Additive Manufacturing of Recycled Plastics: Strategies towards a more sustainable future

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Abstract

Materials recycling and additive manufacturing (AM) present challenges and great opportunities in plastic industries. The rapid developments in AM are transforming the manufacturing industry. Reducing CO_2 emissions,-saving cost, and escaping from landfill are the decisive factors in this transformation.

In this study, to mitigate any risk caused by production speed and scaling and accelerate shift towards a more localized recycling and manufacturing of plastic parts and components, a collection-recycling-manufacturing (CRM) model is built to envision the evaluation of process flow as well as process integration.

The novelty of the CRM model enables optimization between recycling facilities and transportation distance calculation. It further strengthens a seamless integration between recycling and AM processes and envisions the areas that need enhancements. The study reveals that AM creates opportunities such as prototyping, customizing, transportation cost reduction, and creation of jobs in rural areas, which may stop unnecessary immigration; and, most importantly, reducing CO_2 emissions and plastic waste despite challenges such as skills requirement and disadvantages in speed and scale production.

With a combination of recycling and AM, sustainable manufacturing can be achieved effectively, although several conditions must be met and obstacles must be overcome. A few innovations are further proposed in this study to streamline the transformation and to support the "cradle-to-cradle'' approach towards "zero waste" for a sustainable future.

Keywords: Sustainability, Plastics, Recycling, Additive Manufacturing, Energy, CO_2 emission

1. Introduction

1.1 Background

Scientists and environmentalists argue, global warming and climate change are due to human's unchangeable behavior and aggressive consumption of the Earth resources (Union of Concerned Scientists, 2021). An estimate showing growth of world population from present 7.8 billion to 9 billion by 2040 may increase the consumption of resources even further causing scarcity and higher prices for goods and products. Previous research indicates most of CO_2 emissions and climate change are due to transportation, power generation, construction, manufacturing, housing, and agriculture, with manufacturing responsible for 25% of CO_2 emissions worldwide (Fausing, K, 2020). It is time for us to change our behavior and act accordingly towards a more sustainable future.

Sustainable manufacturing has become crucial in the last few decades because of consumption of huge number of resources while generating enormous amount of waste and CO_2. This research proposes a framework covering only manufacturing parts and components consuming recycled plastics by additive manufacturing processes such as Binder Jetting, Stereolithography and Extrusion methods. The framework includes Collection, Recycling and Manufacturing (CRM), Business and Strategy control model to envision coherence of sustainable manufacturing. It further leverages technical assessments to the processes, applications, and human-centric areas to effectively impact the industry through these three models.

1.2 Literature Review

An extensive review has been carried out of literature relating to plastic recycling and manufacturing towards sustainable production. The 5R (Refuse, Reduce, Reuse, Repurpose, and Recycle) approach is commonly recognized in plastics waste management as it reduces materials waste (Bell, S., 2020). However, recycling is the gatekeeper, the method of this study is focused, and the most sustainable ways to achieve 'Cradle-to-Cradle' by taking the 'zero waste' approach (Lazarevic, D., et al., 2010). ISO 14044 standards is applied in life cycle assessment (LCA), and the experiments demonstrated that Integrated Plastic Waste Management (IPWM) (Akinola, 2014) can be the best option rather than incineration or landfill. It is estimated, global plastic recycling to reach 44% in 2050 (Ritchie, H., Roser, N., 2018). While the improvement has been in progress, this study aims to reach 100% plastic recycling with 0% landfill. Since the objective is challenging, this study investigates the facilities as well as process to make improvements. From environmental and economic sustainability perspectives, implementing a model to reduce CO_2 and energy consumption, save the cost, and increase the yield (%) can be crucial (Wiesmeth, H., 2020), and mechanical recycling is the environmentally preferred option linked to energy consumption, climate change and CO_2 emission (Lazarevic, D., et al., 2010).

Monte Carlo Simulation (MCS) is deployed to demonstrate the convergence of the mode-dependent performance index and the optimal performance index (Xin, X. et al., 2022). Through Markov Jump System (MJS) optimal control of multiplayer zero-sum games, there is potential that the nonlinear MJS can be transferred to N new coupled linear subsystems (Fang, H., 2021), and MJS is used to qualify the "jump" process of Markov theory, from the state of "n" to "n+1". Our previous research explored the feasibility of the distance calculation by using pre-defined formula.

Additive Manufacturing (AM) tips the balance between insourcing and outsourcing, and between globalisation and localisation in manufacturing, in favour of insourcing and localisation both (Mourdoukoutas, P., 2015). Local manufacturing via AM is becoming important due to advancements of technologies (Kleera, R., Pillerb, F., 2019) as the dependency of AM on supply chain and logistics can be minimised due to the fact that AM does not require an assembly or tooling process. On the other side, the easy-entry to AM home based manufacturing can be the driving force of distributed local manufacturing (Inimake, 2021) as the new resident in suburban or rural areas can set up home based manufacturing by simply spending few hundreds of US dollars to establish AM business. In addition, under a well-planned demography and efficient workforce allocation, the supply chain and logistics of AM can be significantly reduced (Arora, P., et al., 2021) (Akbari, M., Ha, N., 2020), and through AM, local manufacturing can be integrated in a hub-like network. Home based manufacturing can be a good resource of AM workforce. According to the World Bank (World Bank, 2018), 55% of the world's population is in cities, and this is set to reach 70% by

2050. Rapid population growth in metropolitan areas threatens the environment and causes environmental degradation (Ray, I., 2011), and results in a rapid growth of energy consumption. U.S. has applied AM to fabricate medical equipment to develop job opportunities in rural areas (Legg, H., 2021), and applied advanced manufacturing training in rural areas in preventing rural to urban migration (Jones, F., et al., 2021).

An efficient recycling, optimized solutions, and robust integration between recycling and manufacturing is critical to achieve sustainability however, literature in integrated solutions between recycling and manufacturing has been rare and fragmented, and this is the reason the CRM model is proposed in this study. The existing literatures create values in specific areas; however, LCA requires considerable cyclic tracking rather than evaluation in sub-unit. Most of the existing literature investigates specific area rather than coherence as a whole. Fragmentation of resolution may solve a particular problem but leaves ambiguity in other areas unless an overview is undertaken. Furthermore, most existing literatures do not provide generic form of quantitative analysis; hence the statistics only support a specific scenario rather than a whole. To address the common issues, this research creates framework and aligns technical assessment from CRM model into this study to complete an overall evaluation.

1.3 Methodology

This research focuses on CRM model, as the core area of the framework; bottom-up approach to classify technical elements such as equipment, processes, and interfaces of materials recycling and manufacturing followed by a benchmark between AM and conventional manufacturing (CM) processes. The study produces generic formula in Materials Recycling Facility (MRF) to support the fundamental transformation of plastic industry. CRM model starts with unit cost calculation such as transportation, energy consumption and CO_2 emission, and equipment payback, followed by optimization between transportation distance and recycling sites. Supported by Monte Carlo simulation, the optimized MRF generic formula is derived to guide CRM topology design. The optimized solutions, guide the CRM Model to standardize the process and establish collaboration between small-medium-enterprise (SME) and rural home-based manufacturing. In addition, the recycling facilities and AM planning, and workforce allocation of Strategy Control model can create job opportunities and support rural development if CRM model can fully utilize to its advantages and improve the integration of recycling and AM processes.

This paper starts with strategy of plastics recycling, followed by comparing CM and AM. Then, it explores the sustainable manufacturing through the integration of recycling and AM and novelty of optimized MRF generic formula to maximizes advantages of integrated recycling and AM processes and identifying the barriers. Furthermore, concept of bibliometric analysis method is applied to investigate journal-author-keywords relation for revision in specific discipline (Hoffman, D. L. and Holbrook, M. B., 1993) that includes a variety of techniques that are usually categorized as citation or co-citation.

2. Plastic wastes and Recycling

This study focuses on plastics, which are widely used for their appealing properties such as light weight, durability and comparatively low cost (Hopewell, J., Dvorak, R., Kosior, E. 2009). Production of plastics has grown exponentially since their introduction in the latter half of the 20th century. According to *Our World in Data* (Ritchie, H., Roser, M., 2018), 7.82 billion tons of plastics were produced on planet Earth by 2015.

While plastics can be used in a variety of applications, including medical, aerospace, automotive, sports equipment and home appliances, that contribute tremendously to economies and societies, its non-degradable nature poses burden to the environment if a systematic approach to their end of life is lacking. Consequently, this threatens the Earth both in terms of the environment and society.

Environmental sustainability is a collection of activities aiming to maintain the planet's ecosystem against the depletion of raw materials and to minimize pollution of air, water, and landfill to avoid destruction of the Earth. Mishandling of plastic wastes has caused tremendous problems such as deteriorating landfills and ocean pollution and poses a severe threat to life on Earth.

2.1 Classifications of Plastics

Arising from a range of uses, plastic wastes are presented in a few basic forms such as packaging, bottles, and caps, and from the perspective of materials, they are composed of different types of polymers. According to the Society of the Plastics Industry (SPI) (Hunta, E., et al., 2015), plastic materials are classified into seven categories based on the Resin Identification Code (RIC) system (Sanchez, F., et al., 2020):

- Polyethylene Terephthalate (PET)
- High Density Polyethylene (HDPE)
- Low Density Polyethylene (LDPE)
- Polyvinyl Chloride (PVC)
- Polypropylene (PP)
- Polystyrene (PS)
- Other Plastics (ABS, Nylon, Polycarbonates)

In addition to seven SPI, there are other minor or recently emerged plastic materials, such as PP&A (polyester, polyamide, and acrylic) and poly-hydroxy-butyrate (PHB), a natural biodegradable polymer.

According to 2015 statistics, the main sources of plastic were PP and PET, which contributed to 46% of global production, with 63.4% of PP and PET used in packaging. (Yeo, J., et al, 2018). Depending on the characteristics of materials and sorting capacity, some materials are more frequently recycled and easier to recycle than other types. For instance, PET, which is used in water bottles (uncapped), is the most common recycled plastic. \The second most common recycled plastic is HDPE, usually used for bleach bottles. Other types of plastics are rarely recycled, except for targeted waste products collected in local areas (OpenLearn, 2020). This is a main reason local sorting techniques and local manufacturing play key roles in materials recycling.

2.2 Recycling and handling of polymer composites

Based on the seven categories of plastics, the recycling and handling of polymer composites are described as follows (Shen, L., Worrell, E., 2014) (Conserve Energy Future, 2021);

Polyethylene terephthalate (PET): PET bottles are assumed to be composed of 100% PET. PET is first sent directly to a mechanical reprocessing facility, where it is shredded and granulated to produce flakes, followed by chemically washing to remove paper labels, adhesives, and other hard-to-separate contaminants.

The flakes are then dried using warm air flows and centrifuges, and any fine (dust and paper) are removed through air classification. Finally, the cleaned and dried flakes are fed into a screw extruder, which heats and pressurizes the flakes, and are then forced through a screen. Secondary PET flakes are assumed to substitute for production of primary PET flakes (Haupt, M., Kägi, T., Hellweg, S., 2018).

High-density polyethylene (HDPE): HDPE waste is sent to a HDPE mechanical reprocessing facility, and mixed waste plastic bottles are sent to a plastics sorting facility to separate the PET and HDPE bottles. The separated PET and HDPE bottles are then sent to mechanical reprocessing facility.

