Localised Plastic Recycling and Additive Manufacturing: Sustainability Strategy

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Certificate of Authorship and Originality

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I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree.

In addition, I certify that all information sources, and work of publications used are dedicated to this thesis. Details of the publications related to this research program can be found at Appendix 1.

Signature of Candidate

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Abstract

Plastics bring tremendous benefits to our daily lives. Nevertheless, their nondegradable nature, processing and recycling practices of plastics negatively impact the environment, economy, and society. Studies reveal that the consumption of significant amounts of energy due to processing of primary plastics, recycling and plastic's waste transportation are among major causes of greenhouse gas emissions that result in global warming. Furthermore, energy consumption as the result of human transport between urban and rural areas accounts for huge amounts of CO2 emissions. Therefore, reduction of CO2 emissions has become an important concern globally. The aim of this research is to find solutions for a more sustainable future by understanding and analysing the relationships of climate change, global warming and human activities associated with the use of plastics.

Environmental degradation and climate change are consequences of the desire for fast economic growth, which may result in the societal degradation of rural areas and overpopulation of urban areas due to disproportionate immigration. This study indicates that the best strategy to stop or even reverse immigration from urban to rural areas is by creating jobs and opportunities in the rural areas. This can be achieved by the advancement of additive manufacturing processes that require minimum capital investment and low skills for manufacturing plastic parts and components. This study proposes three models, collection-recycling-manufacturing (CRM), business (BM), and strategic control (SCM) of plastic waste to create the patterns and formulas supporting the relationships among recycling, transportation, and additive manufacturing towards sustainability.

The novelty of this research is the evaluation of the CRM and BM of newly developed plastic additive manufacturing (AM) processes compared with a more traditional process such as injection moulding through energy consumption, CO2 emissions of primary and recycled plastics and transportation optimization. Furthermore, the localisation strategy of the robust integration of AM and recycling of plastics is realised.

This research shows that through integration of AM technologies into the plastics industry, home-based manufacturing (HBM) may be feasible by localising the recycling and manufacturing of plastic parts and components. Ultimately, HBM minimises the reliance on supply chains and transportation, reduces energy consumption and CO2 emissions, saves costs, creates jobs and deals with sustainability challenges in the plastics industry.

Keywords: Sustainability, Additive Manufacturing, Plastics Recycling, Combined models approach, Localisation, Home-based manufacturing

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1. Introduction

1.1 Background

1.1.1 The research aim

This research investigates the key elements and tactical components that impact the sustainability of the plastics industry and offers an improvement plan. The investigation targets the identification and evaluation of the tactical components that impact sustainability, whereas the improvement plan is focused on the processes for how to fully employ the results of evaluation to envision the advantages or challenges of different process and to eliminate the disadvantages.

1.1.2 The research objectives

The research objectives define the scope, the priority, the method, and the model that drive the research.

Scope: First, the scope is broken down into 17 core areas, as listed in Figure 1. Categorisation is based on three major criteria, tactical components, evaluation criteria, and method and approaches, as explained in section 2.1.

<u>Tactical components</u>

- Localisation
- Integration
- Energy consumption
- CO2 emission
- Transportation
- Supply chain

<u>Evaluation criteria</u>

- Recycling
- AM/CM Comparison
- AM Highlight and Challenges
- Plastics applications

<u>Method and approaches</u>

- Workforce
- Collaboration
- Strategic Control
- Society
- Cost pattern
- Standards

Related area (but not in the scope)

- Decentralisation

Figure 1. Core areas of investigation within the research aim

Recyclable plastics are mainly of seven widely used types: polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), and other plastics, based on the resin identification code (RIC) system (Sanchez, F., et al., 2020).

This research does not fully cover all seven types of plastics. PVC is not the focus because the high chlorine content (over 50%) and hazardous contents in PVC require special treatment before mechanical recycling can be proceed. Of the other six types, PET, HDPE, and PP are the main plastic types selected to compare energy consumption in recycling and CO2 emission in manufacturing (as shown in Table 4).

Priority: All the listed core areas are correlated to each other. The priority of evaluation is given to the tactical components rather than the consequences. Furthermore, key elements such as energy consumption, CO_2 emission, and transportation are priorities of investigation in the quantitative analysis.

Method: The processes can be divided into two parts: source materials handlings that cover primary plastics and recycled plastics and the plastics manufacturing including conventional manufacturing (CM) and additive manufacturing (AM). The method of comparison is to evaluate the processes against the key elements and tactical components and to compare the advantages and disadvantages between recycled plastics and primary plastics and between CM and AM.

Model: Based on the outlined scope, the priority settings, and the method applied, this research proposes a combined models approach to leverage the results of the process evaluation to the three aspects of sustainability (environment, economies, and society). The approach envisions the tactical components such as localisation to achieve the research aim and to realize sustainability in the plastics industry.

The criteria of research objectives are highlighted in Table 1. In summary, the author investigates the tactical components across processes, cost, and workforce of plastics industry to make improvements. From the sustainability perspective, scoping the key elements, prioritizing the tactical components, developing methods and models to minimise energy consumption, reduce CO_2 emissions, lower costs, and create job opportunities in rural areas are the research's objectives and crucial areas.

Table 1. The coverage of research objectives

Criteria of research objectives	
Scope	Based on the research aim, 17 related areas are outlined as scope of investigation.
Priority	Within the core areas, tactical components are set as priority to evaluate the metrics of key processes.
Method	Method is applied to evaluate processes of source materials handlings and plastics manufacturing.
Model	Combined models approach is proposed to derive improvement plan based on the evaluation results.

1.1.3 The previous studies

Sustainable development (SD) has become one of the priorities of this decade, particularly for developing nations. Past studies have proposed approaches to investigate the interplay of the environment, society, and the economy. The previous studies have also indicated that the interplay of global strategy and urban-rural balancing is closely linked to sustainable development [1,2,3].

Furthermore, research into recycling processes, green technologies, the environment, and circular economies [4]; into the role and the impact of emerging technologies [5] such as 3D printing; and into collaboration [6] and education [7] is assessed.

Based on these studies, the author proposes models to compare the use of recycled plastics and primary plastics in producing parts and components by conventional manufacturing (CM) and additive manufacturing (AM) to achieve sustainability in the plastics industry.

Sustainability has become crucial in the past few decades because of the irregular consumption of resources (energy and minerals) and the generation of enormous amounts of waste and CO2. SD in the industry is aimed at reducing material waste, energy consumption, CO2 emissions, and cost as well as creating job opportunities in rural areas. However, the lack of policies and industry standards results in slow progress and makes improvements difficult.

Owing to the variety of technologies and applications, the scope of this research is comparatively significant, and it may not be feasible to use one model to cover everything; therefore, the author proposes three models for different aspects of this multidisciplinary study. Followed by the gap analysis and the benchmarking results, the author proposes improvement plans to fill the gap and elaborates on the coherence needed to move the strategies into realisation.

The multiple disciplines include perspectives about technologies, applications, and human-centric factors. To streamline the evolution of the plastics industry, the author proposes a collection-recycling-manufacturing (CRM) model, a business model (BM), and a strategy control model (SCM) to establish a foundation for sustainability. The areas of investigation are listed as follows and are elaborated in the literature review and methodology.

- Key elements assessment in localisation, and environmental and economic sustainability (CRM model)
- Key factors benchmarking of recycled and primary plastics (CRM model)
- Key factors benchmarking of AM and CM (CRM model)
- Seamless integration in supporting localisation, and transportation and supply chain reduction (CRM model)
- Key elements assessment in economic sustainability (Business model)
- Applications assessment in building cost modelling (Business model)
- Cost pattern in ‘divide-and-conquer’ approach (Business model)
- Key elements assessment in social sustainability (Strategic control model)
- Reducing supply chain by localisation and local supply on demands (Strategic control model)
- Workforce, HBM, standardisation, collaboration, and rationalisation in population (Strategic control model)

The author’s existing publications have outlined the three aspects of sustainability and their correlations in the plastics industry and have shed light on technologies, applications, the environment, cost, and education, which are the objectives of this research.

These previous works are listed as follows:

1. **‘The Interference Model Between Environment Sustainability and COVID-19’**

   Urban-rural balancing is closely linked to sustainable development because it affects all of us via mutual supplementation. Its critical role has been highlighted since the spread of COVID-19, which has menaced our lives and impacted our environment. This research scrutinizes the rationalisation process of urban-rural populations and infrastructure to establish a static foundation. It further proposes time-space swap theory to trade ‘space’ for ‘time’, to protect us as a dynamic solution. [1]

2. **‘Education for Environment Sustainability: 3D Printing’s Role in Transformation of Plastic Industry’**
   This paper aims to introduce the role of 3D printing (3DP), focusing on its contribution and impact on the plastics industry. The goal is to provide a solution for increased plastic production and disposal, seeking effective methods to enable 3DP technologies and applications. Recycling of feedstock and reduction of material usage are the main solutions under discussion. [2]

3. **‘The Roles and Approaches of Education to Sustainable Development’**
   Sustainable development has become one of the priorities of the decade, particularly for developing nations. This paper aims to achieve sustainable development (SD) through education, and it proposes a three-step approach to investigate the interplay of environment, society, economy and SD in enabling international education. The study first identifies impact factors and measurable metrics; in addition, it investigates the impact of SD education on topics such as human capital, the environment, and library science and culture to shed light on the SD roadmap. The study applies the case study of an international education program as an example to illustrate the feasibility of SD, and it proposes global strategies and approaches. The principles of the global strategy are finally examined in the context of the elemental characteristics necessary for international education about SD. [3]

4. **‘The Role of Educational Action Research of Recycling Process to the Green Technologies, Environment Engineering, and Circular Economies’**

   The recycling process in waste management reduces the cost of waste handling and raw materials, and simplifies supply chain management. It introduces 3D printing design and circular economies and significantly impacts green technologies and environmental engineering in terms of waste management and materials processing. Educational action research plays a crucial role in communicating to designers, stakeholders, consumers, and distributors in the end-to-end recycling process. It fosters the entities across the value chain and accelerates the modernisation of waste management processes. [4]

5. **‘The Impacts of Emerging Technologies and Education to Creative Industry and the Inspired Economies’**

   For decades creative industry has produced significant values and boosted national identity. Through the globalisation of education and emerging technologies, culture can be economized by creative industry to develop prosperity. From noneconomic perspectives, creative industry augments global exposure and ameliorates international relations. To promote the globalisation of creative industry, an approach was proposed to align education and technologies into a transformation platform to intensify education and training and establish a common model of global collaboration. [5]

6. 'Collaborative Model of Emerging Technologies in Asia Pacific'

Emerging technologies became pervasive in this decade because of the significant growth of high-volume transactions and sophisticated businesses. According to Gartner, the public cloud in the Asia-Pacific region will continue its high growth and hit a minimum of $11.5 billion by the end of 2018. However, the challenge is that only those enterprises that understand agility and collaboration can be winners. Market power for a single firm is very low in a competitive market, so to survive rising competition, companies need to differentiate themselves by customizing their products and services and by quickly adapting to a common platform in the region. To envision the roadmap for regional prosperity, a three-step approach is proposed to align culture, technology, and the economy in a transformation process and eventually to achieve a common model of regional collaboration. [6]

7. 'Effects of Promoting Library Education in Developing Countries'

The realisation of AM in rural development requires infrastructure to establish social sustainability and the stability of the residents' livelihoods. Education is critical to maintaining the workers and their families at a quality of life equal to that enjoyed in urban areas. This paper seeks to provide a suggestion for a 'new vision for education' in the context of library education in developing countries or the rural areas. The author evaluates the effects from past reports and analyses their possibility for future trends. Several types of libraries exist, including public, private, academic and school libraries, but the discussion focuses on library education provided by public libraries. The scope of library education in this paper is concerned with education of all levels, formats and social groups. [7]

Several papers (older and recent) are indexed in References Section. Previous publications are listed as follows.

[1] Wu, H., (2021c), "The interference model between Environment Sustainability and COVID-19", Human Behaviour in the Social Environment, special edition 2021.01

[2] Wu, H., (2019c), "Education for Environment Sustainability: 3D Printing's Role in Transformation of Plastics Industry", Int. J. of Mechanical Eng. & Tech., vol. 10

[3] Wu, H., (2019a), "The roles and approaches of education to sustainable development", Int. J. of Arts and Social Science, vol.2, issue 6

[4] Wu, H., Wu, R., (2019b), "The Role of Educational Action Research of Recycling Process to the Green Technologies, Environment Engineering, and Circular Economies", Int. J. of Recent Tech. & Eng., vol. 8, issue 2

[5] Wu, H., Wu, R., (2019d), "The Impacts of Emerging Tech. and Education to Creative Industry and the Inspired Economies", ICSET-2019 conference, Taipei, Taiwan, 2019 ACM pp.96-100

[6] Wu, H., Wu, R., (2019e), "Collaborative Model of Emerging Technologies in APAC", ICIMP-2019, Vienna, Austria, ACM pp.73-77

[7] Wu, H., (2019f), "Effects of promoting Library Education in Developing Countries", Humanities & Social Sciences Reviews, vol. 7, no. 4

1.2 Outline of this Thesis

The following flowchart (Figure 2) provides an overview of the structure. To create a clear picture of the structure and the comprehension, this thesis is outlined as follows.

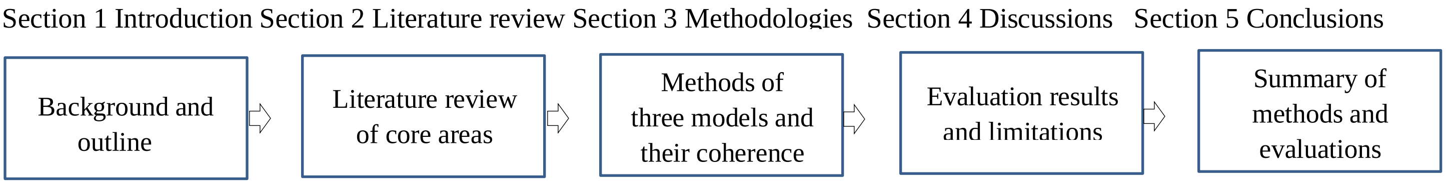


Figure 2. Flowchart of structure and context of this thesis

Literature Review

In the literature review, the author reviews the 17 key elements and four sectors, as well as the literature on AM and CM comparison, cost modelling, and strategic control. The gaps between the current fragments and a full coverage of sustainability, methods being used in comparison, generic format of the quantitative analysis, the strategy and control of sustainability, and irregular migration are the barriers in the existing literature.

Methodology

To fill the gap as listed above, the author proposes the three-model approach in the Methodology Section. In the CRM model, the methods such as key factors assessment, optimisation of transportation distance, and AM seamless integration are elaborated. In the business model, methods such as cost pattern and cost modelling are suggested.

In the strategic control model, the strategy of AM workforce and concept of local supply on demands are introduced. In terms of the coherence of the methods, the author explains how the combined models can realize sustainability and achieves localisation, minimise reliance on supply chain and transportation, reduce CO_2 emissions and lead time, create job opportunities through rural development, eliminate society issues, save costs, and deal with AM’s challenges.

Results and Discussion

Followed by the Methodology Section, in the results and Discussion Section the author outlines the quantitative analysis (such as energy consumption, transportation, CO_2 emission, plastic yield, and cost) and qualitative analysis and explains the reasons why AM is in a good position to achieve sustainability. The section is divided into three models, and in the CRM model, key areas such as recycling, manufacturing, transportation, supply chain, integration, and evaluation are discussed. In the business model, the cost modelling, cost comparison, and results are discussed. In the strategic control model, social sustainability regarding demographic rationalisation, workforce, and job opportunities are discussed. At the end of the Discussion Section, the author outlines challenges, limitations, and future plans.

Conclusions

In the Conclusions Section, the author summarises the evaluation method of critical elements, the results of benchmarking and experiments, and the impacts and contributions followed by the recommendations.

2. Literature Review

2.1 Methodology of literature review

As this research involves a multi-disciplinary investigation, a thematic analysis method (Clarke, V., Braun, V., 2017) is applied in the literature review by grouping different themes of literature. The scope and priority setting follow the research objectives of section 1.1.2 to scope and filter the themes in this review, and the relevant literature are categorized and synthesized. The research gaps are identified, and a strategy dealing with the gap is developed. The scoping and filtering process is demonstrated in Figure 2.

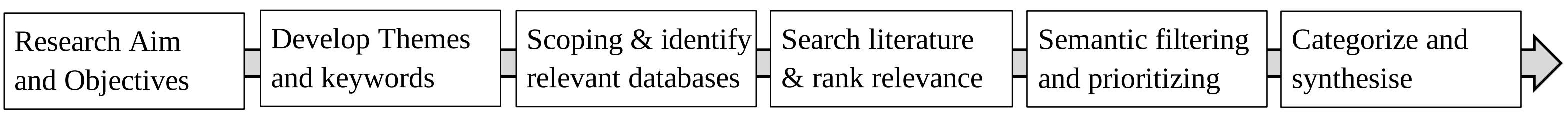


Figure 2. The search and filtering process of thematic analysis in literature review

The classification of review follows the core areas listed in Figure 1 in section 1.1.2, and the grouping is based on the three major criteria: the tactical components, the evaluation criteria, and the method and approaches.

