**A Business Model for Additive Manufacturing of**

**Recycled Plastics towards Sustainability**

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**Abstract**

The manufacturing landscape is ever-changing, and one of the most significant driving forces is the emergence of additive manufacturing (AM), which enables cost-effective and small-scale production towards sustainability. To better align AM with manufacturing in suitable applications, this study proposes a business model in terms of the cost pattern and scaling production supported by three key concepts: standardisation, localisation and collaboration.

The ambiguity of the cost calculation is one of the key factors slowing down AM progress, and a lack of a cost pattern affects decision-making when applying AM to appropriate applications. The business model in this study is focused on applying the data collected from previous research - Collection-Recycling-Manufacturing (CRM) model to discover implications of AM processes on the road to sustainable manufacturing. The novel business model envisions the nature of AM characteristics, and their linkages to cost patterns, so AM applications can be integrated into a cost-effective process. This study contributes qualitative analysis in the cost patterns’ integration. Through this integration, the business model mediates the gap between technologies and applications via the formulas of cost pattern, so AM can perform its appropriate role in the industry mainstream.

The cost modeling, proposed in this study, derives generic formulas via the unit cost of tooling, molding, machine, materials, design, miscellaneous cost, and the batch size. Business model applies the “Divide-and-Conquer” concept, Convergence effect, and data analysis to support quantitative analysis. The model can calculate total cost per unit and accuracy is close to 100%. Through the novelty of this model, AM and conventional manufacturing (CM) cost benchmarking and decision support functions are enabled to aid in stakeholder decision-making. Eventually, appropriate AM technologies and processes can synchronise with localisation, standardisation, and collaboration and ultimately, the impact of AM towards sustainable manufacturing.

**Keywords**: sustainability, collaboration, additive manufacturing, localisation, cost model, home-based manufacturing

1. **Introduction**

**1.1. Background**

Additive manufacturing (AM) processes, particularly the 3D printing of plastics, have revolutionized tmanufacturing sector through the production of parts and components using minimum process steps and a CAD file. Here, in this paper, AM and conventional manufacturing (CM) processes, such as plastic injection moulding are reviewed and compared. Strategies and plans for three key concepts are discussed, followed by AM trend analysis and conclusions.

Sustainable manufacturing has become a critical mission in this decade. A key principle of industrial ecology shall be a close monitoring of sources and sinks of natural resources and promotion of the regenerative function of resources where consumption should not exceed the regeneration rate. For countries that emphasise the importance of recycling and its technology, recycling has significantly reduced environmental impact at the end of life (EOL) while producing tremendous socioeconomic values (Peeter et al., 2017). Cost savings and the advantages of materials recycling are investigated in our previous studies because the material recycling rates in developed countries are low, while in developing countries, the material recycling rates are close to zero (d’Ambrières, 2019).

Because of the huge scope and wide coverage, a cross-disciplinary investigation in technology, industry and policy is proposed to leverage their interferences. For this reason, this research applies a framework to envision the coherence and correlations of different aspects, which covers the models of CRM (Wu et al., 2022), business and strategy control (Wu & Yabar, 2021). Amongst these, the CRM model follows a bottom-up approach from the viewpoint of technical aspects, such as facilities, topology, technologies, materials and processes. The strategy control model takes a top-down approach to guide human factors, such as rural development, facility allocation and job creation to support AM business. The business model aggregates the technical benchmarking from the CRM model into industrial benchmarking and introduces case studies to enable AM capabilities in standardisation, localisation and collaboration. Aligned with CRM and strategy control models, the business model mediates technologies, processes, applications, cost modelling and human factors. It takes a goal-driven approach and aims to guide AM applications into the industry mainstream.

**1.2. Method and Approach**

**1.2.1. Materials Quality via Recycling Process**

The recycling process is investigated in our previous studies. In the CRM model, the assessment leads to preliminary results, and simulation techniques for the design of topological recycling facilities are proposed. Using recycled materials through the proposed optimized transportation can be the most effective method to eliminate energy consumption and CO2 emissions. Compared to primary plastics, use of recycled plastics can save a significant amount of material and energy consumption (Roxanne et al., 2019).

International Standardization Organization (ISO) 14044 standards are applied to life cycle assessment (LCA), and the experiments demonstrated that integrated plastic waste management (IPWM) could be the best option instead of incineration or a landfill (Akinola, 2014). Through various LCA, mechanical recycling is the environmentally preferred option linked to energy consumption, climate change, and CO2 emissions (Lazarevic et al., 2010). However, from a quality perspective, the polymer quality may degrade because of a chain scission caused by water and acidic impurities, and the quality degradation is caused by moisture occurring during each recycling process, which needs improvement (Merrild et al., 2012).

From the chemical composition perspective, toxic substances produced by the chlorine-containing polymers can affect public health, which needs open space and ventilation equipment. The quality of recycled materials requires further investigation to ensure the material properties meet the requirements. This study proposes the monitoring of temperature, installation of dehumidification equipment to eliminate moisture and the dilution of oxygen by nitrogen injection or by vacuum to eliminate oxidisation and to prevent the degradation of material properties.

**1.2.2. ‘Divide-and-Conquer’ in the Manufacturing Process**

In the manufacturing paradigm, the benchmarking of AM against CM through a multidisciplinary evaluation of economies, environment and society indicates that CM is favourable for the current cost models and for high production volumes. However, AM is more suitable for higher complexity or customisation (Pereira et al., 2018). Qualitative complexity is not the only factor in the cost reduction of AM, the missing cost modelling method is the real issue. The novel approach — ‘divide-and-conquer’ — proposed by this study provides convincing evidence that AM offers better potential in the cost reduction of any production scale if the appropriate method is applied. To address the common issues, this research creates a framework and aligns technical assessment from the CRM model into this study to complete an overall evaluation. Consequently, the business model produces quantitative analysis and a generic formula, so the method can be reused in common practices.

AM stands out with enormous potential for changing the distribution of manufacturing and society, which is effective in minimising energy consumption and CO2 emissions. It is estimated that a shift from CM to AM processes in the U.S. aircraft industry will result in a cumulative savings of 1.2–2.8 billion GJ by 2050 and is associated with cumulative GHG emission reductions at 92.1–215.0 million tons (Huang et al., 2016). Local AM using recycled materials and cloud information sharing are all effective means of localisation to minimise supply chain engagement; consequently, it saves on costs and achieves better lead times in the product life cycle as well.

