Evaluation Method and Collaborative Study of Sustainable Additive-Manufacturing

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Summary

It has been commonly recognized that additive manufacturing (AM) enables cost-effective and efficient production towards sustainability. A rigorous evaluation method is required to further investigate the measurement method and efficiency before AM can be well-positioned in sustainable manufacturing and become the industry mainstream.

Cost reduction plays key role in manufacturing industry. Compared to conventional manufacturing (CM), cost of AM is volume independent. In contrary, CM production requires a certain volume to share initial tooling cost to achieve cost reduction. This constraint limits CM from service on demand, and leave ambiguity behind. Invisibility of AM advantage in cost factors blocks AM technologies from appropriate process and affects its applications.

The major issues AM encountering are the scaling, speed and size of products. Enhancement in scaling threshold and cost modeling are the novelty of this study and a breakthrough of AM issues. Through this study, generic equations are derived by using Convergence Effect and Buy-to-Fly (BTF) ratio. The Divide-and-Conquer approach further supports scaling factors and dependencies of conventional manufacturing (CM) cost modeling as well as AM methods. Consequently, appropriate AM technologies and CM convergence threshold can enhance standardization, decision support, and pre-pilot of AM society through this rigorous benchmarking.

Advantages of AM are identified, and a collaboration pattern is proposed to connect large enterprise (LE), SME, and home-based-business (HBB) into an AM society. Through this society, advantages of AM can be fully utilized, scaling and speed issues can be resolved, and AM’s dominant role in sustainable manufacturing becomes feasible.

Keywords: Sustainability, Materials Recycling, Collaboration, Localization, Standard, AM, CM, SME, Home based Business

I. Introduction

This paper starts with an evaluation and measurement of AM and CM processes, following by the derivation of generic equation. Concept of collaboration and collaborative pattern are explored, followed by case studies and conclusion.

Reducing material waste and recycling are both clear advantages with most AM technologies. Through the investigation of previous studies; a full adoption of materials recycling and starting with AM from best-fit technologies and products are recommended. Industrial ecology encourages the formation of synergies between companies across industrial sectors, to systematically review waste seen as an abundant, local and free resource. Therefore, increasing manufacturing efficiency through process and recycling competence are the keys.
This research aims sustainable recycling and manufacturing, and proposes a framework which covers the collection-recycling-manufacturing (CRM) model, Business model and Strategy control model. Among these three models; CRM model deals with technical aspects, Strategy control model guides human factors and finally; Business model, the model this study focuses, aggregates the assessment results from CRM model into a benchmarking. In this study, measurement of AM scaling issue and industrial collaboration are the focuses of investigation which are also tactical factors need be resolved.

II. Evaluation Method and Measurements

Through an extensive investigation, a seamless integration between materials recycling and AM is feasible. By targeting AM from best-fit technologies and products can be genuine entry point to expand AM coverage.

AM has been widely applied to deal with products that demand high complexity, particularly those with complicated shapes or colors, which can be difficult for CM to achieve. Part change becomes very flexible through AM and causes less impact to other parts. Increasingly used of AM in the medical industry, automotive and aerospace industry has become a trend particularly in those light-weighted parts in energy saving and part replacement for different types of products. AM can be the best choice for rapid prototyping as it offers flexibility to make necessary changes in a most rapid and cost-effective manner. It applies computer-aided design (CAD) file and converted stereo-lithography (STL) file to calculate the triangles and sliced shape of each layer to be printed (Wong, K., and Hernandez, A., 2012) (Muthu, S., Savalani, M., 2016). Through additive method of layer by layer, AM achieves significant reduction in design effort and much less materials than CM, to create product prototype once CAD and STL software are ready.

Compared to CM, the subtract technology; AM commits significant waste reduction that only consumes the exact materials the products require. This reduces energy consumption and CO₂ emission well. In addition, AM can produce a piece of part that requires an assembly of many parts from CM and contributes to energy saving through reducing the weight of final products. Cost modeling between AM and CM are different. Cost of each part is a constant for AM however, CM requires a higher volume to achieve cost down due to the initial tooling cost which dominants among other cost. By taking advantages of such AM unique characteristics, this study investigates the point of intersection that CM gain scaling advantage over AM. It further computes the CM convergence that alternative AM technology may offer a lower cost and gain cost advantages over CM.

However, AM has some disadvantages to be resolved before mass production. Compared to AM, CM is fast in parts fabrication while AM prints products with lower speed and the products are limited to premium quality, smaller quantity and smaller size. With the advancement of technologies and measurement, such disadvantages are resolvable and shall not affect AM’s role at all, and the resolutions are all this study aims to achieve. AM can take advantages of its versatile technologies and gain costing advantages by applying the generic formula this study derives. Furthermore, AM can fully utilize the collaborative pattern in a full scale provision. The pattern this study proposes offers good opportunity to HBB in resolving scale and speed issues by taking advantages of AM’s easy entry and inexpensive initial cost.
II-1 Cost Modeling by Divide-and-Conquer Approach

Benchmarking method is critical in cost reduction and decision support. Compared to CM, cost of AM is volume independent, but in contrary; CM production requires a higher volume to share initial tooling cost to achieve cost reduction. This constraint limits CM from service on demand, and leave ambiguity in a volume threshold setting.

A rigorous method of Divide-and-Conquer is proposed to analyze individual cost items and their dependencies through a case study of aerospace industry. The study develops cost modeling pattern in AM and CM evaluation. Finally, general equations are derived through convergence effect to tackle with scaling issue. In parallel BTF ratio, in relevant area, is investigated in this study to evaluate the input weight over output weight. Ti-64 is the materials being used in benchmarking to support the cost modeling.

