Wu, Haishang (2022) Enhancements of sustainable plastics manufacturing through the proposed technologies of materials recycling and collection. Sustainable Materials and Technologies, 31. e00376. ISSN 2214-9937

Enhancements of Sustainable Plastics Manufacturing through the proposed Technologies of Materials Recycling and Collection

Haishang Wu haishang.wu@research.sunderland.ac.uk hswu.academic@gmail.com
Faculty of Technology, University of Sunderland, Sunderland, SR6 0DD, UK

Abstract

With the advancement of technologies and sustainability awareness, sustainable manufacturing has become a trend, and the transformation of manufacturing industries is inevitable. Among all, materials recycling process design has been a challenge affects sustainability. This study proposes a collection-recycling-manufacturing (CRM) model to support manufacturing transformation and envisions process simulation and improvements.

In addition, this study aims to reduce materials waste, cost, transportation, energy and CO_2 emissions. Moreover, it applies simulation techniques to optimise recycling facility management and produce a generic formula in the materials recycling facilities (MRF) topology design and transportation distance calculations.

The procedure eventually enables predictions of operation through the optimisation of MRF number at the cost of transportation, energy consumption and CO_2 emission. Furthermore, the methods strengthen the recycling process and fill the additive manufacturing (AM) gap before becoming industry mainstream.

Overall, this study envisions materials recycling coverage by proposing optimised simulation techniques in the MRF topology design, and transportation distance, and takes full advantage of AM into CRM model integration to penetrate the market. Meanwhile, it identifies AM limitations supported by an enhancement plan to streamline the transformation and support sustainable manufacturing.

Keywords: Sustainability, Manufacturing, Materials Recycling, Plastic, Simulation, Technologies

1. Introduction

Through our recent review, a robust simulation process is necessary to evaluate materials recovery and manufacturing efficiency, in preventing the degradation of industrial ecosystems. Inefficient materials recycling have been the major challenge that impact materials yield, energy consumption and CO_2 emission.

For this reason, recent literatures are reviewed, to derive cutting-edge approaches in dealing with the optimization of MRF number and transportation distance. First, Monte Carlo Simulation (MCS) is deployed to demonstrate the convergence of the mode-dependent performance index and the optimal performance index [1]. 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 [2].

Data-driven simulation is the novelty of this study distinguishes from our previous studies, and MJS is used to qualify the “jump” process of Markov jump theory, from the state of “n” to “n+1”. Our previous research explored the feasibility of the distance calculation by using pre-defined formula.

This study takes MRF number, energy consumption, and transportation distance into calculation through the derived unit values. MCS and MJS optimization approach are introduced and derives the results. In addition, a collection-recycling-manufacturing (CRM) model is proposed to envision the framework and align the values of optimization process to Additive Manufacturing (AM) in cost saving and transportation distance deduction. A high-efficiency recycling process significantly reduces materials' waste and saves costs. In addition, the simulation technique proposed in this study can further improve the recycling process and derive the optimised transportation distance of recycled materials, effectively reducing energy consumption and CO_2 emission.

1.1 Plastic materials categories and waste management methods

Waste plastics are present in a few primary formats, such as packaging, bottles and caps. From the perspective of materials recycling, plastic wastes are composed of different types of polymers. According to the definitions of the Society of the Plastics Industry (SPI) [3], plastic materials are classified into seven categories based on the Resin Identification Code (RIC) shown in Table 1 [4].