Regarding the CRM benchmarking, such as energy consumption, materials yield, CO2 emission, transportation, and machine, a specific cost modelling method is introduced in this study. It is expected to validate a justified method of AM evaluation against CM. Furthermore, it investigates typical cases and proposes guidelines to support AM applications.

**1.2.3. Distributed Local Manufacturing**

Distributed manufacturing refers to a form of decentralised manufacturing. The flexibility of digital manufacturing enables it to collaborate globally and manufacture locally, which has a positive influence on sustainable development (Chen et al., 2015). Local Manufacturing via AM will become even more important because of advancements in technology (Kleera & Pillerb, 2019), and the home-based manufacturing (HBM) of 3D printing can be the entry point of distributed local manufacturing (Inimake, 2021).

AM tips the globalisation and localisation of manufacturing in favour of insourcing and localisation (Mourdoukoutas, 2015). Under the minimum supply chain engagement and logistics, local manufacturing can reduce supply chain. Consequently, the transportation cost and CO2 emissions can be further reduced. According to the Volvo Truck Corporation (Volvo, 2018; Truck driver institute, 2013), trucking costs are estimated as shown in Table 1.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Transportation type | Payload in tons | liters/ 100 km | Fuel consume (liter/ton-km) | Fuel cost ($/ton-km) | Fuel cost/ Total cost | Overall cost ($/ton-km freight) |
| Truck, distribution traffic | 8.5  | 30 | 30/ (100 $×$ 8.5) = 0.035 |  0.035 $× $1.23 = 0.043  | 39%\* | 0.0263/ 0.39 = **0.111**   |

Table 1. Trucking cost calculation in materials transportation

Compared to foreign suppliers or manufacturers, local manufacturing delivered by land (truck or rail) can save a lot on transportation costs. According to the Bureau of Transportation, U.S. Federal Government (Bureau of Transportation, 2018), the assumption for the local land option is applied for 500 km by using 50% truck and 50% rail. The cost will be: 250 × 0.111 (1+ 0.225) = $34.0/ton.

**2. AM and CM Benchmarking**

Sustainability involves complex interferences between economies, the environment and society. Amongst all the alternatives, building a concrete foundation of sustainable manufacturing can be a priority. Hence, reducing materials waste, cost, energy consumption and CO2 emissions are all critical factors.

**Cost Modelling for Plastics**

In this evaluation, the convergence effect and ‘divide-and-conquer’ methods are introduced. The methods support quantitative analysis and an assessment of individual cost items, dependencies and effectiveness that influence AM and CM cost modelling. Through the case study in the aerospace industry, this study develops a cost modelling pattern to benchmark AM against CM. Through the proposed model, CM, AM and their dependencies are evaluated, and general formulas are derived to tackle scaling convergence in a generic form.

In parallel, this study investigates the ‘buy-to-fly’ (BTF) ratio of input weight over output weight for the product parts (Gisario et al., 2019). BTF is usually used in the cost-sensitive materials yield of the composite alloy, which is essential in the aerospace and automobile industry (Daicel Miraizu Ltd., 2021). AM has been a standardised process for these industries. Usually, BTF is not one of the AM advantages in the plastics industry, but it can be a factor for plastic parts when they are needed in the composite materials of these applications (Industry Week, 2021).

**Cost Modelling Generic Formula Using the Convergence Effect**

Through the ‘divide-and-conquer’ approach this study proposes, the convergence effect can be applied to industrial benchmarking between AM and CM, because both have different cost-modelling patterns. The tooling setup cost in each CM batch is high. Hence, the initial cost needs to be broken down for each unit, and it favours mass production.

On the contrary, AM does not require an initial setup cost, implying that the AM cost is volume-independent. In this cost evaluation, the data format from Deloitte Insight (Cotteleer, 2014) is used to illustrate the sub-items as well as how to apply them in the process and produce a generic formula for design.

Injection moulding is the technology used in CM, stereolithography (SLA) is the technology used in AM, and polyamide plastic is the material in benchmarking. The cost sub-model of the AM and CM format is illustrated in Table 2.

*CM: injection molding (20k & 100k) AM: stereolithography (SLA) Materials: polyamide plastic ($/part)*

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Method | Category | AM\_SLA | CM\_20k | CM\_100k | *remark* | *Cost denotation* |  |
| Assembly | Others (“***O***”)such as cleaning, revision, fracture, or deformation | *L* | *L* | *L* | CM ‘Other unit cost’(constant) | ***VH****: very high* |
| Operator | ***H****: high* |
| Materials | ***VH*** | *M: medium* |
| Machine | *L: low* |
| Tooling & Moldings  | Tooling/Moldings (“***T***”) | *L* | ***VH*** | ***H*** | *Condition denotation** CM\_20k: CM method, batch size: 20,000
* CM\_100k: CM method, batch size: 100,000
* AM\_SLA: AM method by using SLA
* CCM (20k): Total unit cost of CM\_20k
* CCM (100k): Total unit cost of CM\_100k
* CAM\_SLA: Total unit cost of AM\_SLA
 |
|  | Total Cost (“***C***”) | *M* | ***H*** | *M* |
| CAM\_SLA | CCM (20k) | CCM (100k) |
| Batch volume | any | 20,000 | 100,000 |

*(data format: Deloitte insight)*

Table 2. Generic format for AM/CM cost benchmarking  *(data format: Deloitte insight)*

Through a differentiation of cost patterns, this study develops a generic formula for the business model, which can be used for AM and CM cost modelling for scaling. The formula is variable-dependent, but the generic form can be easily developed into a software package, and arbitrary variables can be included in a decision support system.

