and has classified them based on the principle of integration (Zhu et al. 2013). Much of the work in this area has focused on directed energy metal deposition processes such as wire welding using metal inert gas, metal active gas (Akula and Karunakaran 2006; Karunakaran et al. 2010; Xiong, Zhang, and Wang 2009) and laser melting due to the relative ease of integration (Jeng and Lin 2001; Amine, Sparks, and Liou 2011). These hybrid systems are formulated by typically retrofitting 3-axis platforms in a CNC machining centre by adding the deposition head into the machine volume. In such processes, hybrid manufacturing is achieved by alternating between additive and subtractive methods after every few layers. Machining is performed after the deposition or formation of relatively thick layers followed by subsequent addition and subtraction steps until the final part is created. Other hybrid processes employ additional rotary axe-based laser-aided deposition processes in which the deposition table is rotated to accommodate overhanging surfaces by depositing materials from multiple directions followed by machining (Liou et al. 2007). In most of the hybrid approaches discussed here, the ability to withstand machining forces depends on the surface area of the part attached to the deposition plate. This would affect the selection of build orientation since the part has to be oriented such that the largest cross-section is always formed in the first layer. Furthermore, the use of cutting fluids is somewhat limited in the hybrid systems described here. This can lead to increased tooling cost for some difficult to machine materials such as nickel superalloys.

The common theme uniting the hybrid systems described so far is that the additive and subtractive operations are carried out on the same piece of equipment and hence, interference/gouge check is critical and making the processing planning and operating sequence very complex. Significant process planning is required and the amount of time spent in tool change operations between depositions and machining is considerable. It is important to develop a hybrid approach that can be integrated with any additive manufacturing system without any or significant modification to the existing equipment.

2. The engineering model – novel hybrid process

In the following sections, we outline the operations of a hybrid direct manufacturing system that uses an additive manufacturing process (e.g. EBM) followed by the use of CNC-RP to form a hybrid direct manufacturing process. However, it should be noted that the developed AIMS system can be implemented using any AM process. Based on the existing hybrid machines detailed earlier (Section 1.2), we desire a hybrid system that would combine 'freeform fabrication' capability of AM processes with minimal machining and limited process planning. Another desired attribute is to combine the existing AM processes using a CNC machine tool with minimal modification (e.g. rotary indexer) as shown in Figure 1.

2.1. *Additive manufacturing*

A commonly used class of additive manufacturing is powder bed fusion, which selectively focuses an energy source (laser or electron beam) on a bed of metal powder (ASTM F2792 REV A; ASTM Designation 2012). There are several studies that detail the specifics of various commercially available powder bed fusion technologies (Mahale 2009; Kruth et al. 2005; Bremen, Meiners, and Diatlov 2012). Since AIMS can be implemented with any of these metal AM processes, an overview of powder bed fusion processes is presented. Atomised metal powders are spread onto a build plate (also known as raking since a rake is used to spread the powders) and a focused energy source is selectively applied based on the STL information. In the case of laser-based systems, the beam is controlled optically and the entire process takes place at room temperature. In the case of electron-beam melting (EBM) system, the beam is controlled electro-magnetically, and the operation takes place in a high vacuum. In all powder-bed fusion processes, overhanging surfaces require sacrificial support materials that are manually removed after the AM process. Due to reduced density and sintering conditions of the support, different process parameters are used (e.g. beam speed, scanning pattern,

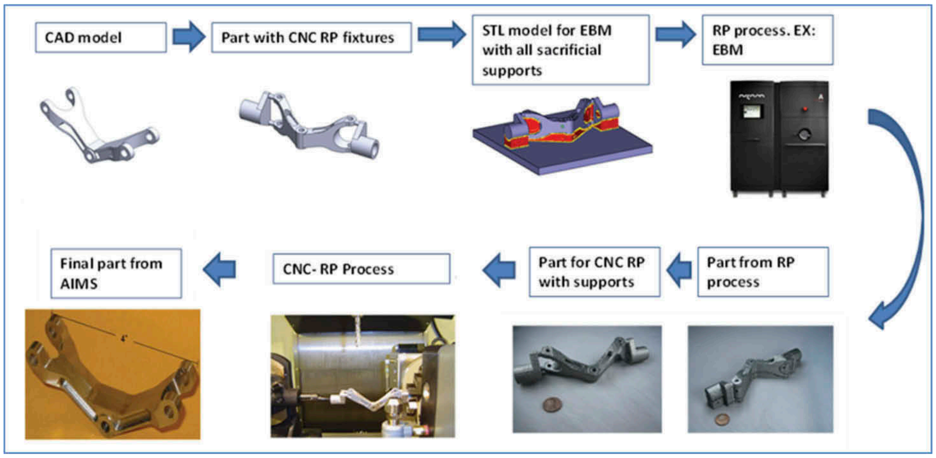

Figure 1. AIMS: Integrated AM and CNC-RP integrated flow illustration.

Figure 2. EBM fabricated Ti6Al4 V biomedical and mechanical components.

beam power, etc.) for support and part volume. Figure 2 shows some examples of biomedical and mechanical parts that have been produced using EBM.

Unlike, laser-based processes; EBM is a hot bed process where the entire powder bed is maintained at elevated temperature throughout the course of the build. Initially, after the spreading of a layer, the electron beam scans the entire bed known as 'pre-heating', followed by creating part-specific features ('melting' and 'supports') and final scanning of the bed known as 'post-heating'. These steps are repeated onto subsequent layers until the final part is produced. In the case of laser-based systems, pre-heating and post-heating do not exist.

2.2. *Subtractive manufacturing – CNC-RP*

CNC-RP uses a 4-axis CNC machine configuration to machine parts directly from bar stock. Based on the selection of machining parameters such as material removal rate (MRR), depth of cut and cutting tool selection, CNC-RP operations can be distinguished into the following sequential stages: (1) roughing, where feature-independent *z*-planar roughing operations with larger depth of cut is used to reduce the cylinder into roughing stock, i.e. area clearance operation, (2) semi-roughing, where feature-dependent island milling is pursued based on visibility analysis and reduces the part to 'near-net' dimensions and finally, (3) finishing, where machining with a smaller cutting tool and small depth of cut is pursued to produce the part to the required dimensions. The stages are grouped into: (1) roughing, semi-roughing and (2) finishing, where the geometric shape of the part is enhanced progressively in each operation. The integration of best practices of both additive (roughing through near-net AM) and subtractive (CNC-RP finishing) processes could provide a solution to the rapid manufacturing of such complex part geometries using exotic alloys to the tolerances typically required for functional assembly components.