Polyvinyl chloride (PVC): Waste PVC is sent from a plastics sorting facility to a mechanical reprocessing facility. The process includes the transportation of raw materials and other input materials to the reprocessor and the production of primary PVC. Secondary PVC pellets are assumed to substitute for production of primary PVC pellets.

Low-density polyethylene (LDPE): LDPE is assumed to consist of 100% plastic film, which is not easy to recycle. Instead of recycling, cleaning and reuse can be alternatives.

Polypropylene (PP): Waste PP is sent from a plastics sorting facility to a mechanical reprocessing facility. PP is used in food containers, dishware, and medicine bottles and is not widely recycled.

Polystyrene (PS): PS is used in the manufacture of products such as disposable hot beverage cups, plastic cutlery, packaging foam, children's toys, and insulation board, which are not widely recycled.

Other (O): These plastics include acrylic, nylon, polycarbonate, and polyactide, which are rarely recycled.

Plastics are indispensable to our lives; however, the way plastic wastes are handled at end of life (EOL) is vital because mishandling often leads to high levels of plastic pollution. Materials recycling in developed countries rates at around 30%, whereas in developing countries recycling it rates close to 0% (d'Ambrières,W., 2019). For the countries that emphasize recycling and its technology, recycling has significantly eliminated EOL environmental impacts and produces tremendous socioeconomic value, resulting in elegant sustainability solutiuons.

Materials recycling is imperative; although there is a steady growing trend of recycling and incineration, more than half of plastic waste on earth ends up discarded. According to 2015 global statistics, discarded plastic waste accounted for 55%, while incineration and recycling accounted for 25.5% and 19.5%, respectively. Among all waste management methods, recycling is the most sustainable and efficient (Lazarevic, D., et al., 2010; Akinola, A., Adeyemi, I., Adeyinka, F., 2014).

Before proceeding to recycling methods benchmarking, a general understanding of the measurement of the plastic flow is necessary for understanding how the methods are implemented. Through a global practice, the governmental sectors of many nations have set goals to minimize plastic wastes.

In 2018, Prime Minister May of the UK launched a 25-year-plan aiming to eliminate all avoidable plastic wastes by 2042 (Prime Minister's Office, 2018). In 2019, the MARINE Initiative governmental project in Japan outlined a plan of "zero plastic waste" in marine areas by 2050 (Ministry of Foreign Affairs of Japan, 2019).

Many international programs have arisen to support plastic waste handlings. Trinidad and Tobago form one case study. The nation encountered serious issues with increasing volume of landfill. To investigate the plastic waste through life cycle assessment (LCA), academia and government of the nation conducted material flow analysis to help the quantification of the flow of products and wastes. After tracking of imports, new products, and their usage, it was discovered that most of the plastics entering the country's landfills was not raw materials, local product nor imported product, but instead, they entered as packaging of the products the imported products (Ketchell, M., 2020). Instead of focusing on plastics waste handlings, tracking can be another critical factor supporting recycling.

2.3 Recycling steps of plastic wastes

Recycling is not a new concept in human civilization. The first recorded recycling of paper was in the Heian era in Japan (794–1195 AD), when people started to reuse the used papers to reduce costs and to conserve materials (HistoryofInformation.com, 2021). Towards used plastic products, recycling is the first and foremost solution. Recycling saves materials and energy and reduces the costs for further manufacturing, and reduces the accumulated wastes which are indeed potential new products laying idle in wasteland or landfill.

However, the recycling process should be benchmarked for each alternative option once the process is optimized, to reduce energy consumption and cost. Typical concerns are material reusability and CO_2 emission. This implies that cost savings in transportation, energy consumption, material recovery, and CO_2 reduction can motivate the bridging of multi-entities such as authorities, stakeholders, and consumers into a consensus regarding a common goal.

Classification and sorting of plastic waste can be the first step in recycling because the wastes come in different forms, shapes and materials. Type of composition and degree of purity require different recycling methods that are already discussed in sub-section 2.2.1 Handling of polymer composites. Plastic recycling usually involves several steps and semi-products, as shown in Figure 1, before the recycled materials can be manufactured into the final products. Basically, the process can be standardized with slight variations depending on the waste configuration.

Flakes: Usually made of mixed materials from bottles which are shredded into small pieces. As caps are made of different types of plastic, they can be separated easily when they float on water.

Pellets: The flakes are washed at high temperatures, dried and melted in molds to produce pellets.

Yarn: The melted pellets are extruded through small holes into yarn and then spun and woven into fabrics.

Fabric: Fabric can be produced by shortcuts or long processes depending on purity and sorting techniques. In shortcut process, PET bottles and other plastic waste are sorted by colors and formation. Sorted PET bottles are washed, with the labels removed by caustic soda, and dried; then the bottles can be used to create fabrics.

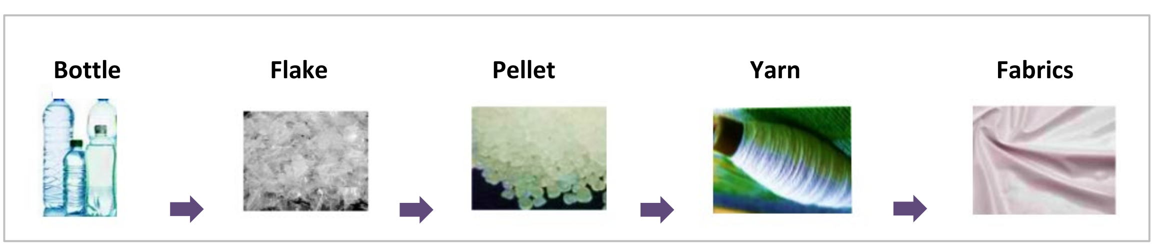

Figure 1. Recycling steps and semi-products of plastic materials

Unsorted and mixed-up materials of different plastic types may lead to fragility and quality degradation. This makes recycling difficult and seriously affects marine and freshwater ecosystems. The assessment, together with the recycling methods, are briefly discussed in sub-section 2.2.1 Handling of polymer composites. There are four basic methods for plastic recycling (Karayannidis, G., Achilias, D., 2007).

1) Primary recycling or 'in-plant' recycling of the scrap of plastic waste: The method refers to direct use of a product without changing or altering the product itself. Given its simplicity and low cost, the method is limited to a single type of uncontaminated waste.

2) Secondary recycling or mechanical recycling: The polymer can be filtered out from the contaminants and prepared for conventional melt extrusion. The method involves sorting, separation, size reduction, and non-chemical melt filtration. Although the method degrades polymer quality because of chain scission caused by water and acidic impurities, it has been widely used and recommended based on its comparatively higher quality over cost (QoC) (Achilias, D. S. et al., 2012).

3) Chemical recycling or tertiary recycling: Chemical recycling or feedstock recycling has been recognized as effective method of de-polymerization of PET to the monomers and then re-polymerization back to the original polymer. The method is more expensive than secondary recycling, though it maintains a certain level of quality and is widely used (Achilias, D. S. et al., 2012).

4) Energy recovery or quaternary recycling: The method is applied to plastic waste mixed with organic materials. Despite incineration method yields high energy recovery through combustion, the method is not well-qualified in terms of sustainability, and the toxic substance produced by the chlorine-containing polymers has been a big public health concern (Department of Health, NY State, 2004). Thus, incineration method is not a prioritized option here.

2.4 Energy consumptions

The energy consumption data shown in Table 1 is based on raw data obtained from Roxanne, et al. (2019) that is used in energy computation and benchmarks.

	Materials type	**PET**	**HDPE**	**PP**
Primary plastic production (MWh/ton)	Energy consumption	19.4	20.9	20.7
Recycled plastic production (MWh/ton)		4.1	2.4	2.4

Table 1. Energy consumption benchmark – Recycled materials vs. primary plastic

Compared with primary plastics, recycling of plastics saves up to 88% of energy, as indicated in Table 1.

2.5 Materials recovery (yield)

According to Roxanne, the yield in production of plastic parts is estimated at around 85% on average. Use of recycled materials can save a huge amount of primary plastic, reducing energy consumption as well as earth's resources. However, from quality perspective, 10% of quality degradation can occur during each recycling process, which needs improvement (Merrild, H. et al., 2012).

The deterioration of product properties is due to chain scission reactions caused by the presence of water and trace acidic impurities that reduce the mechanical performance of the polyimide or polyimide matrix composite. To maintain the polymer average molecular weight during recycling, our study proposes further investigation to avoid moisture in the process such as drying and vacuuming and the use of agents or chain extender compounds to prevent chain scission reactions (Messmer, D., 2019).

2.6 Applications of recycled plastics

Through an analysis of the recycled plastic wastes in 2015 in terms of their applications, statistics show that 146 million tons of plastic polymers went into packaging usages, but 141 million tons were thrown out (Dengler, R., 2017). Among all types of plastics, HDPE, PET, PP and LDPE account for 62% globally (PlasticsEurope Market Research Group, 2015), used in packaging, food and beverage containers and bottles. Plastics used for packing and bottles are controllable based on consumers' behavior. If consumers consider sustainability and follow instructions, 100% recovery of these types of plastic waste is possible. To cope with these issues, plastics recycling industries have successfully recycled the recyclable and marketable types of plastic polymer waste and market either the semi-products, such as pellets or flakes, or the final products, such as bottles, packaging, or plastic art works.

By moving recycled materials into product-based manufacturing, 3D printing is one of the best and most versatile assets for a wide range of functions, shapes, and highly complex products. For instance, it is increasingly used in the medical industry, which requires a high degree of customization, as is necessary for producing dental molds or prosthetics. In the automotive industry, this technology is widely used to make replacement components or parts for different types of vehicles (EOS, 2021; Aimar, A., Palermo, A., 2019; Zahnd, P., 2018).

The beauty of 3D printing is that it can print complex designs. Plastic is a material that can be used in all stages of product development. 3D printers can easily print all types of plastic components, products, and packaging. For prototyping, 3D printing with plastic can be an ideal choice as it offers lot of advantages such as flexibility in complex shape, less design time, and personalization. Based on the characteristics ready to offer, 3D printing can be the best choice for rapid prototyping, as it offers the flexibility to make necessary changes in a most rapid and cost-effective manner (Hendrixson, S., 2016) and significant applications that impact our daily life (Kim, H. et al, 2021; Sahu, M. et al, 2021).

3. Manufacturing processes of recycled plastics

The recycling process is vital to manufacturing in terms of materials and energy saving and cost reduction. Thus, a more efficient recycling process would not only result in further energy and material savings but would also improve the quality of recycled materials for future production.

3.1 Conventional Manufacturing processes

Plastic parts and components are typically manufactured by shredding, melting down and molding into new products. However, other chemicals are added to improve flexibility and durability or to simply add color, which makes the plastics more difficult to recycle.

For this reason, all PET plastic bottles in Japan are produced as transparent, given that PET is much easier to recycle than colored bottles (Thompson, A., 2018). In terms of the manufacturing process, several CM methods handle materials recycling.

3.1.1 Typical CM methods

Casting: Plastic casting (WeProFab, 2021) requires the least complex technologies. Plastic is simply heated to a fluid state, poured into a mold, and left to cool, after which the mold is removed. The casting method is limited to those simple shapes that do not need sophisticated molds.