Sub-section 2.1 – 2.4 (formula 1 – 4) are generic formulas, which are independent of any conditions or applications. However, sub-section 2.5 is dependent of technologies. It does not matter about the technologies being used, and the results, as the only purpose of this example is to illustrate that AM can apply different technology to achieve a more cost-effective result lower than CM’ convergence value. The derivation of the formula is demonstrated as follows:

**2.1. Tooling Cost (Mould Design and Mould Cost)** **Generic Form**

 (Tooling & Moulding unit cost) × (Part counts) = (Mould design cost) + (Mould & Tooling unit cost) × (Part counts)

1. Let‘**TCM(20k)**’be the ‘tooling unit cost’ (mould design cost breakdown + mould cost)in CM\_20k case
2. Let ‘**TCM(100k)**’be the ‘tooling unit cost’ (mould design cost breakdown + mould cost)in CM\_100k case
3. Let ‘**M**’ be the ‘mould design cost’, which is a one-time cost per batch, a constant and volume dependent
4. Let ‘**m**’ be the ‘mould unit cost’ in production, which is a constant and volume independent

For CM\_20k, the balance equation can be represented by: TCM(20k) × 20000 = M + 20000 × m

For CM\_100k, the balance equation can be represented by: TCM(100k) × 100000 = M + 100000 × m

The aforementioned two equations derive: **M = 25000 × (TCM(20k) -TCM(100k)),m = 1.25 × TCM(100k) - 0.25 × TCM(20k)**

* 1. **. Total Cost Generic Form**

**(Total unit cost) × (Part counts) = (Mould design cost) + (Mould unit cost + Other unit cost) × (Part counts)**

1. Let ‘**CCM(20k)**’be the ‘total unit cost’ in the CM\_20k case.
2. Let ‘**CCM(100k)**’be the ‘total unit cost’ in the CM\_100k case.
3. Let ‘**n**’ denote ‘Part counts’.
4. Let ‘**O**’ be the ‘other unit cost’ in production, which is volume-independent.

**2.3. CM Cost Modelling**

By taking the tooling values “M” and “m”, derived from the previous calculation, into the cost modelling based on (Total unit cost) ×(Part counts) =(Mould design cost) +(mould unit cost + Other unit cost) × (Part counts), this derives

CCM × n= M + (m + O) × n or CCM = $\frac{M }{n}$ + (m + O), in a generic form, which satisfies the following two scenarios:

CCM (20k) × n20k = M + (m + O) × n20k or CCM (20k) × 20,000 = M + (m + O) × 20,000 for CM\_20k case and

CCM (100k) × n100k = M + (m + O) × n100k or CCM(100k) × 100,000 = M + (m + O) × 10,000 for CM\_100k case,

where the given ‘C’, ‘M’ and ‘m’ can be derived by: M =25,000 ×(CCM(20k) -CCM(100k)),m = 1.25 × TCM(100k) - 0.25 × TCM(20k).

Using the given ‘O’, and with the derived ‘M’ and ‘m’ values, the CCM value of arbitrary ‘n’ can always be derived through:

CCM = $\frac{M }{n}$ + (m + O) **(1)** *CM generic form*

This implies that the generic formula enables the CM unit cost estimation (CCM) of any arbitrary volume size ‘n’.

**2.4. AM Cost Modelling**

From the other side, the **‘**CAM**’** value in the AM case stays constant, which is independent of the volume.

CAM = Cconstant **(2)** *AM generic form*

AM and CM cost benchmarking for scaling means it is feasible to conduct the following investigations:

1) What is the CM volume, where CM starts to gain a cost advantage over AM? This refers to (n1, c1) in Figure 1.

2) What is the CM convergence, where CM becomes flat? This refers to c2, the purple dashed line.

3) What is the AM method that reduces the cost equal to or lower than the CM convergence value, to gain a cost advantage over CM? This refers to c3, the green line.



Figure 1. Cost-volume correlation in cost modeling

The investigation pinpoints key areas of the business model, which further derives generic forms in response to the three key investigations: intersection, convergence, and technology.

1. **Intersection**: To estimate the CM volume that CM cost start to win over AM cost; let CCM = CAM  at intersection. CCM = $\frac{M }{n}$ +(m + O) = CAM =Cconstant or M +(m + O) × n = CAM × n atCCM , CAM  intersection

 With derived values of ‘M‘, and ‘m‘, and given ‘O’ and ‘CAM’ values;

 ‘n’ value atCCM , CAM  intersection can be easily derived by: **n** intersection **=** $\frac{C\_{AM} - \left(m+O\right)}{M}$ (3)

 In the other word, when n ≥ n intersection ( $or \frac{C\_{AM} - \left(m+O\right)}{M}$ ), CM volume start to gain cost advantage over AM

1. **Convergence**: Let Cconvergence be theCM cost at convergence; the discrete notation can be expressed as followed;

 ∀ (c, n) ∈ {(c0, n0),(c1, n1) . .. (c∞, n∞)}, ∃ Cconvergence  satisfies: Cconvergence ≤ cn ∀ cn ∈ { c0,c1 . .. c∞}

 Since the generic equation CCM = $\frac{M }{n}$ +(m + O) can be expressed by: CCM × n – M – (m + O) × n = 0

 Let (n, CCM)be mapped to (x, y) Cartesian coordinate system;

 The deviation of y-axis (CCM) against x-axis (n) becomes 0 at convergence, which derives;

 $\frac{∂(xy – M – (m + O) x ) }{∂x}$ = 0 which implies; **y**convergence – 0 – $\left(m + O\right) $= 0; or **C**convergence **=** $\left(m + O\right) $ (4)

 **CCM** (convergence) **=** $\left(m + O\right)$ implies: CM unit cost becomes flat when it approaches$ '\left(m+O\right)'$, the lowest cost.

**3) Technology**: When the AM unit cost drops from CAM to CAM-new, which is equal to or lower than CCM (convergence), regardless of how large the CM volume is, CM will be unable to achieve the AM cost.

To demonstrate the feasibility of AM cost reduction, the original conditions are listed:

* Materials: plastic
* CM method: injection moulding
* AM method: stereo lithography (SLA)

To reduce the AM unit cost, from CAM to CAM-new ≤ CCM (convergence), the AM method needs an adjustment. As machine and materials dominate the cost of AM, both values are candidates for cost reduction.

**2.5 AM Method for Cost Reduction**

Amongst all the AM technologies, FDM extrusion can be one of the most cost-effective options, and it is easy to prepare. Hence, FDM extrusion is selected to demonstrate a new cost benchmark. According to the AM machine and materials benchmark (Simpson, 2019), the cross-benchmark within AM is illustrated in Table 3.

|  |  |  |
| --- | --- | --- |
| Method | AM\_SLA | AM\_ Extrusion |
| Materials | *VH* | *H* |
| Machine | *VH* | *H* |

Table3. AM methods (SLA and FDM) for cost modeling *(data format: Simpson, T)*

*VH: very high*

*H: high*

Table 3 provides an estimation of the comparison of the material between SLA and FDM, around 1.0:0.1, and the machine cost is around 1.0:0.75; hence, both values (0.1 and 0.75) are applied in the conversion from SLA to FDM costs. In addition to machines and materials, another cost can be the same for both, and these conditions make the cost projection — from SLA to FDM — feasible. After the projection, the FDM cost is added to Table 3, and the full-scale cost modelling format is illustrated in Table 4.