2.3. *Hybrid processes – EBM and CNC-RP*

In the AIMS hybrid system, the part is processed in two separate machines: (1) the near-net shape fabrication through additive manufacturing (e.g. EBM or direct metal laser sintering (DMLS)), and then (2) a CNC-RP 'finish' machining where in a layered manner in a 4-axis CNC machining centre, the part is produced within specified tolerances (typically as small as 0.005 in; Manogharan, Soundarajan, and Wysk 2011). The major advantage of this approach is that no special tooling is needed and minimal or no part programming is required which would result in elimination or reduction of fixed cost for adding a subtractive process. This approach focuses on complimenting the advantages associated with AM technologies along with already well-established subtractive processes including CNC-RP. The hybrid manufacturing method shown in Figure 1 presents an integrated capability for the rapid manufacturing of complex high precision components, in small batch sizes and with minimal human intervention or engineering expertise. The processing environment in powder bed fusion processes such as EBM or DMLS is not ideal to incorporate machine tools within the build volume. The part is then transferred to a separate CNC machine and machined using only the 'finishing' step in subtractive CNC-RP. This approach expedites the hybrid production of multiple batches (depending on batch build time and only finish machining time) by increasing the availability and efficiency of both the machines. In other words, additive manufacturing of batch '*x*' and subtractive only finish machining of near-net shape units in batch '*x* – *1*' in CNC-RP can be simultaneously conducted. Since, relatively lower percentage of production time per unit part is spent on CNC-RP processing when compared to AM processing, the CNC machine can then be used to process multiple (or other) unit parts when the AM machine processes the next batch. Such a system also ensures availability of the CNC machine for traditional subtractive machining including drilling, trapping of conventionally produced bar stock. With the sacrificial location/orientation fixtures incorporated into the part, the STL file of the required part is ready for EBM process planning. As of now, all the design modifications and operations to the STL part file across the process are manual (generation of CNC-RP fixtures, support structures for EBM, allowances and generation of toolpath). Further investigation into process characteristics of this hybrid process based on material properties, part geometry and part size can help in fully automating this process and is ongoing.

3. Economic model

The following section describes the economic models used to evaluate unit cost and production time as a function of part and support volume for the following systems:

(1) Subtractive manufacturing – CNC-RP
(2) Hybrid manufacturing AIMS
  (a) Additive manufacturing (e.g. EBM)
  (b) CNC-RP (finishing)

Development of the cost model consists of material and manufacturing cost (including setup and tool costs) components. In this cost model, the energy costs of AM and CNC-RP are included in their respective manufacturing cost. The time for preparation of process parameters in terms of NC codes (CNC-RP) and additive manufacturing process files are approximately the same (and small typically < 60 minutes), and the engineering cost is not included in the model. However, for highly complex geometries, it is recommended to include this cost. The cost model is material and activity-based, and the notation for all the major cost factors is detailed in Table 1.

Table 1. Nomenclature used for cost models for additive, subtractive and hybrid processes.

Major notations	Unit	Comments
General factors		
C_{unit}	\$	Cost per unit
Pv	mm^3	Part volume
SPv	mm^3	Support volume-sacrificial supports
$C_{process}$	\$/hr	Operating cost for each process
C_{mat}	\$	Cost of the material in each process
t_{build}	hr	Time to fabricate the part in the additive process
$t_{setup\_process}$	hr	Setup time in each process
$t_{post\_process}$	hr	Post-processing time in each process
CNC-RP specific factors		
Sv	mm^3	Volume of bar stock
t_{hog}	hr	Time for hogging operation
t_{rough}	hr	Time for roughing operation
t_{finish}	hr	Time for finishing operation
t_{tool_life}	hr	Cutting tool life duration
t_{tool_change}	hr	Time for changing tool and tool set-up time
ΔV	mm^3	Total volume removed at each stage in CNC-RP
MRR	mm^3/hr	Material removal rate at each stage in CNC-RP
$C_{tooling}$	\$/tool	Cost of cutting tools
Nt	–	Number of tool changes in each stage
$C_{tooling}$	\$/tool	Cost of cutting tools
EBM specific factors		
n_{EBM}	–	Number of layers in EBM fabrication
P	kg/mm^3	Density of metal powder used
t_{EBM}	hr	Total build time in EBM
t_{plate}	hr	Time to pre-heat the start plate to required temperature before fabrication
t_{cool}	hr	Time to cool the build volume, retrieve part and recycle unused powder

3.1. *Additive manufacturing cost model*

For many additive manufacturing processes, unit cost can be simplified as a function of set-up time, part height (i.e. number of layers), summation of cross-sectional area of each layer and post-processing time. For a part with n layers, where t_{build_i} is the build time for layers i = 1, 2,… n, the total manufacturing time and unit cost are formulated as:

$$C_{\text{unit}} = C_{\text{material}} + (C_{\text{add}} \times t_{\text{add}}), \tag{1}$$

$$t_{add} = t_{setup\_add} + \sum_{i=1}^{n} (t_{build\_i}) + t_{post\_process} \tag{2}$$

The generic model presented in Equations (1) and (2) can be adapted to any layer-by-layer manufacturing methods depending on individual cost components in each layer (e.g. different part and support generation parameters) and the corresponding setup and post-processing time such as annealing. In the following sections, this model is extended to two specific systems: CNC-RP and the AIMS hybrid process.

3.2. *CNC-RP cost model*

In the case of CNC-RP, the manufacturing cost is a function of: cost of the stock, total machining time and the tooling cost. The machining time is determined based on the total volume of metal to be removed from the stock (ΔV) for a givenMRR, i.e. ΔV/MRR. Furthermore, the tool geometry, feed rates and depth of cut will vary in hogging, roughing and finishing stages, leading to decreasing MRR. The setup time ($t_{\text{setup\_CNC-RP}}$) is assumed to be uniform irrespective of the part volume (because the stock is fixtured across two chucks). Furthermore, the material cost (S_v – stock volume) is based on part orientation (a cylinder with a minimum diameter equal to the diagonal of the part). The post-processing step in CNC-RP is the removal of sacrificial supports which takes negligible time and is not considered in the cost model derived from Equations (3)–(6) as shown below:

$$C_{\text{unit}} = (S_v \times C_{\text{mat\_}CNC-RP}) + (C_{\text{CNC-RP}} \times t_{\text{CNC-RP}}) + (C_{\text{tooling}} \times n_{\text{stage}}), \tag{3}$$

$$t_{\text{CNC-RP}} = t_{\text{setup\_CNC-RP}} + t_{\text{hog}} + t_{\text{rough}} + t_{\text{finish}}, \tag{4}$$

$$nt = \frac{(\Delta V)}{\text{MRR}} \times \left(\frac{1}{t_{\text{tool\_life}}}\right), \tag{5}$$

$$t_{\text{stage}} = \frac{(\Delta V)}{\text{MRR}} + \left(nt \times t_{\text{tool\_change}}\right). \tag{6}$$

At every ‘stage’ of CNC-RP (roughing, semi-roughing and finishing), there are two time components namely; machining time and tool change operations Equations (5)–(6). Subsequently, the unit cost of the CNC-RP made part as shown in Equation (3) is derived from the manufacturing time Equation (4), material cost and tooling cost.