1) The tactical components include localisation and integration, energy consumption and CO_2 emission, and the transportation and supply chain that directly impact the plastics industry in terms of the three aspects of sustainability.

2) The evaluation criteria include plastics recycling and primary plastics process, the AM and CM processes, and the AM highlights, challenges, and applications. The tactical components are evaluated against the processes.

3) The methods and approaches include workforce and collaboration, strategic control and society, and cost modelling and standards that connect the process improvement to the context of three aspects of sustainability.
Among the 17 core areas or themes, as listed in Figure 1, the "decentralisation" topic is excluded because this research focuses on plastics recycling and manufacturing in plastics' life cycle assessment (LCA). Even though decentralisation in distribution is part of the LCA, it is not the focus of this research.

2.2 The tactical components

2.2.1 Impacts of energy consumption and CO2 emission in plastics industry

Plastics are widely used for their appealing properties such as light weight, durability, and comparatively low cost (Hopewell et al., 2009). For these reasons, production of plastics has grown exponentially since their introduction in the latter half of the 20^{th} century. Nonetheless, owing to the irregular consumption of plastics resources and energy while enormous amounts of waste and CO_2 have been generated, sustainability has become a critical mission in this decade.

Greenhouse gases (GHG) are a key contributor to climate change, which need tracking in either recycling or manufacturing processes (Khripko et al., 2013), and carbon footprint (CFP) can be a critical indicator of GHG measurement that needs control. Therefore, GHG reduction can be a crucial control in the context of the plastics industry, and reducing energy consumption can be a tactical resolution.

Through an extensive analysis around energy consumption and CO_2 emission, transportation of plastics waste and plastics materials distribution is identified as a significant factor that affects environmental and economic sustainability. An integration of the full utilisation of recycled materials and the localisation of the AM process can be the most effective method to minimise the transportation distance and to reduce energy consumption and CO_2 emissions.

2.2.2 Localisation and integration

Localisation: Local recycling and manufacturing via AM is becoming a trend thanks to advancements of AM technologies (Kleera & Pillerb, 2019). More studies further indicate that the dependency of AM on supply chain and logistics can be minimised owing to the fact that AM does not require an assembly or tooling process. Ben-Ner and Siemsen predicted that localisation will become the future trend and long supply chains will shrink (2017). Meanwhile, local network will replace long supply chain and support collaboration in the sustainability of the supply chain (Blackhurst et al., 2012).

Local manufacturing via AM will become even more important because the HBM of AM can be the entry point of distributed local manufacturing to form an AM community. To that end, the easy entry to AM can be the approach to localisation and driving force of distributed manufacturing (Inimake, 2021). In addition, the cost pattern and workforce of AM need to be planned first, followed by an evaluation, particularly of the applicability of the standards, to shed light on the advantages and challenges of AM and to attract stakeholders to AM investments.

Integration: The integration of AM and plastics recycling process can be crucial as the integration can fully utilize AM's advantages in localisation through a common access of repository. To promote AM to an appropriate standpoint and to become an industry mainstream, a plan needs to be in place. Among all, transportation is a critical factor of the supply chain from both economy and environment perspectives (Akbari & Ha, 2020; Attaran, 2020; Garmulewicz et al., 2016).

In a seamless integration, all the design, materials, prototyping, transportation, manufacturing, products, and EOL are linked in a sustainable loop (Hendrixson, 2016). Compared to primary plastics, use of recycled plastics in an integrated AM process can save a significant amount of material and reduce energy consumption and CO_2 emission (Roxanne et al., 2019).

2.2.3 Transportation and supply chain

Transportation: Transportation can be a crucial element to environmental and economic sustainability. Plastics manufacturers need to develop collaboration with their suppliers to achieve sustainability (AiChin et al., 2015), and recently, the green supply chain approach has been a significant area of growth in this decade (Mohtashami et al., 2020).

On the other hand, AM production is closer to the consumer, which leads to a more sustainable method of production. With the advancement of AM technologies, decentralised AM significantly reduces cost and lead time and increases operational autonomy (Khajavi et al., 2013). In a closed-loop process, transportation can be a more manageable element, and a minimum engagement of logistics can double the advantages of reducing transportation, energy consumption, and CO_2 emission and make cost savings if reverse logistics are considered (Mckinnon & Yongli, 2006; Nikolaoua et al., 2013).

Supply chain: Supply chain and logistics can cause enormous energy consumption and CO_2 emission. AM of recycled plastics has been a preferred method in supply chain elimination. AM prevents constraints from the traditional supply chain, particularly for low-volume, customer-specific items. Its flexibility and agile adaptation to demands create many benefits, such as customised production, localised manufacture and distribution, short lead time, low transport costs, and low carbon footprint (Kubáč & Kodym, 2017).

Reduced supply chain reliance can reduce plastic waste, thanks to the possibility of creating parts on demand (Ribeiro et al., 2020). In parallel, fabricating parts on demand can reduce supply chain reliance because most of the parts and assembly can be completed by one plant. Additionally, in the AM method, heavy components can be substituted with lightweight ones.

2.3 The evaluation criteria

2.3.1 The plastics recycling and primary plastics processing

5R approach: In the manufacturing industry, the 5R approach is commonly used in plastics waste management, which is the most sustainable way to achieve 'Cradle-to-Cradle' (Lazarevic et al., 2010). The 5R approach covers Refuse, Reduce, Reuse, Repurpose, and Recycle, which can reduce materials' waste (Bell, 2020), and the recycling is the gatekeeper.

According to Our World in Data (Ritchie & Roser, 2018), over 8 billion tons of plastics had been produced on Earth by 2015; however, rates of plastics recycling in developed countries are at around 30%, while in developing countries the recycling rates are close to 0%.

Sustainable approach: Among all waste management methods, recycling is the most sustainable and efficient option (Akinola et al., 2014; Lazarevic et al., 2010). Recycling can effectively achieve 'zero waste' objectives, and Integrated Plastics Waste Management (IPLM) in recycling can be the best option rather than the methods of incineration or landfill (Akinola, 2014).

To establish figures of merit in assessing sustainability in the plastics industry, a key principle of industrial ecology should be a close monitoring of natural resources and promotion of the regenerative function of resources where consumption should not exceed the regeneration rate.

Recycling rate: Recycling has significantly eliminated environmental impacts at the end of life (EOL) for countries that emphasise the importance of recycling, while producing tremendous socio-economic value (Peeter et al., 2017). Devising methods for increasing the recycling rate has been a critical mission.

The main reason is because the plastics recycling rates in developed countries are low; while in developing countries, the material recycling rates are close to zero (d'Ambrières, 2019). According to 2015 global statistics, discarded plastic waste accounted for 55%, while incineration and recycling accounted for 25.5% and 19.5%, respectively. In order to increase the recycling rate, industrial ecology encourages the formation of synergies among companies across various industrial sectors (El-Haggar & Salah, 2007) to review the waste seen as an abundant, local, and free resource (UNDP, 2009).

Therefore, increasing manufacturing efficiency through process and recycling competence is the key to sustainability in the plastics industry (Nambiar, 2010), and recycling and reduction of material waste are both high advantages of most AM technologies (Despeisse et al., 2017).

Comparison: Compared to primary plastics, reuse of recycled plastics can save a significant amount of primary plastic and energy consumption. However, from a quality perspective, quality can degrade by around 10% during each recycling process, which needs improvement (Merrild et al., 2012).

Based on the historical statistics and forecast, global plastics recycling will reach 44% in 2050 (Ritchie & Roser, 2018), which may not effectively resolve the issues. Ultimately, the author of this research aims to achieve 100% plastic recycling with 0% landfill. Even though the objective is aggressive and challenging, it is feasible because, through the improvements of AM integration and cost-effective methods, the advantages of plastics recycling in terms of sustainability will attract more investment and gain compliance in plastics recycling.

Recycling methods: According to Karayannidis (2007), there are four common methods of plastic recycling, which are: in-plant recycling (primary recycling), mechanical recycling (secondary recycling), chemical recycling (feedstock recycling), and incineration (combustion). In this research, primary and secondary recycling methods are recommended.

Through the evaluation, mechanical recycling is the environmentally preferred option to minimise energy consumption and reduce CO_2 emissions (Lazarevic et al., 2010). Mechanical recycling has been one of the most economical methods, particularly for single-polymer and low-purity plastic materials. However, mechanical recycling is limited to single-polymers, such as polyethylene (PE), polystyrene (PS), and polypropylene (PP).

2.3.2 The AM and CM comparison

From plastics manufacturing perspectives, AM and CM can be compared by using the following elements and the methods:

Energy consumption, CO_2 emission, and Transportation: The source energy of recycling and manufacturing processes varies, which can be a factor that influences cost in energy consumption. Among all sources, hydropower energy has been the most common method. However, compared to conventional hydropower energy, solar and wind energy save 60% of energy costs, and wind, solar, and electrical actuation can be suitable substitutes for hydropower (Fredbloom, 2021), effectively reducing energy costs.

AM can work directly on complicated shapes which saves time, effort, and cost (Tofail et al., 2018). Simplification of assembly process means a saving in time and cost. Assembly of parts can be simplified in the AM method because they can be printed directly, and this is the critical factor that reduces the transportation distance. Reduction in transportation distance is AM's key advantage. AM saves significant transportation in an integrated CRM model solution because reliance on supply chain and logistics is eliminated (Garmulewicz et al., 2016). Reduction of transportation also reduces CO_2 emissions and cost.

Environmental impacts: From an environmental sustainability perspective, AM is well-positioned to potentially replace some CM processes by significantly reducing energy consumption and CO_2 emission through the reduction of transportation distance. Massive local production and home-based business could improve scaling issues of AM, shorten the end-to-end processes from waste collection to recycling to manufacturing, and streamline the entire recycling process and bring waste management one step closer to consumers, with environmental benefits (Shanmugam & Das, 2020). Through a virtuous circle, the plastics recycling rate and AM efficiency can be significantly improved.

Materials yield: There is no literature that can confirm the advantage of materials yield of AM. According to Futcher (2015), the scrap rates of injection moulding for the CM method can be as high as an additional 10% for plastics, but there is no indication that AM can achieve a better materials yield (%) over CM. Studies indicate that the yield in production of plastic parts is estimated at around 85% on average (Roxanne et al., 2019).

Design Flexibility: Parts design and modification based on customer feedback are essential in particular industries. A good manufacturing method is responsible for a quick replacement or addition of any part based on demand, and no warehouse storage is required. Parts design changes with CM require redesign, mould modification, and even remoulding. However, with AM, design can be modified using the CAD file. Furthermore, AM can combine and link to innovation, design, and manufacturing in a most efficient way to enable embedding of stylish, state-of-the-art design and to distinguish itself among high-quality products (Rajaguru et al., 2020). Compared to CM, AM is more related to computer-based design rather than tooling. AM designers and manufacturers can take advantages of reusable STL and CAD software with less skill. This helps the small-scale AM home-based businesses start manufacturing with relatively low capital investment (Carneiro et al., 2020).

AM can fully take advantages of sharable software to print parts through cloud computing. In addition, AM technologies can be picked up through professional training if the designer already has basic knowledge of design, making training easier and enabling home-based businesses to launch quickly.

Complexity: Although AM fabricates products more slowly than CM, AM can print complex products in one piece or in fewer steps and enhance durability by avoiding fragility between parts. AM applications have been highly recognised for their capability in dealing with products that demand high complexity, particularly those with complicated shapes or colours, which is difficult to achieve with CM (Pereira et al., 2018).

Compared to CM, AM can prototype the design in a much shorter time. AM involves much less time to create product prototypes thanks to the readiness of CAD and standard tessellation language (STL) software (Hendrixson, 2016). Using AM, design modification and prototyping usually save time.

Easy entry: AM producers can build their business easily. AM overcomes the obstacle of initial cost because the capital cost of 3D printers for plastic materials is affordable for home-based businesses. With low capital investment, AM or 3D printers reduces the threshold of needing a certain amount of capital to start (Carneiro et al., 2020).

Speed of production: Unlike CM, which is fast in parts fabrication and automated parts assembly in mass production, AM prints products layer by layer with low speed based on low throughput. Prototyping of AM can be fast and flexible, but the speed of manufacturing can be a constraint in mass production. Many researchers have attempted to solve the issue, but the progress is not fast enough to make a fundamental transformation.

The causes of the challenges vary: it may depend on solidification of one layer before going to the next layer or on the filament's melting time. To solve the speed issue, some companies are developing new 3D printers equipped with thousands of diode lasers, which could significantly accelerate printing time (AMFG, 2020).

Materials feed in AM is slow. Because filament feeds are limited to small volumes, the products are limited to those of high quality with smaller quantity and size. This may not be an issue for home business producers because massive HBM can accumulate many small-scale productions into significant output; however, there is a need for capacity improvement for AM manufacturers of large enterprises (GE Additive, 2020). The resolutions should not be merely based on technologies; approaches such as HBM and collaboration are all important in contributing to the speed and scaling issues.

Applications: When AM and CM are compared against the production time, cost, and quantity, CM takes longer in prototyping but is much faster in manufacturing the final products compared to AM. CM requires high initial cost in tooling and moulding, but average cost per product is reduced when production quantity increases, while AM requires a lower initial setup cost but average cost per item stays the same regardless of quantity, and filament material can be expensive (Cotteleer, 2021).

As a result, CM is more suitable for mass production of same shape in which just one mould design can be reused for the whole batch, while AM is more suitable for higher complexity with lower quantity. Furthermore, AM is able to produce various components individually and repair small components in a short time, without having to remake the whole item from scratch.

This is a critical factor for those products composed of many complex parts and allows for lowering of materials and energy consumption and reducing time and cost of manufacturing. Frost and Sullivan (2016) analysed the AM trends and predicted AM would keep up a 30.2% yearly growth. Amongst all regions, Asia ranks at the top (55.0%), followed by Europe (39.7%). AM is not labour-intensive, but a considerable amount of manpower is required and crucial to ensure seamless workflow through the value chain, which can bring significant cost benefits to the market. According to Frost and Sullivan (2016), FDM (the technology the author recommends) will be commonly used in America and Asia. In addition, a reduction of lead time by 70% or more is currently feasible in AM. This is an important factor in that AM is positioned for those demands that require a short lead time and precise delivery schedule (Sertoglu, 2021).

2.3.3 The AM highlights, challenges, and applications

Unique characteristics of AM: In the plastics industry, AM can be one of the best and most versatile assets for a wide range of shape, functions, and highly complex products. In the automotive industry, AM technology is widely used to make replacement components or parts for different types of vehicles (Zahnd, 2018).

In the prototyping of plastics design stage, AM can be an ideal choice because it offers advantages such as flexibility in complex shape, shorter design time, and personalisation. AM can print highly complex shapes and can print all types of plastic components and products. AM also offers the flexibility to make necessary changes in a most rapid and cost-effective manner (Hendrixson, 2016) and can significantly enhance our daily life (Kim et al., 2021; Sahu et al., 2021). The rapid deployment of AM has created a broad path to economic sustainability through distributed recycling via additive manufacturing (Little et al., 2020), and it differentiates its manufacturing techniques from other methods.

AM prints parts by applying the CAD files into stereo-lithography STL files and slices of each shape to be printed (Muthu & Savalani, 2016; Tofail et al., 2018; Wong & Hernandez, 2012), so all the design, materials, prototyping, manufacturing, products, and EOL can be linked in a sustainable loop (Hendrixson, 2021). AM is also applied to products that need lightweight parts for energy saving and part replacement for different types of products (Huang et al., 2016). AM allows all users to design and customise personal items, especially in times of emergency when there is an urgent need.

For instance, during the early stage of the COVID-19 pandemic, there was a severe shortage of facial masks. Two students in Japan collaborated to print a self-designed mask ‘PITATT’ and provided open-source code (Iju & Hattori, 2021). Through customer feedback, an improved version of the product was enabled by fine-tuning the initial shape to bring greater comfort. Because changing product shapes only requires changing the codes, quality improvements can happen with minimum effort, particularly to those items of daily usage with significant numbers of users.

AM assists development and job creation, especially in rural areas, by means of HBM. Entry-level 3D printing machines usually cost only a few hundred U.S. dollars (Carneiro et al., 2020), and some websites such as Repetier.com provide free CAD software. A digital file can be created anywhere in the world, prototyped elsewhere, stored in the cloud, and accessed anywhere. With AM, the stock parts only need to be stored in a digital format: AM saves stocking costs and improves efficiency (Michelle, 2018). Basic AM design does not require high levels of skills and capital for production, and most people can establish home businesses and become producers. Most designers can apply HBM to improvise with unique creations or folk art (Muthu & Savalani, 2016).

The challenges of AM: Compared to CM, AM prints products at a lower speed and is limited to smaller quantities and smaller products (Lee et al., 2017). Furthermore, the deterioration of product properties can happen to AM owing to the chain scission reactions (Messmer, 2019) in the presence of water and trace acidic impurities that reduce the mechanical performance of plastics in general situations. Quality degradation can be caused by heat and energy supply during plastics recycling, and this issue results in photo-oxidation and internal stresses to the materials produced by the AM process (Pinsky et al., 2019), and eventually, the material strength is degraded (Al-Salem et al., 2009).