Plastic Category	**Plastics Properties**	**Primary Applications and Usages**
1. PET Polyethylene Terephthalate	▪ High temperate resistance ▪ Solvent resistant ▪ Microwave transparency ▪ Tough and strong ▪ Suitable moisture barrier properties	Beverage and salad dressing bottles Fast food package Fiber for clothing Shampoo bottles
2. HDPE High Density Polyethylene	▪ Stress resistant ▪ Moisture barrier properties ▪ Good chemical resistance ▪ Hard to semi-flexible and strong ▪ Waxy surface ▪ Permeable to gas	Food package Milk bottle Detergent and, soap containers Pipes, pots, and toys Furniture
3. LDPE Low Density Polyethylene	▪ Low melting point ▪ Tough and easy bending ▪ Waxy surface ▪ Moisture barrier properties ▪ Excellency transparency ▪ Suitable electrical properties	Grocery bags Sandwich bags Wire and cable Flexible bottles, Shopping bags
4. PP Polypropylene	▪ High melting point ▪ Good chemical resistance ▪ Tough and easy bending ▪ Waxy surface	Food containers Bottle cap, Ketchup and yoghurt bottles Straws for drinking,Fiber for clothing and carpet
5. PVC Polyvinyl Chloride	▪ Good chemical resistance ▪ Tough and strong ▪ Excellent transparency ▪ Good chemical resistance	Credit card Wire and cable Pipes and fittings, Synthetic leather
6. PS Polystyrene	▪ Glassy surface ▪ Tough and hard ▪ Brittle ▪ High clarity	Yoghurt and fast food package Utensils, Cups Toys
7. Others	▪ Any other properties	i.e.; Nylon Multi-material mixed polymers

Table 1. Plastic Materials 7 categories

1.2 Plastics waste management methods

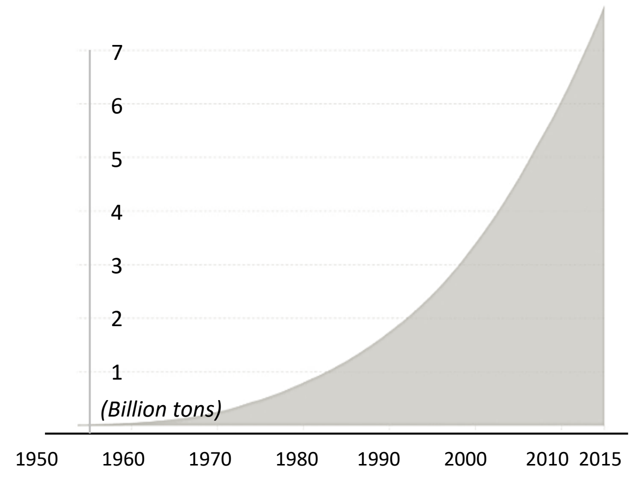
In this study, CRM model is introduced focusing on the optimisation between recycling facilities and transportation distance. Meanwhile, integration across CRM model is proposed and several associated indicators of sustainability are used for evaluation, which include; 1) transportation distance, 2) CO_2 emission, 3) energy consumption (manufacturing and transportation), 4) materials yield, and 5) lead time and cost saving.

Recycling rates in developed countries are around 30%, while recycling rates in many developing countries with a minimal industrial base are still near 0% [5]. Although recycling continues to increase, more than half of the plastic waste on earth is discarded and unrecycled. Thus, material recycling is imperative, and its current status is still far from the 100% recycling target that this study aims to help realise.

The 5R (Refuse, Reduce, Reuse, Repurpose, and Recycle) approach is commonly recognized in plastics waste management [6]. All of these five areas are addressed 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 [7]. From environmental and economic sustainability perspectives, implementing a circular economy to reduce the cost, materials waste, and energy consumption can be crucial [8]. Furthermore, recycling also requires reducing the source of waste support from consumers' behaviour, as proposed in a subsequent section.