Generic Formula derivation

In this cost benchmarking; two AM method (method A and method B), and two CM volume size (20k and 100k) are illustrated in the format indicated in table 1, to measure the interferences of volume/method against cost.

Tooling initial setup cost is ‘0’ in AM case means AM cost is volume independent. However, this cost is very high in CM case need be break down to each part unit. Convergence effect is applied to investigate CM volume against part unit cost. It produces generic formula for prediction, and eventually achieves cost reduction.

<table>
<thead>
<tr>
<th>Item/Method</th>
<th>denotation</th>
<th>AM_method_A</th>
<th>AM_method_B</th>
<th>CM_20k</th>
<th>CM_100k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor</td>
<td>‘O’</td>
<td>L</td>
<td>L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials</td>
<td>‘VH’</td>
<td>H</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine</td>
<td>‘T’</td>
<td>M</td>
<td>M</td>
<td>VH</td>
<td>H</td>
</tr>
<tr>
<td>Tooling</td>
<td>‘C’</td>
<td>C_AM</td>
<td>C_AM</td>
<td>CM_20k</td>
<td>CM_100k</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>batch volume</td>
<td>‘n’</td>
<td>any</td>
<td></td>
<td>20,000</td>
<td>100,000</td>
</tr>
</tbody>
</table>

Table 1. Cost Modeling format for benchmarking

Through differentiation of cost patterns, this study develops generic formula of Business model which can be used in AM and CM cost modeling. The formulas are variables dependent and the generic form can be developed to a software package for decision support. There are two generic formulas. First one is “Divide” that envisions tooling cost through volume dependency, and second one is “Conquer” that moves results into a total cost calculation.

Formula 1. Tooling cost (mold design and mold cost) generic form of CM

Tooling unit cost × Part counts = Mold design cost + mold unit cost × Part counts

Formula 2. Total cost generic form of CM

Total unit cost × Part counts = Mold design cost + (mold unit cost + Other unit cost) × Part counts
To translate the generic formulas into parametric formulas, denotation of parameters are listed in table 2.

<table>
<thead>
<tr>
<th>Denotation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{CM} \text{ (20k)}$</td>
<td>‘Total unit Cost’ in CM_20k case</td>
</tr>
<tr>
<td>$C_{CM} \text{ (100k)}$</td>
<td>‘Total unit Cost’ in CM_100k case</td>
</tr>
<tr>
<td>$C_{AM _method _A}$</td>
<td>‘Total unit Cost’ in AM method_A case</td>
</tr>
<tr>
<td>$C_{AM _method _B}$</td>
<td>‘Total unit Cost’ in AM method_B case</td>
</tr>
<tr>
<td>$n$</td>
<td>‘Part counts’</td>
</tr>
<tr>
<td>$O$</td>
<td>‘Other unit cost’ in production, which is a very small amount and volume independent This is the summation of CM assembly, operator, materials and machine cost approaches 0 independent to batch size, and ‘O’ value is assumed the same for both CM_20k and CM_100k</td>
</tr>
<tr>
<td>$T_{CM \text{ (20k)}}$</td>
<td>‘Tooling unit cost’ (mold design cost break down + mold cost) in CM_20k case</td>
</tr>
<tr>
<td>$T_{CM \text{ (100k)}}$</td>
<td>‘Tooling unit cost’ (mold design cost break down + mold cost) in CM_100k case</td>
</tr>
<tr>
<td>$M$</td>
<td>‘Mold design cost’, which is one time cost per batch, a constant and volume dependent</td>
</tr>
<tr>
<td>$m$</td>
<td>‘mold unit cost’ in production, which is a constant and volume independent</td>
</tr>
</tbody>
</table>

Table 2. Parameters used in Cost Modeling

**CM Tooling** (formula 1) for “Divide”

Tooling (T) in formula 1 is divided into ‘M’ and ‘m’ and translated into:  
\[ T_{CM} \times n = M + 20000 \times m \]

The balance equation can be represented by applying two individual scales, to derive ‘M’ and ‘m’:

\[ T_{CM \text{ (20k)}} \times 20000 = M + 20000 \times m \quad (\text{for CM_20k}) \]
\[ T_{CM \text{ (100k)}} \times 100000 = M + 100000 \times m \quad (\text{for CM_100k}) \]

Through the 2 equations:

\[ M = 25000 \times (T_{CM \text{ (20k)}} - T_{CM \text{ (100k)}}) \quad m = 1.25 \times T_{CM \text{ (100k)}} - 0.25 \times T_{CM \text{ (20k)}} \]

**CM Total cost modeling** (formula 2) for “Conquer”

By taking the tooling values: “M” and “m”, derived from formula 1, into a total cost calculation;

\[ C_{CM \text{ (20k)}} \times 20000 = M + (m + O) \times 20000 \quad (\text{for CM_20k}) \]
\[ C_{CM \text{ (100k)}} \times 100000 = M + (m + O) \times 10000 \quad (\text{for CM_100k}) \]

Total cost in a generic form:

\[ C_{CM} \times n = M + (m + O) \times n \quad \text{or} \quad C_{CM} = \frac{M}{n} + (m + O) \]

CM generic formula can be applied to any scenario including the two CM individual cases which implies;

With a given ‘T’, we can derive ‘M’ and ‘m’ values.

With a given ‘O’; and the derived ‘M’ and ‘m’ values, each $C_{CM}$ value can be derived with a given ‘n’ value.

