Design and Development of a Cost Calculator for Additive Manufacturing

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Abstract—Additive manufacturing is expanding at a fast rate throughout various industries, exploiting new avenues of topology optimization and reduced prototyping time. However, additive manufacturing is a costly and time consuming process in mass production. Recently, bound powder extrusion, a new metal additive manufacturing method based on metal injection molding was brought to market. The economic feasibility of the bound powder extrusion, as desktop ready process, and it applications have not been thoroughly studied relative to other metal additive manufacturing processes.

This research work proposes a costing model of the fused filament fabrication and bound powder extrusion methods to determine their economic feasibility. The similarities between the polymer and metal based methods are exploited to determine the individual part cost based on materials, part processing, consumables, and initial capital cost for each technology. The resulting model was integrated into a custom developed software to be utilized for real world applications. The system also employees an open source fused filament fabrication slicing software to determine the print time, extruded volume, and layer height. The similarities between the novel bound powder extrusion and fused filament fabrication allowed the generation of an accurate cost estimate for the novel method, while encompassing the additional part processing requirements.

To apply the costing model in an applicable scenario, an optimized double cardan H-yoke was considered for metal additive manufacturing. The results show that almost 85% of the part cost is directly related to the initial capital investment to acquire the technology.

The developed costing model is effective and can be further expanded to incorporate various metal additive manufacturing technologies, along with features such as competitive cost analysis between subtractive and additive methods.

Keywords—**Additive Manufacturing (AM), Costing Model, Fused Filament Fabrication (FFF), Bound Powder Extrusion (BPE), 3D Printing**

I. Introduction

Additive Manufacturing (AM) is a growing industry with ever changing technology to reduce machine size, print time, and cost. Recently, a new additive manufacturing method, Bound Powder Extrusion (BPE) was introduced to market. Markforged Inc. and Desktop Metal Inc. have created industrial desktop metal additive manufacturing technologies, named Atomic Diffusion Additive Manufacturing (ADAM[TM]) and Bound Metal Deposition[TM] (BMD), respectively [1]. These two technologies are based on the same principals which is generally categorized as BPE, combining the Fused Filament Fabrication (FFF) with Metal Injection Molding (MIM). FFF is the most popular AM process among hobbyist and professionals alike due to ease of use, low cost, safety, and availability [1]. The FFF method heats a thermoplastic filament into a liquid form and extrudes it onto a build plate. The BPE process uses a compound of metal powder and thermoplastic binder, in the form of a filament, applied to a build plate similar to FFF technology [1].

The advantages of AM overcomes the limitation of tooling required, allowing the cost per part to be independent of production volume [1]. It also opens the door for affordable single or low volume part production. However, a reliable costing model is essential to properly analyze the economic feasibility of AM versus traditional manufacturing. A costing model is a mathematical formulation that analyzes the effects of constraints, personnel, and the manufacturing method to create an accurate cost estimate. In the past, AM costing models have been separated into three main categories as follows: machine cost, material cost, and labour cost [2]. These categories can be further narrowed down to direct and indirect costs, with only the material accounting for the direct cost [3]. It has been stated that printing time, as an indirect cost, has the greatest effect on the total manufacturing cost [2].

In this paper, a costing model for two commercially available AM machines, that have recently been introduced to the market, is presented. The model targets the FFF and BPE AM processes, analyzing the Ultimaker S5 and Markforged Metal X printer, respectively. The similar print configuration allows the printing time of one device to be mapped to another. The costing model is based on three categories, machine cost, material cost, and processing cost. The model is implemented in a custom developed software, for ease of use and simplicity, by employing the slicing capabilities of modern FFF open source software directly to the cost estimate.

The paper is structured in the following way: Section II presents the costing model for both the FFF and BPE methods. Section III shows the comparison between FFF and BPE. Section IV displays the software implementation. A case study is explored in section V, followed by future work in section VI, and finally conclusion in section VII.