Molding: Molding includes injection, compression, joule, blow and rotation. As shown in Figure 2.a, injection molding is a common method ideally used for high-volume orders of small and precise plastic pieces such as handles, housings, and toys. During the injection molding process, liquid plastic is injected into the mold at high pressures. Once the material is cooled, it maintains the shape of the mold, and the desired part is ejected.

Figure 2-b illustrates blow molding that heats a preformed piece of plastic, forced through the cavity by air pressure creating the required shape (PDI Plastic Des Int'l Inc., 2020).

These processes are most suitable for mass production of parts and components resulting in low cost per part. However, mold design and manufacture may take longer, which increases lead time.

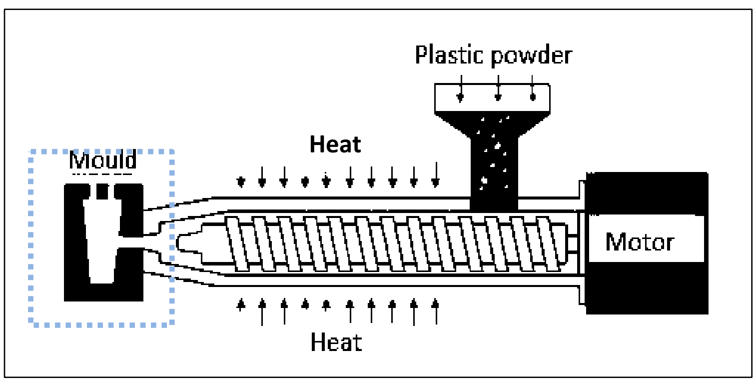

Figure 2.a Injection molding

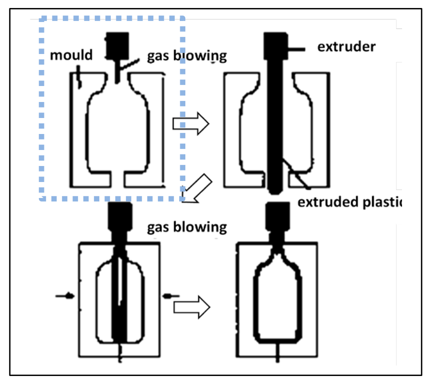

Figure 2.b Blow molding

3.1.2 Materials yield

According to Franklin Associates (2011), average materials yield in plastic molding is estimated at 85%. However, this does not include the metal mold preparation and waste. Furthermore, the yield depends on the shape and size of plastic parts and the metallic mold in which they are solidified.

3.1.3 Energy consumption

Franklin Associates estimated that the CM method (Injection Molding) consumes 25.7 GJ/ton or 7.14 MWh/ton energy (Franklin Associates, 2011). Power sources for manufacturing vary, a factor that can affect energy consumption costs. For instance, wind, solar, and electrical actuation can be good substitutes for common power sources such as coal, nuclear, natural gas, or hydropower (Fredbloom, M., 2021), effectively reducing energy consumption, while control of manufacturing processes can improve productivity as well material and energy efficiency.

3.2 Additive manufacturing processes

Additive manufacturing (AM, or in a common terminology, 3D printing) converts computer-aided design (CAD) files into stereo-lithography or standard tessellation language (STL) files. The CAD-produced file contains information consisting of triangles and slices of each shape to be printed (Wong, K., and Hernandez, A., 2012). Geometry can be the entry point of the AM process, which defines object design and provides reverse engineering information to be embedded in the 3D CAD model (Muthu, S., Savalani, M., 2016). The rapid deployment of AM has created a broad path to sustainable economies through the concept of distributed recycling via additive manufacturing (DRAM) (Little, H., et al, 2020).

3.2.1 AM Manufacturing methods

Classification of AM methods was developed by the ASTM International Technical Committee F42 to promote the technologies and applications through the development of standards. There are seven major additive manufacturing processes based on the classification (Fernández, G., 2021);

1. Material extrusion
2. Binder jetting
3. Powder bed fusion
4. Vat photo polymerization
5. Direct energy deposition
6. Sheet lamination
7. Material jetting

ISO/ASTM AM standards

In a joint ISO/ASTM AM standard, AM is classified into seven categories in terms of technologies and materials. Each category is introduced as follows (Manufactur3D, 2018).

1. Material Extrusion (FDM)

In FDM, melted material flows through a nozzle to create the object's layers. Typically, this category uses fused deposition modeling (FDM), which is commonly used in polymers. The first layer is built as the nozzle deposits material where required onto the cross-sectional area of the first object slice. The following layers are added on top of previous layers. Layers are fused together upon deposition as the material is in a melted state.

2. Binder Jetting

Binder jetting uses powder bed and inkjet head in plaster-based 3D printing. The nozzle deposits a liquid binding agent into the powder, creating each layer of the product. The inkjet printing applies to binder jetting, which can print larger parts and is easier for first-time AM users.

3. Powder Bed Fusion Metal (SLS)

Power bed fusion (PBF) is used to manufacture both plastic and metal parts using polymer or metal powders and uses the bed to support the structure during printing so that it needs no other means of support.

4. Vat Photopolymerization (SLA DLP)

The method requires photopolymers, which start as liquids and harden under light into solid components. This category includes **stereolithography** and digital light processing methods and can build medium-sized parts more slowly than other AM techniques.

5. Directed Energy Deposition

During directed energy deposition, material melts by heating. To generate the heat needed, several technologies are available, such as laser deposition, plasma arc melting, electron beam and laser engineered net shaping. This method can construct a versatile range of sizes from large to small; however, this method is typically more suitable for metals.

6. Sheet Lamination

Sheet lamination is typically used in metal, which offers low cost and high speed by bonding sheets of paper or metal together. Some engineers may use hybrids or ceramics for this process. Technologies used in this AM category include ultrasonic consolidation and laminated object manufacturing.

7. Material Jetting

Material jetting (MJ) is one of the fastest and most accurate 3D printing technologies. It builds parts using liquid photopolymer droplets, which are cured with UV light. Through multi-jet modeling, this method can use polymers, waxes, composites, biologicals, ceramics, and hybrid materials. Unlike other single-color and one-material processes, material jetting does allow for color and material mixing, but it's usually only capable of printing small parts.

Based on the requirements and materials been chosen, end-users can choose the best fit method to print the product by AM, and the materials being used in the processes can be in the form of liquid, powder, or solid.

3.2.2 Materials yield

Compared to CM, AM commits significant waste reduction based on the fact that the additive materials, layer by layer, only consume the exact materials the products require. Based on subtracting and shaving, many CM methods produce a high volume of waste, which strongly affects product cost. Following is the materials yield of AM. As indicated in Table 2, AM materials yield average at around 85%, whereas CM can be much lower than this value. (Roxanne et al., 2019),

Materials	**PET**	**HDPE**	**PP**
Recovery rate	105/123.9 = 84.7%	47/55.9 = 84.1%	1.4/1.6 = 87.5

Table 2. Materials yield of AM processes

3.2.3 Energy consumption

Work	Manufacturing process		Materials	Energy consumption MWh/ton
(Huang, R., 2016)	AM	SLS	Polymer	29.9
		FDM	ABS	23.1
(Stefan S., Matt, R. 2015)		FDM	polymer plaster	23.1
		3DP		14.7
		SLS		14.5
(World Centric, 2018)	CM	Injection Molding	PLA	14
			PET	7
			PP	22.8
			PS	26.5
(Franklin Associates, 2011)			fabricated plastic	7. 14

Table 3. Energy consumption benchmarking – AM vs. CM

Energy consumption of AM and CM varies depending on materials, machine, and method, and a conclusive result cannot be produced. However, the statistics indicated in Table 3 shows that AM may not be the best option for reducing energy consumption.

4. CM and AM comparison

4.1 Advantages and disadvantages

4.1.1 Advantages

In the following paragraphs, both AM and CM are compared, and AM's advantages and disadvantages are highlighted so that appropriate enhancements can address current issues in additive manufacturing.

- **Transportation**: In an integrated CRM model solution, AM saves significant transportation because reliance on supply chain and logistics is eliminated (Garmulewicz, A. et al., 2016). This also reduces CO_2 emissions and cost.
- **CO_2 emission:** According to Khripko et al. (2013), greenhouse gases (GHG) are a vital contributor to climate change, which need tracking in either recycling or manufacturing processes. Carbon footprint (CFP) can be an important indicator of GHG measurement that needs to be controlled. CO_2 emission is unavoidable in the thermoplastic process. Hence, GHG reduction has become a key control in the context of plastic industries toward a critical sustainability agenda, and reduction of energy consumption can be a tactical resolution. Due to the fact that AM can save transportation distance across materials recycling and manufacturing, the associated CO_2 emission can be reduced; Section 5 provides a fuller description.

- **Environment sustainability**: AM is well-positioned to potentially replace some conventional manufacturing processes. In the future, massive local production and home-based business could shorten their end-to-end processes from waste collection to recycling to manufacturing, streamlining the entire recycling process and bringing waste management one step closer to consumers, with environmental benefits (Shanmugam, V., Das, O., 2020).
- **Materials yield**: Compared with CM, AM has a better opportunity for waste reduction based on the layer-by-layer additive method, which consumes only the exact materials the products require. Theoretically, AM in plastics can achieve zero-scrap rates by using special technology (Langnau, L., 2018). On the contrary, the CM method is based on subtraction through processes such as injection molding, which produces more waste that cannot be reused. According to Futcher, the scrap rates of injection molding can be as high as an additional 10% for plastics (Futcher, C., 2015), but there is no indication that AM can achieve a better materials yield (%) over CM.
- **Energy**: Compared with CM, AM reduces energy use because it simplifies the process with fewer steps. With AM, many parts manufactured by CM separately can be combined into one process. A recent investigation from GE LEAP engine (GE Additive, 2016), *New manufacturing milestone* revealed that 30,000 additive fuel nozzles, produced by selective laser sintering (SLS), an AM technology, can be produced in one piece that would require an assembly of 18 parts with CM. However, as these are related to alloy rather than plastics, the energy savings of the AM manufacturing process do not produce a significant advantage over CM.
- **Flexibility**: Parts design modification, based on customer feedback, is essential in particular industries. With AM, change in design is flexible and causes less impact on production time for limited number of parts. Parts design change with CM require re-design, mold modification, and sometimes remolding. However, with AM, design can be modified using the CAD file in no time and almost no cost. In addition, AM can be an evolution that combines and emphasizes innovation, design and manufacturing. Time saving in the part life cycle enables AM to embed stylish, state-of-the-art design and distinguish itself with high quality products (Format Team, 2020).
- **Complexity**: AM applications have been widely applied to deal with products that demand high complexity, particularly those with complicated shapes or colors, which is difficult to achieve with CM. Given the fact that AM prints products more slowly than CM, however, AM can print complex products in one piece or using less steps that can save time in assembly and enhance durability by avoiding fragility between parts.
- **Prototyping**: As a quick start compared to CM, AM commits much less time to create product prototypes upon the readiness of CAD and STL software followed by materials' properties. The prototyping and parts change process usually saves time on the order of weeks to a few months. The Ford case indicated that 4 months lead time saving can be usually achieved through AM (Deloitte University Press, 2014).
- **Assembly**: Assembly of parts can be simplified as they can be printed directly without a 'divide and conquer' strategy. AM can work directly on complicated shapes, which saves time, effort and cost (Tofail, S. et al., 2018).
- **Low capital investment**: AM overcomes the obstacle of initial cost as the capital cost of 3D printers for plastic materials is affordable for home-based businesses. It reduces the threshold of certain amount of capital to start.