This also implies; the generic formula enables CM unit cost estimation ($C_{CM}$) under any volume size ‘n’. 
AM cost modeling

From the other side, “C_{AM}” value in AM case stays constant which is simply independent of volume.

\[ C_{AM} = C_{constant} \]

AM and CM cost benchmarking

AM and CM cost benchmarking in scaling aspects is now becoming feasible to answer the following investigations;

1) What is the volume that CM starts to gain cost advantage over AM. This refers to \((n_1, c_1)\) in cyan dash-line.

2) What is the CM convergence that CM cost becomes flat and volume doesn’t help. This refers to \(c_2\) value of the red dash-line in the figure 1.

3) What is the AM method that reduces cost to a lower value than the value of CM convergence, to gain cost advantage over CM. This refers to \(c_3\), a shift from the cyan dash-line to the green line.

![Figure 1. Cost-volume correlation in Cost Modeling](image)

The investigation pin points key areas of Business model, which further derives solutions to demonstrate 3 key investigations;

1. To estimate the CM volume that CM cost start to win over AM cost; let \(C_{CM} = C_{AM} = C_1\) at intersection. This derives; \(C_{CM} = \frac{M}{n} + (m + O) = C_{AM} = C_1\) or \(M + (m + O) \times n = C_{AM} \times n\) at \(C_{CM}/C_{AM}\) intersection

With derived ‘M’, and ‘m’ values, and the given ‘O’ and ‘C_{AM}’ values, intersection happens at \((n_1, c_1)\);

‘n’ value at \(C_{CM}/C_{AM}\) intersection can be easily derived by; \(n_{intersection} = \frac{C_{AM} - (m + O)}{M}\)

In the other word, when \(n \geq n_1\) (or \(\frac{C_{AM} - (m + O)}{M}\)), CM volume start to gain cost advantage over AM.
2. To find the convergence of CM cost at $C_{\text{convergence}}$ ($C_2$), the discrete notation can be expressed as followed:

Let $c_{\text{convergence}}$ be the CM cost at convergence;

\[ \forall (c, n) \in \{(c_0, n_0), (c_1, n_1), \ldots (c_n, n_n)\}, \quad \exists c_{\text{convergence}} \text{ satisfies: } c_{\text{convergence}} \leq n \quad \forall n \in \{c_0, c_1, \ldots c_n\} \]

Since the generic equation $C_{CM} = \frac{M}{n} + (m + O)$ can be expressed by: $C_{CM} \times n - M - (m + O) \times n = 0$

Let $(n, C_{CM})$ be mapped to $(x, y)$ Cartesian coordinate system;

$C_{CM} \times n - M - (m + O) \times n = 0$ is converted into: $yx - M - (m + O) \times x = 0$

The deviation of $y$-axis $C_{CM}$ against $x$-axis $n$ becomes 0 at convergence indicates;

\[ \frac{\partial (yx - M - (m + O) \times x)}{\partial x} = 0 \quad \text{which implying;} \quad y_{\text{convergence}} - 0 - (m + O) = 0; \quad \text{or } y_{\text{convergence}} = (m + O) \]

$C_{CM} (\text{convergence}) = (m + O)$ is the answer of 2nd investigation, that fully explain CM convergence calculation.

3. When AM unit cost drops from $C_{AM\_method\_A}$ to $C_{AM\_method\_B}$ ($C_3$) which is equal to or lower than $C_{CM-\text{convergence}}$, no matter how large the CM volume is, $C_{CM}$ will not be able to achieve $C_{AM\_method\_B}$, the new AM cost.

To reduce AM unit cost, from $C_{AM\_method\_A}$ to $C_{AM\_method\_B} \leq C_{CM} (\text{convergence)}$, AM method needs an adjustment.

As machine and materials contribute majority of AM’s cost, both are best candidates of cost reduction.

**AM method for cost reduction**

<table>
<thead>
<tr>
<th>Method</th>
<th>$AM_method_A$</th>
<th>$AM_method_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>VH</td>
<td>H</td>
</tr>
<tr>
<td>Machine</td>
<td>VH</td>
<td>H</td>
</tr>
<tr>
<td>H: high</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. AM materials and machine cost format

As CM convergence happens at $C_{CM} (\text{convergence}) = (m + O)$ The value can be lower than method A. However, with new AM method (method B), as $C_{AM\_method\_B} < C_{AM\_method\_A}$, unit cost of AM lower than CM is feasible.

As indicated in table 3, the new cost format; $C_{AM\_method\_B} < C_{CM} (\text{convergence})$ or $C_{AM\_method\_B} < (m + O)$

1) CM batch size at a value of $n = \frac{C_{AM} - (m + O)}{M}$ or higher will gain cost advantage over AM.

2) CM cost convergence happens $C_{CM} (\text{convergence}) = (m + O)$, that $C_{CM} (\text{convergence})$ can be lowest cost.

3) When AM method is changed with lower machine or materials cost; there is a possibility that new AM cost: $C_{AM\_new}$ can be lower than $C_{CM} (\text{convergence})$. The example is illustrated in next paragraph by using live data.
II-2 Applications of Cost modeling in industry live cases

Cost modeling pattern is derived in previous paragraph, and the generic formulas are applied to the real case as a verification of the results. Table 4 illustrates different criteria of focus in AM and CM benchmarking; assume the conditions are well-prepared and the benchmarking criteria is the technologies for AM, and batch size for CM.