3.3. *AIMS cost model*

The developed hybrid process has two steps: AM and ‘finishing’ stage of CNC-RP. First, the cost model for AM is developed by integrating EBM-specific process steps for the total build time in Equation (7).

$$\sum_{i=1}^{n} (t_{\text{build\_}i}) = t_{\text{plate}} + t_{\text{raking}} + t_{\text{preheating}} + t_{\text{melt\_}i} + t_{\text{support\_}i} + t_{\text{postheating.}} \tag{7}$$

In this process cost model, the total build time as shown in Equation (7) is further expanded to differentiate individual operations in each layer *‘i’* namely; pre-heating of the plate, raking of the metal powder, pre-heating the powder bed, melting the contour (or edges) and part volume, support structures and finally, post-heating scan. Constant plate pre-heating, raking, pre-heating and post-heating duration are assumed. For each layer *‘i’*, the melting and support generation time are formulated based on EBM process parameters as shown below in Equations (8)–(9).

$$t_{\text{melt}_i} = \sum_{i=1}^{n} \left(\frac{\text{Contour scan length}}{\text{Contour speed}}\right) + \sum_{i=1}^{n} \left(\frac{\text{Melt scan length}}{\text{Melt speed}}\right), \tag{8}$$

$$t_{\text{support\_}i} = \sum_{i=1}^{n} \left(\frac{\text{Support scan length}}{\text{Support speed}}\right). \tag{9}$$

In the case of EBM, the post-processing involves cooling down of the build chamber, part retrieval and recovery/recycling of unused powder. Hence, the overall cost-time of the EBM component in this hybrid process is defined as:

$$t_{\text{EBM}} = t_{\text{setup\_EBM}} + \sum_{i=1}^{n} (t_{\text{build\_}i}) + t_{\text{cool}}, \tag{10}$$

$$C'_{\text{EBM}} = (\eta \times (P_v + SP_v) \times \rho \times C_{kg}) + (C_{\text{EBM}} \times t_{\text{EBM}}). \tag{11}$$

Unlike the complete CNC-RP, the subtractive stage of the hybrid system consists of only the finishing stage. Since the sacrificial fixtures used in the subtractive stage are considered as ‘EBM-made part volume’, there is no additional material cost associated with the subtractive stage. The ‘near net’ part from EBM is the stock volume and hence the cost-time CNC-RP component in this hybrid process is defined as:

$$C_{\text{Hybrid}} = (C_{\text{CNC-RP}} \times (t_{\text{setup\_CNC-RP}} + t_{\text{finish}})) + (C_{\text{tooling}} \times n_{\text{finish}}) + C'_{\text{EBM}}). \quad (12)$$

Currently, the cool-down time for EBM processing is a significant part of the total EBM time about 20 hours, Manogharan, Harrysson, and Wysk (2013). However, currently, work is being performed to reduce the cool-down time in the case of EBM. This is considered in this study through sensitivity analysis of cost variables.

3.4. Case study

The economic models developed are now analysed using a case study of the part shown in Figures 3 and 4. The unit cost and time are determined for manufacturing the case study part through CNC-RP and AIMS. Also, the impact of low-volume batch production is also investigated. The material selected for this study is Ti6Al4 V, which is one of the more popular metal alloys processed through additive methods. The part geometry selected in this study is typical of an additive manufacturing part that when processed through traditional machining would require multiple refixturing and location qualification.

For the process variables in CNC-RP, it was assumed that the operating cost was $ 25/hour (Bureau of Labor Statistics 2013) with a stock setup time of 10 minutes and a tool change of 10 minutes including qualification of the tool length. The cutting tools used were four flute carbide flat end mills with diameters of 25.40, 6.35 and 3.18 mm for roughing, semi-roughing and finishing, respectively. The machining parameters were estimated for the surface speed of 508 mm/s with a chip load of 0.05 mm in the case of roughing and semi-roughing and 0.03 mm in the case of finishing. The layer thickness (depth of cut) considered were 5.08, 0.51 and 0.05 mm in the case of roughing, semi-roughing and finishing operations, respectively. The stock volume for this study was a cylinder with a diameter of 63.50 mm and a length of 203.20 mm with a cost of $ 400 per bar. The average tool life was assumed to be 100 minutes of the machining time and the tooling cost of $20/tool.

In the case of EBM, the operating cost was estimated to be $ 104/hour (the charge for service work at NC State University) and the layer thickness used during this study was 0.07 mm (current parameter used for contract work at NC State University is 0.05 mm). The setup time in EBM including lowering the pressure in the build chamber down to the appropriate vacuum level and pre-heating

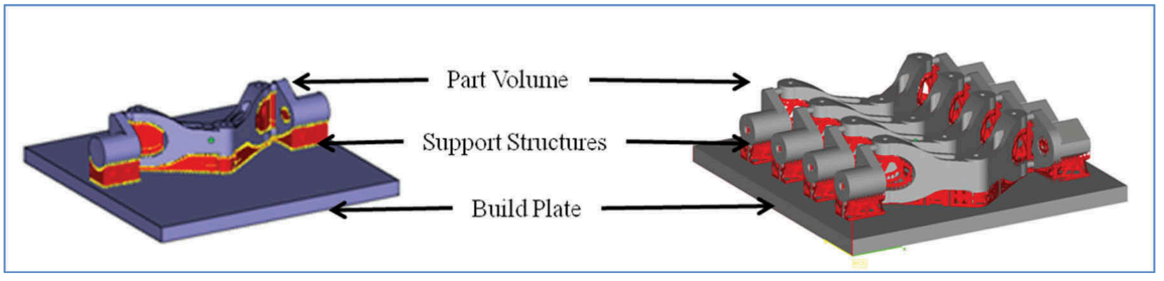

Figure 3. Unit and batch production of sample part in EBM with sacrificial supports for the subtractive stage.