In addition, 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, H.H. et al., 2020).

- **AM service**: Compared with CM, AM is more related to computer-based design rather than tooling. AM can fully take advantages of sharable software through cloud computing to produce parts. In addition, AM technologies can be easily learnt through professional training if the designer already has basic knowledge of design, making training easier and enabling home-based businesses to start quickly.

4.1.2 Disadvantages

- **Speed of production**: Prototyping of AM can be fast and flexible, but the speed of manufacturing can be a constraint in mass 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. The causes vary: they 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).
- **Capacity**: As 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, however; there is need for capacity improvement for AM manufacturers of large enterprises (GE Additive, 2020).

4.2 Manufacturing process evaluation of parts produced by recycled plastics

In a broad sense, manufacturing using recycled plastics starts with waste collection and recycling, followed by CM or AM processes. In the full CRM model landscape, the process groups are divided into "C' (collection) zone, "R" (recycling) zone, and "M" (manufacturing) zone. The process routes are outlined in the following categories in Figure 3, and the routes are defined as followed (Achilias, D. S. et al., 2012) (Sanchez, F., 2020) (Santander, P., et al, 2020) (Singh, N. et al, 2017) (S.M. Al-Salem, P. Lettieri, J. Baeyens, 2009).

Route **a**: Recycling local dynamic AM

Route **b**: Recycling local AM

Route **c**: Recycling distributed AM

Route **d**: Recycling centralized AM

Route **e**: Recycling CM

Route **f**: Primary plastic AM

Route **g**: Primary plastic CM

Route **h**: Combustion for energy

Route i: Landfill

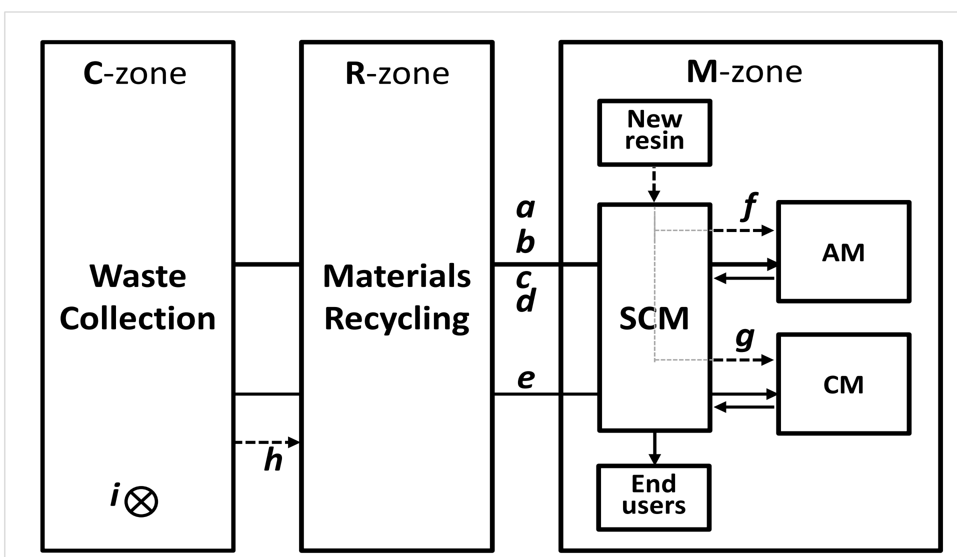

Figure 3 All possible routes in CRM model

Plastic manufacturing routes can be categorized into seven regular categories, in addition to two special categories, combustion and landfill, which do not produce any product. Among the seven, a, b, c and d are the categories sourcing recycled materials and fabricated by AM, whereas category f applies primary plastic for AM manufacturing.

The other two are category e, which sources recycled materials fabricated by CM, and category g, which applies primary plastic for CM manufacturing. These nine categories cover all possible plastic product life cycles.

Among these nine categories; category a, b, c, d, and e pass through generic collection and recycling before reaching manufacturing. Direct manufacturing is the entry point of category f and g, which use new material.

Category h, combustion, is the last option, and category i, landfill, is intended not to be the alternative solution.

The manufacturing process is differentiated from the collection and recycling processes because each category processes materials by different sub-process under different manufacturing conditions.

Routes a–e pass through common routes in collection and recycling and are processed differently in manufacturing and supply. This is the reason the collection and recycling process do not differentiate in the evaluation process. However, the other four categories (f–i) must be evaluated individually in terms of collection and recycling.

5. Role of CRM model towards sustainable manufacturing

5.1 Waste management: CRM Model Process Overview

To maximize reusable materials, and to minimize energy consumption and CO_2 emission, the objectives can be represented by a simple notation:

$$\textbf{max. (MRR – CFP – NMC)} \tag{1}$$

1. **MRR**: Materials recovery ratio (Materials as primary and Energy as option) by comparing yield (%) at previous EOL and present yield
2. **CFP**: CO_2 emission measurement, which represents carbon footprint (CFP), the indicator of greenhouse gases (GHG)
3. **NMC**: Non-materials cost evaluation (Energy consumption, transportation, amortization setup fee and miscellaneous cost)

max. (MRR - CFP - NMC) is a simple notation explaining our objective through three key factors. This notation guides the derivation of subsequent equations and requires translation into monetary or other evaluation vectors before moving into industrial applications.

The CRM model aims to cover the full life cycle between raw materials and product. The overview, as shown in Figure 4, can be broken down into a generic form. The individual C, R and M sub-models can be independently constructed and integrated.

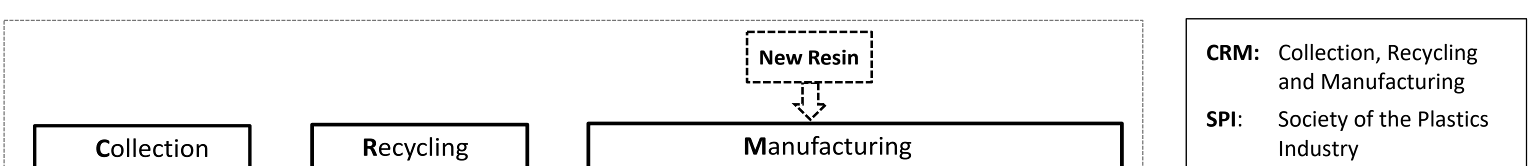

Figure 4. CRM Model Process Flow

The main objective of integrating recycling and manufacturing processes is to maximize materials recovery and minimize energy consumption and CO_2 emissions, thus saving the environment. MRR is the ratio of recovery weight over the weight at EOL before recycling. For instance, a product weights 100kg and reaches EOL. After recycling, the materials yields 90 kg, so the MRR of the recycling % yield would be 90%. For a primary material, its MRR always remains '0'. On the other side, non-materials cost and CO_2 emission, as an indicator of GCG, are the two factors that must be minimized. When the overall objective is breakdown into individual zones of C, R and M, the generic form of the optimized CRM process can be represented as followed (Garmulewicz, A. et al., 2016):

$$\sum_{g=1}^{m} \boldsymbol{f_g} \times \mathbf{C}_{\boldsymbol{g}} + \sum_{h=1}^{n} \boldsymbol{f_h} \times \mathbf{R}_{\boldsymbol{h}} + \sum_{i=1}^{p} \boldsymbol{s_i} \times \mathbf{M0}_{\boldsymbol{i}} + \sum_{j=1}^{q} \boldsymbol{r_j} \times \mathbf{M}1_{\boldsymbol{j}} + \sum_{k=1}^{r} \boldsymbol{r_k} \times \mathbf{M}2_{\boldsymbol{k}} \qquad (2)$$

$\boldsymbol{f}$**:** binary activator (1/0) of recycling facilities (only the shortest route is active and others are inactive)

$\boldsymbol{s}$**:** binary activator (1/0) of supply chain (s = 0 means direct supply from recycling to manufacturing)

$\boldsymbol{r}$**:** binary activator (1/0) of manufacturing method (r_j and r_k are mutually exclusive: either 1/0 or 0/1)

$\boldsymbol{C}$: optimized Collection Process: min.(facility setup + operational transportation fee) + max.(Waste Recycling rate) "C" and "R" are connected closely however, "C" can be differentiated from "R" for the waste handling before the waste arriving MRF site. This mainly covers the number of MRF (MRF setup cost), the transportation distance, and recycling rate. To minimize the loss of the first two and maximize the third item are the objectives.

$\boldsymbol{R}$: optimized recycling process: max. (recycling output – input) + min. (primary plastic + energy consumption)

$\boldsymbol{M0}$: optimized route at supply chain management (SCM): min. (SCM distribution) or min. (transportation)

$\boldsymbol{M1}$: optimized additive manufacturing: max. (rec. materials output – input) + min. (primary plastic + energy cost)

$\boldsymbol{M2}$: optimized conventional manufacturing: max. (rec. materials output – input) + min. (primary plastic + energy cost)

In equation (2), g, h, I, j, k, m, n, p, q, and r are the arbitrary numbers of the individual values of combination. For instance; there are 'm' options or routes between source and sink in collection process. We can enable routes by setting the activators 'f' of particular routes to '1' and other non-preferred routes to '0'.

As optimization of overall efficiency is our objective rather than and any individual route,

$\sum_{g=1}^{m} \boldsymbol{f_g} \times \mathbf{C}_{\boldsymbol{g}}$ is the item of optimization that minimizes the loss.

The same concept is applied to the recycling facility (MRF): $\sum_{h=1}^{n} \boldsymbol{f_h} \times \mathbf{R}_{\boldsymbol{h}}$.

Finally, the optimization of manufacturing, $\sum_{i=1}^{p} \boldsymbol{s_i} \times \mathbf{M0}_{\boldsymbol{i}} + \sum_{j=1}^{q} \boldsymbol{r_j} \times \mathbf{M}1_{\boldsymbol{j}} + \sum_{k=1}^{r} \boldsymbol{r_k} \times \mathbf{M}2_{\boldsymbol{k}}$,

indicates the flexible option between AM and CM.

If AM is applied, then all $\mathrm{r_j} = 1$, all $\mathrm{r_k} = 0$, and the loss through supply chain M0 can be minimized, as in many local manufacturing cases, $s_i = 0$ can be essential.