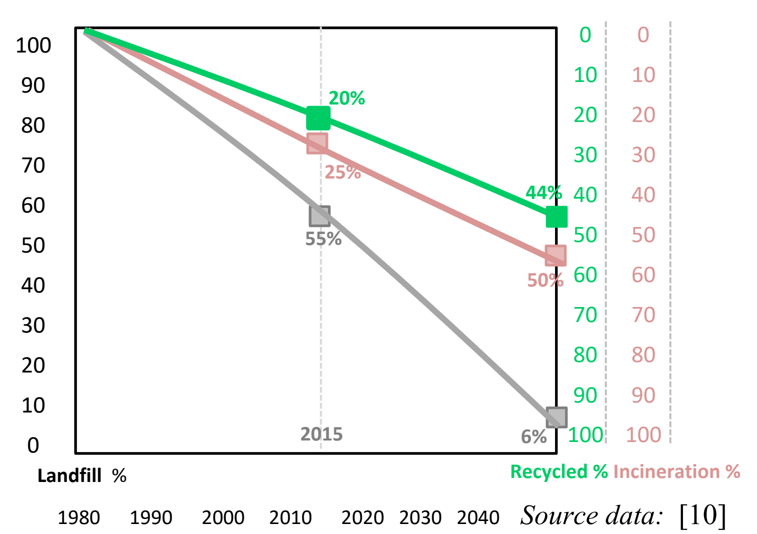
2. Materials recycling process overview

Plastic materials recycling can be challenging and, at the same time, a great opportunity. It is challenging because of the threats to the environment and resources if the materials recycling process is not well-established. However, it is a great opportunity because of the sustainability of circular economies, green ecology systems and a stable society. As lightweight, low cost, non-fragile and durable materials, plastics have tremendous advantages and contribute to economies and societies. Nevertheless, their non-degradable nature poses threats to the environment. Eventually, they threaten global sustainability in economies, the environment and society. This study focuses on plastic polymers because they have been commonly used, since they are typically durable and comparatively low cost [9].



Source data: [10]

Figure 1. Cumulative global plastic production



Source data: [10]

Figure 2. Plastic waste management and prediction

Previously, plastic polymers have caused tremendous problems, as they can severely impact ecological systems. However, according to 'Our World in Data' [10], plastic production has been growing exponentially since its debut, with over eight billion tonnes of plastic produced so far. As indicated in Figure 1, it reached over seven billion tonnes by 2015.

As predicted in Figure 2, global plastic recycling reached 20% in 2015 and will reach 44% in 2050. While these improvements have been in progress, this study aims to achieve 100% plastic recycling with 0% landfill. Since the objective is challenging, this study investigates the facilities and processes required to make improvements. The facilities required for materials recycling have different complexities from those handling solid waste. For example, they may come from a single source without sorting or from multi-sources but are sorted based on the type of materials and handling processes.

2.1 Collection and materials recycling processes

As indicated in Figure 3, the whole process starts with collection and recycling, followed by manufacturing. In manufacturing, the supply chain (SCM) is involved in either the inbound or outbound distribution of the AM and conventional manufacturing (CM) processes. In recycling, facilities comprise collection stations (CS), transfer stations (TS), MRF and optional filament facilitators (FF) (Figure 4).

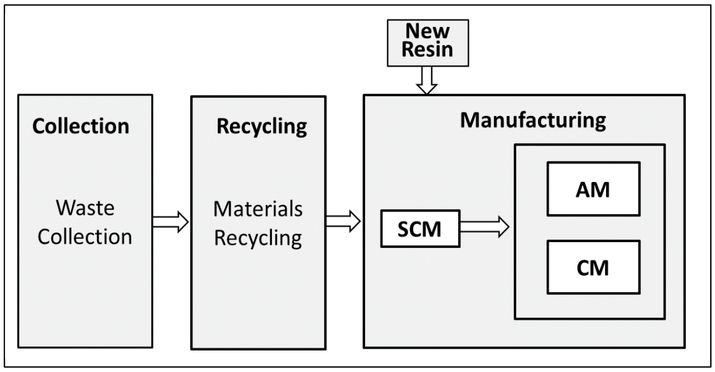


Figure 3. Collection and Recycling process flow

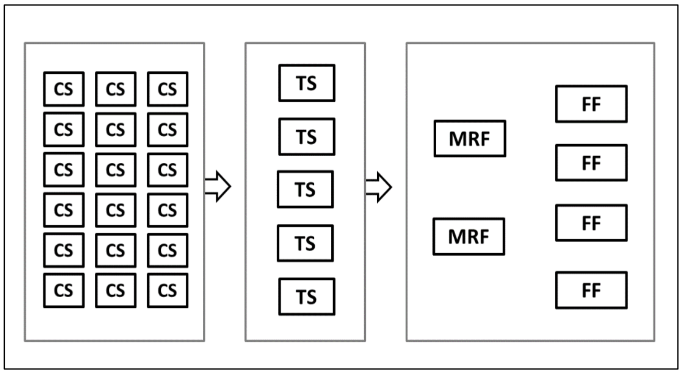


Figure 4. Recycling facilities topology

The objective is to achieve:

max (Product-Recovery-Ratio – non-Materials-Cost – CO_2 **emission)**

As the formula implies, materials recycling aims to optimise the full performance of recycling facilities from cost saving, materials recovery, energy reduction and CO_2 elimination perspectives. Based on this objective, a generic formula is breakdown to the following (C_{CS}) and MRF (R_h), which covers collection processes.