To prevent mechanical property degradation and maintain the polymer average molecular weight during recycling, Messmer (2019) and Merrild et al. (2012) proposed an enhancement approach to avoid moisture in the process such as vacuuming, drying, or the use of agents or chain extender compounds to prevent chain scission reactions. In addition, speed and scale are the challenges to AM. To solve the scale and speed issue, the industry is developing new AM technologies equipped with thousands of diode lasers in one printer, which could significantly increase the scale and accelerate printing time (AMFG, 2020). Meanwhile, an AM community supported by AM multi-entities and HBM can resolve scale and speed issues based on local manufacturing on demand (GE Additive, 2020).

The applications of AM: Since emerging in the 1980s, AM has grown exponentially in terms of technologies, market, and applications. The ASTM Standard categorises AM into seven types of technology: binding jet, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerisation (ASTM International, 2013).

Basically, the seven technologies have their specific applications depending on the materials and products. Selection of the right technology is the key in the AM process (Özkan et al., 2015; Santander et al., 2020), 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 application.

Manufacturing methods are carried out in different applications via different techniques. The materials can be solid, liquid, or powder, and different types of material have respective advantages depending on the applications. The main components needed for an AM machine are: frame, printer head and movement mechanics, build platform, stepper motors, electronics, firmware, software, filaments, as well as support substances (3D Insider, 2020).

Among all types of plastics, HDPE, PET, PP, and LDPE account for 62% globally (Plastics Europe Market Research Group, 2015) that is used in packaging, food, and beverage containers and bottles. In these four types of plastics, the primary plastic sources, PP and PET, contribute to over 45% of global plastic production, and over 60% of these are used in the packaging industry (Yeo et al., 2018). These types of plastic waste are popular and easy to recover. For instance, PET, the most prevalent plastic used in daily life in water bottles, is the most commonly recycled plastic, and 100% recovery of these types of plastic waste is possible. The applications of plastics in the manufacturing industry are versatile, and the advantages of plastics for AM and successful stories in the typical applications are explained as followed;

Applications in automotive industry: In the automotive industry, one automotive vehicle can be composed of hundreds or thousands of parts, and capabilities in prototyping. Easy prototyping reduces time to production, and flexibility simplifies the design. Easy prototyping and flexibility are the unique AM characteristics in spare parts design and maintenance, and these are the critical factors to automotive.

As an AM company, Stratasys improves the efficiency of BMW. The jigs and fixtures department of the car manufacturer has decided to use AM as an alternative to replace CM. According to the results in production, AM can save time and cost (The 3D Printing Solutions Company, 2014). It not only saves costs but also leads to higher quality and fewer errors. For some giant manufacturers, the shift from CM to AM means a more significant impact on sustainability.

Applications in aerospace industry: In the aerospace industry, manufacturing and repair of spare parts on demand is one of the key strengths of AM. Supported by computer-aided design (CAD), the ability to design and manufacture the components based on demand greatly assists the aerospace industry. Space items, including rovers, satellites, and spacecraft, demand highly customised, unbreakable, and lightweight components able to withstand extreme environments. The space industry is greatly different from other industries.

The International Space Station requires more than 3,200kg of spare parts annually to facilitate the living space for astronauts. According to NASA (Gaskill, 2021), AM developed by “Made in Space” is enabling the mission in an environment with microgravity by feeding plastic material layer by layer to create three-dimensional objects. In addition, it allows remote manufacturing to send a design from the ground to the manufacturing system.

Applications in medical industry: Among all sectors, the medical industry can be one of the fastest-growing applications of AM (Watson, 2019). For instance, AM is increasingly used in the medical industry, which requires a high degree of personalisation and customisation (EOS, 2021). Particularly when AM is used in producing dental moulds or prosthetics (Aimar & Palermo, 2019), high personalisation and customisation are the basic requirements of medical instruments and implants. Applications in the medical industry are versatile, from eyeglasses, hearing aids, and orthodontics to tissue repair and organ transplantation.

An emerging technology of Medicare has been developed by the State University of New York. The method – ‘FLOAT’ – is able to print human body parts in a few minutes (Anandakrishnan et al., 2021). This development enables AM capability with high potential to save millions of lives by allowing rapid organ transplantation.

Applications in architecture industry: AM in the architecture industry is promising in construction. AM advantages include environmental friendliness, low cost, reduced injury, and time saving (Hager et al., 2016). AM gives users flexibility to design and adjust based on their own location in simple in-situ construction. These advantages are particularly important to those developing societies or those working in adverse conditions such as the aftermath of disasters.

2.4. The methods and approaches

2.4.1 Priority of evaluation method

The priority of evaluation method is to identify the key elements in terms of energy consumption, CO_2 emission, transportation, plastic yields, and cost, which implements a simulation process to optimise transportation distance. Among all, localisation is a key differentiator between AM and CM, and between the plastics recycling and primary plastics processes.

To form an integration and AM community, the home-based manufacturing (HBM) and demographic rationalisation can develop the AM workforce in rural areas. Under a well-planned demography and robust integration to the AM workforce, the localisation is feasible, and the supply chain and logistics of AM can be significantly reduced (Akbari & Ha, 2020; Arora et al., 2021).

2.4.2 Workforce and collaboration

Workforce: From the perspective of the AM community, HBM can be a good resource for the AM workforce, and relocating the overcrowded population to form an AM community can be a win-win approach. According to the World Bank population density division (2018), 55% of the world's population live in cities, and this is set to reach 70% by 2050. Rapid population growth in urban areas threatens environmental sustainability (Ray, 2011).

From the perspective of social and economic sustainability, overcrowding in major cities results in a rapid growth of energy consumption and degradations of the ecosystem. To mitigate the issues, the United States has developed several programs, applied AM to fabricate medical equipment and create job opportunities in rural areas (Legg, 2021), and applied advanced manufacturing training in rural areas to help the residents to establish their careers in preventing rural-to-urban migration (Jones et al., 2021).

Collaboration: AM is not ready for high-volume and large parts production at this stage, which limits it to small batch production. The Wabtec Corporation is a case study presented for multirole collaboration. Wabtec Corporation collaborated with Hewlett-Packard and launched an AM centre (Wabtec India AM Center), which 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 its individual customers, which is a typical example of collaboration among machine/material provider, SME, and HBM end-users (Chandavarkar, 2020).

In addition, HBM workers can take advantage of AM's low entry cost, less space, and easy setup to start individual businesses by cumulating small but massive HBMs. In a full collaboration of multiple types of providers and entities, the volume issue of AM can be overcome, compatible with CM production. In addition, the multitasking approach at Bennett Plastics is another case study showing that one worker is sufficient to handle multiple 3D-printing machines to increase productivity (Hanna, 2021). Furthermore, adding multiple print heads can aid in increasing the speed of AM (Attaran, 2017).

2.4.3 Strategic control and society

Migration issues: Rural development is important to sustainable development, and rural industrialisation and job opportunities are the priorities of rural development (Sundar & Srinivasan, 2009). This implies that rural development requires stable residents to devote their efforts to the AM community or HBM. However, abnormal migration from rural to urban areas may cause significant impacts to rural development. Sociologists (Chowdhury et al., 2012; Hussain et al., 2014; Todaro, 1980) indicate that poverty has been the most significant factor of migration and that surplus labour in urban areas destroys the balance in an uncontrolled system, accelerating unemployment rates of lower-income labourers and potentially leading to increased disease and crime rates. Abnormal migration can affect sustainability from all aspects of environment, economies, and society, particularly regarding the rural areas' ecosystem, which should be protected for its sustainable development and service delivery opportunities. In addition, rural residents deserve the same infrastructure and services to create a resilient society (Shaw, 2019).

Strategic control: Across the social issues, overcrowding has been a major issue degrading sustainability. Moving the overcrowded population now in urban areas into rural areas could provide a powerful workforce to support AM. Local manufacturing via AM is becoming a trend thanks to technological advancements (Kleera & Pillerb, 2019), and under a well-planned AM demography and workforce control, supply chains and logistics can be significantly reduced or even avoided (Akbari & Ha, 2020; Arora et al., 2021).

The Crowdedness Index and rural population ratio are the key indicators of control metrics to regulate demography. They align rural or suburban development to AM, resolve the social issues caused by crowdedness, and drive sustainability into a virtuous circle. In contrast, with the advent of industries and effective land usage, strategic control can be the guideline as economies, society, and the environment correlate under certain conditions and come in turn to support one another (Patnaik, 2018).

A Strategic Control model can strengthen AM advantages, eliminate supply chains, and relocate overcrowded populations to rural areas (Arora et al., 2021). The model also attracts workers by offering job opportunities and supporting the same quality of life of the rural AM community as is enjoyed in urban areas (Kjaerheim, 2005), helping achieve a more social sustainability.

AM greatly contributes to social sustainability when it comes to specific tools or items for targeted demands (Beltagui et al., 2020). This particular feature of AM fills a gap in CM by meeting the needs of a niche market or producing fully customised products for individuals.

Society issues: Society is part of this research to ensure that the manufacturing process does not affect social sustainability. An urban-centric approach does not favour pandemic crisis handling and can damage a harmonic society. For instance, vagrant people in large cities contribute to the virus's spread, and social distance became a significant issue owing to the shortage of accommodation. These factors threaten a healthy society and cause significant impacts on quality of life. Moving the overcrowded population now in urban areas into rural areas could provide a powerful workforce to support AM.

AM plays a significant role in assisting emergency handling such as the medical supply chain (Belhouideg, 2020). Rapid prototyping enabled the design of urgent equipment such as medical devices to be instantly materialised, and it provided tremendous value because components can be made on demand locally instead of depending on overseas production. These factors not only save time and cost but also reduce pollution and CO_2 emissions through the elimination of supply chains and logistics. AM applications in crisis handling and medical care are unique advantages of AM, and distributed plastic recycling for open-source programs (Santander, 2020) is a typical example of plastic AM applications in this area. Because AM has the potential to reduce complexity and reliance on supply chains, it supports humanitarian organisations in emergencies by enabling local production and maximising the benefit in humanitarian purposes (Corsini et al., 2020).

2.4.4 Cost modelling and standards

Challenges: The difficulty of cost estimation between AM and CM has been a bottleneck to decision support because the decision makers may apply a wrong method. Cost saving has been one of the AM objectives. With the advancement of AM technologies, cost reduction is always feasible from time to time. AM's versatile technologies favour cost reduction in general cases and AM can fully utilise the proposed collaborative pattern in a full-scale provision (GE Additive, 2020). It supports the cost model and offers a good opportunity for HBMs to solve scale and speed issues through its easy entry and inexpensive initial costs. However, AM is not always cost effective in any situation. Furthermore, compared to AM, CM is fast in the fabrication of parts, while AM prints products at lower speed and is limited to producing premium quality, smaller quantity, and smaller size (Lee et al., 2017; Pereira et al., 2018). All the AM challenges are resolvable and should not affect AM's role at all; however, the cost model is crucial to benchmarking for decision support. 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 the cost evaluation, the data format from Deloitte Insight (Cotteleer, 2014) can be used to illustrate the sub-items as well as how to apply them in the process and produce a generic formula for design.

Importance of cost modelling: In the aerospace industry, the Boeing Company evaluates a manufacturing method based on three key factors: cost, part performance, and lead time (Sertoglu, 2021). AM meets all three criteria because its design and prototyping are fast, the lead time is short, and a variety of improvements can further reduce the cost. However, the lack of a generic cost pattern prevents AM from entering mass production. In addition, cost benchmarking is crucial to cost reduction because invisibility does not support cost reduction in decision support (Smith & Kerrison, 2013).

Cost modelling and standard: A missing in standard can be the weakness of AM that affects the construction of a solid cost-modelling approach. Compared to CM, AM is in its infancy, and standardisation can be critical to supporting AM in becoming industry mainstream. Standardisation starts with the materials' LCA regarding recycling, design, manufacturing, and quality assurance. From the technical aspects such as energy, transportation, or CO_2 emission, the cost assessment of this research in recycling and manufacturing is sufficient. However, a business model to evaluate the cost of the product applications should be the priority for improvement. Testing standards need to be in place to make the products more reproducible and reliable to build a concrete foundation of cost modelling (Dizona, 2018).

Standard definition: By definition, standards refer to technical methods, processes, and specifications 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, materials specification, technologies being used, and 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).

Global standard: New industry is in crucial need of standards for safety and quality of products and machinery, as well as the working environment. ISO and ASTM are currently the largest organisations for standardisation. In 2013, the two organisations jointly agreed to develop global standards for AM. Besides, there are other standard development organisations that are in the process of developing standards for specific domains of AM (Gumpinger et al., 2021). 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). With different AM technologies, parameters and standards are crucial to guiding the AM development. To make the products more reproducible and reliable, standards need to be in place (Dizona, 2018). AM materials have large anisotropy and a variety of technologies, materials, and applications (Kim et al., 2021; Sahu et al., 2021). To drive the global standard, ASTM International formed the F42 Committee in 2009 for AM Technologies.

2.5 Gaps Analysis

Based on the classification of the three categories (tactical components, evaluation criteria, and methods and approaches), as illustrated in section 2.1, the literature review produces a summary of three major categories of gaps for what is missing and what areas need improvement.

First, the fragmentation of the literature is the most serious issue that affects sustainability, as discussed in section 2.4 (the methods and approaches). Second, the inconsistent viewpoints of key elements, which links to section 2.2 (the tactical components), can hinder the improvement plan. The third, conflicts across different areas and the lack of a method to balance these conflict areas can affect the validity of the method and cause a barrier to the process, and this is touched upon in section 2.3 (the evaluation criteria).

For instance, transportation can be a crucial element for both environmental and economic sustainability. According to Mohtashami (2020), the green supply chain approach can only solve issues from an environmental perspective. It is true that green supply chain produces less CO_2 emission, but reducing transportation distance can be as great a priority to support both environmental and economic sustainability.

Akbari and Ha (2020) proposed rationalisation of demography to reduce the supply chain logistics of AM. However, the impacts on society and the control metrics of demography are not addressed. In addition, reduction of the supply chain cannot merely rely on the balancing of population as transportation plays critical role in the supply chain reduction. For instance, energy saving in transportation can be crucial, as indicated in section 2.2.3.

Peng (2020) considered that it may not be easy for AM to simultaneously fulfil the diverse requirements of different parts by using the uniform process parameters. But in reality, as transportation is the tactical component involved in the design, use, recycling, transport, and manufacturing processes, and localisation, reduction of transportation distance can be the method of action that connects all 3 aspects of sustainability to a wider evaluation in terms of the cost modelling, workforce, and optimisation in any balancing cases.

Another example regards rural development. Sundar and Srinivasan (2009) considered job opportunity the key factor of rural development, and Chowdhury (2012) stated that abnormal migration from rural to urban areas is caused by poverty. Their viewpoints are partially correct, but there is still a significant portion of abnormal migration caused by problems related to infrastructure (including education), and the authorities' role is neglected in their research.

Based on these examples, List 1 highlights the gap and proposes methods to fill in the gap, which cover:

1) Proposing a combined models approach integrating different methods into a synthesis, and producing the framework or methods to fulfil the research objectives in terms of scope, method, and model;

2) Moving the technical assessment into the applications and management level to produce key metrics of cost patterns and strategic control and aligning different roles and their viewpoints into a validation process of the skeleton, to fulfil the research objectives in terms of method and priority; and

3) Identifying key elements of sustainability, and proposing evaluation methods for key elements in source materials processing (plastics recycling and primary plastics) and plastics manufacturing (AM and CM). The evaluation requires a wide enough scope to cover process, applications, and management to fulfil the research objectives in terms of scope, method, and priority.

List 1. The categories of gap and methods to be proposed

Category	Gap	Methods to fill the gap
Fragmentation (section 2.4)	The existing literature covers a specific area rather than a full coverage of sustainability.	A combined models approach is critical to aggregate the assessments of different aspects into one method.
Inconsistency (section 2.2)	There are three main roles in the plastics industry (designer, stakeholder, and authority) that are involved in decisions on different layers with inconsistent viewpoints.	Key elements identification and tactical components assessment are critical to consolidating different layers and roles.
Conflicts (section 2.3)	Many conflicts across sustainability can multiply the issues.	The optimisation process can reduce the conflicts and gap in the literature.

Gap 1. Fragmentation: An overview and correlations between 3 aspects are missing

Through the review in section 2.4, the existing literature focuses on a single aspect rather than an overview of 3 aspects of sustainability. As a result, correlations between all 3 aspects are invisible makes the improvement difficult.

A genuine method to fully cover sustainability is needed to optimise the 3 aspects of sustainability and their correlation, and to ensure the improvements in one aspect do not cause conflict in another aspect, and this is the main reason the combined models approach is critical to the methodology to fill in the gap.

Based on the review of evaluation methods, most of the existing studies do not facilitate a genuine method of evaluation, and their authors have failed to compare and conclude the energy consumption and its environmental and economic impacts.