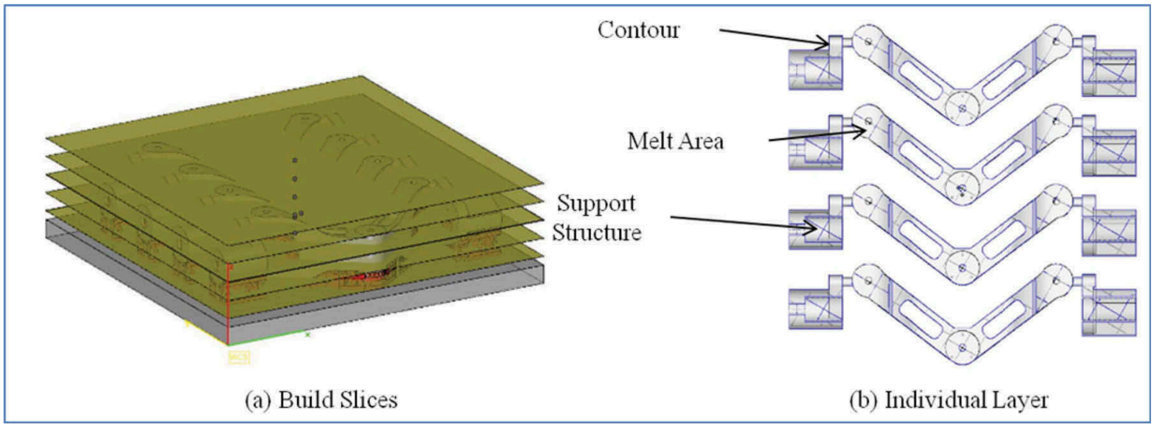

Figure 4. (a) Schematics of EBM build slices and (b) Individual layer showing the support and melt features for the sample part in this study.

the EBM plate was assessed to be 90 minutes. The cost of the EBM powder used was $ 300/kg and a 5% loss in powder during handling was also considered. Figure 4 shows the build slices (a) and several individual layers (b). The individual layers illustrate the contour, support and melt features. These component features will change as a function of the build direction. Constant beam speed conditions throughout melting and support generation are assumed in this study, although it is recognised that in reality the EBM slightly adapts the beam speed throughout the process. However, the proposed model can be used for varying processing conditions to replicate the exact physical build conditions across each layer. In this experiment, a multi-spot Arcam A2 was used and the effective contour speed was 17.18 mm/s and the support speed was 50 mm/s. In the case of melting, the beam overlap of 0.20 mm was used and hence the effective beam travel distance per unit is defined by the total melt area per overlap. Constant raking duration per layer (10 seconds), pre-heating (12.5 seconds) and post-heating duration (12.5 seconds) per layer are assumed. During this experiment, the melt beam speed used was 500 mm/s and the total number of layers was 528. The total cooling time for the build and part retrieval was estimated to be 1200 minutes. In the case study, the total melt area of a unit part was calculated to be 152,255 mm^2 and the total contour distance was found to be 21,605 mm. In the case of support structures, the total support distance were calculated to be 7766 mm. Also, based on the EBM wafer support and given jaw-contact length (during CNC-RP), the total volume for the sacrificial fixture in this study was 21,548.42 mm^3.

During batch production using CNC-RP, the process plan is repeated according to the batch size since stock is replaced after each run. In contrast, the number of parts in a single build can be increased in additive processes subject to build envelope restrictions as shown in Figure 4. In such batch runs using EBM, the processing time to set-up the build plate, plate pre-heating, raking, layer pre-heating and post-heating does not change (fixed costs per batch). However, the layer processing time varies based on the area and perimeter of the cross-sectional geometry of each layer. Therefore, the hybrid system could benefit from batch production in the additive stage in some cases followed by 'finishing' operation of every 'unit' in the batch separately in repeated CNC-RP operation.

3.5. *Results*

Using exclusively CNC-RP to produce the part through roughing, semi-roughing and finishing stages for machining parameters for Ti-6Al-4 V resulted in a processing time of 23.42 hours and a unit cost of $1358.25 as shown in Table 2. The material chosen is a difficult to machine material, so long machining times were not unexpected.

This is representative for machinability of many of the alloys used in aerospace applications such as Ti-6Al-4 V and superalloys such as Inconel 625. Such alloys have desired high temperature strength when compared to other metals with superior machinability such as aluminium alloys and most steels. This also leads to higher tool wear resulting in the consumption of multiple cutting tools. In addition, the cost of stock for those alloys is significantly higher than that of other commonly used material such as aluminium, steel and brass. When considering the volume of parts to produce (larger batch production) using the CNC-RP process, the unit price remains the same because the same process is repeated for each part. Thus, there will be no affects with CNC-RP as batch size changes.

In the case of the additive stage of EBM in the hybrid process, the unit price varies as shown in Table 3 for unit and batch production. It can be observed that increasing batch size reduces the unit cost because there is a significant fixed cost for each run. This can be attributed to the significant amount of time required in EBM for cool-down, plate pre-heating and part retrieval. The material cost of alloys used in EBM (and other AM processes) is often greater than wrought stock due to the preparation of materials through atomisation of the powder. From prior studies, material cost for AM processing is typically one to two orders of magnitude higher than polymer and metal material costs for most traditional manufacturing methods (injection moulding, casting, machining, etc.) (Manogharan, Harrysson, and Wysk 2013). The immediate implication here is that AM

Table 2. Breakdown of CNC-RP operation and tooling cost for sample parts.

CNC-RP stage	Setup time (hrs)	Machining time (hrs)	Number of tool changes	Tooling cost ($)	Tool change time (hrs)	Stage time (hrs)	Operating cost ($)	Total cost including material ($)
Roughing and hogging	0.17	14.04	8	160	1.33	15.37	417.50	1358.25
Finishing		9.38	5	100	0.83	10.21	276.00	
Total CNC-RP	0.17	23.42	13	260	2.17	25.59	698.25	

Table 3. EBM cost-components in unit and batch production for sample parts.

Batch Size	Setup-plate time (hrs)	Build time (hrs)	Cool time (hrs)	Total time (hrs)	Material cost ($)	Total cost ($)	Unit cost ($)
1	1.5	6.53	14	22.03	104.23	2395.35	2395.35
2	1.5	12.48	16	29.98	138.97	3256.89	1628.45
3	1.5	18.43	18	37.93	185.30	4130.02	1376.67
4	1.5	24.38	20	45.88	247.07	5018.59	1254.65

Table 4. Hybrid process unit and batch production for sample parts.