$$\sum_{s1=1}^{m1}(f_{s1}\times C_{s1})\sum_{s2=1}^{m2}(f_{s2}\times C_{s2})\sum_{s3=1}^{m3}(f_{s3}\times R_{s3}) \;+\; \sum_{i=1}^{p} s_i\times M0_i \;+\; \sum_{j=1}^{q}(r_{j1}\times M1_j + r_{j2}\times M2_j)$$

$f_{s1,s2,s3}$: Binary activator (1/0) for activated/de-activated of Collection, Transfer and Recycling facility (CS, TS & MRF)

$C_{s1,s2}$: Optimized sorting and routing solutions for Collection, Transfer and Recycling facility (CS, TS & MRF)

R_{s3}: Optimized solution for MRF Recycling Process

$M0_i$: Optimized solution for Supply chain management

$M1_j$: Optimized solution for Additive Manufacturing Method

$M2_j$: Optimized solution for Conventional Manufacturing Method

s_i: Binary activator (1/0) for activated/de-activated of AM/CM

$r_{j1,j2}$: Binary activator (1/0) for activated/de-activated of AM/CM

2.2 Objective and key metrics

The objective: **max (Product-Recovery-Ratio – non-Materials-Cost –** CO_2 **emission)** is the foundation of CRM model and the root of subsequent formula and equation (2) - equation (12). A breakdown of this root notation to any aspect such as collection and recycling, supply chain, or manufacturing is essential however; to aggregate and integrate any individual aspect into a consolidate equation is unnecessary and impossible, as each aspect can be optional rather than mandatory. In the initial breakdown of the objective principle; the three factors of this notation is described as followed;

1. Product Recovery Ratio (PRR) is a measurement of recycling ratio by comparing yield (%) at previous EOL (which is assumed 0%) and present yield (which can be 80 - 100% in usual cases).

2. Non-Materials Cost (NMC) evaluation represents any initial setup such as MRF cost, or operational cost such as; energy consumption, transportation, amortization setup fee and miscellaneous cost.

3. CO2 emission represents newly increased Carbon Footprint (CFP), or the indicator of Greenhouse gases (GHG) which appears in formula but not in final equations due to monetary limitation.

The individual C, R and M sub-models can be independently constructed and integrated. The main objective of integrating recycling and manufacturing processes in this root notation is to maximize materials recovery, minimize energy consumption and CO2 emissions saving the environment. The notation: max (Product-Recovery-Ratio – non-Materials-Cost – CO_2 emission) is to maximize materials recycling rate and yield ratio (%), to minimize cost (energy of transportation and processes, transportation and logistics, amortization, and any other miscellaneous cost), and to reduce CO_2 emission.

To further explain the concept of PRR; for instance, a product weights 100kg and reaches EOL and to an uncertain subsequent handling, the yield (5) is 0% at EOL. After recycling the materials yields 90 kg, so PRR of the recycling % yield will be 90%. For a primary material, its PRR always stays with 0% as no recycled material is involved.

On the other side, non-materials cost and CO2 emission, as an indicator of GCG, is the two factors need to 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 [11].

Within NMC, there are an optimization process need a simulation which is also one of the core areas of this study, as both initial investment (MRF amortization) and daily operational cost (transportation distance) are involved. The more MRFs are allocated, the higher amortization cost is involved but the lower operational cost can be expected as the transportation distance can be reduced. 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 generic forms.