II. Costing Model

To create an accurate costing model, the manufacturing process is split up into three sections: post processing, material, and machine cost. Profit and overhead costs must also be included in the model. These two elements of cost highly depend on the manufacturer's location and business model. The final cost to the customer can be expressed as:

$$C_{Customer} = C_P \cdot (1 + E_O) + C_{Profit} \tag{1}$$

With the profit calculated as follows:

$$C_{Profit} = C_P \cdot (1 + E_M) \tag{2}$$

Where:

C_P: Part manufacturing cost ($)
E_O: Overhead Percentage (%)
E_M: Markup Percentage (%)

The values of E_O and E_M are subjected to the manufacturer, as they depend on market demand, location, and facilities costs. While overhead cost is varying from case to case, the AM cost itself can be calculated with an acceptable accuracy. This cost can be expressed as the direct summation of the three aforementioned sections, as shown:

$$C_P = C_{PP} + C_{Mat} + C_{Mach} \tag{3}$$

Where C_{PP}, C_{Mat}, and C_{Mach}, is the cost of post processing, material, and machine, respectively. The cost elements are further broken down as follows while being applied to both the FFF and BPE technologies.

A. Post Processing

AM requires additional steps to the manufacturing process besides the fundamental layer by layer creation of a part. A large post processing task for FFF is the removal of support materials and smoothing of the part surface. In the BPE process, in addition to removing the supports, two more post processing steps, washing and sintering, are required. Each post processing step can be further broken down based on the utilized method.

1) FFF: The FFF process requires supports to facilitate overhangs over a certain range. In a single extrusion system, the support structure is made of the same material as the final part. When dual extrusion is present, e.g. Ultimaker S5, soluble support can be printed. The solubility significantly reduces the post processing cost as the part is simply submerged in water to remove the support. In the case where soluble supports are not compatible with a FFF machine, manual labour is required to remove them. The following equation is used to determine the post processing cost of FFF in which manual labour is the only factor. Water required for soluble support removal was neglected due to negligible cost effect.

$$C_{PP} = T_{PP} \cdot C_L \tag{4}$$

Where:

T_{PP}: Post processing time (hr)
C_L: Labour cost ($/hr$)

2) BPE: The BPE printing process produces a much larger "green part" in which the part is comprised of binder and metallic powder. A two step post processing method is required to produce the final 96% dense metal part [4]. The part is first washed in a solvent to separate the binder material and metal powder. The part is then placed inside the furnace to sinter the metal powder, which increases the density and improves mechanical properties. During post processing the part shrinks to the desired size. The post processing is usually automated and requires electricity and consumables such as the Opteon SF-79 for debinding as well as argon for sintering [5]. The volume of Markforged sinter and wash can accommodate several parts simultaneously. Therefore, a cost per volume of part metric is used. Additionally, placement and orientation of the parts within these systems play a key role in the economic efficiency of these steps. The cost of processing a BPE manufactured part is calculated using the following equation that accounts for manual labour for loading and unloading.

$$C_{PP} = C_W + C_S + T_L \cdot C_L \tag{5}$$

Where:

C_W: Wash cost ($)
C_S: Sinter cost ($)
T_L: Logistics time (hr)

The wash is equipped with the Opteon SF-79 fluid that must be changed out after a set number of hours. Therefore, the cost of washing a part is based on the fluid cost per hour of lifetime and the power cost as shown below.

$$C_W = \left(\frac{V_P \cdot T_W \cdot C_F}{T_{FL} \cdot E_W} + \frac{P_W \cdot V_P \cdot T_W \cdot C_{PW}}{V_W \cdot E_W} \right) \tag{6}$$

Where:

V_P: Part volume (cm^3)
V_W: Wash volume (cm^3)
E_W: Wash volumetric efficiency (%)
T_W: Wash time (hr)
T_{FL}: Fluid life (hr)
P_W: Wash power consumption (kWh)
C_F: Fluid cost ($/cm^3$)
C_{PW}: Power cost ($/kWh$)