	Hybrid process						
	EBM stage			CNC-RP			
Batch size	Time (hrs)	Material cost ($)	EBM cost ($)	Time (hrs)	CNC-RP cost ($)	Total cost ($)	Unit cost ($)
1	22.03	104.23	2395.35	10.55	383.75	2779.10	2779.10
2	29.98	138.97	3256.89	21.10	765.50	4024.39	2012.20
3	37.93	185.30	4130.02	31.65	1151.25	5281.27	1760.42
4	45.88	247.07	5018.59	42.20	1535.00	6553.59	1638.40

processing will be limited to smaller batch sizes because of the higher material cost.

The hybrid process results as shown in Table 4 include the setup of the 'near-net' part in CNC-RP, finish machining and tool change time and costs.

For the given part geometry and available build volume of EBM, CNC-RP was more economical for batch sizes of up to four parts. Furthermore, the unit cost for the analysed part reduced by 41% with increased batch sizes d of four. This indicates that with greater build volume and/or nesting of parts into a single AM build with smaller part volume would further reduce the hybrid cost. For instance, in this case study, the unit cost of batch size of five can be lowered by two runs of three and two parts, respectively. This indicates that the build plan could be further optimised with different parts of varying batch sizes based on the build volume and part geometries. This could lower the unit cost for each of those hybrid parts. From Figure 5, it is recognised that the batch size does not impact the unit cost when producing a part through CNC-RP (including roughing and semi-roughing). From Table 3, it is evident that the capability to fabricate in batches can reduce the unit cost in the EBM stage in this example. This is primarily due to the time involved in raking, pre-heating and post-heating in each layer and, importantly, the cool down time as shown in Figure 6. By increasing the number of parts that can be accommodated in the AM build, the significant cooling time is spread across all units in the EBM build-batch.

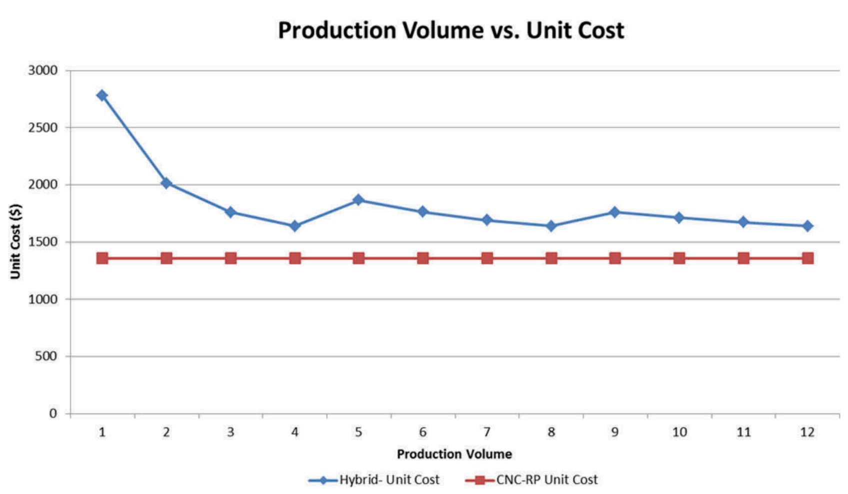

Figure 5 Unit cost through batch production in CNC-RP and hybrid process AIMS for the sample part.

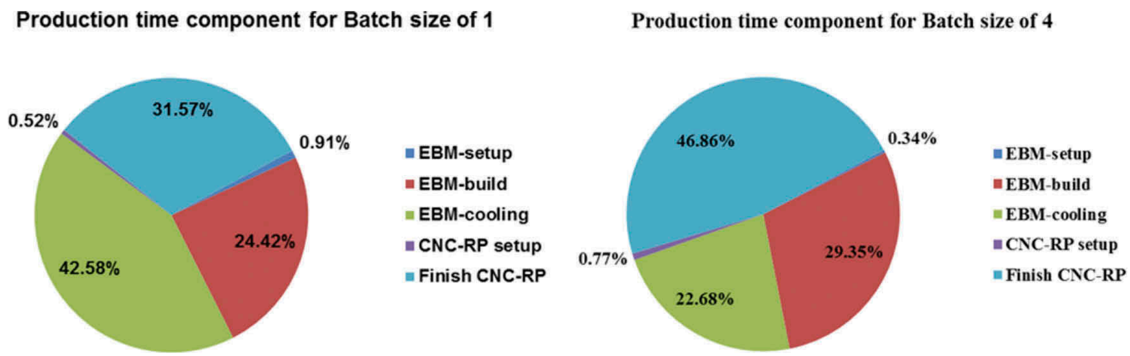

Figure 6. Time components in the AIMS production based on batch size for sample part.

4. Sensitivity analysis - influence of cost components

The previous economic analysis was conducted for only a single part geometry made from a hard to machine metal. One could argue that for other part geometries where CNC-RP would make swarf of a large per cent of the initial stock, the economics of hybrid processing would be better. The same argument could also be made for other independent variable cost parameters. For instance, the cost of materials for AM processing is 1–3 orders of magnitudes higher than that of traditional processes. Similar costs are present in the processing time and cost associated with AM when compared to traditional methods. Furthermore, with significantly higher fixed cost of the equipment (an order of magnitude greater for metal-AM), the unit AM cost is much greater. While, combining AM with CNC-RP in the AIMS system mitigates this effect to some extent, metal AM is often considered to be an infant process for production application. This is a consideration to the newness of metal AM (a couple of decades) when compared to other metal processing technologies which have existed for more than half a century. As with any developing processing technology, the cost-driving components will be improved with further research and development. In order to identify those critical components for AIMS, a sensitivity analysis is conducted. The following sensitivity analysis studies the major factors for the case study in order to evaluate the impact of the cost components. The variables include: cost of materials, AM operating cost, MRR ratio and AM production time.

The cost of materials varies significantly in EBM (and other AM) based on the alloys such as Ti-6Al-4 V, Inconel, etc. and also, the method and quantity of production through atomisation. In the case of CNC-RP, the cost of machining stock also varies significantly based on the materials such as aluminium and Ti-6Al-4 V. Machinability is an important factor for the unit cost, since selection of machining parameters can vary based on the materials (aluminium, Ti-6Al-4 V), available cutting tools (high speed steel, coated carbides) and machine tools. It should be noted that the MRR ratio is with respect to the previous study. Hence, the lesser the ratio, the greater the MRR when compared to the case study. Additional analysis showed that 15% reduction in the volume of materials used for the sacrificial fixture used in AIMS resulted in the lowering of unit cost by 30%. This shows that with further studies on ‘optimisation of sacrificial fixtures’ in AIMS (e.g. machining forces vs. fixture geometry), the overall unit cost of AIMS can be further lowered.