From the perspective of CO_2 emission, as it is not easy to translate this item into the monetary evaluation, so this item is omitted in the final equations however, based on the simulation, it is suggested to apply the minimum number of MRF to construct recycling site, to minimize transportation distance under optimization process, to reduce CO_2 emission. Plastic sorting capability plays a critical role in subsequent processing. The sorting of different plastic categories depends on the materials' characteristics and the sorting capacity.

According to Yeo et al., the primary plastic sources, Polypropylene (PP) and Polyethylene Terephthalate (PET), contribute to over 45% of global plastic production, and over 60% of these are used in the packaging industry [12]. These types of plastic waste are popular and easy to recover and recycle. For instance, PET, the most prevalent plastic used in daily life in water bottles, is the most commonly recycled plastic.

2.3 Semi-products

Plastic recycling involves complex processes and semi-products. It usually involves several steps to produce semi-products before recycled materials can be manufactured as the final products. However, the process can be standardised with slight variations, depending on the form. The standard method is as follows:

1. **Flakes:** Usually made of mixed materials from bottles that have been shredded into small pieces.
2. **Pellets:** The flakes are washed at high temperatures, dried and melted in the mould to produce shots.
3. **Yarn:** The melted pellets are extruded through tiny holes into yarn and then spun and woven into fabrics.
4. **Fabric:** Fabrics can be made by short or long processes, depending on the purity and sorting techniques.

Sorting plastic waste must be the first recycling step because the wastes come in different forms, shapes and materials. Unsorted and mixed-up materials of varying plastic types may lead to fragility and quality degradation in the end product. Among these four types of semi-products, yarn and fabric are used in textiles, while flakes and pellets are mainly used in bottles and packaging. The following methods deal with different types of semi-products based on their applications to ultimate their utilisation.

2.4 Recycling methods

The four methods of plastic recycling, according to Karayannidis [13], are as follows: in-plant recycling, mechanical recycling (secondary recycling), chemical recycling (feedstock recycling) and incineration (combustion). In this study, primary and secondary recycling methods were recommended.

1. In-plant (primary recycling) of scrap plastic waste refers to the direct use of a product without changing or altering the product itself. Thus, it only deals with the recycling of clean waste. Because of the simplicity and low cost of in-plant recycling, primary recycling is limited to a single type of uncontaminated waste. Therefore, the process is deemed reusable or recoverable, which can be the most efficient way to keep the product in a closed loop.

2. Secondary recycling first filters the polymer out from the contaminants, followed by conventional melt extrusion. Mechanical recycling first sorts, separates, reduces the size and then melts filtration that does not involve a chemical process. Although mechanical recycling degrades polymer quality due to the chain scission caused by water and acidic impurities, it has been widely used and recommended based on its comparatively higher quality over cost (QoC).

3. Feedstock recycling is considered an effective method of de-polymerising PET to the monomers and then re-polymerising back to the original polymer. However, chemical recycling changes the chemical structure as it

turns polymers back to monomers. As a result, it costs higher than mechanical recycling, though it maintains a certain level of quality and is widely used.

4. Incineration is a type of energy recovery usually applied to waste mixed with organic materials or when sorting is difficult. As these cases are problematic for the above three methods, incineration is only used where these cases apply. However, despite the incineration method yielding high energy recovery through combustion, it is not well qualified in terms of sustainability. Furthermore, the toxic substance produced by chlorine-containing polymers can affect public health.

2.5 Evaluation criteria

From the perspective of sustainability, efficiency, cost and materials savings are the criteria that require evaluation. As recycling methods and materials vary, this study envisions the prerequisites and aligns the natural process with the appropriate materials.

The evaluation benchmarks the process metrics according to the status of the materials – recycled materials or new resin. The process metrics cover 1) energy consumption, 2) materials recovery, 3) transportation distance and 4) CO_2 emission. The evaluation also produces metrics of unit cost to support the assessment. Furthermore, the unit costs of transportation and energy consumption are applied to derive the generic equation of optimisation.

2.5.1 Energy consumptions

Raw data shown in Table 2 [14] is for an energy benchmarking between recycled and new resin.