The final step of sintering encompasses an electric sinter that uses argon, as an inert gas, to provide shielding. The argon fills the sinter upon each instance and therefore is consumed. The respective cost is as follows:

$$C_S = \left(\frac{V_P}{V_S \cdot E_S} \right) (V_S \cdot C_A + P_S \cdot T_S \cdot C_{PW}) \tag{7}$$

Where:

V_S: Sinter volume (cm^3)
E_S: Sinter volumetric efficiency (%)
T_S: Sinter time (mm/s)
P_S: Sinter power consumption (kW)
C_A: Argon cost ($/cm^3$)

B. Material

Both the FFF and selected BPE method use material in filament form. However, the common metric for purchasing thermoplastic FFF filament is per kg, where Markforged sells their filament per cubic centimeter. In order to accurately calculate the cost, the material cost is analyzed as a cost per kilogram or cost per cubic centimeter. In the case of two extruders, the material cost is the sum of all materials as seen in (8) and (9).

The filament for FFF is calculated based on the mass of the print and the cost per mass of the filament. The result is a modular formula for every material that interfaces with the printer, as shown below.

$$C_{Mat} = C_{GE1} \cdot M_{E1} + C_{GE2} \cdot M_{E2} \qquad (8)$$

Where:

C_{GEx}: Cost per gram of material of extruder x ($\$/g$)
M_{Ex}: Mass extruded from extruder x (g)

Then a similar approach is followed with Markforged as the material cost is represented per cubic centimeter as follows:

$$C_{Mat} = C_{CE1} \cdot V_{E1} + C_{CE2} \cdot V_{E2} \qquad (9)$$

Where:

C_{CEx}: Cost per cm^3 of material of extruder x ($\$/cm^3$)
V_{Ex}: Volume extruded from extruder x (cm^3)

V_{E1} and V_{E2} of (9) can be calculated as follows:

$$V_{Ex} = V_x \cdot (1 + P_S) \qquad (10)$$

Where:

V_x: Volume extruded from extruder x (cm^3), from a slicing software
P_S: Part Shrinkage (%)

Part shrinkage (P_S) is a AM material property and must be provided by the filament manufacturer i.e. Markforged filament shrinkage is 30%.

C. Machine

The most expensive part of AM is the cost inferred from acquiring the machine and supporting equipment. In order to distribute this cost correctly over a series of parts, the cost is separated based on a specified payback period. It is not feasible to run any additive manufacturing machines for 24 hours a day, due to part change over and filament replacement. Therefore, the average run time for the machine is used and can be calculated in (11), based on an average of 21.5 working days in a month.

$$C_{PH} = \frac{C_{PC}}{P \cdot 21.5 \cdot H_{ut}} \qquad (11)$$

Where:

C_{PH}: Cost of unit and support equipment ($\$$)
H_{ut}: Operational efficiency (hr/day)
P: Payback period ($months$)

The complete cost of operating the printer for a set period of time is as follows:

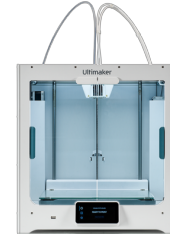$$C_{Mach} = T_P \cdot C_{PH} + C_{MP} + (T_C + T_{SU}) \cdot C_L \qquad (12)$$

Where:

T_P: Print time (hr)
T_C: Material changeover time (hr)
T_{SU}: Machine setup time (hr)
C_{PH}: Machine cost per hour ($\$/hr$)
C_{MP}: Machine power cost ($\$/hr$)

Additionally, the cost of electricity is calculated in (13), where P_M is the average power consumption of the machine in kWh.

$$C_{MP} = P_M \cdot T_P \cdot C_{PW} \qquad (13)$$

III. PRINTER CHARACTERISTICS & COMPARISON

To create a costing model that can analyze the FFF and BPE in parallel, a comparison was conducted between the technologies. The major similarity between FFF and BPE is the method of material extrusion [5]. The Markforged Metal X and the Ultimaker S5 both operate with an extruder mounted on a XY gantry and a build plate operating along the Z axis. The machine similarities can be seen in Fig. 1a and b.