The total AM production time which is a function of pre-heat time, rake time, melt time and cooling or heat-treatment time is important, since advancements in AM methods have been improving rapidly. Hence, it is important to analyse the effects of reducing this time component. The unit EBM time component reduces based on batch size as shown in Figure 6. Therefore, this sensitivity analysis of single unit batches includes multiple units in a single build where the unit EBM time is reduced. Also, the unit material cost is a function of the part volume and hence does not vary for different batch sizes. Furthermore, since AM is a relatively new technology when compared to machining, considerable training and experience are required in the workforce to operate the equipment. As a result, the operator costs are almost four times on average to that of a machinist. Finally, this analysis studies the impact of these variables on the unit cost for hybrid and CNC-RP production. It should be noted that batch production is not considered for CNC-RP since the same process plan is repeated for each unit with a bar stock. The analysis was performed on the same part design detailed in Section 3.4 for the following conditions shown in Table 5 with optimistic conditions (50% improvement) and most optimistic conditions (100%) in the cost factors.

The price of atomised Ti-6Al-4 V metal powder for EBM is approximately $ 300/kg, and it is expected that with gaining popularity of metal AM, the overall production volume will increase and hence the powder cost would be lowered. It should be noted that the cost of the

Table 5. Variable conditions for AIMS hybrid process.

Variables	Current level	Optimistic	Most-optimistic
EBM material cost ($/kg)	300	150	30
CNC-RP stock cost ($/unit)	400	200	40
Ratio: MRR/MRR-case study	1	0.5	0.1
EBM production time (hrs/part)	20	10	2
EBM operating cost ($/hrs)	104	66	33

metal powder varies based on the material and process selection (laser vs. EBM). The cost of round stock for machining is higher for superalloys such as Ti-6Al-4 V and lower for steel and lowest for aluminium. Hence, the CNC-RP stock cost is considered to be 50% and 10% of Ti-6Al-4 V cost to simulate the effects of processing steel and aluminium. Similarly, the machinability of steel and aluminium is of the same order in terms of MRR. With improvements to current processing capabilities and techniques (e.g. cool down external to the EBM machine), the production time would be reduced. Finally, with growing workforce and skilled operators, the operating cost of metal AM such as EBM would reduce in the future.

The influence of the major factors on hybrid unit cost is shown in Figure 7. In Figure 7, it was observed that EBM (AM) production time tremendously affects the unit hybrid cost along with production cost. It was found that a 50% reduction in EBM production time resulted in lowering the unit cost by 40% and when EBM production time was reduced to 90%, the overall unit cost was reduced by 72%. Similarly, a 36% reduction in operation cost reduced the unit cost by about 30%. For the analysed part design and volume, it was found that the material cost had lesser effect on the unit cost where 50% reduction in material cost resulted only in 8% reduction in unit cost. Furthermore, increasing the material removal rate (machinability) of the material during finish-machining by 100% reduced the unit cost by 10%. This can be attributed to the fabrication of 'rough stock' through AM leading to minimal machining.

Increasing the machinability (MRR) by 50% and 100% in CNC-RP positively influenced the CNC-RP unit cost by 35% and 52%, respectively, as shown in Figures 7 and 8. However, reducing the material cost by similar orders had a lesser effect on the unit cost (13% and 25%), and when compared to the case study, this can be attributed to the significant amount of machining time leading to high tool costs. In other words, machining time is more dominant on unit cost than the material cost because increased machining time results in higher production time as well as more tool wear. The values for cost and rates used in the case study were typical costs for the effect of these rates should illustrate typical responses for changes in the manufacturing efficiencies and material costs.

It can be identified from this analysis that the cost of the hybrid process can be greatly reduced by reducing the production time and operator cost in EBM (or AM). In the case of CNC-RP, the unit cost can be greatly reduced by increasing the material removal rate significantly and lower the starting material cost. This can be attributed to the amount of additional machining time required to machine alloys such as Ti-6Al-4 V (MRR ratio = 1) and brass (MRR ratio > 0.33). In many ways, this study reflects the current state of additive and machining-based manufacturing processes, where expensive alloys with part designs requiring multiple fixtures are preferred to be processed through AM (particularly, for low volume

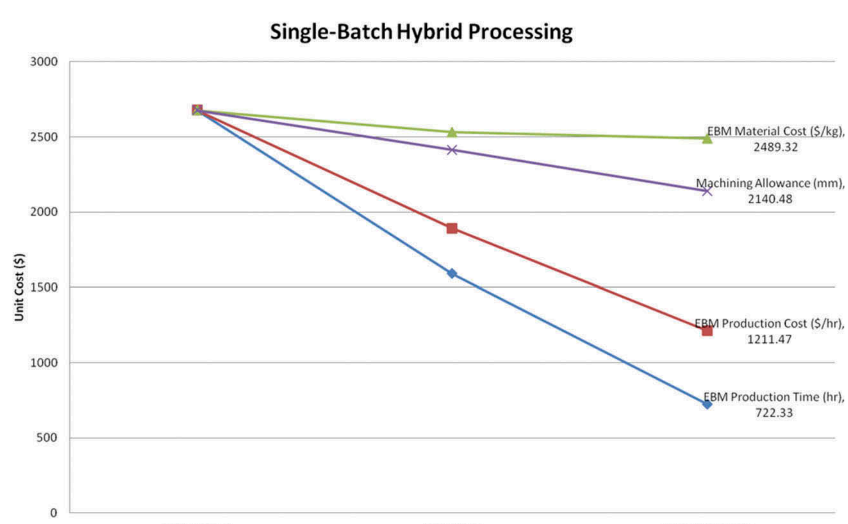

Figure 7. Influences of cost-factors on single-batch production through hybrid AIMS process for sample part.