*CM: injection molding (20k & 100k) AM: Extrusion (SLA & FDM) Materials: polyamide plastic*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Method | denotation | AM\_SLA | AM\_Extrusion | CM\_20k | CM\_100k | *remark* |
| Assembly | Others ‘**O**’ | *L* | *L* | *L* | *L* | CM ‘Other unit cost’(constant) |
| Operator |
| Materials | ***VH*** | ***H*** |
| Machine |
| Tooling | Tooling and molding ‘**T**’ | *0* | *0* | ***VH*** | ***H*** |  |
| Total  | Total cost ‘**C**’ | *M* | *L* | ***H*** | *M* |  |
| CAM (SLA) | CAM (FDM) | CCM (20k) | CCM (100k) |  |
| batch volume |  | any | any | 20,000 | 100,000 |  |

*VH: very high*

*H: high*

*M: medium*

*L: low*

*VH: very high*

*H: high*

*M: medium*

*L: low*

Table 4. Cost items in full-scale modeling between AM (SLA & FDM), and CM (20k & 100k)

As CM convergence happens at **CCM (convergence) =** $\left(m + O\right)$The value can be lower than **CAM** (SLA). However, as **CAM** (SLA) > **CAM** (FDM) when $\frac{C\_{AM (SLA)} }{C\_{AM (FDM)} }$approaches 2.0, **CAM** (FDM) <$ \left(m + O\right)$then AM cost can be lower than CM no matter how large the CM batch size is.Through this model,key metrics are summarized as followed;

1. **Intersection**: When CM volume is equal to or higher than $\frac{C\_{AM} - \left(m+O\right)}{M}$ , CM gain cost advantage over AM.
2. **Convergence**: CM cost convergence happens at: **CCM** (convergence)**=** $\left(m + O\right)$, that can be the lowest CM cost.
3. **Technology**: With a changed AM method (i.e; from SLA to FDM), as **CAM** (new) can be lower than **CCM** (convergence). The cost of new AM method gains cost advantage over CM without any dependency from CM volume.

Formula 1 and 2 are the generic formulas for the unit cost calculation of CM and AM while formula 3 and 4 are the another formulas for the estimation of AM-CM intersection and CM convergence. All of these four formula are independent of conditions and sub-section 5 investigates the condition that the cost of AM can be lower than CM cost at convergence. It doesn’t matter whether the cost of SLA can be much lower than FDM, and lower than CM cost at convergence, but something critical is; at smaller batch volume (less than the intersection point), cost of AM can be lower than cost of CM. In addition, as technology is a dominant cost items of AM, lower cost of AM than convergence of CM is feasible based on the technology being applied.

**3. Discussions**

Based on the benchmarking between AM and CM, AM has a high potential to become mainstream and leveraged at the industry and society level if the weakness can be removed.

Studies indicate (Pereira et al., 2018; Slant 3D, 2019) that the 3D printing (AM) of parts and components using recycled plastics has the potential to replace the parts produced using conventional processes, such as casting and injection moulding, particularly on a small scale with an insignificant loss on properties. For this reason, improvement plans are initiated. In the following paragraphs, three key concepts — localisation, collaboration, and standardisation — are discussed to fulfil and enable the business model. However, localised manufacturing and replacing CM using AM requires standardisation and collaboration within the industry.

**3.1. Local Recycling and Manufacturing**

**3.1.1. Collaborative Pattern**

To support the boom of AM, the advantages are identified in terms of quantitative measurement as well as qualitative characteristics. The business model, as a goal-driven model, further takes advantage of AM and proposes collaborative patterns and common practices. An investigation reveals the fact that AM reduces the threshold of required capital to achieve economies of scale, and flexible customisability reduces the capital required to achieve the scope. From a sustainable manufacturing perspective, AM distinguished itself from CM because it saves materials and costs. Tooling, moulding, cutting, assembly and maintenance are troublesome in CM cases, which take time and cost more, even for a part change, but these are not required in AM cases.

The benefits doubled in the reverse-engineering case when the product required a spare part or maintenance at EOL. AM can easily produce or reuse the part based on the demands instead of repeating the long cycle that CM follows. Consequently, compared with most of the manufacturing methods, AM consumes less energy and therefore produces a lower amount of CO2. From an agility viewpoint, AM supports on-demand manufacturing, saves time and cost in prototyping and simplifies customisation and personalisation. Additionally, AM streamlines the supply chain process as distributed manufacturing and flexibility enable localisation of manufacturing and the supply chain. Based on this foundation, AM saves a tremendous amount of energy, materials and time at a much lower cost, creating a more resilient supply chain. Compared to AM, CM methods require centralised design, offshore manufacturing, long-period tooling, logistics and high energy consumption and create a much higher CO2 emissions.

The prolonged supply chain of conventional manufacturing processes may also promote the use of AM processes because of the quick response to customer requirements. The benchmarking and case studies produced by the business model are used as a verification of the technical assessment produced by the CRM model. In parallel, it synchronises with the strategy control model to direct rural development, creating job opportunities and encouraging home-based manufacturing.

**3.1.2. Barriers in Localisation**

Recycling and AM localisation simplify supply chains and minimise transportation of waste materials, resulting in lower fuel consumption and CO2 emissions. However, there are some bottlenecks that need to be resolved. According to Garmulewicz. et al., (2016), a lack of standards, skills and scales (3S) are barriers to localised manufacturing. To overcome these barriers, standardisation, collaboration, education and AM scalability need to be addressed.

**3.2. Collaboration Between Multiple Entities**

AM is a new technology booming across different regions and has become a dominant trend around the world. ‘Started from prototyping to one of product and then mass production’ can be a strategy for AM industry development. Hence, the collaboration between HBM, small-to-medium enterprise (SME), and large enterprise (LE) play a crucial role in AM transformation.