As indicated in section 2.4.1, because setting up is less expensive to establish AM businesses, new residents of AM communities can easily set up HBM. Under a solid foundation of AM community and HBM, localisation minimises supply chain reliance and transportation distance. Local recycling and manufacturing can minimise energy consumption and CO_2 emission because localisation reduces transportation distance. For this reason, optimisation in transportation distance can fully use the advantages of AM's characteristics to reduce reliance on the supply chain.

The model-driven approach cross-validates the methods of each model and considers the assessments and their impacts of sustainability in a coherent evaluation. The combined models cover the CRM mode, business model, and strategic control model. In the CRM model, localisation is a key differentiator between AM and CM and between plastics recycling and primary plastics processes. To form an integration and AM community, the author proposes home-based manufacturing (HBM) and demographic rationalisation to develop the AM workforce in rural areas.

Under a well-planned demography and robust integration to the AM workforce, the localisation is feasible, and the supply chain and logistics of AM can be significantly reduced and simplified. The business model differentiates itself from the CRM model in that cost saving in the CRM model is based on the technical assessment of key elements, whereas the business model envisions the cost pattern of products or parts based on the applications' assessment; this is indicated in section 2.4.4.

Finally, the strategic control model envisions social sustainability through human-centric approaches. The model aims to allocate the workforce to support rural development, as indicated in section 2.4.3. The demographic rationalisation guides the authorities to relocate the overcrowded population from urban to rural areas to support the AM industry in rural areas.

Gap 2. Inconsistent: Lack of consensus from different viewpoints

In addition to the three aspects of sustainability, the main reason the combined models approach can be the core area of this research is the heterogeneity of different viewpoints from different roles, and these are reflected from the results of the review in section 2.2.

In the plastics industry, there are three major roles (designers, stakeholders, and authorities) critical to decision making in terms of sustainability. However, almost all of the existing literature is limited to the technical evaluations by using life cycle assessment (LCA) without any indication of the viewpoints from different roles, and that makes the improvements difficult.

For instance, all three roles understand that AM can reduce transportation distance, energy consumption, and CO_2 emission, as indicated in section 2.2. However, stakeholders may reject the cooperative plan of the AM pilot site if they do not foresee how many recycling facilities they need to build to gain a cost saving, or what volume of AM batch size the AM can offer on scale production. The issues are beyond the authorities' control because they may be unable to find a workforce to support plastics recycling or recruiting labour to support AM in rural areas. The authorities may understand this can drive a significant return on investment (ROI) and achieve sustainability in all the aspects, but how much investment in recycling facilities to gain a cost saving, and how the scale and speed challenges of AM can be resolved are unknown.

Basically, the designers are focused on the technologies or process assessment, the stakeholders are focused on the applications or costing model, and the authorities are focused on the strategy and control of those human-centric metrics. Missing a combined models approach causes issues due to the inconsistency of viewpoints, and the barrier cannot be easily solved by any role across different layers. For this reason, a combined models approach is needed to fill in the gap. In this approach, different models can effectively take different views into a synthesis process and improve the processes.

Gap 3. Conflict: Difficulty in establishing mutual benefits across the core areas

Lack of key elements identification and uncertainties have slowed down AM's growth. In addition, the absence of a thorough comparison of the major criteria within recycling and manufacturing, and weakness in a generic form of quantitative analysis are the common issues and gaps. As indicated in section 2.3, methods of identification and evaluation of key elements are critical to this research. Based on this foundation, sample data can be used to derive generic formula and produce the equations.

Based on this foundation, the integration of AM and plastics recycling process play significant role as the integration can fully utilize AM's advantages in localisation through a common access of repository. As indicated in section 2.2.2, localisation requires all processes to be integrated to strengthen the foundation. It also requires the workforce to support AM localisation in rural areas. From plastics waste collection and recycling to manufacturing, an efficient process, optimised solutions, and robust integration between recycling, transportation, and manufacturing are critical to achieve sustainability however, there are some issues that are invisible to the industry that need an optimisation.

As shown in the review in section 2.3, no literature has been found that applied an optimisation process to balance the areas of conflict. Ideally, a method that can commit to all three aspects of sustainability would be best, but in reality some of the conflicts within different aspects of sustainability are invisible or unresolvable in the literature. One of the examples is the optimisation between the transportation distance and the investment of recycling facilities; another example is the cost modelling that need an optimisation between CM and AM to balance the unit cost and batch size.

3. Methodology

To investigate and understand the correlations between plastic recycling, additive manufacturing and sustainability, the research method or methodology in this thesis is summarised in four categories:

1. Previous studies (the author’s previous publications and the literature review)
2. Collection-Recycling-Manufacturing (CRM) model
3. Business model
4. Strategy control model

As indicated in section 2.5 (the gap analysis of the literature review), the combined model approach is proposed as the methodology to cope with the fragmentation issues in the literature, to integrate viewpoints of different roles, and to deal with the correlation of three aspects of sustainability by optimisation. As demonstrated in Figure 3, the three models proposed in the combined models approach fully cover those three major roles to represent their viewpoints.

As indicated in section 2.5 (Gap 2), there are three major roles critical to decision making in terms of sustainability. The designers’ viewpoints are close to the CRM model, the stakeholders’ viewpoints are focused on the business model, and the authorities are represented in the strategic control model. However, almost all the literature applied LCA in the assessment without any indication of the viewpoints from different roles. The combined models approach cannot be replaced by LCA or sLCA because of the multi-roles and multi-aspects of sustainability. In general, LCA concerns the environment rather than economies or society, and sLCA has more emphasis on society than on economies or environment, and so may not cover all aspects and all three roles in one methodology. The coverage of combined models approach is described in Figure 3.

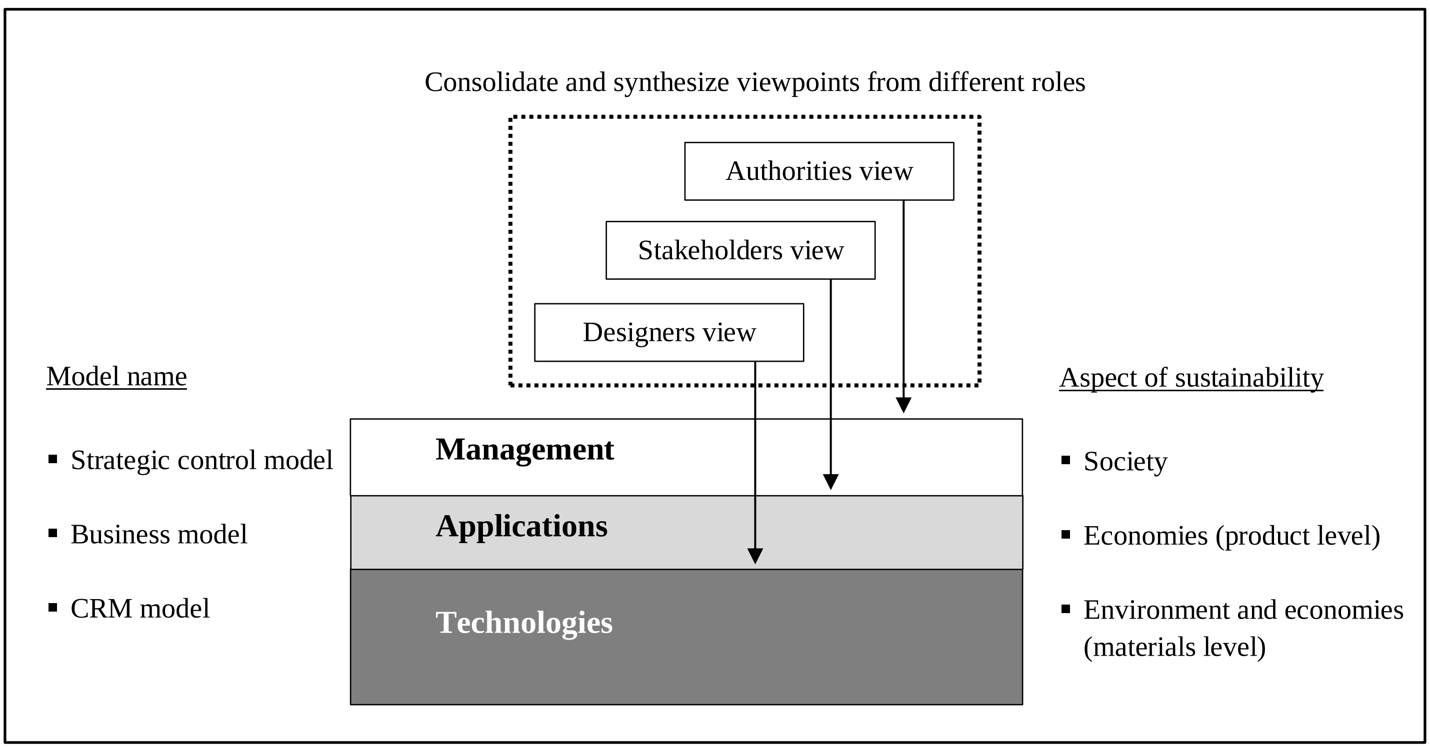


Figure 3. Combined models approach

The combined models approach proposed in the methodology is linked to the result of the gap analysis in section 2 (literature review). The validation of the approach is based on a multi-steps process, as demonstrated in List 2. In the validation process, the final step of verification, the data collection protocol, and limitations are common to all three models, and the theoretical development, the assumptions being made, and the need for the method are different across different aspects.

List 2. The validation process of the method and the models

Model vs. validation steps	CRM model	Business model	Strategic control model
Need for the method	Evaluate key elements of sustainability between recycled and primary plastics, and between AM and CM.	Compare the unit cost in the manufacturing process, and derive formulas of cost pattern in products level.	A human-centric approach needs to be in place to regulate population and provide workforce.
Assumptions	Envision designers' view to support other viewpoints through synthesis process. Key elements and advantages of processes are discovered.	Envision stakeholders' view to support other viewpoints through synthesis process. Key elements and advantages of processes are discovered.	Envision authorities' view to support other viewpoints through synthesis process. Key elements and advantages of processes are discovered.
Theoretical development	Create an overview of CRM process, propose localisation, AM integration, and HBM and implement formula of optimisation in transportation. Optimisation process between transportation distance and number of plastic recycling facilities.	Outline business model process and implement formula to evaluate the intersection of batch volume between AM and CM. Optimisation process of batch volume between AM and CM, linked to CM convergence.	Apply strategic planning and control metrics to relocate overcrowded population to rural areas to support AM by creating job opportunities. Strategic planning in relocation and control metrics in population distribution.
Limitations	Notation or generic formula is unaffected by sample data, but there is dependency of equations on sample data. There is also a dependency of individual model on the other two models to establish the methodology through a combined-models approach.		
Data collection protocol	Through a rigorous assessment and cross-validation from highly reputational journals paper or industrial white papers to apply a generic formula (data free) to derive equations.		
Validation and verification	All the formulas and equations derived from the combined models approach are validated through a comparison between the software calculation and manual calculation. In the verification process, all three models are tested by using real data and the generic formulas to derive equations (Wu, H., 2021a) (Wu, H., 2021b) (Wu, H. et al, 2022c). The optimisations of transportation by Monte Carlo simulation and AM-CM intersection by divide-and-conquer approach, as well as the top-cities-index and rural population ratio, are manually calculated and compared with the simulation results. No defect was found.		

3.1 Previous Studies (the Author's Previous Publications and the Literature Review)

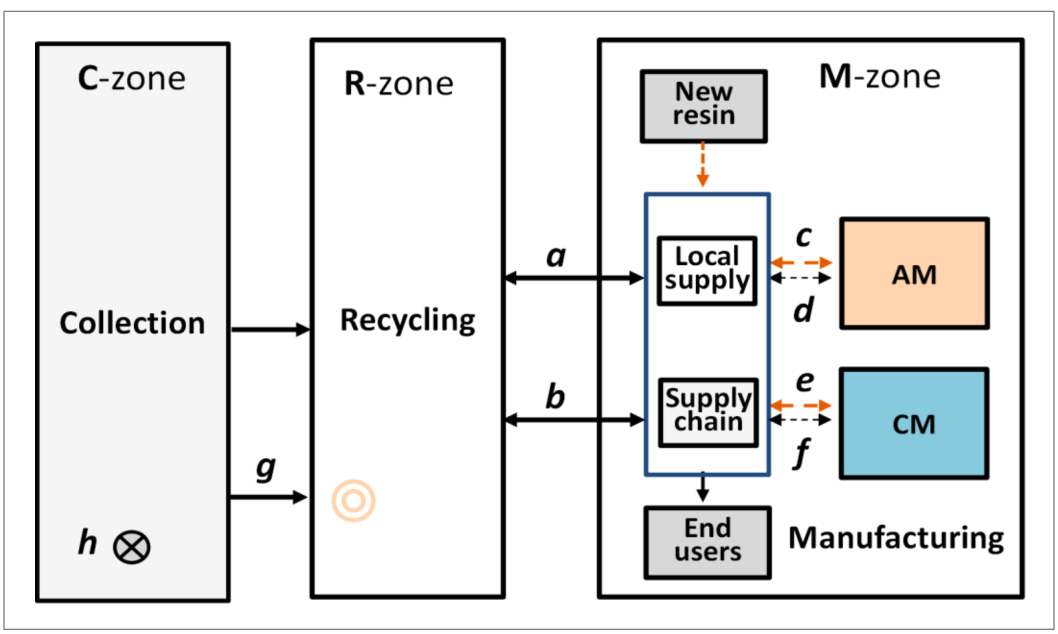
The definitions of sustainability and sustainable development originated from the UN Brundtland Report (1987) that segmented sustainability into three aspects – economy, environment, and society. The terms 'sustainability' and 'development' are two irrelevant concepts. Sustainability is concerned with nature and its finite resources, while humans dominate development without upper limits (Wu, H., 2019a). For this reason, human behaviour and acts need to be changed for a more sustainable future.

A thorough literature review (Section 2) on the recycling and manufacturing of plastics indicates that there is a gap between current and previous research by scientists and environmentalists on the topic of sustainability. The previous literature merely focused on single or partial aspects of sustainability. However, the author's existing publications comprise several categories that encompass the connections between plastic recycling, manufacturing and sustainability. Categories such as localisation, supply chains, standardisation, collaboration, energy consumption, CO_2 emissions, transportation, recycling, the comparison of AM and CM, cost patterns, applications, strategic control, population distribution (the workforce) and society are fully covered in the author's existing publications.

To reinforce the correlations across different aspects of sustainability, a combined models approach is proposed. The CRM model (Wu, H. et al., 2022a) aims to support environmental and economic sustainability in technical level, and BM (Wu, H. et al., 2022b) targets economic sustainability in applications level, while the SCM focuses on social sustainability (Wu, H. et al., 2022c).

3.2 **CRM Model –** Collection, Recycling and Manufacturing (Technical Evaluation)

The CRM model assesses the technical dimension of plastics recycling and manufacturing. The process routes provided in Figure 4 (Wu, H, 2021a) are an overview of the following categories, with the routes defined as follows:



a: Local supply
b: Through supply chain
c: Primary plastics by AM
d: Recycling plastics by AM
e: Primary plastics by CM
f: Recycling plastics by CM
g: Combustion for Energy
h: Landfill

Figure 4. Main routes in CRM model (Wu, H, 2021a)

A quantitative method was used to identify, evaluate, and calculate several key elements presented in the following subsections. In the evaluations, the priorities and improvement plan are initiated in the next section.

In the CRM model, the processes of plastics handling or LCA, from the end of a cycle (waste) to the beginning of a new product, are grouped into the 'C' (collection) zone, 'R' (recycling) zone, and 'M' (manufacturing) zone. CRM process can be categorized into a few categories or routes.

Among these, 'a' is the route of local supply, and 'b' is the route through supply chain. In AM, sourcing recycled plastics (d), or primary plastics (c) are the possible options, and for CM, sourcing recycled plastics (f), or primary plastics (e) are also the options. All of these four possibilities may source via local supply (a), or source via supply chain (b). CRM model targets route via 'a-d' (Wu, H., 2021a) which indicates AM through local supply of recycled plastics is the objective. In addition, category 'g' stands for combustion and 'h' is going to landfill, thus both are not to be solutions in this research.

3.2.1 Method of Evaluation

The novel CRM model demonstrates a comprehensive assessment comparing AM and CM and recycled plastics and primary plastics (Wu, H. et al, 2022a). Key elements of the evaluation are energy consumption (in the recycling and manufacturing processes and in transportation), distance of transportation, CO_2 emissions, material yield (%), and cost evaluation.

Recent studies (Wu, H., 2021a) have found that transportation consumes significant amounts of energy and produces CO_2 emissions that threaten environmental and economic sustainability; however, not many studies were found that address this issue. The CRM model applies AM integration to support localisation and optimise transportation distance within the plastic industry.

The plastic recycling process aims to maximize the recycling rate, reduce CO_2 emissions, and minimize cost. The cost consists of plastic recycling facilities (PRF) payback, plastic waste transportation, and energy consumption, but CO_2 emissions may not be easily evaluated through a monetary transaction (Wu, H. et al, 2022a). However, because CO_2 emissions are closely linked to energy consumption, minimizing energy consumption means reducing CO_2 emissions.