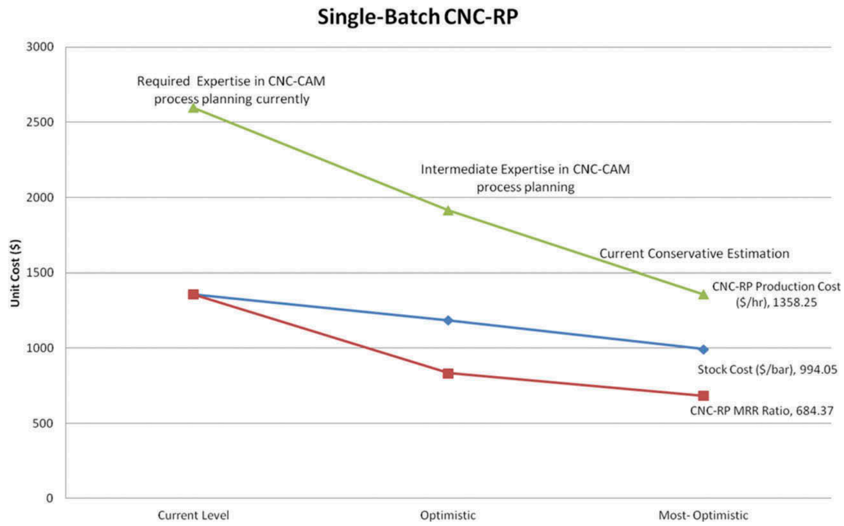

Figure 8. Influences of cost-factors on single-batch production through CNC-RP for sample part.

batches). The mass production of easier-to-machine alloys like aluminium, brass, etc. can be easily processed through machining with a higher material removal rate. From this study, it was analysed that EBM production time (which includes cool-down time) and EBM operator cost are the major levers for lowering the hybrid unit cost. In the case of AIMS, the analysis above identified the interaction between the important variables on unit cost for the case study for single-unit and batch production. The number of parts that can be included in a single EBM build (and other AM processes) is limited by the available AM build volume and build orientation. Furthermore, based on the case study, it was identified that the batch size does not impact the CNC-RP unit cost. Hence, in this analysis, the batch size of one that can be accommodated along the shortest build height is only considered for CNC-RP.

Based on findings from the first order influence of independent variables (Figure 7), the interaction between EBM production time and cost appears to be critical. In order to compare AIMS to CNC-RP, that interaction is extended to single-batch production and is presented in Figure 8. It was found that the unit cost of AIMS was lesser than that of base-study CNC-RP ($1358.25), when either the production time was lowered to 2 hours or when the production cost was $33/hour and also, when the production time was lowered to 10 hours (for $66/hour). Based on the economic information provided, it appears that reducing the total time on the AM machine is a critical variable. If the time can be reduced by 75%, the economics of AM only or hybrid processing will improve significantly. This is also a current focus of the next generation of AM (e.g. EBM machines), where post-AM processing time including cool-down/annealing time will go down significantly. Also of significance is lowering the production cost of AM (e.g. EBM). This can be achieved by broadening the AM-experienced talent pool through appropriate workforce training and education. So far, the noted findings have been for a single-batch production as shown in Figure 9.

It can be identified that the production cost significantly affects the hybrid unit cost and its effects are greater at larger production time (in the case of EBM→ cooling time). The impact of higher EBM production cost and time is mitigated by increasing the batch size. This also shows that by 'nesting' multiple unique parts (of single-batch), the overall unit cost of each part can also be lowered. For instance, combining single-order parts of different geometries during the AM stage would lower the overall unit cost of each part.

5. Discussion

From this study, it is observed that the machining duration of CNC-RP only production (including roughing and semi-roughing) is significantly longer than AIMS (only the finishing stage of CNC-RP). This is attributed to the machining parameters such as feed and depth of cut employed for milling alloys such as Ti-6Al-4 V. For instance, the machining time would be drastically lower in the case of processing relatively softer materials such as aluminium or brass. However, since the operation cost of CNC-RP is much lower than the operation cost of relatively newer technologies such as EBM (and other metal AM), the CNC-RP unit cost is lower for a single unit when compared to AIMS. It was also observed that long cooling time (and/or heat treatments) has a major influence on the unit hybrid cost. However, material utilisation in terms of part-stock volume of expensive, tough to machine materials is a critical factor based on part geometry while processing solely in CNC-RP. This is

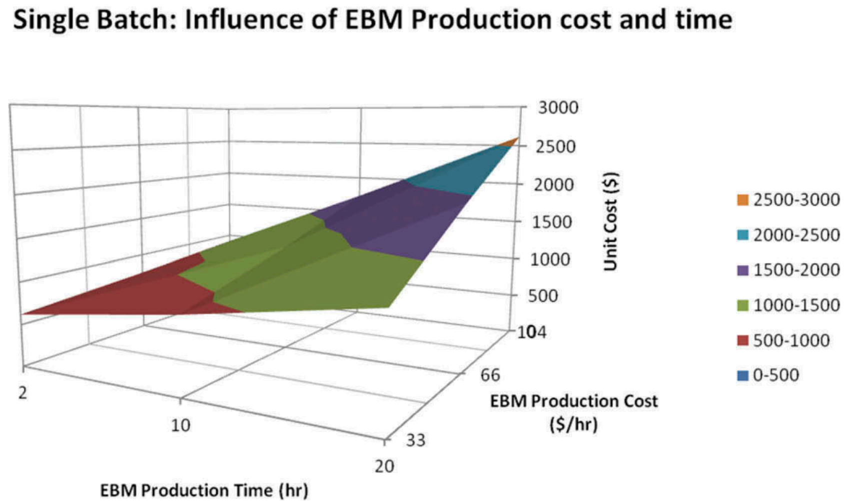

Figure 9. Influences of EBM production time and cost on single-batch production through AIMS.

important in the case of expensive superalloys used in aerospace and mechanical applications.

The hybrid process demonstrated higher material utilisation of expensive alloys in EBM along with the ability to 'finish' machine through CNC-RP. If machining can be limited to only the critically tolerance surfaces as shown in Figure 10, the CNC-RP time will be reduced significantly.

It can also be noted that the ability to batch produce 'near-net' shaped parts in a single build lowered the EBM-component in the total cost. Another critical factor is the part design limitations with subtractive methods. For instance, it is not feasible to produce non-conventional features such as mesh or lattice structures through CNC-RP. By integrating such part design within surfaces as shown in Figure 10 and finish machining through CNC-RP, the hybrid process enables an increased strength-to-weight ratio along with precision feature and surface accuracy. This is particularly critical in the case of expensive alloys.