Standardisation of common industry practices, software specification and AM file formats are also determinants in the evolution. The Wabtec Corporation, in collaboration with H.P., launched an AM centre (Wabtec India AM Center), focused on accelerating the design, standard 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), one of the typical examples of the collaboration between machine/materials provider, SME and HBM end-users (Chandavarkar, 2020). In academic research, the MIT’s Fab Lab center is a typical example for a collaborative hands-on design of digital fabrication and computation. A Fab Lab is also a technical prototyping platform for innovation of additive and subtractive manufacturing tools and applications (MIT Fab Lab, 2021).

To support the AM transformation, minimize risk, and establish a concrete foundation, a road map is necessary to guide the collaboration and corporative strategy by taking a step-by-step approach and to streamline the transformation. In this road map, there are six stages of transformation, with three roles in the collaboration. The three roles are as follows:

* LE: Companies that manage recycled materials and AM materials near materials recycling facilities (MRF)
* SME: Companies that work with LE and HBM as suppliers of AM materials, printers and services
* HBM: Registered home-based manufacturing that deals with AM printing and produces AM products

Transformation into AM is not easy, particularly for traditional companies to deploy new concepts and technologies in the CM environment. Hence, action research is proposed to support the business transformation by using the following guidelines. So, LE-SME-HBM can take a step-by-step approach in any movement to minimise risk and generate significant impact.

Focus on small and highly complex plastic components to produce convincing evidence that AM can save materials and cost. The benchmark can be extended to the characteristics between AM and CM, so the company can fully understand how AM achieves customisation and flexibility.

Stay open with the existing CM process and use AM to compare high-cost materials and apply high-tooling and high-machining products to produce benchmarking results.

Create a fully transparent environment between LE, SME and HBM and keep track of the AM materials cost in each AM community. Because the relationship within the AM community is for a long-running purpose, the AM materials cost and services shall be monitored under authorities’ control. The cost is expected to be small in range, which is much lower than foreign retailers. One reason is that AM materials are fabricated by local manufacturing, and another reason is because of AM community business as usual (BAU). The stable relationship between LE, SME and HBM shall be maintained in a steady way.

Machine and materials can increase AM cost up to 60% and 30% individually. The 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 the business model and involve AM society and the community.

AM characteristics should be fully utilized in short design-to-manufacturing and fast time-to-market as a value proposition. Try to resolve AM weakness in volume limitation, slow manufacturing process, and product size. Once the business model is established and entities collaborate, the bottlenecks shall be eliminated.

AM characteristics should be fully utilized in product innovation based on the flexibility of AM. This may require designers to redesign products, expand product scope and features and reduce materials cost or durability.

**3.3. Standardisation**

Standards refer to technical methods, processes, specifications and definitions with respect to a physical system on which there is general agreement as promulgated by the recognised standards of organisations (Clark, 2017). With the different AM technologies, printing parameters and considerations, test standards are crucial to guide mechanical tests in any application. To set a foundation to make the products more reproducible and reliable, test standards need to be in place (Dizona, 2018).

According to ASTM, standards cover applications such as 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).

Digital manufacturing makes AM flexible because the files and software are transparent and sharable across cloud systems, which is sharable to AM workers based on demands and saves tremendous design costs caused by prototyping, design effort and trial and error. Furthermore, each part of the product can be easily standardised and maintained through digital data instead of storing the moulds or spare parts. Under a sharable platform, standardisation is feasible but because of the wide coverage, the scope is huge and complexity is high. This study investigates the scope and provides the following guidelines.

**3.3.1. Terminologies of Materials Recycling and AM**

Terminology mapping for AM and recycling can be the basic criteria of standardisation to prevent confusion. The following examples illustrate cases of terminology mapping across different criteria.

AM, in another terminology, ‘3D printing’, indicates the same technology with an emphasis on the characteristics of its flexibility in three-dimensional design. Usually, the terms ‘AM’ and ‘3D printing’ are of mixed use in relevant technology, but if the printing method is used for a specific scope, such as prototyping, then ‘3D printing’ is better terminology.

However, if the manufacturing method is used for large-scale production, then ‘AM’ would be more suitable. From the design perspective, both AM and 3D printing start with software followed by a specific printing file format, such as STL, to control the printing head. There are basically four methods of plastic recycling in the core areas of materials recycling (Karayannidis & Achilias, 2007).

As Table 5 shows, the terminologies across different standards can be mapped to each other.

|  |  |  |
| --- | --- | --- |
| ISO 15270 | ASTM-D5-33 | General terminology |
| Mechanical re-extrusion recycling | Primary recycling | Closed-loop recycling |
| Mechanical recycling | Secondary recycling | Downgrading |
| Chemical recycling | Tertiary recycling | Feedstock recycling |
| Energy recovery | Quaternary recycling | Valorization |

Table 5. Terminology mapping of different standards

**3.3.2. Design Strategy**

Compared to CM, AM is in its beginning, and standardisation can be critical to support AM to strengthen its foundation. Standardisation mainly covers the material’s full life cycle in terms of recycling, design, manufacturing and quality assurance. This study applies design strategy to guide the standardisation, mainly in the process controlled, materials applied and technologies selected. Basically, the AM process covers the following steps:

1. Computer Aided Design (CAD) and Computer Aided Engineering (CAE) software
2. Design software STL file
3. Prepare raw materials: granules, scrap or powder
4. Make the filament for the extrusion methods
5. Manufacturing process
6. Inspection and testing

Amongst these, CAD, CAE, STL files, materials type and properties need to be verified, and mechanical property testing needs to be conducted after the process is completed. First, CAD and CAE software need standardisation to match the requirement of 3D printers so the model can be directly printed without any conversion or correction (Wong & Hernandez, 2012). Meanwhile, the real-time tracking system will support higher accuracy and speeds to improve the quality of the product being printed and to correct the error. The tracking system monitors and detects any missing steps to make the necessary change in the program code. In the long run, a circular model will be established, and the manufacturers will assume full responsibility for their products across the full life cycle.

As manufacturers have sufficient information to track their products and fully customise recycling and AM into a seamless integration, such responsibility increases the Return Over Investment (ROI) of the companies and establishes mutual benefits to each entity. However, materials used in AM vary, depending on the method and the quality of the requirements of the final product. Based on the materials selection, different machines and technologies are applied to produce prototypes and finished products. Because this research focuses on polymers, an assessment is required to apply the best AM technology and machine to produce the products based on the best options.