Evaluation of individual sub-models

C, R, and M sub-models can each be represented as followed,

<u>C-zone and R -zone: Collection and recycling sub-models</u>

Objectives: Optimized (Facility initial cost, Transportation cost and Sorting capability) for CS, TS and MRF

$$\sum_{i=1}^{n} \boldsymbol{f_i} \times (\boldsymbol{M}_i - \boldsymbol{A_i}) - \sum_{i=1}^{n} \boldsymbol{f_i} \times (\boldsymbol{E}_{IN\_i} \times \boldsymbol{M}_i + (\boldsymbol{t_i} + \boldsymbol{e_i}) \times \boldsymbol{M}_i \times \boldsymbol{d_i}) \tag{3}$$

(*"-" sign denotes loss, and "+"sign denotes profit)*

$\boldsymbol{fi}$**:** binary activator (1/0) of recycling facilities (only the shortest route is active, and others are inactive)

$\boldsymbol{M}_i$: Materials at i^{th} MRF ready for recycling

$\boldsymbol{A_i}$: Amortization cost at i^{th} MRF facility setup fee, including land cost

$\boldsymbol{E}_{IN\_i}$: Energy consumption (mWh/ton) in recycling process

$\boldsymbol{t_i}$: unit cost of transportation (\$/ton-km) at i^{th} site

$\boldsymbol{e}_i$: CO_2 emission (ton of CO_2/ton of materials) caused by transportation at i^{th} site

$\boldsymbol{d}_i$: distance (km) of transportation at i^{th} site

Equation (3) represents the generic formula of collection and recycling processes. '*f*' is the activator of each MRF. Initially, we can keep all '*f*' open ('1') and deactivate some of them ('0') in the simulation if necessary. Alternatively, we can activate the n^{th} MRF and then $n+1^{th}$ MRF and compare their deviation to determine whether the installation of $n+1^{th}$ MRF can be a gain or loss.

By taking the notation - equation (1) into the assessment at process level, materials weight $\boldsymbol{M}_i$ is a gain, and the other four factors ($\boldsymbol{A_i}$, $\boldsymbol{E}_{IN\_}$, $\boldsymbol{t}_i$, $\boldsymbol{e}_i$) are the loss. $\boldsymbol{M}_i$ in "primary plastic" stays with '0' and for recycling and can be 100%. From the other side, loss caused from MRF setup cost and operational cost (energy and transportation) must be optimized. Optimization means the more MRFs being constructed, the shorter transportation distance can be expected and vice versa.

The integrated collection and recycling processes have been vital, challenging and problematic and require investigation. To establish quantitative analysis of equation (3), this study contributes novelty through the optimized MRF generic formula, which is supported by a Monte Carlo simulation (IBM Cloud Education, 2020) and Markov Jump theory, which are used to qualify the "jump" process of the theory, from the state of "n" to "n+1". Through the unit cost calculation and the derived generic formula, the correlation between MRF count and transportation distance can be constructed, so the random inputs can derive the optimized values.

M0-zone - Supply chain and Manufacturing sub-Model

Objectives: Minimize materials distribution, logistics, delivery time and distance of shipment

$$-\left(\sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} \boldsymbol{f}i \times \boldsymbol{M}_i \times (\boldsymbol{t}_{\boldsymbol{i,j}} + \boldsymbol{e}_{\boldsymbol{i,j}}) \times \boldsymbol{d}_{\boldsymbol{i,j}}\right) \tag{4}$$

("-" sign denotes loss)

$\boldsymbol{f}i$**:** binary activator (1/0) of recycling facilities (only the shortest route is active and others are inactive)

$\boldsymbol{M}_i$ materials weight $\boldsymbol{t}_i$: unit cost of transportation (\$/ton-km)

$\boldsymbol{e}_i$: CO_2 emission (ton of CO_2/ton of materials) caused by transportation

$\boldsymbol{d}_i$: distance (km) between supplier and manufacturer

Equation (4) represents the supply chain assessment through transportation and CO_2 emission. As this is always a loss, transportation distance $\boldsymbol{d}_i$ can be the determinant of the whole value. This study proposes local recycling and manufacturing to minimize transportation distance.

M1-zone - Additive Manufacturing sub-Model

Objectives: Maximize AM product yield ratio and quality, and minimize energy consumption and CO_2 emission:

$$\sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} \boldsymbol{f_i} \times ((\boldsymbol{M}_{OUT\_i} - \boldsymbol{M}_{IN\_i} - \boldsymbol{M}_{NEW\_i}) - (\boldsymbol{E}_{IN_i} + \hat{e}_i)) \tag{5}$$

$\boldsymbol{M}_{IN\_i}$: Recycling materials input at i^{th} site of AM

$\boldsymbol{M}_{OUT\_i}$: output of AM

$\boldsymbol{M}_{NEW\_i}$: Primary plastic of AM

$\hat{e}_i$: CO_2 emission in AM process

$\boldsymbol{E}_{IN\_i}$: Energy consumption (mWh/ton) in AM process

Equation (5) represents the assessment of AM process complies with equation (1).

For primary plastic, $\boldsymbol{M}_{NEW} = \boldsymbol{M}_{IN_i}$, so $\boldsymbol{M}_{OUT\_i} - \boldsymbol{M}_{IN\_i} - \boldsymbol{M}_{NEW\_i}$ can be -110% if materials yields at 90% mean 110% resource consumption. For recycling cases, as $\boldsymbol{M}_{NEW} = 0$, $\boldsymbol{M}_{OUT\_i} - \boldsymbol{M}_{IN\_i} - \boldsymbol{M}_{NEW\_i}$ derives -10% at 90% yield. The loss factors are limited to energy consumption and CO_2 emission in the manufacturing process. The transportation is aggregated into the M0 supply chain process, which can be minimized in the AM case.

M2-zone - Conventional Manufacturing sub-Model

Objectives: Maximize CM Product % yield and quality and minimize energy consumption and CO_2 emission

$$\sum_{i=1}^{n} \boldsymbol{f}_{\boldsymbol{i}} \times ((\boldsymbol{M}_{OUT\_i} - \boldsymbol{M}_{IN\_i} - \boldsymbol{M}_{NEW\_i}) - (\boldsymbol{E}_{IN_i} + \hat{e}_i)) \tag{6}$$

$\boldsymbol{M}_{IN\_i}$: Recycling materials input at i^{th} site of CM

$\boldsymbol{M}_{OUT\_i}$: output of CM

$\boldsymbol{M}_{NEW\_i}$: Primary plastic of CM

$\hat{e}_i$: CO_2 emission in CM process

$\boldsymbol{E}_{IN\_i}$: Energy consumption (MWh/ton) in CM process

Equation (6) represents how the assessment of the CM process complies with equation 1. The calculation is similar to equation (5), although the CM process can be extensively involved in equation (4) supply chain calculation.

5.2 Local recycling and Manufacturing

Local recycling and manufacturing save transportation costs and CO_2 emission under the minimum supply chain engagement and logistics. Consequently, transportation cost, supply chain cost, and delivery timeframe can be reduced. According to Volvo Truck Corporation (Volvo Truck Corporation, 2018; Truck Driver Institute, 2013), trucking cost is estimated and illustrated in Table 4, $0.111/ton-km, as shown in Table 4.

Transportation type	Payload in tons	liters/ 100 km	Fuel consumption (liter/ton-km)	Fuel cost ($/ton-km)	Fuel cost/ Total cost	Overall cost ($/ton-km freight)
Truck, distribution traffic	8.5	30	30/ (100 × 8.5) = 0.035	0.035 × (0.75 $/liter) = 0.0263	39%*	0.0263/ 0.39 = **0.111 #**

Table 4. Transportation cost (by land: Fuel cost: 39% of total cost * $0.111 is the total cost per ton-km #)

Delivery method	Water	Rail	Truck	Air
Cost ratio	0.156	0.225	1	7.30

Table 5. Transportation cost (multi-options)

Compared with domestic suppliers or domestic manufacturers, local manufacturing delivered by land (truck or rail) can save huge transportation costs. Table 5 demonstrates the benchmark of cost by different transportation options. According to the US Federal Government Bureau of Transportation (2018), assume local land option is applied 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 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). The associated CO_2 emissions may be a similar figure.

Japan's Eco Town Program (Kawasaki Eco-town, 2018) is a typical case study of local recycling. The concept was inspired by Kalundborg, Denmark. Since 1997, 26 Eco Towns have been approved by the Japanese government as of 2005.

Focusing on recycling plastics and home electronics, zero emission is a concept pertaining to local communities and local revitalization. The process requires the plan, developed by cities, towns, or business unions, to get a signature from their prefectural governments, which, along with the cabinet designate cities as zero emissions. After gaining approval from the Ministry of the Environment (MoE) and the Ministry of Economy, Trade and Industry (METI), the communities receive support from the ministries. According to a brief calculation of MoE, the establishment of Eco Towns has led to the reduction of 96 thousand tons of final waste and 46 thousand tons of CO_2 in 2011 in the 26 regions. The establishment has also boosted the economy, by drawing a $1.70 billion investment.

5.3 Energy savings

As indicated in the benchmarking of recycling materials and primary plastics, energy consumption is listed in Table 1 (Pinsky, R. et al, 2019). Recycled materials can save energy up to 88%, particularly in HDPE and PP cases. Manufacturing from scratch can be pricey and labor intensive to gather, move, and process the original resources. Because recycled materials have already been refined, this makes the manufacturing much less energy-intensive than the first manufacture. Table 6 provides the energy cost estimation of different energy sources. The raw data is provided by Community Choice Energy (2017). Among all sources, solar and wind energy reduce energy costs by up to 60%. From sustainability and cost reduction perspectives, this study recommends expanding the coverage of solar and wind energy, as their current utilization is still comparatively low.

Sources	Wind	Solar	Natural gas	Micro-turbine	Biomass	Coal	Geo-thermal	Nuclear	Hydropower	Fuel cell	Diesel
Cost (¢/kWh)	4.5	4.6	6	7.5	8.5	10	10	10	12	13.5	24

Table 6. Energy cost from different energy sources

As indicated in the benchmarking of AM and CM, energy consumption varies depending on the machines and method. In general, AM may not be the option of energy saving for the same weight of materials input.

Energy recovery through Incineration (Combustion): The raw data is based on the estimation of Tsiamis and Castaldi (2016). Combustion is the last option to consider, as the toxic substance produced by chlorine-containing polymers has been a big public health concern. Energy recovery is converted into MWh/ton and then into the monetary values of both hydropower and wind energy equilibrium. Table 7 illustrates energy recovery though different materials, and LDPE and PP provide the highest recovery rates. In this evaluation, higher heating value (HHV), the energy contents of materials are used for benchmarking (Chapman, j., 2021). When they are converted to hydropower or wind/solar energy, the indicated value ($/ ton) represents their monetary values.

Energy Source	**PET**	**HDPE**	**PVC**	**LDPE**	**PP**	**PS**	**Others**	**Average**	Gas oil	Petroleum
HHV (MWh/ton)	6.9	11.1	6.7	12.8	12.2	11.1	11.4	10.6	11.7	11.7
$/ton (Hydropower)	576	927	560	1069	1019	927	952	885	977	977
$/ton (Wind energy)	216	348	210	401	382	348	357	332	366	366

Table 7. Energy recovery and monetary values of different plastics (Chapman, j., 2021)

5.4 CO_2 emissions

CO_2 emission has grown exponentially since the 1950s, and the growth pattern matches that of plastic production. Reduction of energy consumption can result in a reduction of CO_2. Meanwhile, greenhouse gases (GHG) are a vital contributors to climate change and must be tracked in both recycling and manufacturing processes (Khripko, D. et al, 2013). CFP can be an important indicator of GHG measurement that needs a control. CO_2 emission is essential to the monomer-to-polymer process (PET, HDPE, LDPE, PP, PS, PVC, PC, Nylon) or in polymers-to-polymer transformation. Reduction of GHG emission has become a key control in the context of plastic industries and in a critical sustainability agenda.