3.2.2 Optimization Process

One of the main reasons the plastic recycling rate has been low is the cost of recycling plastics, and among all the key elements, transportation distance plays a dominant role in energy consumption and recycling costs.

Therefore, optimization of transportation not only minimizes transportation distance and cost, but also improves the plastic recycling rate. Through the optimisation process, CO_2 emissions and costs can be reduced, a circular economy can be achieved, and the plastic recycling rate can be improved (Wu, H., Wu, R., 2019b).

To improve the efficiency of the plastics recycling process, Monte Carlo simulation (Wu, H. et al, 2022a) was applied to optimise transportation distance and the number of PRFs. Monte Carlo simulation predicts possible outcomes based on an estimated profit and a range of input values of revenue and cost that are connected to recycling rate or profit, PRF payback, transportation, and energy consumption.

To maximise the outcomes, a targeted profit value was predefined and the Python code was executed. Through one thousand simulations running in just a few seconds, the optimised values of the number of PRFs and the associated transportation distances were derived (Wu, H., 2021a). When a greater number of PRFs are installed, the PRF payback can be higher however; the transportation distance can be minimized. Consequently, energy consumption, transportation cost, and CO_2 emissions can be reduced. Among the limited candidates for suitable PRF counts, the maximum one can achieve the minimum of transportation distance under the optimized cost, and simultaneously support better environmental and economic sustainability.

3.3 Business Model (Cost Modelling)

The ambiguity of the cost evaluation between AM and CM has been one of the drawbacks slowing down the advance of AM, and the lack of a cost pattern affects decisions about the use of AM in appropriate applications to reduce costs. For this reason, the BM aims to help stakeholders evaluate the cost of plastic manufacturing at the applications level. The evaluation criteria include batch volume, the AM–CM intersection, CM convergence, tooling, and machine and materials costs (Wu, H., 2021b).

In recent studies (Wu, H., 2021b), different batch sizes (20k and 100k) were used to demonstrate the criticality of volume size to CM, and different technologies (FDM and SLA) of AM were used to demonstrate the significance of technology to AM. Finally, the individual formulas of CM and AM were derived to predict the values of the AM–CM intersection and CM convergence. The flowchart in Figure 5 demonstrates the approach of the BM.

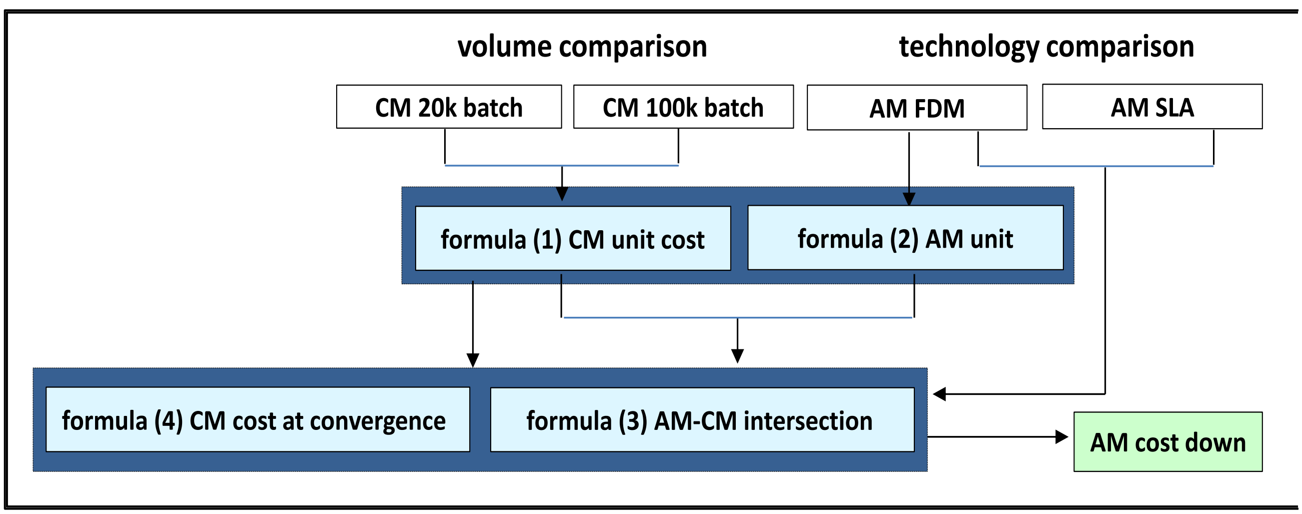


Figure 5. Flowchart and approach of Business model (Wu, H. et al., 2022b)

3.3.1 Method of Evaluation

In the plastics industry, the recent transformation has consolidated all resources into a systematic integration to further achieve cost reduction, high agility and rapid time-to-market, along with a comparison of the unit costs of AM and CM to provide an important direction for cost modelling in the transformation towards sustainability.

To support the cost evaluation, the BM creates a cost pattern to calculate the unit cost of each part and to achieve cost savings in suitable applications (Wu, H., 2021b). The BM derives formulas to calculate the individual costs of CM and AM, the intersection value between AM and CM, and the convergence value of CM.

The model suggests the suitable range of batch volumes for both AM and CM and recommends the type of technology to be deployed. In general, the volumes at the AM–CM intersection and the CM convergence suggest a prediction for the manufacturing process and provide a direction for improvement so that AM can deploy new or preferred technologies in suitable applications to reduce costs.

3.3.2 Cost Modelling

Whereas the BM focuses on cost patterns at application levels such as moulding and materials, the CRM model evaluates the cost at technical levels such as energy consumption and transportation. A recent study (Wu, H., 2022b) has further indicated that the unit cost of AM per part is volume independent, while CM needs an initial cost for mould design that is not applicable to AM, and this constraint limits CM from service on demand. Supported by a 'divide-and-conquer' method (Wu, H. et al., 2022b), the BM constructs a generic form of the cost pattern to calculate unit costs. The 'divide-and-conquer' method is based on the concept of:

(total unit cost) × (part counts) = (mould design cost) + (mould unit cost + other unit cost) × (part counts)

To derive the CM unit cost, cost at convergence, and volume at the AM–CM intersection, different batch sizes are applied to divide the CM cost of each part into several cost items that can be volume independent (such as moulding design), and volume dependent, (such as the tooling cost). Because AM does not require moulding, the technologies are the dependency, and FDM and SLA are used as examples in the illustration.

3.4 Strategic Control Model (Human factor)

Although the methods of the CRM and BM are more related to the planning and design strategies that enable AM's capability in environmental and economic sustainability, the SCM aims to achieve social sustainability and to realise the CRM and BM based on human factors such as population distribution, workforce allocation, job opportunities and the establishment of resilience in social sustainability.

A strategic human-centric plan cannot be achieved in one stroke, and the regulation of control metrics requires tremendous analysis and customisation. The SCM relies on human factors to initiate strategic planning and control metrics to regulate operations, but these factors are unclear in the existing literature. In addition, the impacts of human-centric approaches on the plastics industry are missing and make it difficult to realise the methods (Wu, H. et al, 2022c). To fill the gap, methods of planning and regulation are proposed.

3.4.1 Strategic Planning

To investigate population distribution, the terminology of demography theory (World Bank definitions of *cities* and *rural*, 2020) was applied:

- Any area with a population of > 50,000 inhabitants with a density of > 1,500 inhabitants/km^2 is urban.
- Any land area with a population density < 300 inhabitants/km^2 is rural.

In this research, the crowdedness level is classified into four classes as shown in Table 2:

Table 2. Terminologies for the crowdedness level and definitions (Wu, H., Yabar, H., 2021)

crowdedness level	terminology	population (residents/km^2)	minimum population
L0	Top-300 cities	varied (but this is highest among L1)	none
L1	Urban	> 1500	50,000
L2	Suburb	300 – 1,500	none
L3	Rural	< 300	none

The methodology proposed here comprises 1) a strategy for population balancing to regulate population distribution, promote rural industrialisation, and develop a labour force that supports AM or HBM towards sustainability; and 2) facility and relocation support to improve the resilience of residents' livelihoods. To that end, the causes of problems are investigated and solutions are proposed (Wu, H. et al, 2022c).

- **Population distribution**: To analyse population flow, the driving force of irregular balancing was investigated. In this investigation, job opportunity was identified as the major driving force of population flow (Wu, H., Yabar, H., 2021). If the labour market can drive those living in poverty from rural to urban areas, then the same driving force can move people in the reverse direction should they be offered careers in rural areas. Above all, job opportunities can be a tactical component and an effective driving force that causes irregular population distribution.

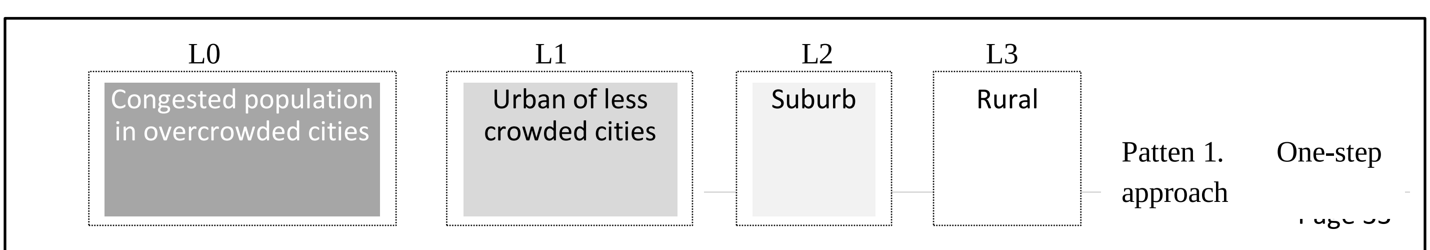
To regulate population distribution, a method for regulation is proposed. There are two patterns of resolutions for solving overcrowding issues (Wu, H., Yabar, H., 2021):

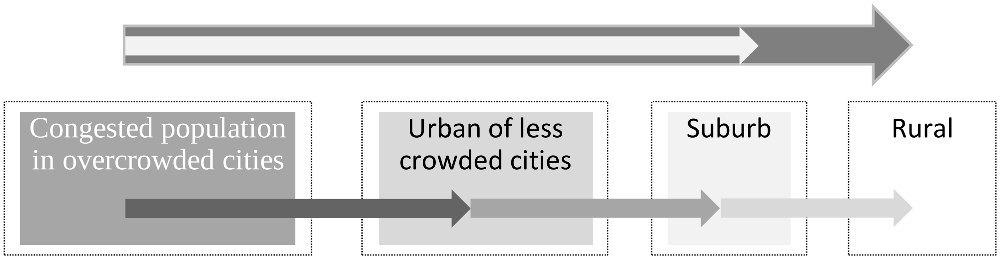
- Pattern 1: Mitigate L0 first, then L1, to solve overcrowding before solving the nation's population issue. This pattern relocates the overcrowded population directly to rural or suburban areas without a buffer at urban areas to save time and effort and reduce the risks caused by massive movement.

- Pattern 2: Mitigate L1 first to manage urban populations before solving the overcrowding issue. This step-by-step approach provides an opportunity to adjust and shape the final distribution through a few steps' adjustment, but much effort, time and personnel will be involved in this gradient movement.

Both patterns are illustrated in Figure 6. However, Pattern 1 is recommended, because it could be a better option that moves the strategic planning directly into the control metrics to effectively rationalize demography and produce a workforce for AM (Wu, H. et al, 2022c).

Furthermore, compared to rural areas, the urban and suburban areas should not be the priorities in the movement because the risk and complexity can be high, so pattern 2 can take more effort and time and may not effectively implement the strategic plan.





Patten 2. Multi-steps approach

Figure 6. Patterns for the population regulation (Wu, H., Yabar, H., 2021)

- **Infrastructure**: Infrastructure measures facilities and services to ensure sufficient resilience is established in the inhabitants' livelihoods in rural areas, so the residents can devote their careers to AM or HBM to develop sustainability where they live (Wu, H. et al, 2022c).

  In this movement, equal opportunity to education and access to public infrastructure and its hub-like topologies and connections should be planned in advance so that strategy can add value to infrastructure in rural areas and improve residents' stability in rural development towards sustainability.

3.4.2 Control Metrics

To establish a foundation for this top-down approach, the SCM applies the following indicators or control metrics to regulate population balancing (Wu, H. et al, 2022c) and to allocate the congested population to the rural areas to support the workforce for AM or HBM.

- **Rural Population Ratio (RPR)**: RPR is the sum of the population in rural areas divided by the total population of a nation. For instance, imagine that the sum of the population of a nation is 100 million, and the sum of all rural areas (rural as defined above) is 10 million; then the RPR of that nation would be 10%. To those developed nations, a low RPR can cause over-urbanization that affects sustainability in all aspects, so a control metric is needed to prevent overpopulation and to fully utilise the rural areas.

- **Cities In the Top 300 (CIT)**: CIT is an indicator of crowdedness. For each country, the sum of the population of all cities in the global top-300 list divided by the sum of the land area of the cities derives CIT as a crowdedness indicator for that country.

  CIT can be different when it measures the population density of a nation, because CIT is an indicator of crowdedness of those top congested cities in a nation rather than a general statistic of the density of a nation. CIT needs a control range because if a city's population density is lower than the lower limit, that city can lose advantages from urbanization, and its economy will be affected; however, if the density is higher than the upper limit, the city risks issues and may not achieve sustainability.

4. Results and Discussions

Based on the categories aligned to the literature review and methodology, the approaches were proposed and evaluated. Supported by the author’s existing publications, the results of evaluation were discussed, and the analysis and the consistency of the combined models are illustrated in Table 3.

Table 3. Overview of the analysis and consistency of 3 models towards sustainability

Method	**Technologies**	**Process**	**Cost**		**Applications**	**Human factors**	**Novelty**
			materials level	product level			
CRM	√	√	√		√		Improvement
BM				√	√		Decision supports
SCM					√	√	Realisation
Objectives	1. Key elements evaluation, and Localisation 2. Supply chain and Transportation reduction			1. Decision supports 2. Cost reduction		1. Workforce 2. Society	Integration and Optimisation

4.1 Foundation of Sustainability

Sustainability requires a systematic review from different perspectives to ensure all aspects are addressed. The approaches to sustainability also need an assessment of their correlations to ensure they satisfy different scenarios (Wu, H., 2019a). A suitable approach can be either a win-win case that favours all aspects or an optimisation case that balances different aspects so that the advantages are maximized. Based on the methodology this thesis proposes, both approaches are applied to deal with different scenarios. The win-win approach can be deployed in the localisation and balancing of populations and the reasons are as follows:

- Localisation fully utilizes AM’s natural characteristics to achieve all three aspects of sustainability.
- Rationalisation of populations resolves overcrowding issues, provides a workforce, and protects ecosystems.

Conversely, the optimization approach can be deployed in transportation distance and cost modelling:

- Optimisation of transportation and PRF counts can achieve environmental and economic sustainability.
- Balancing of cost modelling at the AM–CM intersection can maximize advantages of different applications.

4.2 Strategy of the Three Aspects’ Correlation

Because AM does not require assembly and moulding, it has the potential to establish a foundation of localisation through a multi-entity collaboration (Wu, H., et al, 2022c). However, full localisation requires a significant workforce including HBM to pave the way, and this is not in place currently.

A robust AM integration would improve collaboration and shorten the transportation distance in AM communities (Wu, H et al, 2022a) which is inevitable in this transformation. Through collaboration, the key information of an AM network could be stored and shared in a repository for common access. In addition, the integrated skeleton could effectively shorten transportation distances based on a robust mechanism between demands and supplies (Wu, H., 2019c). The reduced assembly lines and supply chain would not only save materials and costs, but also save time.

The technical assessment confirms that AM is in a better position to understand the CRM model because AM integration is feasible via a transformation (Wu, H., Wu, R., 2019b). Integration strengthens AM's capabilities in flexibility, customisability, adaptability, and scalability towards sustainability. Unified integration relies on a source of collaboration and standards, which integrates plastic recycling and AM processes into a strong framework and coordinates multi-entities and distributions through a collaborative pattern. The AM integration strengthens AM's role as a main channel in the plastic industry. A full picture is shown in Figure 7.