<table>
<thead>
<tr>
<th>conditions</th>
<th>AM_method_A</th>
<th>AM_method_B</th>
<th>CM_20k</th>
<th>CM_100k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
<td>Stereolithography (SLA)</td>
<td>Fusion deposition modeling (FDM)</td>
<td>Injection molding</td>
<td>Injection molding</td>
</tr>
<tr>
<td>Batch size</td>
<td>any</td>
<td>any</td>
<td>20,000</td>
<td>100,000</td>
</tr>
<tr>
<td>Materials</td>
<td>Plastic polymer</td>
<td>Plastic polymer</td>
<td>Plastic polymer</td>
<td>Plastic polymer</td>
</tr>
</tbody>
</table>

Table 4. Cost Modeling benchmarking in different criteria

Benchmarking conditions

In this cost benchmarking example; the application is in aerospace industry. Injection molding is the technology used in CM, the batch sizes for benchmarking are 20k (20,000 and 100k (100,000) individually. The Stereolithography (SLA) is the original technology used in AM (AM_method_A), and Fusion deposition modeling (FDM) is the new method of AM (AM_method_B). Among all AM technologies, FDM extrusion can be one of the most cost-effective options and easy to prepare. Hence, FDM extrusion is selected to demonstrate a new cost benchmark (AM_method_B). Polyamide plastic is the material used in evaluation, and raw data from Deloitte Insight (Cotteleeer, M., 2014) is used to demonstrate the method of cost modeling for how the derived generic equation can be applied in industrial real scenario to contributes decision support.

<table>
<thead>
<tr>
<th>Method</th>
<th>AM_SLA</th>
<th>CM_20k</th>
<th>CM_100k</th>
<th>($/part)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly</td>
<td>0.01</td>
<td>0.06</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Operator</td>
<td>0.14</td>
<td>0.01</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Materials</td>
<td>0.43</td>
<td>0.01</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Machine</td>
<td>0.83</td>
<td>0.05</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Tooling</td>
<td>0</td>
<td>3.48</td>
<td>1.30</td>
<td></td>
</tr>
</tbody>
</table>

Total $1.41 $3.61 $1.39

(raw data: Deloitte insight)

Table 5. Live data for AM and CM benchmarking

As indicated in table 5, for the 20,000 pieces of CM parts, the unit cost ($3.61) is 2.5 times higher than AM ($1.41) however, when the batch size is increased to 100,000 pieces, the unit price drop to $1.39, which is even slightly lower than AM’s cost. Among each cost item; tooling (including molding), dominants from all and contributes over 95% of CM’s cost.

AM cost pattern is different from CM as machine and materials contribute 60% and 30% of AM cost individually. By taking “Divide-and-Conquer” approach, derived from generic formulas, into the parametric calculation;
CM Tooling  \[\text{(formula 1)}\]

\[M = 25000 \times (T_{CM\ (20k)} - T_{CM\ (100k)}) \quad m = 1.25 \times T_{CM\ (100k)} - 0.25 \times T_{CM\ (20k)}\]

\[M = 25000 \times (3.48 - 1.30) = 54,500 \quad m = 1.25 \times 1.30 - 0.25 \times 3.48 = 0.755\]

\[M = 54,500 \quad m = 0.755\] implies the mold design costs $54,500 per batch and mold costs $0.755 per unit.

CM Total cost modeling  \[\text{(formula 2)}\]

\[C_{CM} = \frac{M}{n} + (m + O)\]

As the summation of rest 4 items - assembly, operator, materials and machine cost accounted around 0.1 and taking only 5\% of the total cost, which is independent to the batch size. To simplify the equation; let the sum of these 4 items be the “other cost”: \[o = 0.1\] a fixed cost and independent of batch size.

\[C_{CM} = \frac{54500}{n} + (0.755 + 0.1) \quad C_{CM} = \frac{54500}{n} + 0.855 \quad (CM\ generic\ equation)\]

AM cost modeling

From the other side, “\(C_{AM}\)” value in AM case stays constant ($1.41) which is independent of volume.

\[C_{AM} = 1.41 \quad (AM\ generic\ equation)\]

Key parameters calculation

1. To estimate the CM volume that CM cost start to win over AM cost; let \(C_{AM} = C_{CM}\) be the point at equilibrium.

This leads; \[1.41 = \frac{54500}{n} + 0.855\] at equilibrium and the “\(n\)” value can be easily derived by: \[\frac{54500}{n} = 0.555\]

In the other word, when \(n \geq 98198\), the CM volume start to gain cost advantage over AM

2. To find the convergence of CM cost at \(c_\infty\), the discrete notation can be expressed as followed;

Let \(c_{convergence}\) be the CM cost at convergence.

\[
\forall (c, n) \in \{(c_0, n_0), (c_1, n_1), \ldots (c_\infty, n_\infty)\}, \quad \exists c_{convergence} \text{ satisfies: } c_{convergence} \leq c_n \quad \forall n \in \{c_0, c_1, \ldots c_\infty\}\]

Since the generic equation \(C_{CM} = \frac{54500}{n} + 0.855\) can be expressed by: \(C_{CM} \times n - 54500 - 0.855 \times n = 0\)

Let \((C_{CM}, n)\) be mapped to \((y, x)\) Cartesian coordinate system.