- CO_2 emission caused by **Transportation** applies raw data from EPA

Energy consumption	CO_2 emission (per gallon of gasoline)	Gallon of gasoline (per ton-km freight)	CO_2 emission (ton per ton-km plastic)
Truck, regional traffic	8.887 kg	0.0214 (litter/ton-km) × 3.785 (gallon/litter) = 0.081 (gallon/ ton-km)	0.008887/ 0.081 = **0.11** (ton of CO_2/ton-km plastic)

Table 8. CO_2 emission caused by transportation

- CO_2 emission caused by **Manufacturing**

Raw data source: (Pavlo, 2019)	Method: AM (Mechanical Recycling)					
Materials type	PET		HDPE		PP	
CO_2 emissions (ton CO_2/ton plastic)	new	recycling	new	recycling	new	recycling
	2.78	**0.91**	**1.89**	**0.56**	**1.84**	**0.53**
Unit CO_2 handling fee ($/ton of CO_2)	$24/ton of **$CO_2$**					
CO_2 emission handling fee ($/ton plastic)	66.72	21.84	45.36	13.44	44.16	12.72
Raw data source: (World Centric, 2018)	Method: CM (injection molding)					
Materials type	PET		PLA		PP	
CO_2 emission (ton CO_2/ton plastic)	**1.4**		**4.16**		**4.98**	

Table 9. CO_2 emission caused by CM manufacturing

The evaluation of CO_2 emission is separated by two major groups: transportation (Table 8) and manufacturing (Table 9). Transportation by trucking contributes 0.11 tons of CO_2 emission in each ton-km of materials waste transportation.

According to Balogun et al. (2015), CO_2 emission is proportional to energy consumption and can be simplified by a calculation of 0.5 ton × energy consumption (MWh/ton).

AM does not gain significant energy advantage over CM for the same weight of materials. However, as CM waste materials are produced through subtraction, less materials are used, particularly for those with high complexity and flexible shape. In general, energy consumption and CO_2 emission of both AM and CM remain at the same level, and AM is better suited to save energy and reduce CO_2 emissions.

5.5 Collection and Recycling Process Evaluation

Optimized MRF Simulation

Objectives: The optimized MRF number and distance between source and sink are the factors of evaluation. In equation (3), the collection and recycling process can be represented by:

$$\sum_{i=1}^{n} \boldsymbol{f_i} \times (\boldsymbol{M}_i - \boldsymbol{A}_i) - \sum_{i=1}^{n} \boldsymbol{f_i} \times (\boldsymbol{E}_{IN\_i} \times \boldsymbol{M}_i + (\boldsymbol{t_i} + \boldsymbol{e_i}) \times \boldsymbol{M}_i \times \boldsymbol{d_i})$$

Since all the factors $(\boldsymbol{A_i}, \boldsymbol{t_i}, \boldsymbol{e_i}, \boldsymbol{d_i})$ *are* loss except the fist $\boldsymbol{M}_i$ *we* use a profit notation $\boldsymbol{P}_{balancer}$ to translate $\boldsymbol{M}_i$ into monetary dimension for evaluation. $\boldsymbol{P}_{balancer}$ is a factor of \$/ton which is a translator and optimizer to move the whole equation into a positive and maximum value.

As monetary evaluation is the common dimension for each factor, CO_2 emission will not be involved in this monetary evolution. Furthermore, equation (3) is based on one MRF. If we have n count of MRFs, we shall multiply all relevant factors by 'n'. We also assume that all $\boldsymbol{f_i}$ stay with '1' as default value, in this assessment.

Let n be the count of MRF. By taking these into transformation and reformatting, equation (3) is converted into:

$$n \times \boldsymbol{M} \times \boldsymbol{P}_{balancer} - (\mathrm{n} \times (\boldsymbol{A}_{i-MRF} + \boldsymbol{M} \times (\boldsymbol{t}_{i,j} \times \boldsymbol{d}_{i,j} + \boldsymbol{E}_{IN})) \geq 0 \qquad (7)$$

Let $\boldsymbol{A}_{i-MRF}$ (\$/unit-day) be the amortization breakdown of initial setup cost per MRF

Let $\boldsymbol{M}_i$ (ton/MRF) be daily recycling capacity per MRF

$\boldsymbol{t_i}$: the unit cost of transportation is estimated at \$**0.111**/ton-km (derived from table 4)

$\boldsymbol{d_i}$: the distance of transportation, the dependent factor pending on the number of MRF being set up

$\boldsymbol{E}_{IN}$: the unit cost of energy consumption which is derived from table 6 and 7. Assume solar energy is applied in PET case, this derives $4.1 \times 4.5 \times \frac{1000}{100} = \$184.5/\text{ton}$

$\boldsymbol{n}$ **:** the number of MRF to be set up within a specific radius of circle

$\boldsymbol{f_i}$: activator (1/0) and by default it shall be "1" (activated) in this assessment

Among these denotations; $\boldsymbol{d}_i$, $\boldsymbol{A_i}$, and $\boldsymbol{C_{OP}}$ are variables as ttransportation distance ($\boldsymbol{d}_i$) depends on the number of MRF, amortization ($\boldsymbol{A_i}$) depends on the capacity of MRF design, and daily operational cost ($\boldsymbol{C_{OP}}$) depends on $\boldsymbol{A_i}$**.** Unit cost of transportation ($\boldsymbol{t_i}$), CO_2 emission ($\boldsymbol{e_i}$), and Energy consumption ($\boldsymbol{E}_{IN\_}$) at i^th^ site are parameters as they are derived from sub-section 5.2, 5.3, and 5.4 of unit cost calculation.

Let $\boldsymbol{C_{OP}}$ be the operation cost which covers (energy and transportation).The optimized MRF generic formula (equation 7) implies; the total cost per MRF involves in 2 criteria's assessment: the initial setup ($\boldsymbol{A}_{i-MRF}$) and operational cost ($\boldsymbol{C_{OP}}$). Optimization between $\boldsymbol{A}_{i-MRF}$ and $\boldsymbol{C_{OP}}$ means; the more number of MRF allocation in an area with a constant radius, the higher MRF setup cost will be involved. However, this will save operational cost in daily operation as the distance is minimized.

<u>**Initial setup cost**</u> (amortization): n $\times \boldsymbol{A}_{i-MRF}$ <u>**Operational cost**</u>: $\boldsymbol{C_{OP}} =$ n $\times \boldsymbol{M}$ (tons/day) $\times (\boldsymbol{t}_{\boldsymbol{i,j}} \times \boldsymbol{d_{i,j}} + \boldsymbol{E}_{IN})$

- **Transportation distance:** In an arbitrary location L_i with a circle whose radius = r_0 and let $r_0 =$ 1,000km. Assume there are n MRFs installed and let r_n be the radius circle covered by each MRF. Theoretically, the addition of n small circles covered by n MRFs with radius r_i shall fully cover the total area of r_0. As r_i is the radius of a MRF's coverage we derive,

  n $\times \pi {r_i}^2 = \pi {r_0}^2$ or $r_i = \frac{r_0}{\sqrt{\text{n}}}$ when r_0 = 1000, we derive $r_i = \frac{1000}{\sqrt{\text{n}}}$ or $\boldsymbol{d_i} = \frac{1000}{\sqrt{\text{n}}}$ (I = 1 .. n)

$$\boldsymbol{d_{i,j}}^2 \propto \frac{1}{\text{MRF count (n)}} \text{ or } \boldsymbol{d_{i,j}} \propto \frac{1}{\sqrt{\text{n}}} \text{ or transportation distance } (d_{i,j}) \propto \frac{1}{\sqrt{\text{number of MRF } (n)}} \quad (8)$$

Equation 8 implies; in a fixed radius area, the distance of transportation is inversely proportional to root of MRF count, and optimization in both criteria (MRF count and distance of transportation) can be achieved. "n" value can be derived from a simulation between the sum of the cost (energy, transportation and MRF amortization) and profit balance. From environmental point of view, a slight incensement of 'n' value than the optimized 'n' value can even shorten transportation distance and reduce CO_2 emission without a notable impact to cost saving.

Supported by equation 7 and 8, optimized MRF generic formula can be used in the estimation of MRF count and the associated transportation distance. The details of simulation techniques will be further demonstrated in next study; and Monte Carlo simulation technique will be deployed to support the generic formula for the software prototyping purpose.

5.6 Job opportunities and migration

Rural development is critical to sustainable development, and rural industrialization and job opportunity are usually priorities of rural development (Sundar, K., Srinivasan, T., 2009). To realize sustainable manufacturing, this research proposes a close alignment between materials recycling, AM manufacturing and rural development. Through win–win cases, the alignment achieves circular economies and ultimately contributes to sustainability.

Migration caused by poverty has been a significant issue for sustainability. As such, the UN Human Settlements Program advised that rural to urban migration requires critical review, as both areas belong to a harmonious continuum, where any goal to be achieved on one side shall help the other side's development. Sociologists (Hussain, N. et al., 2014; Chowdhury et al, 2012; Todaro, M., 1980) further indicated that poverty has been the most significant factor of migration and that surplus labor in urban destroying balance in an uncontrolled system accelerate unemployment rates of lower-income labor, potentially leading to increased disease and crime rates. The UN Human Settlements Program (UN-Habitat, 2017) advised critical review as government and authorities should be cautious, particularly regarding the rural area's ecosystem, which should be protected for its sustainable development and service delivery opportunities (Gebrea, T., Gebremedhinb, B., 2019). In addition, rural residents deserve the same infrastructure and services to create a resilient society (Shaw, R., 2019). To address the issue, a strategy control model is proposed that deploys a human-centric and top-down approach for supporting sustainable manufacturing in rural areas.

6. Additive manufacturing of recycled plastics model

6.1 The Model

AM fits well into the CRM model: the model is based on energy consumption, CO_2 emissions and cost of production due to transportation and additive manufacturing of recycled plastics.

Objectives: The optimized MRF number and transportation distance are the factors of evaluation.

From equation (1), our objective in AM Plastic Manufacturing is max. (MRR – CFP – NMC).