In addition, the following relationship can be derived from above:

$$t_{\text{Pre-finishing}} = t_{\text{setup-CNC-RP}} + t_{\text{hog}} + t_{\text{rough}}, \tag{13}$$

and if:

$$C_{\text{Rough stock}} = (C_{\text{machining}} \times t_{\text{pre-finishing}}) + C_{\text{tool}(H)} + C_{\text{tool}(R)} + C_{\text{CNC-RP-stock}}, \tag{14}$$

and:

$$C_{\text{Rough stock}} \le C_{\text{EBM}}. \tag{15}$$

Hence, it is considered to be optimal to choose the CNC-RP process over the hybrid process (neglecting any geometric constraints) when the cost of rough stock is lesser than that of EBM. Otherwise, the hybrid process provides the least costly solution. Any situation that increases the pre-finishing time i.e. costs of roughing or semi-roughing tooling, or stock costs will shift the decision in the direction of the hybrid process and 'near-net' shaping using additive processes. This is intuitive and explains why significant research thrusts in the additive manufacturing arena are towards nickel-based superalloys and other difficult to machine materials. It is also somewhat instructive as to why (again neglecting any geometric constraints) aluminium research in these AM processes is somewhat muted, as the machinability of

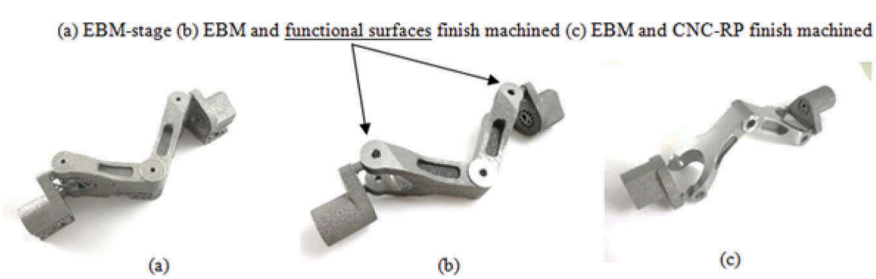

Figure 10. Functional surfaces and CNC-RP finish machining.

aluminium is much greater than that of cobalt chrome and titanium alloys. Other situations may not be as intuitive. Parts that require relatively little roughing or semi-roughing time, such as parts where part volume approaches that of the rough stock size in CNC-RP will favour CNC-RP, and parts where the majority of the material removal is done by the relatively large and rigid roughing tool will again favour CNC-RP. As shown, parts with a lower aspect ratio (with a lower ratio of material removal to stock volume) are preferred to be processed through CNC-RP. Parts with a higher aspect ratio and thin walls, greater concave areas and small internal features (internal to the convex hull) will favour the hybrid process.

The impact of the batch size on the hybrid process is significant because, it is near-net shaping 'n' units of rough stock for finish CNC-RP with a single set-up in EBM and amortising processing time of raking, pre-heating and post-heating of each layer (which consists of 'n' units). Hence, the selection criteria of economical process can further extended as:

$$C_{\text{Rough stock}} \geq (C_{\text{EBM}})/n. \qquad (16)$$

If the cost of roughing and semi-roughing through CNC-RP solely for a single unit is greater than processing 'near-net' shape EBM-made rough stock in a batch, AIMS is more economical. This criterion should be considered simultaneously for: (1) batch size, (2) build orientation and (3) part shape. For example, if a larger batch size (~10) of a part with a higher aspect ratio is required, it would be efficient to select the build orientation along the part length to accommodate the batch size in a single AM build. For commercial AM production, if even one part is being manufactured in an AM, it could be paired with other parts in a single AM build so that n in Equation (16) will be kept as high as possible and the resulting cost will be as low as possible.

The ability to address fixturing for subtractive operations prior to fabricating the part provides a unique advantage to analyse the location and geometry of fixtures on non-functional or desired surfaces, the orientation of part fabrication in the additive process can also be adapted to surfaces requiring precision finish (e.g. upward facing surfaces have better finish than downward facing or overhanging surface). Successful implementation of the integrated hybrid system will improve material utilisation and eliminate manual finishing processes and the requirement for multiple fixtures. The AIMS system can be employed through any AM process such as selective laser sintering (SLS), selective laser melting (SLM), etc. One of the highlights of this system is the requirement for a single STL/CAD to generate process plan for the entire hybrid system. Such approach can be employed in combining advantages of similar additive and subtractive processes; in this case EBM and rapid CNC machining (CNC-RP).

6. Conclusion

This article presented a model to determine the economics of additive and subtractive processing of mechanical parts. It also identified the critical cost components using sensitivity analysis by varying the variables of the cost models. Through integration of additive manufacturing processes with a subtractive manufacturing-based CNC-RP, the inherent economic advantages were demonstrated for each individual system through near-net shape part production, enabling the processing of otherwise difficult to machine materials, geometric flexibility, and rapid deployment of additive manufacturing. Such a hybrid approach results in simplified fixturing and reduced process planning for subtractive manufacturing. The proposed hybrid system was demonstrated through a case study of a single part using EBM and CNC-RP where the part is a functional load-bearing assembly part made of difficult to machine titanium alloy, Ti-6Al-4 V. Also presented is an economic model of the AIMS system. The need for lower AM production time (50% reduction leads to 40% lower unit cost) and cost (30% lower unit cost at 36% lower operating cost) were identified as the critical cost component. This is not a surprising finding since materials cost for additive materials are close to two orders of magnitude greater than the materials costs for materials used in traditional processes, and processing time for additive manufacturing is also close to two orders of magnitude greater than for traditional processes like injection moulding

Also, it was shown that the decision to use CNC-RP versus the hybrid system is impacted by the machinability and material cost, along with geometric and size considerations of the part. The hybrid approach is more economically attractive for more expensive and harder to machine materials while CNC-RP is favoured for less expensive and easier to machine materials (10% improvement in unit cost with 100% increased machinability). The hybrid system also becomes less expensive when multiple parts can be produced in the AM process simultaneously (either lot size increases beyond a single unit or pairing with other parts or orders in a single EBM build) subject to build volume-orientation constraints. It was found that AM processing time (EBM cooling time, heat-treatment of other powder-bed AM processes) and AM manufacturing cost greatly affect the cost of hybrid processing.

This sequential hybrid approach utilising built-in sacrificial fixtures can be adapted with any existing AM techniques including powder-bed fusion processes such as EBM, DMLS and binder jetting processes where the processing environment is not suited for simultaneous subtractive machining. This hybrid manufacturing system has not been previously demonstrated. It can be used to process a wide variety of geometries and materials while reducing engineering and material costs related to fixtures and tooling. Furthermore, this system can be readily implemented with no modifications to their currently deployed systems and only requires a rotary indexing CNC capability. Future work for this study will focus on analysing costs for a wide range of materials, AM technologies (SLM, Binder-Jetting), part designs (conventional prismatic parts, AM-friendly lattice structures, etc.). In addition, a detailed energy-consumption factor will be included in additional studies to better understand the sustainability and scalability of this hybrid approach.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Science Foundation [grant number CMMI −1161926].

ORCID

Guha Manogharan http://orcid.org/0000-0002-9756-1220

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