(a) Ultimaker S5: A low cost professional FFF machine [6].

(b) Markforged Metal X System: A new BPE based machine comprised of a printer, wash, and sinter [5].

Fig. 1. FFF and BPE industry available additive manufacturing technologies

The similarity allows the BPE printing time to be calculated from an open source slicing software, such as Ultimaker's Cura [7]. The metrics used to compare the Ultimaker S5 and Metal X are as follows: layer height, nozzle diameter, print speed, and shrinkage due to the BPE process. Therefore, the respective BPE print time is calculated as follows:

$$T_B = T_F \cdot R_1 \cdot R_2 \qquad (14)$$

Where:

T_B: BPE print time (hr)
T_F: FFF print time (hr), from the slicing software

The print times T_B and T_F will be accordingly substituted as T_P in (12) based on the technology i.e. FFF or BPE. Ratio R_1 applies the difference in print speed and layer height.

$$R_1 = \underbrace{\left(\frac{V_{E1} \cdot S_{M1}}{V_{Tot} \cdot S_{U1}} + \frac{V_{E2} \cdot S_{M2}}{V_{Tot} \cdot S_{U2}} \right)}_{\text{Print Speed}} \underbrace{\left(\frac{H_M}{H_U} \right)}_{\text{Layer Height}} \quad (15)$$

Where:

V_{Ex}: Extruded volume of extruder x (cm^3)
V_{Tot}: Total extruded volume (cm^3)
S_{Ux}: Ultimaker S5 speed of extruder x (mm/s)
S_{Mx}: Metal X speed of extruder x (mm/s)
H_M: Ultimaker S5 layer Height (mm)
H_U: Metal X layer Height (mm)

Ratio R_2 addresses the nozzle cross sectional area, and the scaling of the Metal X part to the "green" state to account for shrinkage.

$$R_2 = \underbrace{\left(\frac{V_{E1} \cdot A_{M1}}{V_{Tot} \cdot A_{U1}} + \frac{V_{E2} \cdot A_{M2}}{V_{Tot} \cdot A_{U2}} \right)}_{\text{Nozzle Diameter}} \underbrace{\left(\frac{V_P \cdot (1 + P_S)}{V_P} \right)}_{\text{Part Shrinkage}} \quad (16)$$

Where:

A_{Ux}: Ultimaker S5 area of extruder x cross-section (mm^2)
A_{Mx}: Metal X area of extruder x cross-section (mm^2)

The post processing step as outline in II-A is significantly different and can not be compared. However, the time comparison effects the machine cost, which has the most dominate effect on the final cost [2].

IV. IMPLEMENTATION

A custom software was developed to provide a user-friendly interface for the implementation of costing model in real-world applications. The interface, shown in Fig. 2 applies the direct comparison between the BPE and FFF processes. The software allows the user to alter the values and define the process parameters on the main interface, as well as each configuration window (see Fig 3).

Due to the high cost associated with printing time, the software employed the capability to parse a presented G-code file. The G-code is sliced from a three-dimensional part file using the Cura software. The resulting G-code for the Ultimaker machines (S5, S3, 3, or 3 extended) is equipped with an additional header at the top of the G-code. The header displays accurate print information, where any data not presented can be extracted from the main G-code file. Table I displays the information parsed from the G-code file.

The parsed data is then used to evaluate the costing model proposed above. Implementing G-code data instead of using an approximation allows the costing model to work with an accurate printing time. The Ultimaker S5 and Markforged Metal X systems utilize the parsed data in different ways to correctly evaluate the model.