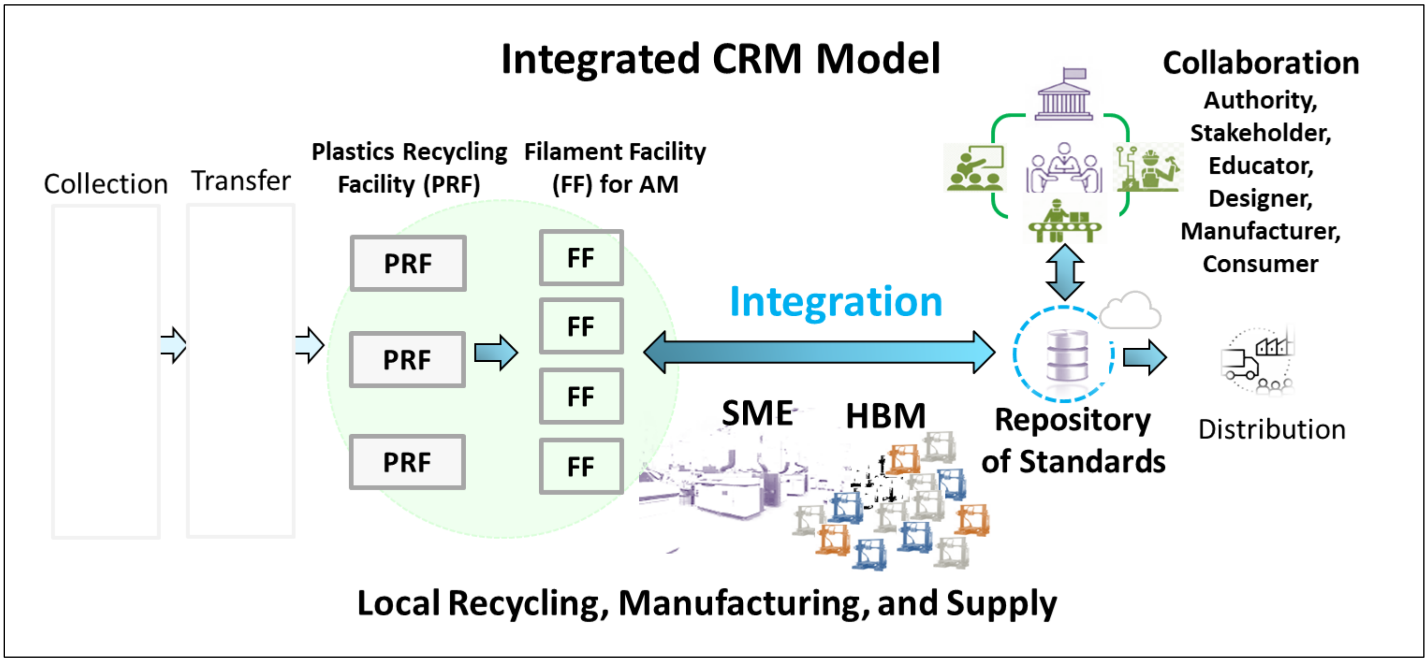


Figure 7. Main routes in CRM model (Wu, H., et al, 2022c)

AM standards can be also important in this transformation (Wu, H., 2021b). Standardisation establishes a foundation that makes the products more reproducible and reliable, which starts with the materials' full lifecycle in terms of recycling, design, manufacturing, and quality assurance.

To that end, AM needs to engage in more global activities to establish a collaborative model and attract more entities to strengthen its foundation, making AM standards fully transparent and more complete (Wu, H et al, 2022a). This is particularly important to AM localisation, and all entities should fully utilize the repository to build a concrete foundation of AM standards in support of sustainability.

4.3 CRM Model – Technical Evaluation

As indicated in the Methodology Section, several indicators of sustainability are used for evaluation: transportation distance, energy consumption (including recycling, manufacturing and transportation), CO_2 emissions, materials yield, and cost savings. The comparisons between plastic recycling and primary plastics, and between AM and CM (Wu, H et al, 2022a) are reviewed in this section.

The unit costs of the key elements in the CRM model are summarised in Table 4, which is the entry point for evaluation.

Table 4. Unit cost of the key components data sources: (Wu, H. et al, 2022a) (Wu, H., 2021a)

Element	Unit	R: *Recycled*, P: *Primary* green: *better*, pink: *worse* yellow: *similar*					
Transportation	$/ton-km plastic	**Method and unit Costs**					
		Truck (default $0.111), Rail ($0.025), Sea ($0.017) & Air ($0.810)					
AM scenario		500 km (50% truck and 50% rail) 250 × (0.111+ 0.025) = **$34.0**					
CM scenario		2200 km (1000 km by air + 1000 km by sea) + domestic 200 km (100 km by rail and 100 km by truck) 1000× (0.81 + 0.017) +100 × (0.111+ 0.025) = **$841.2**					
Recycling	MWh/ton (wind)	**Method and unit Costs**					
		PET (**R**)	PET (**P**)	HDPE (**R**)	HDPE (**P**)	PP (**R**)	PP (**P**)
Energy Consumption	MWh/ton (cost: $/ton)	**4.1** ($184.5)	**19.4** ($873.0)	**2.4** ($108.0)	**20.9** ($942.5)	**2.4** ($108.0)	**20.7** ($931.5)
CO_2 Emission (Transportation)	ton CO2/ton-km plastic	**0.11** (CO_2 emission due to Transportation)					
Manufacturing	MWh/ton (wind)	**Method**		**Materials**		consumption	cost (wind)
Energy Consumption	**AM**	FDM		Polymer		23.1	($1039.5)
		3DP				14.7	($661.5)
		SLS				14.5	($652.5)
	CM	Injection Moulding		PLA		14	($1192.5)
				PET		7	($315.0)
				PP		22.8	($1026.0)
				PS		26.5	($1192.5)
CO_2 Emission (Manufacturing)	ton CO_2/ton-plastic	**AM**					
		PET (R)	PET (P)	HDPE (R)	HDPE (P)	PP (R)	PP (P)
		0.91	2.78	0.56	1.89	0.53	1.84
		CM					
		1.4	n/a	4.16	n/a	4.98	n/a
Yield (%)	Plastics yield (%) of both AM and CM are at around **85**% with some deviation regarding plastics' form.						

4.3.1 Energy Consumption in Recycling

Energy consumption of recycled plastic (PET) is estimated at 4.1 MWh/ton. When wind energy is applied (the unit cost is estimated at $45/MWh), energy consumption in the recycling of PET is estimated at **$184.5 per ton** (4.1 MWh/ton × $45/MWh). The results reveal that energy consumption in primary plastics ($873.0 per ton) is four times more than in recycled plastics (Wu, H. et al., 2022a).

4.3.2 Energy Consumption in Manufacturing

In the scenario of 3DP, and when wind energy is applied, the energy consumption is estimated at 14.7 MWh/ton, or $661.5 per ton (14.7 MWh/ton × $45/MWh). The comparison of energy consumption between AM and CM reveals that both methods consume a similar range of energy in the manufacturing process (Wu, H. et al., 2022a).

4.3.3 Energy consumption in Transportation

The unit cost of transportation is 0.111 ($/ton-km freight). Assume local land option is applied in AM to travel for 500 km by using 50% truck and 50% rail. The cost will be: 250 × 0.111 (1+ 0.225) = **$34.0**/ton. Assuming foreign option is applied in CM to travel for 2000 km by 50% by air and 50% by water plus 200 km domestic by 50% truck and 50% rail, the cost will be 1000 × 0.111× (7.3 + 0.156) +100 × 0.111(1+0.225) = $**841.2**/ton, which is 25 times that of the local option (**$34.0**/ton) (Wu, H., 2022a).

4.3.4 Transportation distance

The transportation distance can be an indicator of energy consumption in transportation. This element is a significant impact factor to environmental and economic sustainability as reduction of the transportation distance means reduction of energy consumption, CO_2 emissions, lead time, and cost (Wu, H. et al, 2022a).

4.3.5 Optimisation

Optimisation aims to balance transportation and the number of PRFs. By optimising the number of PRFs, localisation can be promoted to achieve better sustainability in the economy and environment. Optimisation starts with an assessment of the number of PRFs to be installed.

As illustrated in Figure 8. In an arbitrary location (i.e.; a city) with a circle whose radius = r_0, and let r_0 = 1,000km. Assume there are n PRFs installed, and let r_n be the radius circle covered by each PRF. Theoretically, the addition of n circles covered by n PRFs with radius r_n shall fully cover the total area of r_0. In the calculation, $\boldsymbol{r_n}$ is the radius of a PRF's coverage, which is also the maximum transportation distance ($\boldsymbol{d}$).

The relation between d and r_0 can be derived by: $\text{n} \times \pi \boldsymbol{r_n}^2 = \pi r_0^2$ or $\boldsymbol{r_n} = \frac{\boldsymbol{r_0}}{\sqrt{\mathbf{n}}}$ (1)

Assume r_0 = 1,000km, that derives $\boldsymbol{r_n} = \frac{1000}{\sqrt{\text{n}}}$ or $d = \frac{1000}{\sqrt{\text{n}}}$ (where 'n' is the number of PRFs)

In a simple notation: this implies transportation distance $\propto \frac{1}{\sqrt{number\ of\ PRF}}$ or $\boldsymbol{d} \propto \frac{1}{\sqrt{\boldsymbol{n}}}$

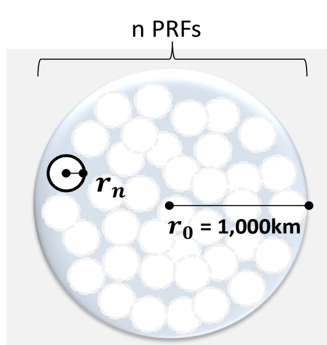


Figure 8. The coverage of each PRF (r_i)

Based on this concept, the optimization process in CRM model leads to the preliminary results:

1. Through the relation between the transportation distance (***d***) and number of PRFs (***n***), the optimisation process is feasible by using Monte Carlo Simulation to derive the 'n' value and obtain 'd' quickly.
2. The optimisation process can reduce CO_2 emissions, save cost, and improve the plastic recycling rate. Optimisation for the recycled plastic transportation can be applied to the manufacturing process. Compared to CM, AM can reduce a significant amount of transportation cost with similar figure in energy and CO_2 emissions.

The same notation (as proposed in the Methodology Section) is applied to develop the formula;

max. (Plastics recycling rate – Costs in PRF payback, and Energy in Transportation and Recycling)

Based on this notation, the optimisation formula was developed to optimise the values between transportation distance and the number of PRFs and to balance the gain and loss to maintain a positive profit (Wu, H. et al., 2022a):

$$n \times \boldsymbol{M} \times \boldsymbol{P}_{balancer} - n \times (\boldsymbol{A} + \boldsymbol{M} \times (\boldsymbol{t} \times \boldsymbol{d} + \boldsymbol{E})) \geq 0 \qquad (2)$$

The preceding equation can be divided into three parts:

i) The first part is the initial setup or PRF payback per day: $n \times \boldsymbol{A}$ when n PRFs are installed
- PRF capital cost is estimated at $15,000,000 per unit for 10 years' service at a capacity of 20,000 tons/year.
- The recycling capacity is derived as: M = 20,000 tons/365 = 54.8 tons/day
- PRF payback $\boldsymbol{A}$ = $15,000,000/(10 × 365) = $4110/day (for one PRF)

ii) The second part is the daily operational cost: $\boldsymbol{n} \times (\boldsymbol{M} \times (t \times \boldsymbol{d}) + \boldsymbol{E})$ when n PRFs are installed
- $\boldsymbol{d}$ is the transportation distance, $\boldsymbol{n}$ is the number of PRF, and both are the values for optimisation
- ***M*** is the daily capacity per PRF ***M*** = 20,000 tons/365 = 54.8 tons/day as derived from i)

iii) The third part is the $\boldsymbol{P}_{balancer}$ ($/ton), which is a fixed value and predefined profit balancer, to move the whole equation into a positive and maximum value. The derived equations can be applied once the $P_{balancer}$ is given, to derive the number of PRFs and transportation distance through Monte Carlo simulation.

The unit costs of the key factors are the given values listed in Table 4:
- Transportation energy cost per ton per km '$\boldsymbol{t}$' = $0.111/ton-km
- Recycling processing energy cost per ton $'\boldsymbol{E}' =$ $184.5/ton (based on the PET)
- Payback *(**A**)* = $15,000,000 n/(10 × 365) = $4110 n/day for n PRFs (based on the assumption as above)
- '$\boldsymbol{n}$' is the PRF number, and '***M***' is the PRF's daily capacity (tons/day)

4.3.6 Monte Carlo Simulation

Simulation was executed by Python code, which only took a few seconds. With a targeted profit ($P_{balancer}$), Equation (2) calculates the deviation Δ_n between n and n+1, and optimisation between 'd' and 'n' is derived.

Through a thousand simulations, the Δ_n value was evaluated against each increase of PRF (n → n+1). Finally, the optimized 'n' value was generated (Wu, H., 2021a), and the associated 'd' was derived via Equation (1).

Qualitative evaluation

The qualitative evaluation revealed the CRM model is feasible for AM, and Figure 9 demonstrates the evaluations.

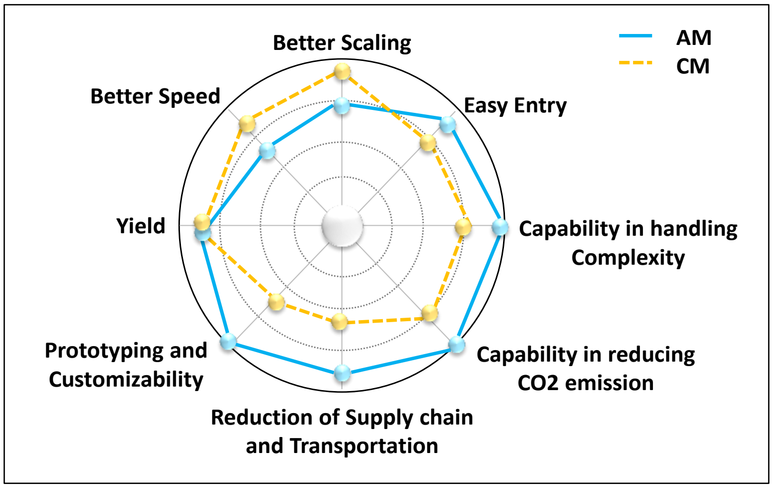


Figure 9. Qualitative comparison between AM and CM

Among all the advantages of AM over CM, localisation and design flexibility could be the strategic aspects that enable AM to fully develop and integrate optimised plastic recycling. The evaluation leads to conclusive results:

1. CM takes a longer time in prototyping. CM can be faster in the production of each part unit, but when a long assembly process is involved, each product can take longer than AM in lead time (Wu, H. et al., 2022a).
2. AM has better flexibility in prototyping and design thanks to software control (Wu, H. et al, 2022d). AM can repair small components based on demands and quickly print and replace a part.
3. As a result, CM is appropriate for mass production of homogenous products, while AM is more suitable for unique, complex designs with higher quality and lower quantity production in the current situation.

Quantitative Evaluation

Quantitative evaluation leads to a summary as indicated in Figure 10, and the comparisons (between 'R' and 'P', and between AM and CM) are based on the key elements of evaluation. The green icons mean the element of that method is a better performer, while yellow icons mean the elements of both methods have similar performance. The quantitative evaluation can be summarised in the following conclusive results:

1. Replacing primary plastics by recycled plastics can save up to 85% of waste material, and up to 88% of energy consumed in the production of primary plastics (Wu, H. et al., 2022a). This is indicated in Table 4.
2. Compared to CM, AM achieves a better performance in most key elements. AM has the potential to reduce transportation costs 25-fold with a similar figure in energy consumption and CO_2 emissions (Wu, H. et al., 2022a). Because AM design is controllable by software and does not need assembly and tooling, flexibility and shorter lead times are two of the main advantages of AM (Wu, H., Wu, R., 2019b).
3. Both AM and CM consume similar amounts of energy and produce almost the same yield (%) in the manufacturing process.

Denotation

R: recycled plastics

P: primary plastics

Energy: energy consumption

M: energy consumption in manufacturing

T: energy consumption in transportation

CO_2: CO_2 emission

Y: plastics material yields (%)

C: cost saving

L: lead time

Advantage (better performance)

Competitive (similar performance)

Figure 10. Comparison between AM and CM, and between recycled and primary plastics

4.4 Business Model – Cost Modelling

The BM enables a cost evaluation method via the AM–CM intersection, CM convergence effect, batch size, and AM technologies. Based on the 'divide-and-conquer' approach (Wu, H. et al, 2022b), generic formulas are derived to guide the appropriate AM applications and cost reduction. The BM supports stakeholders with decision-making by benchmarking and comparing the cost of CM and AM.

Cost pattern

Moulding is the dominant cost of CM, and the simple notation about CM moulding cost can be represented by;

Total cost of moulding of a batch = (mould design cost) + (moulding unit cost) × (part counts)

When the 'other' cost is added, a simple notation as shown below can be the entry point deriving the formulas;

(total unit cost) × (part counts) = (mould design cost) + (mould unit cost + other unit cost) × (part counts)

a) Let '**C_{CM}**' be the total unit cost of each part
b) Let '**n**' be the 'Part counts' or the number of part in a batch. '**$n_{intersection}$**' is the batch volume at intersection.
c) Let '**M**' be the 'mould design cost', which is a one-time cost per batch
d) Let '**m**' be the 'mould unit cost' in production, which is a constant and volume independent
e) Let '**O**' be the 'other cost' of each unit in production

Based on this notation, the four approaches are applied, and equations are derived (Wu, H., 2021b);

- The CM unit cost calculation: $C_{CM} \times n = M + (m + O) \times n$ or $C_{CM} = \frac{M}{n} + (m + O)$ (1)
- The AM unit cost calculation: The unit cost of AM is constant, therefore; $C_{AM} = C_{constant}$ (2)
- The cost at intersection between AM and CM: At intersection; $C_{CM} = \frac{M}{n} + (m + O) = C_{AM}$

This derives: $n_{intersection} = \frac{M}{C_{AM} - (m+O)}$ (3)

- The cost at convergence of CM:

  At CM convergence, the unit cost is the lowest. In formula (1), we derive $C_{CM} = \frac{M}{n} + (m + O)$

  At CM convergence, as $\frac{M}{n}$ diminish when $n \rightarrow \infty$ ($\frac{\partial M}{\partial n} = 0$), this derives: $C_{convergence} = (m + O)$ (4)

Applications

The evaluation results of cost pattern and AM–CM comparison (Wu, H. et al., 2022b) are illustrated in Figure 11. When the sample data (**m** and **o)** is transmitted into the equations, the $n_{intersection}$ and $\mathbf{C}_{convergence}$ values are derived.