The deviation of y-axis (‘\(C_{CM}\)’) against x-axis (‘\(n\’) becomes 0 at convergence, which lead;

\[
\frac{\partial (xy - 54500 - 0.855 x)}{\partial x} = 0 \quad \text{which indicates: } y_{convergence} - 0 - 0.855 = 0; \quad \text{or } y_{convergence} = 0.855 \quad \text{This implies:}\]

CM unit cost becomes flat when approaching CM\ convergence: $0.855 is the lowest unit cost despite of batch size.
1-3. When AM unit cost drops from $1.41 to CM convergence or lower than the convergence value (C_{AM} \leq 0.855), no matter how large the volume of CM is, CM will not be able to achieve this AM cost.

To reduce AM unit cost from $1.41 to $0.855 or even lower, the AM method needs an adjustment.

In Deloitte case, as machine and materials contribute 60% and 30% of AM’s cost individually, both cost values are candidates of cost reduction.

**AM method for cost reduction**

Among all AM technologies, FDM extrusion can be one of the most cost-effective options and easy to prepare. Hence, FDM extrusion is selected to demonstrate a new cost benchmark.

According to AM machine and materials benchmark (Simpson, T., 2019), the materials and machine cost are different for different method.

<table>
<thead>
<tr>
<th>Method</th>
<th>AM_SLA</th>
<th>AM_FDM_Extrusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>$175–250/kg</td>
<td>$20/kg</td>
</tr>
<tr>
<td>Machine</td>
<td>$200,000 +</td>
<td>$150,000</td>
</tr>
</tbody>
</table>

(data source: Simpson, T)

Table 6. Materials and machine cost for AM with different methods

Table 6 provides an estimation of the materials comparism between SLA and FDM is around 1.0 : 0.1, and machine cost is around 1.0 : 0.75 hence; both values (0.1 and 0.75) are applied in a conversion from SLA to FDM cost.

In addition to machine and materials, other cost can be similar for both methods of SLA and FDM. The details of a full-scale cost items of 2 AM methods and 2 CM methods are listed in table 7.

<table>
<thead>
<tr>
<th>Method</th>
<th>AM_SLA</th>
<th>AM_FDM_Extrusion</th>
<th>CM_20k</th>
<th>CM_100k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly</td>
<td>0.01</td>
<td>0.01</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>Operator</td>
<td>0.14</td>
<td>0.14</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Materials</td>
<td>0.43</td>
<td>0.04</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Machine</td>
<td>0.83</td>
<td>0.62</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Tooling</td>
<td>0</td>
<td>0</td>
<td>3.48</td>
<td>1.30</td>
</tr>
<tr>
<td>Total</td>
<td><strong>$1.41</strong></td>
<td><strong>$0.81</strong></td>
<td><strong>$3.61</strong></td>
<td><strong>$1.39</strong></td>
</tr>
</tbody>
</table>

Table 7. Full-scale of AM and CM cost items
By taking the data from table into plotting, the comparison between AM (both FDM and SLA technologies) and CM (both 20k and 100k) is demonstrated in figure 2; and the benchmark is demonstrated in figure 3.

Figure 2. Cost items comparison between AM (SLA & FDM), and CM (20k & 100k)

Figure 3. Convergence Benchmark of CM and AM cost based on 3 investigations

Figure 3 further demonstrates the results from the live case as indicated in the following three key statements;

At $C_1$ ($C_{AM (SLA)} = 1.41$), the intersection happens at $n_1 = 98198$. When $n < n_1$, $C_{AM} < C_{CM}$ and vice versa.

At $C_2$ ($C_{CM (convergence)} = 0.855$), $C_{CM}$ approaches this lowest cost value when batch size is increased.

At $C_3$ ($C_{AM (FDM)} = 0.81$), $C_{AM} < C_{CM}$ is always true under this adjustment.
II-3 BTF Applications - Digital-Alloy Metallic Materials Case study

BTF is the terminology commonly used in CM aerospace industry citing the ratio of the input weight of raw material over the output weight of the product parts. Hence the design focuses on the higher CM BTF ratio and heavy weight of complex parts. BTF is usually used in metallic materials though it can be plastics as well.

As CM is subtractive technologies, the BTF ratios of CM technologies varied which ranged from 6:1 to 33:1 depends on the materials and applications. This implies; the amount of discarded material ranged between 83 and 97 percent. According to Barnes Group Advisors (Digital Alloys, 2019), 11:1 is the averaged ratio in aerospace and 30:1 is usual for higher complexity parts. Pereira (Pereira, 2018) indicated the higher the complexity or customization required AM is better suited. Usually AM stay with 1:1 or close to 100% which means the input materials is fully utilized in the process. In addition, through customization, materials’ weight can be further reduced to eliminate CO₂ emission. This effect is amplified particularly for the parts that being used in aerospace, automobile or any light-weight applications. In Northwest Airlines’ case; generic bracket, made by 3-D printers, save weight for over 10kg and it was estimated that the aircraft will achieve $440,000 per year in cost savings.

Followed by the convergence study of cost modeling, Boeing Company and many other large manufacturers measure AM against CM by using 3 key factors: part performance, cost and lead time. 1) AM can design and prototype parts very fast that shorten lead time. 2) Due to digital manufacturing, advancement of technologies in AM is more agile and faster than CM. Based on convergence effect; reducing AM’s cost through new technologies is always feasible. 3) With advancement of technology such as joule printing (Digital Alloys, 2019), AM can achieve speed and cost, and stay in competitive position with CM/CNC method. CNC is a common term denotes "computer numerical control", and as CNC is a subtractive manufacturing process which typically employs computerized controls and machine tools to remove layers of material from a stock piece, materials yield is low.