A. Ultimaker S5

The costing model implementation for the Ultimaker S5 printer is straight forward as the core data required is the printing time and extruded volumes. The parsed data provides the material type and extruded volume for each extruder. Thus, knowing the material density, the mass extruded (M_{Ex}) in (8) can be evaluated. The remaining cost components can be calculated as per the costing model by filling the required fields by the user in the software.

B. Markforged Metal X

The Metal X requires the calculation of print time described in (14). The software needs the user to enter the current nozzle size, desired layer height, and printing speeds of both selected materials into the configuration window (see Fig. 3a). Once initially set, the values remain within the database unless altered. During the two-step post processing of BPE, the part must remain in a sinter furnace or washing chamber for a set period of time. In order to incorporate the cost of sintering and washing, the bounding box volume parsed from the G-code was used to evaluate (6) and (7). The required volumetric efficiencies (E_S and E_W) are subjected to the part geometry, user knowledge, and packing method.

C. Customization

The software was designed to be used by an industrial partner in the manufacturing industry to determine the feasibility of AM as an alternative to traditional machining in low quantity production. Therefore, the costing model was implemented in the software based on the preferences of the industrial partner and all entered information are stored in a local user database. On the instance of a material, nozzle, or printing speed change the costing model is recomputed to ensure no misinformation is portrayed. The software was developed prior to the free release of Eiger; Markforged slicing software which determines the print times, material consumption, and material cost of Markforged machines [8].

V. APPLICATION

In order to demonstrate the capability of the costing model, a case study was explored with a topology optimized part.

TABLE I
PARSED G-CODE DATA

Variable	Location	Units	Dependant Equations
Extruder 1 Speed Extruder 2 Speed	G-code	mm/s	(15)
Extruder 1 Volume Extruder 2 Volume	Header	mm^3	(8), (9), (15)
Extruder 1 Diameter Extruder 2 Diameter	Header	mm	(15)
Extruder 1 Material Extruder 2 Material	Header	-	-
Print Size X Print Size Y Print Size Z	Header	mm	(6) (7)
Layer Count	G-code	-	(16)
Print Time	Header	s	(12), (13), (14)

Cost Calculator

3D Printing Cost Calculator

Labour Cost/Hour ($): 100.00   Electricity Cost (¢/kWh): 1.00
Workable Hours/Day (h): 18   Argon Cost ($/L): 1.00

Ultimaker S5 | **Metal X**

Settings

Ultimaker S5

Extruder 1 Material: ABS-Black (Ultimaker)
Extruder 2 Material: ABS-Black (Ultimaker)

Extruder 1 | Extruder 2

Material 1 Volume 0 cm³ | Material 2 Volume 0 cm³
Material 1 Mass 0 g | Material 2 Mass 0 g
Spool Cost ($) 29.99 | Spool Cost ($) 29.99
Spool Mass (kg) 1.00 | Spool Mass (kg) 1.00
Material Cost $ 0.00 | Material Cost: $ 0.00

Print Time & Characteristics

Printer Cost ($): 10,000.00 | Payback Period (m): 48
Print Time 0: 0: 0 | Time Cost $ 0.00

Pre/Post Processing

Change Over Required ☐
Soluable Support Enabled ☐ | Post Pro Time (min) 0
Set Up Time (min) 0 | Processing Cost $ 0.00

Add/Remove Material

Add Material | Remove Material

Settings

Metal X

Extruder Material 1: A2 (MarkForge)
Extruder Material 2: A2 (MarkForge)

Extruder 1 | Extruder 2

Material 1 Volume 0 cm³ | Material 2 Volume 0 cm³
Material 1 Mass 0 g | Material 2 Mass 0 g
Spool Cost ($) 299.99 | Spool Cost ($) 299.99
Spool Vol (cc) 200.00 | Spool Vol (cc) 200.00
Material Cost $ 0.00 | Material Cost: $ 0.00

Print Time & Characteristics

Printer Cost ($): 260,000.00 | Payback Period (m): 60
Print Time 0: 0: 0 | Time Cost $ 0.00

Pre/Post Processing

Change Over Required ☐
Sintering Time (hr) 28.50 | Wash Time (hr) 69.00
Set Up Time (min) 0 | Processing Cost $ 0.00

Add/Remove Material

Add Material | Remove Material

Ultimaker Cost: $ 0.00   Metal X Cost: $ 0.00

Upload GCODE File

Fig. 2. Costing model main interface: in which the user interacts to load a G-code file and change processing times.