In equation (3), the collection and recycling process can be represented by

$$\sum_{i=1}^{n} \boldsymbol{f_i} \times (\boldsymbol{M}_i - \boldsymbol{A_i}) - \sum_{i=1}^{n} \boldsymbol{f_i} \times (\boldsymbol{E}_{IN\_i} \times \boldsymbol{M}_i + (\boldsymbol{t_i} + \boldsymbol{e_i}) \times \boldsymbol{M}_i \times \boldsymbol{d_i}).$$

Because all the factors $(\boldsymbol{A_i}, \boldsymbol{t_i}, \boldsymbol{e_i}, \boldsymbol{d_i})$ *are* loss except the fist $\boldsymbol{M}_i$ we use a profit notation $\boldsymbol{P}_{balancer}$ to translate $\boldsymbol{M}_i$ into monetary dimension for evaluation. $\boldsymbol{P}_{balancer}$ is a factor of \$/ton, which is a translator and optimizer to move the whole equation into a positive and maximum value. As monetary evaluation is the common dimension for each factor, CO_2 emission will not be involved in this monetary evolution. Furthermore, equation (3) is based on one MRF. If we have n count of MRFs, we multiply all relevant factors by 'n'. We also assume that all $\boldsymbol{f_i}$ stay with '1' as default value, in this assessment. Let n be the number (count) of MRF. By taking these into transformation and reformatting, equation (3) can be converted into equation (7)

$$n \times \boldsymbol{M} \times \boldsymbol{P}_{balancer} - (\text{n} \times (\boldsymbol{A}_{i-MRF} + \boldsymbol{M} \times (\boldsymbol{t}_{i,j} \times \boldsymbol{d}_{i,j} + \boldsymbol{E}_{IN})) \geq 0$$

$\boldsymbol{A_{MRF}}$ = \$15,000,000/(10 × 365) = \$4110 n/day (for n MRFs), this will derive A_{MRF} = **\$4110 $\boldsymbol{n}$ /day**

$\boldsymbol{M}_i$ (ton/MRF) = 20,000 tons/365 = **54.8 tons/day** By passing the Parameters to equation (7) and (8);

$$n\ \boldsymbol{M}\ \boldsymbol{P}_{balancer} - n\,(\boldsymbol{A}_{i-MRF} + \boldsymbol{M} \times (\boldsymbol{t}_{i,j}\ \boldsymbol{d}_{i,j} + \boldsymbol{E}_{IN})) \geq 0 \quad (7)$$

From equation (8): ; $\boldsymbol{d_i} = \frac{1000}{\sqrt{\text{n}}}$

Let $\boldsymbol{M}_i$ (ton/MRF) be daily recycling capacity per MRF (**54.8** tons/day)

$\boldsymbol{t_i}$: the unit cost of transportation is estimated at **\$0.111/ton-km** (derived from table 4)

$\boldsymbol{d_i}$: the distance (km) of transportation, the dependent factor pending on the number of MRF being set up

$\boldsymbol{E}_{IN}$: the unit cost of energy consumption per ton of plastic waste, which is derived from table 6 and 7. Assume solar energy is applied in PET, this derives $4.1 \times 4.5 \times \frac{1000}{100}$ = **\$184.5/ton, :** the number of MRF to be set up

In this experiment, A_{MRF} (\$/unit-day) is the amortization breakdown of MRF initial setup cost daily. MRF capital cost is estimated at \$15,000,000/MRF-unit for 10 years' service at a capacity of 20,000 tons/year. After amortization breakdown, constants of A_{MRF} and daily recycling capacity are derived as followed,

A_{MRF} = \$15,000,000/(10 × 365) = \$4110 × n/day for n MRFs, this will derive A_{MRF} = \$4110 × n /day

Daily recycling capacity: M_i = 20,000 tons/365 or M_i = 54.8 tons/day

Equation (7) can be expressed as: $54.8\,(P_{balancer})\,\mathrm{n} - 4110\,n$ - $54.8\;\;0.111\;\frac{1000}{\sqrt{\mathrm{n}}}$ - $54.8 \times \boldsymbol{E_{IN}} \times 184.5$

we derive: $\mathrm{n}\;\;54.8\;\;(P_{balancer}) - (4110\,\mathrm{n} + (\frac{6083}{\sqrt{\mathrm{n}}} + 10111)\,\mathrm{n}) \geq 0$ (based on the estimation and assumption)

M is in tons/day, $P_{balancer}$ is in \$/ton, $\boldsymbol{t_{i,j}}\;\;\boldsymbol{d_{i,j}}$ is in \$/ton or (\$/ton-km × km) , $\boldsymbol{E_{IN}}$ is in \$/ton

$n\,\boldsymbol{M}\;\;\boldsymbol{P_{balancer}}$ is in \$/day, $\boldsymbol{A_{i-MRF}}$ is in \$/day, $\boldsymbol{M}\;\;(\boldsymbol{t_{i,j}}\;\;\boldsymbol{d_{i,j}} + \boldsymbol{E_{IN}})$ is in \$/day or (ton/day × (\$/ton +\$/ton))

Finally, all the items n ($M\,P_{balancer}$), n (A_{i-MRF}), n M ($t_{i,j}\;d_{i,j}$), and (n E_{IN}) are in the unit of "\$/day".

The optimized MRF generic formula (equation 7) implies the total cost per MRF involved in the assessment of two criteria: the initial setup ($\boldsymbol{A_{i-MRF}}$) and operational cost ($\boldsymbol{C_{OP}}$). Optimization between $\boldsymbol{A_{i-MRF}}$ and $\boldsymbol{C_{OP}}$ means that the greater the MRF allocation in an area with a constant radius, the higher MRF setup cost will be involved. However, this will save operational cost in daily operations because the distance is minimized.

<u>Initial setup cost</u> (amortization) : n $\boldsymbol{A_{i-MRF}}$ <u>**Operational cost**</u>: $\boldsymbol{C_{OP}}$ = n $\boldsymbol{M}$ (tons/day) ($\boldsymbol{t_{i,j}} \times \boldsymbol{d_{i,j}} + \boldsymbol{E_{IN}}$)

- **Transportation distance:** In an arbitrary location L_i with a circle whose radius = r_0 and let r_0 = 1,000km. Assume there are n MRFs installed and let r_n be the radius circle covered by each MRF. Theoretically, the addition of n small circles covered by n MRFs with radius r_i fully covers the total area of r_0. As r_i is the radius of a MRF's coverage, we derive equation (8);

  $\mathrm{n}\pi r_i^{\,2} = \pi r_0^{\,2}$ or $r_i = \frac{r_0}{\sqrt{\mathrm{n}}}$ when r_0 = 1000, we derive $r_i = \frac{1000}{\sqrt{\mathrm{n}}}$ or $\boldsymbol{d_i} = \frac{1000}{\sqrt{\mathrm{n}}}$ (I = 1 .. n)

  $\boldsymbol{d_{i,j}}^{\,2} \propto \frac{1}{\text{MRF count (n)}}$ or $\boldsymbol{d_{i,j}} \propto \frac{1}{\sqrt{\mathrm{n}}}$ or transportation distance ($d_{i,j}$) $\propto \frac{1}{\sqrt{\text{number of MRF }(n)}}$

Equation 8 implies that in a fixed radius area, the distance of transportation is inversely proportional to root of MRF count, and optimization in both criteria (MRF count and distance of transportation) can be achieved. "n" value can be derived from a simulation between the sum of the cost (energy, transportation and MRF amortization) and profit balance. From the environmental point of view, a slight incensement of 'n' value than the optimized 'n' value can even shorten transportation distance and reduce CO_2 emission without a notable impact to cost saving.

6.2 Data Preparation

Unit Cost of Transportation and Energy

From section 5.2 and 5.3, we derive the unit cost of transportation and energy, which can be a generic case:

$\boldsymbol{t_{i,j}}$ = <u>\$**0.111**/ton-km</u> $\boldsymbol{E_{IN}}$ = \$184.5/ton

MRF Daily Amortization and Daily Capacity

By estimation, A_{MRF} amortization and daily capacity are $\boldsymbol{A_{MRF}}$ = \$4110 × n /day and $\boldsymbol{M_i}$ = 54.8 tons/day individually.

Association between Number of MRFs (n) and Transportation Distance (d_i)

By assumption of an arbitrary circle whose radius r_0 = 1,000km, and equation (8), we derive $\boldsymbol{d_i} = \frac{1000}{\sqrt{\mathrm{n}}}$.

By passing the parameters to equation (7), we derive $\mathrm{n} \times 54.8 \times (P_{balancer}) - (4110 \times \mathrm{n} + (\frac{6083}{\sqrt{\mathrm{n}}} + 10111) \times \mathrm{n}) \geq 0$ (based on the estimation and assumption).

6.3 Data analysis by Monte Carlo Simulation

Qualify n+1th MRF's installation

By taking the equation derived from case study into n+1th case and comparing their deviation (between nth and n+1th) by Monte Carlo simulation we can determine whether the installation of n+1th MRF is a gain or loss.

Finally, a simple equation can be expressed as $0.009 \times \boldsymbol{P}_{balancer} - 2.34 - (\sqrt{n+1} - \sqrt{n})) \geq 0$.

$\boldsymbol{P}_{balancer}$ is a pre-defined profit and performance indicator. For instance, when $P_{balancer}$ is set to \$265/ton, we derive n = 123 (the minimum number of MRF to keep the whole system optimised) and $\boldsymbol{d_{i,j}} = \frac{1000}{\sqrt{n}}$ = 90 km.

The MRF designer has the flexibility to increase the amount of MRF (n) to a higher value (than 123), if transportation distance is a higher priority than MRF cost. Supported by equation 7 and 8, the optimized MRF generic formula can be used to estimate MRF count and the associated transportation distance with dependencies of the cost and capacity of each MRF. The strategy of the simulation can be applied to any scenario and can be further implemented into machine learning packages such as Python or R for on-site support.

7. Discussion

In this study, the CRM model is proposed to optimize materials recycling process in terms of the number of MRFs, and transportation distance. In addition, the CRM model explores the potential enhancements through a seamless integration between recycling and manufacturing.

7.1 Feasibility study of CRM model through AM processes

Efficiency of materials recycling is one of the foundations of sustainable manufacturing, as a well-designed MRF topology which can minimize transportation distance, reduce CO_2 emission, and save cost and lead time. Furthermore, a smooth integration between collection, recycling and manufacturing supports the theory of localized manufacturing recycled plastics by AM processes.

Recycling process maximizes its values through local manufacturing as in the CRM model, localisation is important. Through integration, all the associated entities can be aligned and a closed-loop cycle can be built rapidly. For instance, designers can easily collaborate with their local market to simplify assembly, stakeholders can develop strategy of "design-for-reuse" to achieve sustainability, and producers can determine which parts need recycling and improve the design through a controllable closed-loop cycle. Distributed local manufacturing eliminates reliance of supply chain and logistics, shortens the transportation distance, and reduces CO_2 emission.

As indicated in Table 10, from a viewpoint of sustainability, the literature review, and the model this study provided, AM is in a good agreement with achieving the objectives of CRM model to realize sustainable production. Weakness of AM in scale production and standardization are controllable with the development of technologies and materials. In addition, human factors such as multi-entity collaboration are also important.

Conventional manufacturing processes generally are based on centralised manufacturing, which rely on multi-plants to fabricate different components and the final plant to assemble the parts. Multi-plant dependencies escalate risks, slow down lead time, and increase CO_2 emissions and transportation cost.

In contrast, AM can print the products or parts in fewer steps with less reliance on supply chain and logistics engagement. This implies that all the processes (from the collection of plastics wastes, MRF, the filament fabricator, AM manufacturer or home-based manufacturing, and finally to the warehouse, distributer, or end-users) can be integrated into individual societies and corporations. Through CRM model, the seamless integration effectively activates the values of optimized recycling processes and maximizes the advantages of AM towards sustainable production.