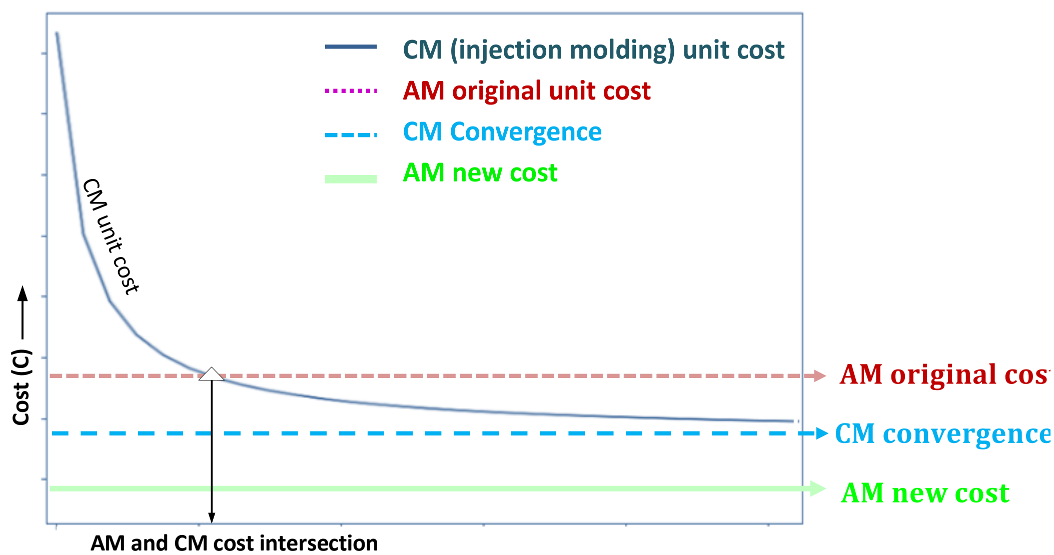


Figure 11. Cost pattern and overview of AM–CM comparison

To justify cost modelling in the appropriate AM applications, the BM requires a few essential factors – standardisation, localisation, and collaboration – to build a concrete foundation for sustainability. Consequently, the model can target niche markets, increase coverage, reduce costs, and achieve sustainability (Wu, H. et al, 2022b). The conclusive results are summarized as follows:

1. In a smaller batch volume, AM can be the more cost-effective method. For urgent replacements or service on demand, AM can save a significant amount of cost and time as there is no moulding process involved in AM.
2. When CM volume is equal to or higher than the AM–CM intersection, CM gains a cost advantage over AM.
3. The metrics of measurements support AM's deployment in appropriate applications and provide direction to improve AM in the areas of technology, scale, speed, and cost saving towards sustainability (Wu, H., 2021b).

4.5 Strategic Control Model - Human-centric Approach

The strategic control model supports the realisation of CRM and business model. It fills the gap of human-centric issues; eases many AM bottlenecks, such as scale and speed issues; and saves cost and effort (Wu, H. et al, 2022c).

The model mainly deals with sustainability's societal issues through population (workforce), and resources distribution, and this is indicated in Table 5.

Table 5. Impact areas of strategic control model (Wu, H. et al, 2022c)

Criteria	Workforce	Localisation	Environmental impacts	Economic impacts	Social impacts
	Relocate over-crowded population to rural areas	Local recycling, manufacturing & distribution	Reduce transportation, energy consumption, and CO_2 emission	Save supply chain cost, materials, and transportation	Jobs, social issues, pandemic crisis, collaboration
AM	+++	++	++	++	+++
CM	+		+	+	+

4.5.1 Population Distribution

Strategic control can be a win-win scenario (Wu, H., 2021c) because strategic planning creates job opportunities in rural areas, and reduces the number of job-seeking immigrants from rural areas to the congested cities, and spreads a more uniform population distribution.

The SCM can realize localisation through a human-centric approach to factors such as the workforce, population, policies, and regulations that fully support rural and suburban development (Wu, H., 2022c). Furthermore, the model can rationalise population distribution, eliminate potential issues such as pandemic crises or social problems, and strengthen the development of the AM community.

The workforce is a key factor of industrialisation; however, overpopulation damages the ecosystem, increases pandemic crises, affects balance in an unorganized system, and heightens unemployment rates, potentially leading to criminal cases or pestilence (Wu, H., 2022c). Reducing immigration from rural to urban areas and relocating the workforce from crowded areas back to rural areas are crucial methods for the support of localisation. The strategic planning of the model elaborates the demographic rationalisation and prevents the abnormal labour movement from rural to urban contexts. The model further derives the control metrics and suggests a 2,000 – 3,000 CIT and a 30 – 50% RPR as the optimized range of the control metrics (Wu, H. et al., 2022d).

4.5.2 Social Impacts

In the past few decades, abnormal migration from rural to urban areas has reduced the necessary workforce in rural areas and created tremendous social issues such as violence and pandemic crises in urban areas (Wu, H., 2021c).

The SCM plays a crucial role in social sustainability because the model relocates congested populations to rural areas, produces a workforce to support the development of rural communities, and strengthens localisation (Wu, H et al, 2022c). The model also creates job opportunities in rural development by introducing AM and HBM.

Rationalisation of the population between rural and urban areas is important for social sustainability. Lessons learnt from recent COVID-19 pandemic issues indicate that rationalization of the population between rural and urban areas is an important criterion to be considered for social sustainability (Wu, H., 2021c). Furthermore, to improve localisation through AM integration and HBM, creating an infrastructure based on education and training is essential and required (Wu, H., Wu, R., 2019b).

For the progression of AM to local manufacturing, education and training play a crucial role in communication among the stakeholders, designers, producers, and consumers. To provide education and training, local public libraries are recommended (Wu, H., 2019f)

4.6 Summary of the Results

In section 2, the three major issues that affect the sustainability in plastics industry are reviewed and identified.

- Fragmentation issue: the literature has not covered a full picture or offered correlation across sustainability.
- Inconsistency: inconsistent viewpoints of key elements from different roles block the improvement plan.
- Conflicts: not optimising causes an unbalance in the conflict areas and a barrier to the process.

To eliminate the gap, the review results and gap are taken into a methodological implementation.

- Propose the combined models approach to integrate different methods into a synthesis and produce the framework.
- Identify key elements and tactical components of sustainability and methods of evaluation and improvement.
- Aggregate the assessment results to the applications and management level, and optimize the conflict areas.

Key finding in the context of state of the arts (SOTA) and the novelties are summarised as follows:

The combined models approach fully covers three aspects of sustainability and enables evaluation of key elements such as transportation, energy consumption, CO2 emission, cost, and yield (%) to establish process assessment in tactical components by comparing the processes between AM and CM, and between recycled and primary plastics.

Through this assessment, the areas that require optimisation such as the balancing between transportation distance and PRF number, or the batch volume between AM and CM are identified, and the generic formulas are derived.

This research envisions the criticality of localisation to enable local supply, local manufacturing, and the integration of the plastics recycling process and AM to estimate the reduction of transportation, supply chain, energy consumption, CO2 emission, and cost. The human-centric approach in strategic control is further proposed to relocate overcrowded population in urban areas, to eliminate social issues, to create job and HBM opportunities, and to support rural development in AM and plastics recycling.

In addition, this research applies Monte Carlo simulation to optimize transportation and the number of PRFs and applies a “divide-and-conquer” method to establish cost modelling for decision making.

The human-centric approach by strategic control, optimisation process by Monte Carlo simulation, and “divide-and-conquer” method are new approaches in this theme. The reasons the new findings are important to the sustainability in plastics industries include that strategic control can realize CRM and the business model by providing efficient workforce that eases social issues, provisions AM’s characteristics in localisation through integration, and simultaneously improves the three aspects in sustainability. Furthermore, the optimisation process enables the capability of balancing different elements or aspects that originally may be ignored or rejected by decision makers once the conflicts are detected.

4.7 Challenges, Limitations, and a Future Plan

The investigations of the three models in the previous subsections indicate that recycling and AM or 3D printing of plastics have a high potential for localisation and HBM, though several challenges need to be addressed.

4.7.1 Scale Production and Speed

AM faces some challenges, such as the lack of reliable standards, in moving the prototyping to production scale. Consequently, scale, speed, and size are drawbacks that slow down advances in AM (Wu, H. et al., 2022d).

AM prints products layer by layer with lower speed and lower throughput, mainly caused by the slow speed of filaments melting and solidification. Because filament feeds are limited to small volumes, the products are limited to those of smaller size and high quality. This may not be a big issue; however, there is a need for capacity improvement for AM manufacturers of large enterprises.

For these reasons, some companies are developing emerging technologies of 3D printers equipped with thousands of diode lasers in one printer, which could dramatically accelerate printing time (Wu, H. et al., 2022c). Slow speed also affects scale production, which needs a separate study; however, challenges of AM in scale production and standardisation are controllable with the advancement of technologies and materials, as well as the human factors such as HBM and multi-entities collaboration in the AM community.

4.7.2 Quality

Use of recycled materials can save significant volumes of primary plastics, as well as lowering energy consumption. However, from a quality perspective, many collection stations do not fulfil a full waste sorting and leave the mixed waste proceeded to PRF (Wu, H. et al., 2022a). Unsorted and mixed-up materials of different plastic types may lead to fragility or quality degradation. An estimated 10% degradation in quality can occur in each recycling process, which needs improvement.

In addition to the sorting capability, the author proposes to process recycled materials in more suitable forms. Material forms such as flakes, pellets, or powder can minimise quality degradation because they can reduce processing time and eliminate the reaction kinetics of photo-oxidation by nitrogen pumping.

Furthermore, the author also suggests limiting AM to premium products in the current stage. High-quality and smaller-scale products such as parts for aerospace and medical usage are ideal products at this time. AM mass production can be expected at the time AM standards and technologies reach a certain level of maturity.

In the recycling process, mechanical recycling is the preferable method although the method can result in chain scission reactions which can cause the deterioration of product and exhibit a nonlinear effect on mechanical properties (Wu, H., 2021a). To maintain the polymer average molecular weight during recycling, it is proposed to avoid moisture by using chain extender compounds to prevent chain scission reactions. Furthermore, monitoring of temperature, dehumidification equipment, and diluting oxygen by nitrogen injection or by vacuum can reduce oxidisation and minimise materials' properties' degradation.

Finally, toxic substances produced by the chlorine-containing polymers can damage public health, which needs a resolution (Wu, H. et al., 2022a). Among all, open space and ventilation equipment may solve the problem, and this is particularly important to HBM because most AM individual workers may not have sufficient knowledge about toxicity, and to include these in HBM education is a critical responsibility of the authorities.

4.7.3 Future Plan

i) **Creative Industries**

Because of the capability of complex shaping and easy prototyping, plastics made by AM could be a typical AM application in creative industry (CI). Therefore, AM education and technologies are important criteria for creative industry and HBM. In addition, AM education could be fully supported by technologies (Wu, H., Wu, R., 2019d) such as information and communications technology (ICT), cloud computing and the context of AM techniques to train the applicants. Education and AM technology advancement, localisation, HBM and CI would develop economic sustainability as well as social sustainability (Wu, H., Wu, R., 2019d).

ii) **Culture Candidates**

AM can enable the linkage between technology and the state of the art that touches human consciousness with a high impact on culture and moral character, and it further improves quality of life. Although the linkage is complex, it can be an important area to which AM or 3D printing can contribute, and the investigation of the mechanisms of this connection can be a long-running plan in social sustainability.

iii) **Cost-Effective Applications**

Further investigation into the plastics trend is expected. The trend towards a cost-effective manufacturing paradigm and efficient production is leading to favourable growth in AM (Wu, H et al, 2022b). Furthermore, AM’s flexibility, supply on demand, and ability to manufacture heterogeneous materials enable wider usage in cost-effective applications particularly in the automotive and aerospace industries and customised manufacturing.

iv) **AM Energy consumption, Yield (%), and Standards**

Because the scope of this research is wide, evaluation of energy consumption in the manufacturing process and materials yield (%) needs further investigation as there is no evidence that AM can be a beneficial option for these two factors. The possible reason is the wide coverage of technologies and applications that can be dependent on energy consumption and materials yield (%), and the standardisation can help to streamline the evaluation in complex conditions. Eventually, AM standards can be the priority that turns the invisibility into full transparency to continue a more profound investigation in energy consumption and plastic materials yield (%).

5. Conclusions

There is an immediate need to tackle plastic waste and avoid further pollution of the land and seas. One approach to tackle plastic waste is recycling. However, only a limited amount of plastic waste is recycled, and the rest ends up in landfills and in the ocean.

This research, based on author's previous research, a thorough literature review and combined models approach constituting CRM, BM and SCM – suggests a totally different and innovative strategy for manufacturing plastic parts and components by advancing additive manufacturing processes.

The combined models approach contributes to the investigation of correlations and commits to a full coverage of sustainability. The approach evaluates key components to discover tactical components such as localisation, integration, transportation, cost patterns, and control metrics. Through the assessment, the generic formulas of optimisation and the patterns are developed, and finally the equations are derived by feeding in the sample data.

This research fully commits the research aim set in section 1. It identifies key components of plastics recycling and the plastics manufacturing process as well as tactical components that affect sustainability. The improvement plan of the research aim has also been smoothly developed. The plan sheds light on the localisation and the integration between the plastics recycling process and AM that can effectively reduce and simplify transportation, supply chains, energy consumption, CO2 emissions, and costs. The novel human-centric approach is further developed to solve the overcrowding issue and produce workforce or HBM to support AM in rural areas. In addition, this research applies the Monte Carlo simulation to optimize transportation and number of PRFs, and applies a "divide-and-conquer" method to establish cost modelling for decision making for additional contributions.

To validate this new vision, a technical analysis was used to compare the injection moulding process, one of the most-used processes for manufacturing plastic parts, with relatively new AM processes (3D printing) and to evaluate key elements such as energy consumption, CO_2 emissions and yield. The study shows insignificant differences in terms of energy consumption of manufacturing process and yield between CM and AM processes per kilogram. Furthermore, the model emphasises the use of recycled plastics to manufacture parts because of much lower energy consumption and CO_2 emissions compared with primary plastics synthesis, thus reducing plastic waste and saving the Earth's resources.

However, the important outcome from this research occurs through strategy control model, which indicates the possibility of significant energy savings and CO_2 reduction by reducing the supply chain and transportation costs through localisation. According to Monte Carlo simulation, AM integration supported by collaboration and standardization plays a crucial role in the CRM model. The AM of recycled plastics, locally, has potential for saving energy and reducing CO_2 by minimising transportation compared with CM processes.

Among all, the key element is localisation. This means that recycling, design and manufacturing based on local demand and consumption avoid transportation costs. Moreover, the 'divide-and-conquer' approach by the BM provided convincing evidence that AM can be cost effective for production volumes less than the AM–CM intersection.

Nevertheless, the combination of the CRM and BM and lower supply chain and transportation costs may not fulfil the required criteria for localisation because of the lack of a skilled workforce. Therefore, the SCM proposed in this research focuses on a more uniform distribution of the population (workforce) between urban and rural areas. The model suggests a 2000–3000 CIT in urban areas and a 30–50% RPR for a nation are the optimized ranges for a more uniform population distribution. Acknowledgement of the SCM strengthens AM's foundation in both the CRM and BM.

Finally, this thesis consolidates 5 recent publications from well-known journals, and 9 previous publications that offers an innovative approach for the plastics industry via the collection-recycling-manufacturing, business and strategy control models. Through the combined models, localisation of recycling and manufacturing plastics using the recycled materials of additive manufacturing is feasible.

Local recycling and AM integration reduce energy consumption and CO_2 emissions by using less transportation and reducing the amount of primary plastic. More importantly, AM creates jobs in rural areas, minimizing immigration and therefore supporting a more uniform distribution of the population, which is an important approach to sustainability.