Metal X Configuration

Printer Information | Material | Post Processing

Default Print Speed (mm/s) 70 | Extuder 1 Speed (mm/s) 30 | Sinter Power Cons (W) 600
Layer Height (mm) 0.10 | Extruder 2 Speed (mm/s) 30 | Sinter Gas Cons (L/HR) 1.00
Nozzle 1 Diameter (mm) 0.40 | | Sinter Volume (cc) 3020
Nozzle 2 Diameter (mm) 0.40 | | Sinter Volume Eff (%) 70
Power Consumption (W) 60 | | Wash Power Cons (W) 1200
| | Wash Fluid Lifetime (Hr) 1000
| | Wash Tank Volume (cc) 18356
| | Wash Volume Eff (%) 70
| | Wash Fluid Cost ($/L) 1.00
| | Wash Fluid Volume (L): 1000
| | Part Shinkage (%) 30
| | Post Pro Logistic (min): 0

Close

Ultimaker Configuration

Printer Information | Material

Default Print Speed (mm/s) 30 | Extruder 1 Speed (mm/s) 20
Layer Height (mm) 0.15 | Extruder 2 Speed (mm/s) 20
Nozzle 1 Diamater (mm) 0.40
Nozzle 2 Diameter (mm) 0.40
Power Consumption (W) 600

Close

(a) Markforged Metal X configuration.   (b) Ultimaker S5 configuration.

Fig. 3. User configuration for the selection FFF and BPE manufacturing methods.

The double cardan H-yoke shown in Fig. 4 was optimized for BPE manufacturing based on the Metal X capabilities and its 17-4PH stainless steel material [4]. The optimization resulted in complex internal cavities within the part that can only be manufactured using AM. The part was sliced in Cura for the Ultimaker S5 with 100% infill and 25% triangular support. The G-code was then loaded into the cost calculation software. The results (see Fig. 5) identify that the large purchase cost of the Metal X system has a significant effect on the part cost. Therefore, it is not economically viable to manufacture the optimized part, except for scenarios where light weight is extremely important and cost is not a concerning factor such as racing cars.

VI. FUTURE WORKS

The costing model presented in this paper is based solely on FFF and BPE processes, but can be expanded to additional AM method. Future works must be focused on the implementation of other slicing software such as Autodesk Fusion 360 [9]. Additionally, subtractive manufacturing methods can be incorporated to facilitate a direct cost comparison. Finally, the current software can be modified into a plug-in for Cura, as it operates as an open source software.

VII. CONCLUSION

In conclusion, a costing model has been developed in this paper to estimate the manufacturing cost when implementing FFF and BPE processes. The costing model focuses on the three main costs of AM, machine, material, and post processing; all of which require consumables or manual labour. The model was integrated into a software and was made available to industrial partners to determine the economic feasibility of AM. The software depended on a well known FFF slicing software to calculate the required material volume and print time. The interface displayed the manufacturing cost, all while adjusting the model to the users material, speed, and post processing requirements. Additionally, a case study was conducted showing that more than 85% of the AM cost is linked to the purchase of the AM system. The costing model is a simple and effective tool for modern machine shops looking to explore the feasibility and cost effectiveness of AM.

Fig. 4. Topology optimized double cardan H-yoke.

Fig. 5. Cost calculation results of the optimized double-cardan H-yoke.

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