Following example demonstrates how AM achieve better cost modeling through a comparison of BTF ratio. Let x denotes BTF and y denotes unit cost. AM Ti-64 materials cost $300/kg, the AM (Joule Printing) stays with a constant: y = 300 (independent of x). CNC comes with lower materials cost: $100/kg and stays with a simple equation: y = 100 x. AM and CM cost intersection happens at BTF = 3. In this Titanium (Ti-64) case, with a typical BTF ratio 17:1, AM save cost for $1400/kg compared to CM/CNC.

![Figure 4. AM-CM benchmark in Ti-64 case](image-url)
III. Collaborative Pattern

As indicated in previous paragraph, part performance, cost and lead time are key factors to manufacturing industry. AM prototypes parts in a very fast manner that shorten lead time. Through new technologies and convergence effect, AM has better opportunity in cost reducing and part performance than CM; and BTF ratio effect further favors AM in cost reduction.

AM has high potential to become industry mainstream if the weakness can be removed. It may not be limited to scaling, speed and size issues however, these can solve the critical issue AM is currently facing and better position AM’s role in sustainable manufacturing. For this reason, a collaborative patterns is proposed to consolidate multi-entities’ capacity and align their individual motivation and tendency into a robust workforce (Ghomashchi, V., 2012).

In this collaborative pattern, a 3-dimentional framework is proposed. It leverages multi-entities’ motivation and tendency, and consolidate the synthesis of capacity into a robust workforce to solve the issues.

As indicated in figure 4; alignment of the AM’s advantages to the appropriate applications and collaborative pattern, through a fully transparent cloud platform, are critical. Under such alignment, a concrete collaborative pattern can be built (Rauch, E., et al., 2016).

![Collaborative Pattern Diagram](image)

Figure 4. Alignments between advantages, applications and collaboration

As indicated in table 8, HBB, SME and large enterprise (LE) are multi-entities play diverse and crucial role in AM transformation. The collaboration of entities form an AM society enables localization of end-to-end process in a most dynamic way. It covers materials recycling, supply chain, and AM manufacturing.

<table>
<thead>
<tr>
<th>Role</th>
<th>Activities and responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>LE</td>
<td>Companies that manage recycled and AM materials nearby materials recycling facility (MRF)</td>
</tr>
<tr>
<td>SME</td>
<td>Companies that manage recycled materials, AM materials and HBB services</td>
</tr>
<tr>
<td>HBB</td>
<td>Registered HBB that deal with AM printing and products</td>
</tr>
</tbody>
</table>

Table 8. Roles in collaborative pattern
Case study of collaborative pattern

The Wabtec Corporation can be a case study. The company collaborated with HP and launched an AM Center (Wabtec India AM Center), focused on accelerating the design and production of integrated 3D-printed components in India. Wabtec-HP offers end-to-end solutions, consulting, and support to Micro, Small, and Medium Enterprises (MSMEs) which can be one of typical examples of the collaboration between machine/materials provider, SME and HB/end-users (Chandavarkar, A., 2020).

III-1 Key activities of Collaborative Pattern

Tasks identification is expected to guide the collaboration strategy by taking step-by-step approach, to streamline the transformation. Meanwhile, rural habitants are encouraged to join the collaboration to establish a mutually beneficial AM society as strong urban rural partnerships make a resilient society (Shaw, R., 2019). In this roadmap; there are four stages transformation and three types of roles for the collaboration. They are defined as followed;

As illustrated in figure 5; Key factors the AM collaboration leveraged are; MRF recycling, AM source materials, AM technologies, services, and printers, AM standardization and cloud platform, and AM products innovation.

To ultimate coverage of collaboration, each entity shall not limit their role. For instance; LE or SME can be a provider of AM printer, materials or MRF facilitator, or they can be 100% pure manufacturer. LE is mainly responsible for MRF and AM source materials; SME covers AM printers, materials and AM standards, and is expected to promote HB business. HBs are randomly distributed in their AM society within a 100km radius circle, and they are expected to increase family income through a standardized process, consequently they support SME and LE in resolving AM volume issues. The topology of the collaborative domain is illustrated in Figure, where the collaboration can be focused on the MRF, Filament facility (FF) and the downstream distribution.

Figure 5. Process topology of Recycling and AM manufacturing
The four stages are outlined in table 9:

<table>
<thead>
<tr>
<th>Stage</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stage 1</strong></td>
<td>Assessment: Strategic analysis of distributed (local) recycling, supply and manufacturing HB register and shows their interest to do HBB in AM and receive support from government or enterprises to start their HBB in specific AM products. SME explores the feasibility of adding new AM business at minimum investment. The business mainly covers AM printers, AM materials, and AM maintenance and AM services for HB and LE. LE considers adding new AM process even they are not seeking radical alterations in either supply chains or products, but explore AM material sources for specific products, and set up new MRF, or add branch MRF side, to serve SME and HB in a radius of 100km surrounding.</td>
</tr>
<tr>
<td><strong>Stage 2</strong></td>
<td>Distribution: a distribution topology of AM community at 100km MRF surrounding is setup HBB starts to setup their printers and filaments based on their products selection. Government and authorities are suggested to launch loan or minimum financial support to HBB to setup HBB without any financial concern. HBB starts to receive minimum training in AM printings. SME analyzes company’s key strength and decide the AM business strategy and start to add or open new AM business. SME takes advantage of scale economics offered by AM as a potential enabler of supply chain transformation for the specific products.</td>
</tr>
<tr>
<td><strong>Stage 3</strong></td>
<td>Standardization: AM society, led by LE and SME, establish cloud platform for common practices. HB starts to work closely within their AM community by exchanging message and information sharing. Each HBB share same information through their cloud platform, so each HBB work with a SME to secure AM materials, printing services, adaptor and software in an efficient way. SME promote their AM business for a wider coverage that focus on the standardization of AM technologies. As all SME and LE share same cloud platform and use same standard, SME ensures “service on demands”, standardized AM technologies and software are established. SME may also take the key role to support home-based-business in navigating the AM ecosystem and exploit resulting business opportunities (Heising, W., 2020). LE lead AM community, the SME and HBB, to seek best practices in their community which covers the emerging technologies for AM source materials, best-fit materials and printing technologies for specific products, and any collaboration for innovative activities.</td>
</tr>
<tr>
<td><strong>Stage 4</strong></td>
<td>Establishment: Business as usual (BAU) is established, both quantity and quality are resolved. HBB maximizes their productivity by bringing-in their families into AM community to increase volume of same AM pattern. Meanwhile, as the standard process and software has been established, HBB operates AM business by BAU and fully contributes AM scalability. SME fully support HBB in a long-running business. Together with LE, SME enables virtualization in a distributed (local) recycling, supply and manufacturing environment. SME continue to provide most update information and software at cloud platform to serve their HBB clients. LE continues to lead the AM development. Together with SME, LE serves AM community by providing periodical forums. LE considers forming joint venture with SME to transform AM into mainstream, and use CM as backup solutions to support unexpected volume issue.</td>
</tr>
</tbody>
</table>