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Appendix 1: Publications List

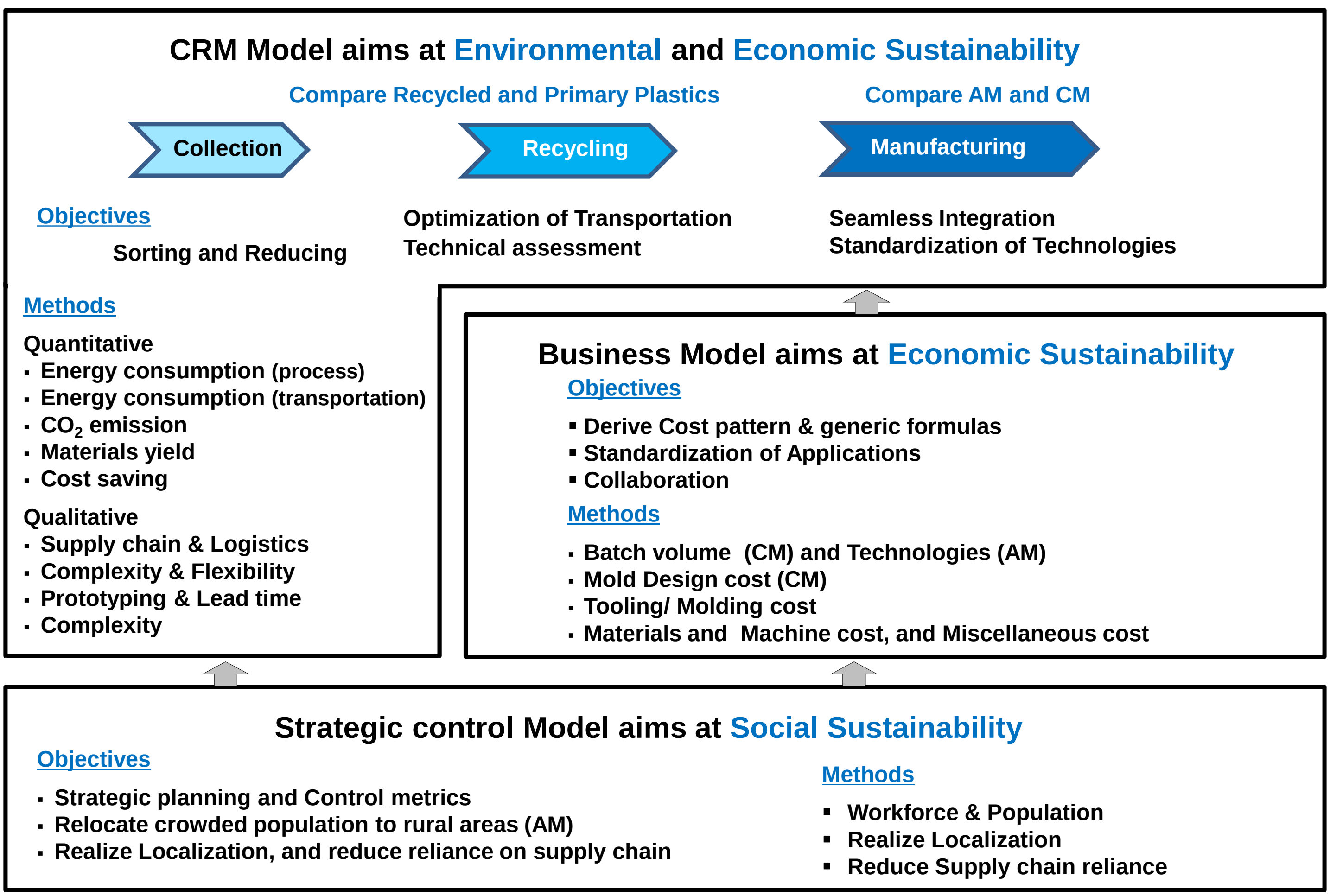
Category	Journal Papers	Journal	Publisher	(co-) Authors/ Web Access
CRM Model	Additive Manufacturing of Recycled Plastics: Strategies towards a more Sustainable Future	Journal of Cleaner Production	Elsevier *vol. 335, 2022.02*	Wu, H., Mehrabi, H., Karagiannidis, P., Naveed, N. https://doi.org/10.1016/j.jclepro.2021.130236
CRM Model	Enhancements of Sustainable Plastics Manufacturing through the proposed Technologies of Materials Recycling & Collection	Sustainable Materials and Technologies	Elsevier *vol. 31, 2022.04*	Wu, H. https://doi.org/10.1016/j.susmat.2021.e00376
Business Model	A Business Model for Additive Manufacturing of Recycled Plastics towards Sustainability	International Journal of advanced Manufacturing Tech.	Springer *vol 120, 2022.05*	Wu, H., Mehrabi, H., Naveed, N., Karagiannidis, P. https://doi.org/10.1007/s00170-022-09269-y
Business Model	Business Model and Methods of Evaluation in Sustainable Manufacturing	Manufacturing Review	EDP Science *vol. 8, 2021.11*	Wu, H. https://doi.org/10.1051/mfreview/2021026
Strategic Control Model	Impact of strategic control and supply chain management on recycled plastic additive manufacturing	Journal of Cleaner Production	Elsevier *vol. 364, 1, 2022.09*	Wu, H., Mehrabi, H., Naveed, N., Karagiannidis, P.
		Special edition: Sustainable Cleaner Production through Process Integration, Modelling & Optimisation		
Social Sustainability	The interference model between Environment Sustainability and COVID-19	Human Behaviour in the Social Environment	Taylor & Francis *Special ed. 2021.01*	Wu, H. doi: 10.1080/10911359.2020.1851333
Strategic Control Model	Impacts of additive manufacturing to sustainable urban–rural interdependence through strategic control	Results in Control and Optimization	Elsevier *2021 vol. 5*	Wu, H., Yabar, H doi:10.1016/j.rico.2021.100066
Environmental Sustainability	The Role of Educational Action Research of Recycling Process to the Green Technologies, Environment Engineering, and Circular Economies	International Journal of Recent Technology and Engineering	IJRTE *vol. 8, issue 2, 2019*	Wu, H., Wu, R. doi: 10.35940/ijrte.b2384.078219
Sustainable Development	The roles and approaches of education to sustainable development	Int. J. of Arts and Social Science	IJASS *vol.2, issue 2019.06*	Wu, H. https://www.ijassjournal.com/2019/V2I6/4146574880.pdf
Environmental Sustainability	Education for Env. Sustainability: 3D Printing's Role in Transformation of Plastics Industry	Int. J. of Mechanical Eng. & Technology	IAEME *vol 10, 2019.04*	Wu, H. IJMET/10/04/2019/IJMET_43115
Sustainable Development	Effects of promoting Library Education in Developing Countries	Humanities & Social Sc. Reviews	Maya Global Education Society *2019 vol. 7, no 4*	Wu, H. DOI: 10.18510/HSSR.2019.7441
Category	Conference Paper	Conference		(co-) Authors/ Web Access
Sustainability	Sustainable Manufacturing by Home Based 3D Printing	International Conference on Sustainable Engineering & Advanced Tech. ICSEAT 2022		Wu, H., Mehrabi, H., Karagiannidis, P., Naveed, N.
Economic Sustainability	The Impacts of Emerging Tech. and Education to Creative Industry and the Inspired Economies	ICSET, *Taipei, 2019 ACM pp.96-100*		Wu, H., Wu, R. doi: 10.1145/3355966.3355987
Economic Sustainability	Collaborative Model of Emerging Tech. in APAC	ICIMP *Vienna, 2019 ACM pp.73-77*		Wu, H., Wu, R. doi: 10.1145/3312714.3312721
Category	Book	Book name		(co-) Authors
Sustainability	How 3D Printing achieves Sustainability	3D Printing & Sustainable Product Development (abstract accepted) Taylor & Francis		Wu, H., Naveed, N., Mehrabi, H.

Appendix 2: Research Framework

The novel CRM model provides an overview of landscape. It applies Monte Carlo simulation techniques to predict the optimized transportation distance and the number of PRF, through generic formulas. It also performs technical assessments such as transportation, CO_2 emissions, energy consumption, materials yield (%), and lead time and cost saving, and envision criticality of localisation through a robust integration.

CRM model covers technical cost assessment, which is suitable to recycling process but not appropriate to manufacturing. Business model applies cost pattern to support manufacturing applications in cost assessment.

Strategy control model is a human-centric method. It supports local demands and supplies in workforce, realize localisation, reduce reliance on supply chain, and support both business model and CRM model in realisation.



Appendix 3: Coherence of Methodology and Approaches

Methodology and Approaches		
CRM Model	Objectives	Compare critical factors of Sustainability between Recycled and Primary plastics, and between AM and CM. Initiate strategy of Optimisation process between Transportation Distance and number of PRFs.
	Methods	Strategic analysis of impact factors (Energy, Transportation, CO_2, Materials yields, Cost, & PRF topology). Apply Monte Carlo simulation method to derive the Optimized Transportation vs. number of PRFs.
	Novelty	Create an overview of Collection-Recycling-Manufacturing integrated process via insight of each key factor. Optimisation process derives: $(d_{i,j}) \propto \frac{1}{\sqrt{\text{number of PRF } (n)}}$ relation to reduce CO2 emission and save cost.
	Impacts	A robust CRM model supports AM process to reduce CO2 emission and save cost towards Sustainability. Optimisation process supports AM Localisation and AM integration that reduce Energy and CO2 emission.
CRM Model extension	Objectives	Conduct quantitative analysis on CRM model by using real data, to derive more formulas and equations in details. Investigate Localisation, Distributed Manufacturing, and Standardisation and impacts on AM process.
	Methods	Data-driven approach is applied to derive quantitative analysis in Optimisation process, and equations in details. Qualitative analysis method is applied to investigate interactions between Localisation and Optimisation process.
	Novelty	Through data-driven approach, the Optimized PRF-Distance generic equation is derived to achieve Sustainability. AM Sustainability is feasible through integration of CRM model, Localisation, Standardisation & Optimisation .
	Impacts	Compared with primary plastics, recycling of plastics reduces up to 88% of energy and CO2 emission. Local manufacturing & Optimisation can save up to 25-fold transportation cost compared to the foreign suppliers.
Business Model	Objectives	Business model applies generic formulas to investigate the unit cost of higher level of a macro view impact factors. To compare the unit cost in the manufacturing process between AM and CM, and applications based on conditions.
	Methods	Apply key factors (materials, tooling, design, machine, batch volume, & other costs) to build generic formulas. Apply “Dive-and-Conquer” approach to derive generic formulas, and use given data to derive unknown factors.
	Novelty	Four formulas are derived, to build CM and AM generic formulas, cost at AM/CM intersection and convergence. Envision criticality of standardisation in to move more specific conditions into more optimized generic formulas.
	Impacts	The four generic formulas enable cost patterns to calculate the unit cost based on batch volume and conditions. The strategy highlights areas need a standardisation, to remove dependencies and make formulas more generic.
Business Model extension	Objectives	To derive more generic formulas in cost patterns, and create in-depth insight by transferring data into formulas. To build collaborative pattern, to shift the AM-CM intersection batch volume to a higher value.
	Methods	Data-driven approach is applied to derive quantitative analysis in cost pattern, and equations in details. Qualitative analysis method is applied to investigate collaborative pattern, to improve AM scaling production.
	Novelty	In the extension version, ten generic formulas are derived, to support cost pattern through data-driven approach. A collaborative pattern is proposed to enable LE-SME-HBM integration, to support low cost of high volume.
	Impacts	Envision cost pattern in multi-entities collaboration, so stakeholders understand conditions of AM cost advantage. Propose standardisation, localisation, and collaboration, to build the foundation of AM application in cost pattern.
Strategic control Model	Objectives	Through the evaluation, sustainability is feasible to AM, but human-centric factors need be in place. Envision key factors for the realisation of CRM and business model, and support localisation and standardisation.
	Methods	Apply strategic planning and control metrics to relocate overcrowded population to rural areas to support AM. Strengthen localisation, through control metrics and robust LE-SME-HBM integration, to eliminate supply chain.
	Novelty	Narrows down AM’s focus to local supply of workforce based on demands, to achieve sustainability.. Envision criticality of transportation, and apply localisation to eliminate reliance on supply chain and logistics.
	Impacts	Realisation of localisation can save up to 25-fold transportation cost compared to the foreign suppliers. It eliminates reliance on supply chain, save transportation cost, reduce CO2 emission, and create job opportunities.

Appendix 4: Short names and notations

Short name

3S	Standards, skills and scales
5R	Refuse, Reduce, Reuse, Repurpose, and Recycle
AM	Additive manufacturing
AMCoE	AM Centre of Excellence
AMSC	Additive Manufacturing Standardisation Collaborative
BAU	Business as usual
BTF	Buy-to-fly
CAD	Computer-aided design
CAE	Computer-aided engineering
CFP	Carbon footprint
CIT	Crowdedness Index of Top 300 cities
CM	Conventional manufacturing
CRM	Collection-recycling-manufacturing
CS	Collection Station
CTE	Career and Technical Education
DRAM	Distributed recycling via additive manufacturing
EOL	End of life
EPI	Environmental Performance Index
FDM	Fused deposit ion modeling
FF	Filament Facility
GDP	Gross domestic product per capita
GHG	Green house gases
HBM	Home-based manufacturer
HDPE	High Density Polyethylene
IPWM	Integrated Plastic Waste Management
LCA	Life cycle assessment
LDPE	Low Density Polyethylene
LE	Large enterprise

METI	Ministry of Economy, Trade and Industry
MJ	Material jetting
MJS	Markov Jump System
MoE	Ministry of the Environment
MRR	Materials recovery ratio
MSME	Micro, small, and medium enterprise
NMC	Non-materials cost evaluation
PBF	Power bed fusion
PET	Polyethylene Terephthalate
PHB	Poly-hydroxy-butyrate
PP	Polypropylene
PP&A	Polyester, polyamide, and acrylic
PRF	Plastics Recycling Facility
PS	Polystyrene
PVC	Polyvinyl Chloride
RIC	Resin Identification Code
RPR	Rural Population Ratio
SCM	Supply chain management
SDOs	Standard development organisations
SLADLP	Vat Photo polymerisation
SLM	Selective laser melting
SLS	Selective laser sintering
SME	Small-medium-enterprise
SME	Small-and medium-sized enterprise
SPI	Society of the Plastics Industry
STL	Standard tessellation language
TS	Transfer Station

Appendix 5: List of Abbreviations (symbolic notation)

$\boldsymbol{A_i}$	Payback cost (Amortisation, in $/unit-day) at ith PRF facility setup fee including land cost
$\boldsymbol{C}$	Optimized Collection Process: min.(facility setup +operational cost) +max.(materials Recovery)
$\mathbf{C}_{CM(100k)}$	The 'total unit cost' in the CM_100k case
$\boldsymbol{C_{OP}}$	The daily operation cost which covers energy and transportation
CFP	CO_2 emission measurement of Carbon Footprint (CFP) and the indicator of Greenhouse gases
CS	Collection Station, the first facility that collects and sorts the source of wastes
$\boldsymbol{E_{INi}}$:	Energy consumption (mWh/ton) in recycling process
$\boldsymbol{e_i}$	CO_2 emission (ton of $\mathbf{CO_2}$/ton of materials) caused by transportation at ith site
$\hat{e}_i$	CO_2 emission in AM process
$\boldsymbol{d_i}$	Distance (km) of transportation at ith site
$\boldsymbol{f}$	Binary activator (1/0) of Recyclin**g** facilities (only the opted route is active)
FF	Filament Facility, the factory that make filament directly produced from the products of PRF.
m	The 'mould unit cost' in production, which is a constant and volume independent
M	The 'mould design cost', which is a one-time cost per batch, a constant and volume dependent
$\boldsymbol{M_{IN\_i}}$	Recycling Materials input at ith site of AM
$\boldsymbol{M_{OUT\_i}}$	Output of AM
$\boldsymbol{M_{NEW\_i}}$	Primary plastic of AM
$\boldsymbol{M_i}$	Materials at ith site (ton/PRF) of daily recycling capacity per PRF
$\boldsymbol{M0}$	Optimized Route at SCM: min.(SCM distribution +transportation distance)
$\boldsymbol{M1}$	Optimized AM: max.(rec. materials output – input) + min.(primary plastic + energy cost)
$\boldsymbol{M2}$	Optimized CM: max. (rec. materials output – input) + min. (primary plastic + energy cost)
MRR	Materials Recovery Ratio by comparing yield (%) at previous EOL and present yield
$\boldsymbol{n}$	The number of PRF to be set up within a specific radius of circle
NMC	Non-Materials Cost ie; energy consumption, transportation, payback and miscellaneous cost
O	The 'other unit cost' in production, which is volume-independent
$\boldsymbol{P_{balancer}}$	An optimizer (in $/ton) to move the whole equation into a positive and maximum value
$\boldsymbol{r}$	Binary activator (1/0) of Manufacturing method (AM or CM)
$\boldsymbol{r_0}$	An arbitrary radius of service circle of all PRFs (assume 1,000km)
$\boldsymbol{r_i}$	The radius of one PRF's coverage

$\boldsymbol{R}$	Optimized Recycling Process: max.(recycling rate) +min.(primary plastic +energy consumption)
$\boldsymbol{s}$	Binary activator (1/0) of Supply chain (s = 0 means direct supply from recycling to manufacturing)
$\boldsymbol{t_i}$	Unit cost of transportation ($/ton-km) at i^{th} site
T	Tooling/Moldings cost
TS	Transfer Station, which is responsible for transmitting similar types of waste, from CS, to PRF
$\mathbf{T}_{CM(20k)}$	The ‘tooling unit cost’ (mould design cost breakdown + mould cost) in CM_20k case
$\mathbf{T}_{CM(100k)}$	The ‘tooling unit cost’ (mould design cost breakdown + mould cost) in CM_100k case