Category	**Environment**		**Society**		**Economies**				
method	Transportation and Logistics	CO_2 emission	Job opportunity	Rural development	Energy saving	Materials yield	Mass production	Lead time	Prototyping
AM	+	+	+	+	AM and CM are in similar range. Insufficient indicators to meet varieties of conditions. Separate study is required.			+	+
CM							+		

Table 10. Evaluation of AM and CM from sustainability point of view

Figure 5 illustrates the advantages of integration of optimized recycling with localized AM manufacturing. The AM community can be built up based on a robust integration of recycling, filament facilitator, AM manufacturer; home-based 3D printing manufacturers, and multi-entities and authorities. Across this integration, Collection Station (CS) is the first facility that collects and sorts the source of wastes. Transfer Station (TS) is responsible for transmitting similar types of waste, after preliminary sorting from CS, to MRF. Filament Facility (FF) is the factory that make filament (or any other type of source materials for AM) directly produced from the products of MRF.

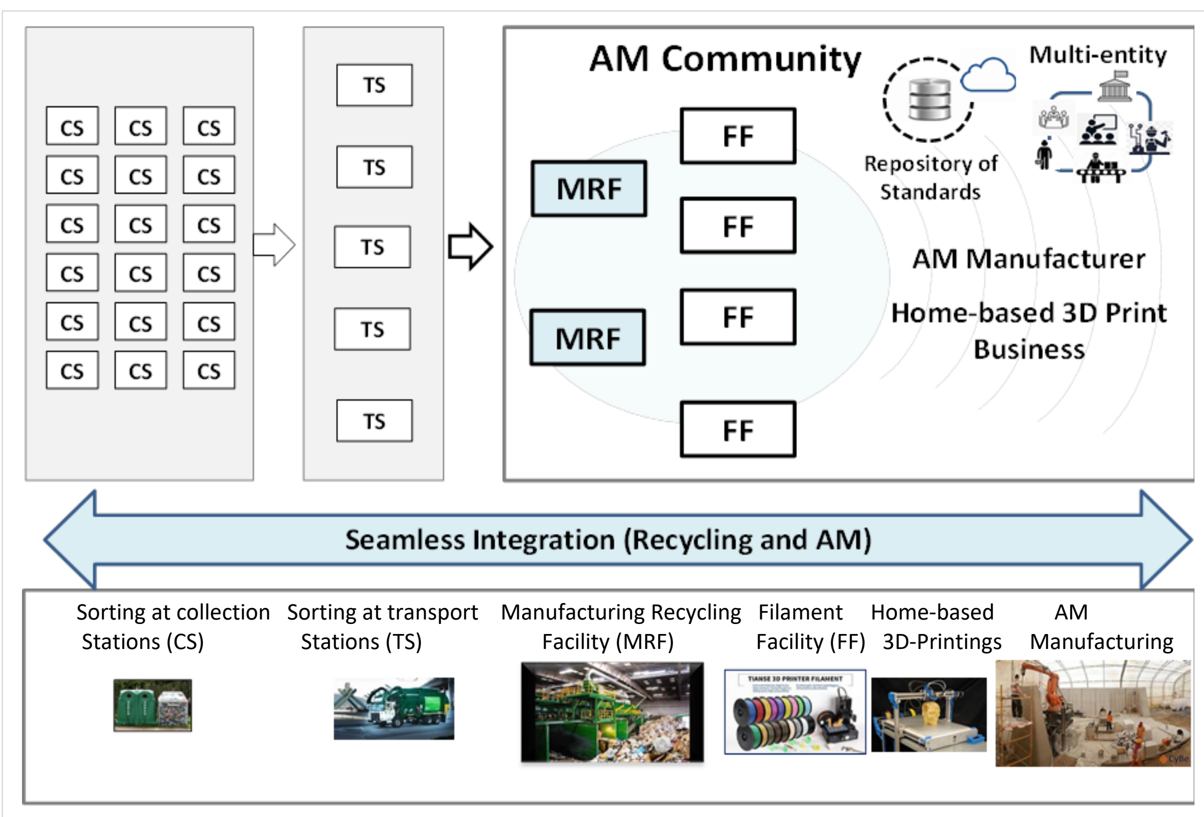

Figure 5. An overview of smooth integration between the optimized Recycling and AM

7.2 AM Challenges

AM has some bottlenecks, as the industry has been cautious about embracing it because of the lack of reliable standards in moving from prototyping to production on a scale. Consequently, scale, speed, and size can be the drawbacks that cause a delay in AM becoming manufacturing mainstream. In 2009, ASTM International formed the ASTM F42 Committee for Additive Manufacturing Technologies to develop standards specific to AM. In 2011, ISO created its committee for AM standards development, ISO/TC 261. In 2013, ASTM and ISO jointly agreed to develop global standards for AM. In addition to these two organisations, there are other standard development organisations (SDOs) setting standards for specific domains of AM.

However, to solve standard issue, AM requires more global activities to be involved and more entities to engage in strengthening its foundation and making AM standards concrete. To address the issues of scale, speed, and size, AM technologies must speed up innovations in automation and multitasking functions and capacity, such as multiple print heads or robots, to enhance AM's scaling capability.

On the other hand, AM requires a collaborative pattern to connect large enterprises, SMEs, and home-based businesses to fully utilize its advantages through localization and distributed manufacturing. Under this foundation, the improvement of recycling process and a smooth integration between recycling process and AM can be realized. Through this integration, the AM bottlenecks in scaling, speed and size issues can be eliminated, and mass production can be expected. Consequently, reduction of CO_2 emission, environment protection, job opportunities in rural areas, and cost saving in circular economies will become possible.

7.3 Limitations

Given the facts that AM is in a good position to realize the CRM model, with sufficient evidence that it can significantly reduce CO_2 emissions, support rural development, reduce cost, and many other advantages; this researcher would like to explore several areas that may not be fully covered in the current study.

First, due to the flexibility of design, AM can be a bridge between technology and the state of the art that touches human consciousness with high impact on culture, moral character, and spirituality and further improves quality of life. This can be one of the major differentiators of AM, but it's almost non-existent in the existing literature. Given that the linkage between technologies and consciousness is complex, although it can be an important area to which AM or 3D Printings can contribute, this research wishes to investigate the mechanisms in a long-running plan.

Second, evaluation of energy consumption is simpler in transportation, as the case study of a common scenario demonstrates that the transportation costs can be reduced 25-fold in AM processes and the associated CO_2 emissions can be reduced with a similar figure well. However, AM and CM processes vary significantly and require further study to investigate individual process energy consumption, efficiency, and CO_2 emissions.

Finally, there is no conclusive indicator to demonstrate that materials yield (%) can be one of the advantages of AM over CM. While some references (Futcher, C., 2015) indicate that materials yield (%) of AM can be slightly higher than CM up to 10%, and save energy for that associated value, there are many conditions and variations to consider before a formative conclusion can be made. Therefore, a separate investigation in materials yield (%) across AM and CM is expected in the future.

8. Conclusions

While plastic material has many advantages that contribute to economies and societies, its non-degradable nature poses a severe burden to the environment due to lack of a systematic approach of plastic waste handling. Over 8 billion tons of plastics have been produced in the past. However, materials recycling in developed countries rates at around 30%, while in developing countries recycling rates are close to 0%. Consequently, this threatens the sustainability of environment, societies, and economies. Robust plastics recycling improves recycling rates and strengthens the foundation of sustainable manufacturing, as a well-designed recycling strategy maximizes efficiency, minimize transportation distance, reduce CO_2 emission, and reduce cost and lead time. Consequently, the efficient recycling streamlines the processes of plastics collection, recycling, and manufacturing on the road towards a more sustainable future.

To achieve this goal, the CRM model is introduced, focusing on the optimisation between recycling facilities and transportation distance calculation. Meanwhile, a seamless integration across CRM processes is investigated, for making a concrete integration between recycling and manufacturing. Several indicators associated with sustainability are used, including 1) transportation distance, 2) CO_2 emissions, 3) energy consumption (manufacturing processes and transportation), 4) materials yield (%), and 5) lead time and cost saving. When AM and CM are compared against these five indicators, there is no evidence that AM can achieve a notable advantage of materials yield (%) or manufacturing energy saving over CM. However, AM is in a better position to minimize transportation distance, reduce CO_2 emission, eliminate energy consumption caused by transportation, and commit cost saving and shorter lead time. Among all key factors, design flexibility and localization can be the tactical factors enabling AM to fully utilize the CRM model, and to augment the advantages of AM.

In contrast to CM, design flexibility enables the AM designer to print parts or end-products directly by software and does not rely on a long process of molding. Also, the unique AM characteristic in local manufacturing eliminates reliance on supply chain and logistics, which can shorten the transportation distance and reduce CO_2 emissions. As illustrated in section 5.2, a common scenario of local manufacturing can save 25-fold transportation cost compared to the foreign suppliers. The important point is the cost of transportation, which can be a brief indicator of the fuel being used and CO_2 being emitted, indicating that the associated CO_2 emissions can be reduced to a similar figure.

By using Monte Carlo method, the simulation applies the derived formulas to estimates the optimized MRF number and the $\text{transportation distance } (d_{i,j}) \propto \frac{1}{\sqrt{\text{number of MRF } (n)}}$ The optimized "n" value of the number of MRF can be derived by qualifying the deviation (of the gap) between the n^{th} and $n{+}1^{th}$ MRF, which can be further implemented into machine learning package for on-site usages.

CRM model accelerates the transformation of AM into the industry mainstream; however, there is no single step to reach the end. This study identifies standardization, scale, speed and size as weak points that can be challenges to AM; and it suggests more entities and activities to engage, and proposes a collaborative pattern to build up AM society and to connect large enterprises, SMEs, and home-based manufacturing to support seamless integration. Through this pattern, the AM bottlenecks can be mitigated, and sustainable production can be realized. Consequently, reduction of CO_2 emission, environment protection, job opportunities for rural development and cost saving in circular economies can be achieved.

List of symbolic notation

$\boldsymbol{A_i}$: Amortization cost (in \$/unit-day) at ith MRF facility setup fee including land cost

$\boldsymbol{C}$: optimized Collection Process: min.(facility setup + operational cost) + max.(materials Recovery)

$\boldsymbol{C_{OP}}$: the daily operation cost which covers energy and transportation

CFP: CO_2 emission measurement of Carbon Footprint (CFP) and the indicator of Greenhouse gases (GHG)

CS: Collection Station, the first facility that collects and sorts the source of wastes

$\boldsymbol{d}_i$: distance (km) of transportation at ith site

$\boldsymbol{e}_i$: CO_2 emission (ton of CO_2/ton of materials) caused by transportation at ith site

$\hat{e}_i$: CO_2 emission in AM process

$\boldsymbol{E}_{IN\_i}$: Energy consumption (mWh/ton) in recycling process

$\boldsymbol{f}$: binary activator (1/0) of Recycling facilities (only the opted route is active and others are inactive)

FF: Filament Facility, the factory that make filament directly produced from the products of MRF.

$\boldsymbol{M}_{IN\_i}$: 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/MRF) of daily recycling capacity per MRF

$\boldsymbol{M0}$: optimized Route at Supply Chain Management (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 MRF to be set up within a specific radius of circle

NMC: Non-Materials Cost such as energy consumption, transportation, amortization and miscellaneous cost

$\boldsymbol{P}_{balancer}$: 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 MRFs (assume 1,000km)

$\boldsymbol{r_i}$: the radius of one MRF's coverage

$\boldsymbol{R}$: optimized Recycling Process: max.(recycling output – input) + 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 ith site

TS: Transfer Station, which is responsible for transmitting similar types of waste, from CS, to MRF

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