Table 9. Key activities in 4 stages
III-2  Strategy of collaborative pattern

Through the benchmarking of AM and CM in previous session, advantages of AM are clearly outlined that AM can design and prototype parts very fast that shorten lead time, and the advancement of technologies and processes are more agile and faster than CM. Based on the illustration in this study, reducing AM’s cost through new technologies to a lower values than CM’s convergence value is feasible. AM can achieve speed and cost, and stay in competitive position with CM once collaborative pattern is established, and the strategy is described as followed;

- The collaboration work shall start with a focus on highly complex plastic components that AM can save materials and cost.
- Benchmark those high-cost materials and apply high BTF ratio in AM and CM benchmarking in high tooling and machining products, to demonstrate the evidence and build confidence in AM advantages, to streamline the collaboration.
- Machine and materials take AM cost up to 60% and 30% individually. AM society and each community shall initiate collaborative research for how to cut AM machine and materials cost. The research activities shall be covered in business model and get AM society and community to involve.
- Create a fully transparent cloud environment between LE, SME and HB and keep tracking of AM materials price in each AM community. As the relationship within AM community is for a long-running purpose, the AM materials shall be monitored and under related authorities’ control. The materials cost is expected to be lower than existing retailers. One of the reasons is; instead of supply chain, the AM materials are fabricated by the local manufacturing, and the other reason is due to AM community BAU.
- The steady relationship between LE, SME and HB and mutual benefit can save sales’ margin and drop the cost to a very lower level than existing supply chains.
- Try to resolve AM weakness in volume limitation, slow manufacturing process and product size. Once the business model is establish and entities are collaborated, AM volume issue shall be resolved.
- Consider AM characteristics in short design-to-manufacturing and fast time-to-market as a value proposition. Fully utilize AM characteristics in product innovation based on AM flexibility, which may engage designer to re-design product to expand product scope, features, reduce materials cost, or durability.
- In order to set a foundation to make the products more reproducible and reliable, test standards need be in place (Dizona, J., 2018). According to ASTM; standards cover applications, design, materials, process, terminology, and test methods. The standards define terminology, measure the performance of different production processes, ensure the quality of the end products, and specify procedures for the calibration of AM machines (ASTM International, 2021).
- Compared to CM, AM is in its infancy and standardization can be critical to support AM to become industry mainstream. Standardization mainly covers the materials full life cycle in terms of recycling, design, manufacturing, and quality assurance.
### III-3 Roadmap of collaborative pattern

A roadmap is necessary to streamline the AM transformation, to minimize risk, and to establish concrete foundation of AM industry. Figure 6 demonstrates the mapping matrix between 3 roles, key activities and 4 stages.

<table>
<thead>
<tr>
<th>Role</th>
<th>Key Responsibility</th>
<th>Deliverables</th>
</tr>
</thead>
<tbody>
<tr>
<td>LE (large enterprise)</td>
<td>Manage MRF, AM materials</td>
<td>AM source and refining materials</td>
</tr>
<tr>
<td>SME (small to medium enterprise)</td>
<td>AM facilities, standard and service</td>
<td>AM printers, materials delivery and services</td>
</tr>
<tr>
<td>HB (home business)</td>
<td>AM printing and products innovation</td>
<td>AM Products</td>
</tr>
</tbody>
</table>

Figure 6. Roadmap of collaborative pattern – 3 roles in 4 stages

### IV Discussion

#### Global AM Forecast

Cost-effective manufacturing and flexibility is leading to favorable growth in AM, and an increase in the development of heterogeneous material manufacturing capability further favor a wider usages of AM in particular applications such as medical, automotive and aerospace industries and any other products require extensive customized manufacturing. With AM, to develop an agile manufacturing became feasible hence, to reduce the lead time from conception to the production stage by 70% or more, depending on the type of manufacturing. Frost & Sullivan (Frost & Sullivan's Global Research Team, 2016) analyzes AM trend and predict AM will keep a 30.2% yearly growth, and reach $21.50 B in 2025.