**3.3.3. Polymer Characteristics Standard**

AM process parameters exhibit a non-linear effect on mechanical properties. One of the challenging aspects is maximising the fusion bond and related process parameters of the polymer structure for thermoplastics, semi-crystalline materials, composites and thermosets (Forster, 2015).

A sample of ASTM mechanical properties is indicated in Table 6, which shows the physical and mechanical properties of some polymers, and these could be used as a standard format in mechanical property testing. The real values need verification from the updates of the ASTM standards.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Materials Char. | Tensile Strength (MPa) | Elongation (%) | Compressive Strength (psi) | Hardness Shore D | Joule Impact(ft-lb/in) | Coefficient of Friction (%) | Thermal Expansion (10-5 in./°F) | Heat Deflection (°F at 160 psi) | Dielectric Strength (V/mil) | Water Absorption (24 hrs%) |
| ASTM test | D638 | D638 | D695 | D785, D2240 | D256 |  D1894 | D696 | D648 | D149 | D570 |
| HDPE | 8,000 - 11,000 | - | 4600 | D69 | 1.3 | - | - | - | - | - |
| LDPE | 6,100 | 160 | 1400 | D45 | No Break | - | 4.2 | 173 | 514 | 0.05 - 0.08 |
| PET | 14,000 | 60 | - | M105, R126, Shore D 85 | No Break | 25 | 2.6 | 306 | 480 | 0.5 |
| PP | \* | \* | - | 1.5 | - | 43 | 0.9 | - | - | 0.4 |
| PVC | 1,500 - 3,000 | 100 - 200 | - | Shore D 55 | No Break | 10 | 8.9 | 250 | 400 - 500 | < 0.01 |

 Table 6. ASTM standards for physical and mechanical properties of some plastics (ASTM International, 2020)

Basically, there are four methods of plastic recycling (Karayannidis & Achilias, 2007), which may influence the mechanical properties of the recycled materials: (a) primary recycling - direct use of a product without changing or altering the product itself; (b) mechanical recycling - the method includes first sorting, separating and reducing and then proceeds to melt filtration without a chemical process (despite the method degrading polymer quality because of chain scission caused by water and acidic impurities, it has been widely used and recommended based on its comparatively higher quality over cost [QoC; Achilias et al., 2012]); (c) chemical recycling - an effective method of depolymerisation of PET to the monomers and then repolymerise back to the original polymer (the method costs more than mechanical recycling, though it maintains a certain level of quality and is being widely used as well [Achilias et al., 2012]) and (d) energy recovery — the method is applied to the mixed organic materials. This method is not well-qualified in terms of sustainability, and the toxic substance produced by the chlorine-containing polymers has been a big concern that can affect public health. Hence, the incineration method is not prioritised as an option.

Amongst these four methods, mechanical recycling is the preferred method. However, chain scission reactions can result in the deterioration of product properties caused by the presence of water and trace acidic impurities that reduce the mechanical performance of the polyimide or polyimide matrix composite. To maintain the polymer average molecular weight during recycling, our study proposes a resolution to avoid moisture in the process, such as drying and a vacuum, and the use of agents or chain extender compounds to prevent chain scission reactions (Messmer, 2019).

**3.3.4. AM Technology Categories and Standard**

According to the ISO and ASTM International, there are seven types of AM technologies to support printing, and selection of the right technology is key in the AM process (Santander et al., 2020; Özkan et al., 2015). Basically, the seven technologies have their specific applications depending on the materials and products, but there is flexibility in multi-choice scenarios subject to the demands for whether cost, materials recovery, time or quality is the priority, so the best option can be used for that specific process.

To understand the AM technologies and applications, the ISO and ASTM International provided a list of AM technologies to differentiate them by the materials and methods used. Each designer and technician need to know the technologies and how to apply them to different types of materials and products by using different technologies and machines to maximize the benefits of AM. These technologies have advantages and disadvantages depending on the applications. There are several common AM technologies that are applied in plastic industries. The fusion deposition modelling (FDM) extrusion process, selective laser melting (SLM), and stereolithography (SLA) and binder jetting (AM Additive Manufacturing, 2019) are covered in Table 7.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Method | Fusion deposition modeling (FDM) | Binder Jetting (BJ) | Selective laser melting (SLM) | SLA Photo polymerization  | Directed Energy Deposition (DED) | Sheet lamination (SL) | Material Jetting (DOD) |
| Primary Materials | Plastic | Metal andPolymer | Metals, polymers, ceramics, and composites  | Metals, plastics, ceramics, rubber, silicones & porcelains | Metal and metal-hybrid  | Plastics, hybrids and ceramics | Polymer, biological composites, waxes, ceramics, and variety of hybrid materials |
| Pros. | Common for prototyping | Cost and time saving | Complex shape, good mechanical properties, and fast lead time | Wider part size | Wider part size & full control of crystal grain  | Save time and cost | Coloring and materials mixing features |
| Cons. | Need support  | Fragile between layers  | Low build rate and support removal can be a burden |  Lower speed | Usually used in repair case | part resolution is linked to sheet thickness | Limited to small size and need a support |
| Technology | Melted materials flow deposition  | Agent bindingPowder bed and inkjet | Sequential removal & deposition of different powder materials | Stereo lithography apparatus | Deposition | Heat binding | Agent binding |

 Table 7. ASTM standard for AM technologies

**3.3.5. ISO/ASTM Standard and Applications**

There has been significant investment from the public sector and enterprises around the world to foster AM growth. AM equipment in handling polymers is becoming more accessible to the public, which builds the foundation of HBM. Both ISO (in Europe and Asia) and ASTM (Americas) are global standards that guide the standardisation of technologies and industry practices. Table 8 illustrates the standard identifier, criteria and scope they cover:

|  |  |  |
| --- | --- | --- |
| Standard  | Criteria | Scope |
| ISO/ASTM 52921:2013  | Standard terminology for additive manufacturing (AM) | Define terms, descriptions of terms, nomenclature, and acronyms associated with coordinate systems and testing methodologies for AM technologies  |
| ISO/ASTM 52903-2:2020  | Material extrusion-based additive manufacturing of plastic materials | Describes a method for defining requirements and assuring component integrity for plastic parts created using material extrusion-based additive manufacturing processes. This covers the process, equipment and operational parameters. Processes include all material extrusion-based AM processes |
| ISO/ASTM 52910:2018 | Additive manufacturing Design Requirements, guidelines and recommendations | Describes the design of all types of products, devices, systems, components or parts that are fabricated by any type of AM system. This covers decision for which design considerations can be utilized in a design project or to take advantage of the capabilities of an AM process |
| ISO/ASTM 52901:2017 | Additive manufacturing General principles for AM parts trading | Defines and specifies requirements for parts trading made by additive manufacturing including order, part definition, feedstock, part characteristics and properties |
| ISO/ASTM 52900:2015 | Additive manufacturing General principles in Terminology | Defines terms used in additive manufacturing (AM) technology, which applies the additive shaping principle and thereby builds physical 3D geometries by successive addition of material |
| ISO 17296-2:2015 | Additive manufacturing Process Fundamentals | Describes the process fundamentals of AM. It gives an overview of existing process categories, and describes which type of material is used in different process categories |
| ISO 14044:2006 | Define the goal of Materials Recycling and scope of LCA | Define life cycle inventory analysis (LCI) phase, life cycle impact assessment (LCIA) phase, life cycle interpretation, limitations and conditions of LCA  |

Table 8. ISO/ASTM standards for AM common practices

ISO/ASTM standards for AM are illustrated in Table 8. This study highly recommends ISO/ASTM 52903-2 (ISO/ASTM 52903-2:2020E, 2020), which covers plastic parts created using material extrusion-based additive manufacturing processes. There are two parts of ISO/ASTM 52903-2.

Part one is intended for use by the manufacturers of materials, feedstock, plastic parts or any combination of the three using material extrusion-based AM.

Part two leverages three types of quality requirements and provides three classes of process specifications:

Class I: The most rigorous process specification, the highest quality parts with the highest degree of confidence

Class II: a rigorous process specification intended for use in producing high-quality parts

Class III: a general process in processing quality parts using best practices with minimum traceability

A case study based on fused deposition modelling (FDM) was demonstrated by Sanchez. The case study positions the evaluated machine according to the ANSI-ISO International Tolerance (IT) grades for evaluating the accuracy and performance of 3D printers (Sanchez et al., 2014). Additionally, the AM society, such as forums or associations, is encouraged to contribute specific technologies or applications in terms of standardisation, and AM Medical (AM Medical Summit, 2021) is a typical example of these contributors.

**4. AM Trend**

**4.1. Global AM Market, Forecast to 2025**

The AM trend aims to analyse the AM future market and investigates the adoption of AM in production across different industry sectors. Furthermore, this study evaluates the business models and sheds light on the areas that need focus. An increasing trend toward a cost-effective manufacturing paradigm and rapid production is leading to favourable growth in AM, and an increase in the development of heterogeneous material manufacturing capability favours a wider usage in automotive and aerospace applications and customised manufacturing.

With AM, it becomes possible to develop an agile manufacturing paradigm that can reduce the lead time from conception to the production stage by 70% or more, depending on the type of manufacturing. Frost and Sullivan (Frost & Sullivan Global Research Team, 2016) analysed the AM trends and predicted AM will keep a 30.2% yearly growth while reaching $21.50 billion in 2025. As indicated in Table 9 and Figure 2, amongst all regions, Asia ranks at the top (55.0%), followed by Europe (39.7%).

|  |  |  |  |
| --- | --- | --- | --- |
| **Region** | **2015** | **2025** | **Yearly growth** |
| N. Americas | $2.35 B | $7.65 B | 32.6% |
| Europe | $1.81 B | $7.18 B | 39.7% |
| Asia | $1.01 B | $5.56 B | 55.0% |
| Rest of the world | $0.14 B | $1.11 B | 7.9% |
| Global expansion | $5.31 B | $21.50 B | 30.2% |

Table 9. AM yearly growth prediction of different regions (Frost & Sullivan's Global Research Team, 2016)

Amongst all industry sectors, consumer electronics ranks at the top (28%), followed by automotive (20%), medical (16%) and aerospace (15%). This is indicated in Figure 3.





Figure 2. AM growth prediction to 2025 (Frost & Sullivan, 2016) Figure 3. AM sector coverage (Frost & Sullivan, 2016)

**4.2. The Role of AM in Supply Chain Reduction**

A supply chain can be significantly reduced both inbound and outbound. Besides cost, the elimination of supply chain engagement also reduces CO2 emissions caused by transportation and saves lead time. The following are some additional advantages that can be achieved through the supply chain reduction of AM processes.

* The number of suppliers and vendors is poised to reduce.
* Logistics costs will be reduced because most materials and finished products are supplied locally.
* The need for warehouses will reduce exponentially because most products are made-to-order based on demands.
* Operations with respect to the tooling and maintenance of multiple machines are completely ruled out.
* Short lead, cycle times and logistics costs can be reduced by more than 80%.

AM is not labour-intensive, but a considerable amount of manpower is required to ensure seamless workflow through the value chain, which can cause significant cost benefits for the APAC market. It may not be easy to predict precise AM technology trends; however, according to Frost and Sullivan (2016), FDM (the technology this research recommends) will be commonly used in the Americas and Asia. This is indicated in Table 10.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Region**  | SLA | FDM | SLM | EBM | LOM |
| N. Americas | **H** | **H** | M | **H** | M |
| Europe | **H** | M | **H** | **H** | L |
| Asia | M | **H** | M | M | L |
| Rest of the world | M | M | L | M | L |

(H: high, M: medium, L: low)

 Table 10. AM technologies distribution in different regions (Frost & Sullivan, 2016)

**4.3. APAC Projects**

Amongst all regions, the AM growth in Asia ranks at the top (55% yearly), and many AM projects are in progress. Some typical examples of AM development in the Asia Pacific (APAC) are booming.

Ultra Clean Asia Pacific (Japan) launched a gigantic 3D-printing facility in Singapore. Carima and Sentrol (South Korea) introduced AM SLS/SLM machines. Addie (Taiwan) has developed a low-cost 3D printer based on a similar binder jetting technology and formed a partnership with several inkjet manufacturers. Singapore’s Economic Development Board and Nanyang Technological University developed 3DP-driven start-ups. Botzlab’s Drona (India) has been developed to provide competition for FDM printers. The Chinese Ministry of Industry and Information Technology (MIIT) has just unveiled its national plan for 3D printing.