As indicated by table, among all regions, Asia ranks top (55.0%), followed by Europe (39.7%). Among all industry sectors, consumer electronics ranks top (28%), followed by automotive (20%), Medical (16%), and Aerospace (15%).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 20 July 2021
doi:10.20944/preprints202107.0436.v1
AM Applications

With the advancement of AM applications, supply chain can be significantly reduced. In addition, CO₂ emission can be eliminated and lead time, logistics and warehouses cost can be reduced as well.

AM has a broad future and wide range of applications. The common AM examples are the prototyping and making parts for a variety of industries. Through AM, metallic materials which have various properties are used to make high-performance parts, specifically in the aerospace industry, and medical industry is projected to be among one of the fastest growing application of AM (Watson, J., 2019). Examples are;

- Printing spare parts and making the prototyping as a standard part are the common usages of AM in the automotive sector. Short life cycle and flexibility are the unique AM characteristics in spare parts design and maintenance that CM lack with.
- The aerospace industry has been in high demands of highly customized and lightweight components that can save materials cost and save cost from petroleum and eliminate CO₂ emission (Huang, R. et al., 2015).
- Construction industry considers AM as a potential method that can rapidly create low-cost construction materials. Meanwhile, as AM can print sheet and variety shape easily, which can enhance resistance of the road surface.
- AM has wide application cases in Medical industry from orthodontics, organs transplants, implants, hearing aids, to eyeglasses that require high levels of personalization and customization that AM can fully perform its functions.
- In sports industry, designers require frequent prototyping and testing of equipment with athletes. For this reason, AM can be the best option for sport instruments.

Challenges need be addressed

Given the facts that AM can be future trend with tremendous advantages it will bring-in, the limitations need be addressed. AM have encountered two major bottlenecks need be resolved before mass production can be preceded.

1. AM is not ready for high volume production and large size parts in this stage, that make AM only limited to small batch. Compared to CM, AM is better fit in small to medium volume of small part fabrication of high-quality products.

To solve the issue first, tremendous HBB workers can take advantage of AM’s low entry cost, less space, and easy setup to start their business right away. By cumulating small but high quantity of HBBs, the production volume of AM can promote its standpoint compatible to CM. Meanwhile, the case study of multi-tasking at Bennett Plastics explains that one worker to handle multiple 3D-Pring machines is feasible to increase productivity (Hanna, K., 2021). In addition, adding multiple print heads can also aid in increasing the speed of AM (Attaran, M., 2017).

2. Mechanical recycling is the most economical way of recycling particularly for those plastic single-polymer and less purity plastic materials. Mechanical recycling is limited to single polymers PSW such as PE, PS and PP and quality degrade usually caused by heat and energy supply during recycling which result in photooxidation and internal stresses to the AM materials (Pinsky, R., Sabharwall, P, Gaffney, A., (2019). Eventually materials strength gets degraded as an end-product (Al-Salem, S. et al, 2009).

To address AM material quality issue caused by recycling process, this study proposes installation of dehumidification equipment to eliminate moisture, diluting oxygen by nitrogen injection or by vacuum to eliminate oxidization to prevent materials properties degrade.
V. Conclusions

Cost reduction plays key role in manufacturing industry and requires a Business model to mediate the gap between technologies, industry and market. From the other side, collaboration between multi-entities plays key role to ultimate the values of emerging technologies in common practices. These factors are crucial to AM’s role in the sustainable manufacturing, and also the objectives of this study.

In this study, a rigorous evaluation method is proposed to evaluate the measurement method and efficiency. CM production requires a certain volume to share initial tooling cost to achieve cost reduction. However, compared to CM, cost of AM is volume independent. Ambiguity of their cost intersection, CM convergence threshold, and impacts of AM technologies to the threshold are areas of focuses and the novelty this study contributes.

Through this study, a Divide-and-Conquer approach is proposed and generic equations are derived by using Convergence Effect and BTF ratio. The generic equations take scaling factors and dependencies into cost modeling and produce AM and CM cost intersection, CM convergence threshold, as well as cost prediction of AM new technologies. Consequently, appropriate AM technologies and CM convergence threshold can be produced, to improve standardization of AM applications and decision support through a rigorous AM and CM benchmarking.

In the benchmarking, advantages of AM are identified, so AM can fully utilize the advantages to strengthen foundation of AM collaborative pattern this study proposes. In this AM society, collaborative patterns is expected to connect large enterprise (LE), SME, and home-based-business (HBB) into an AM society. Consequently, appropriate AM applications can be fully utilized in this society, scaling and speed issues can be resolved, and AM’s dominant role in sustainable manufacturing becomes feasible.

Industry values cost reduction, product performance and lead time as these key factors play key roles in sustainable manufacturing. AM meets all of these, and

Cost Modeling Generic Equations by using Convergence effect and BTF ratio are derived in this study will support rigorous measurement, so the AM advantages, applications and collaboration can be aligned in a fully transparent cloud platform.

However, AM has some weakness need improvement before becoming industry mainstream such as scaling, speed and size issues. By cumulating small but high quantity of HBBs, AM can improve scaling issue in production through collaborative pattern. Meanwhile, one worker to handle multiple 3D-Pring machines or adding multiple print heads are feasible to increase productivity. In term of quality degrade issue caused by recycling process; this study proposes installation of dehumidification equipment to eliminate moisture, diluting oxygen by nitrogen injection or by vacuum to eliminate oxidization to prevent materials properties degrade.

This study also encourages a wider-scope of multi-entities such as enterprises, government, manufacturers, consumers and AM designers to establish a common platform to keep a full transparency, traceability and tracking mechanism to guide AM technologies into a mainstream through collaboration and standardization processes.
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