**4.4 AM Applications**

Sustainable manufacturing covers durability and closed-loop recycling. Through a circular economy, all the design, materials, prototyping, manufacturing, products and EOL are linked in a sustainable loop (Hendrixson, 2021). AM has a broad future and a wide range of applications. Because AM applications are dramatically expanding through innovations, other significant applications can be expected.

According to Watson, the global AM market is expected to reach $23.33 billion by 2026. This covers metallic materials, which have various properties to make high-performance parts, specifically in the aerospace industry. The medical industry is also projected to be one of the fastest-growing applications of AM (Watson, 2019).

Common AM applications are prototyping and making parts for a variety of industries, and typical examples are illustrated as follows:

**Automotive**: Printing spare parts and prototyping are common usages in the automotive sector. Short life cycles and flexibility are the unique AM characteristics in spare parts design and maintenance that CM lacks. The ‘divide-and-conquer’ approach further differentiates the gap.

**Aerospace**: The aerospace industry has been in high demand of highly customized and lightweight components that can save materials costs and costs from petroleum while eliminating CO2 emissions.

**Construction**: The construction industry considers AM a potential method for rapidly creating low-cost construction materials. Meanwhile, AM can print sheets and a variety of shapes easily, which can enhance the resistance of the road surface.

**Medical**: AM has wide applications in the medical industry, such as orthodontics, organ transplants, implants, hearing aids and eyeglasses, which require high levels of personalisation and customisation that AM can fully perform.

**Sports**: In the sports industry, designers require frequent prototyping and testing of equipment with athletes. For this reason, AM can be the best option for sports instruments.

**5. Applicability and Limitations**

The qualitative analysis of this study builds up the strategy of cost modelling and critical factors of AM and CM that impacts the item cost. The qualitative analysis in section 2 derives four generic formulas that are independent of the manufacturing conditions including the technologies being used while the sub-section 2.5 raises a feasibility study of AM cost reduction through an optimized technology. In the current situation, as AM standardization is still in early stage, questions for how to optimize manufacturing conditions based on the applications, and how to integrate non-generic cases into standard processes are pending on some more in-depth investigation that need a separate study.

AM is highly recognized for its wide range of functions, shapes, and products of high complexity. For instance, the increasingly used in the medical industry, which requires a high degree of customization, as is necessary for producing dental molds or prosthetics. In the automotive industry, this technology is widely used to make replacement components or parts for different types of vehicles (EOS, 2021; Aimar, A., Palermo, A., 2019; Zahnd, P., 2018). As filament feeds are limited to small volumes, and the products are limited to those of high quality with smaller quantity and size. In addition, there is no evidence that AM can better achieve those products that require high surface quality. Comparatively, CM has long history and mature technologies in surface finish, polishing and trimming. A separate study in AM tooling of surface quality is expected in near future.

In terms of AM’s limitations; there are three areas need separate studies before the business model can be deployed into industry practices, which include; standardization, scaling production, and quality of the recycled materials. There is still a lack of understanding of the materials properties, as well as AM technologies. AM standards need some more investigation to evaluate the accuracy of AM in term of surface finish, fabrication speed, volume, and data formats. A sharable platform and global communication are the recommendation to speed up AM standardization.

AM weakness in volume limitation, slow manufacturing process, and product size require a separate study in localization, HBM, and human-centric study of the AM workforce, and control metrics. This study suggests solving the scale issue before an investigation of the quality of recycling materials and AM process improvement.

From a quality perspective, an estimated 10% in quality reduction can happen in each recycling process, which needs improvement. This study proposes to process recycled materials in more suitable forms, to reduce processing time and eliminate the reaction kinetics of photo-oxidation by nitrogen pumping.

**6. Conclusions**

The lack of a cost evaluation method is the barrier in an emerging technology and affects the decision makers’ priority in the investment. Through our previous studies, advantages of AM over CM processes were concluded, however; decision makers hesitate investing due to the ambiguity of cost evaluation. In order to overcome the barrier, this study proposes a business model - to take the results from technical assessments to industrial evaluation - with cost evaluation being the priority in this study.

The business model advocates industry applications in terms of three key aspects - standardisation, localisation and collaboration towards sustainable manufacturing. Through the ‘divide-and-conquer’ approach, the business model demonstrates novelty in the evaluation method via the convergence effect, batch size and AM technologies which are the key contribution of this study. Based on this approach, cost modelling generic formulas is derived to support the quantitative cost analysis for individual parts in plastics manufacturing, and the correlations for the key factors envision the threshold settings aimed at cost reduction. Based on this model the total unit cost, close to100% is estimated.

The second priority of this study is based on the shortcomings of AM, such as scaling and speed in mass production, as well as the filament feed rate. Compared to AM manufacturing company, HBM can be a cost-effective method to resolve mass production issues as some plastic 3D printers cost few hundreds dollars. Through the cost evaluation method, this study bridges materials recycling and AM in a seamless integration to address scaling and speed issues and to reduce the reliance on supply chain and cost. Consequently, the LE-SME-HBM collaboration can be applied to the appropriate applications to eliminate the AM weakness in scaling and speed issues.

In terms of sustainability, use of recycled materials can save primary plastics, reducing energy consumption as well as the Earth’s resources. However, from a quality perspective, unsorted and mixed-up materials of different plastic types may lead to fragility and quality degradation. An estimated 10% in quality reduction can happen in each recycling process, which needs improvement. To address the issues, this study proposes to process recycled materials in more suitable forms, such as flakes, pellets or even powder, which can reduce processing time and eliminate the reaction kinetics of photo-oxidation by nitrogen pumping. Furthermore, this study suggests limiting AM to premium products in the early stage, such as parts for aerospace and medical use, and taking a few steps to reach mass production. These limitations require additional investigation in a separate study.

Because AM is an emerging technology, standardisation and common practices are still in their infancy. However, more organisations and industries are recognising the criticality, and the global mainstream is under development. With advancements in technology, solving these issues is feasible if the business model can be realised to attract more investment from stakeholders, and to speed up the resolutions for AM weakness.

The world is shifting towards a highly personalised, agile, customised, individualised, on-demand distributed and sustainable manufacturing model. To envision the AM cost pattern and to maximise the AM advantages, multiple entities, such as enterprises, government, manufacturers, consumers and AM designers are encouraged to join the AM society. Through a common platform in full transparency, a clearer picture of the AM advantages, improvement requirements, traceability and tracking mechanism will help the industry move AM plastic businesses into the industry mainstream.

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