Materials type : Energy consumption		**PET**	**HDPE**	**PP**
New resin	(mWh/ton)	19.4	20.9	20.7
Recycle		4.1	2.4	2.4

Table 2. Energy consumption benchmark – Recycled materials vs. new resin

Raw data shown in Table 3 is for energy benchmarking between AM and CM.

Facilitator	**AM/CM method**		**Materials**	**Energy consumption** (mWh/ton)
[17] [18] [19] [20]	AM	SLS	Polymer	29.9
		FDM	ABS	23.1
		FDM		23.1
		3DP	polymer plaster	14.7
		SLS		14.5
	CM	Injection Molding	PLA	14
			PET	7
			PP	22.8
			PS	26.5
			fabricated plastic	7.1

Energy cost from different sources is indicated in Table 4 [19].

Table 3. Energy consumption in AM and CM cases

Sources	Winc	Solar	Natural ga	Micro-turbine	Biomass	Coal	Geo-thermal	Hydropower	el cel	Diesel
Cost (¢ent/kWh	4.5	4.5	6	7.5	8.5	10	10	12		13.5

Table 4. Energy cost from different energy sources

Energy benchmarking leads to the following results:

- Compared to new resin, recycled materials save up to 88% of energy.
- Compared to conventional hydropower energy, solar and wind energy save 60% of energy costs. Power sources for manufacturing vary, which can be a factor that impacts cost in energy consumption. For instance, wind, solar and electrical actuation can be suitable substitutes for hydropower [20], effectively reducing energy costs.
- By taking the PET and wind energy scenario into the unit cost calculation, the energy consumption in the recycling process can be derived as 4.1 mWh/tonne 4.5 ¢ent/kWh **= $184.5**/tonne which is the energy unit cost during the recycling process.
- The energy consumption of AM and CM varies depending on the machines. However, Table 3 show that both AM and CM are competitive, and AM does not produce a convincing result in energy saving.
- Form of feedstock (i.e. filament, powder) in table 3 was well-tuned based on the technologies being used. However, the form of feedstock can be a dependency of energy consumption. For instance, filament for FDM is stable, but calibration powder, produced by recycled materials, can consume more energy than filament.
- CM, as a substantive method, can cause significant materials loss. Materials yield (%) is the measurement of the ratio of the product weight over materials being processed [17] [18] [21] [22]. The yield ratio averaged around 11:1 for the alloys, which means 91% of CM materials became waste though the plastics can be far below that value. Therefore, yield ratio (%) makes AM the better standpoint in energy saving, materials yield and CO_2 elimination.
- Energy consumption involves two parts: facility-based and transportation-based consumption. Therefore, the analysis is limited to facility-based consumption, and transportation-based consumption is discussed in the transportation session.

2.5.2 Materials recovery (yield)

Table 5 demonstrates materials recovery at around 85% [14]. Mechanical recycling is the method.

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

Table 5. Materials recovery after recycling

Materials recovery benchmarking leads to the following results:

- The weight yield of plastic materials recycling is estimated at around 85% on average, according to raw data provided by Roxanne et al. [14]. Meanwhile, 10% quality degradation can occur in each recycling.

The deterioration of product properties is due to chain scission reactions caused by water and trace acidic impurities. This study proposes drying, vacuum and the use of chain extender compounds to prevent the polymer's average molecular weight from being degraded.

2.5.3 Transportation

Based on the raw data provided by Volvo [23] [24], trucking costs can be estimated as shown in Table 6.

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	8.5	30	30/ (100 × 8.5) = 0.035	0.035 × (0.75 $/liter) 0.0263	39%*	0.0263/ 0.39 = **0.111**

Table 6. Transportation costs (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 7. Transportation costs (multi-options) (source data: [25])

Transportation calculations lead to the following results:

- Waste transportation costs $**0.111**/tonne-km by local trucking.
- Local recycling and manufacturing save high transportation costs. An example is demonstrated as follows.

  In this scenario, both domestic and foreign use cases are considered. Assume the domestic land option is applied to travel for 500 km, 50% by truck and 50% by rail; the cost will be 250 0.111 (1 + 0.225) = **$34.0/tonne.** Assume the foreign option is 2000 km, 50% by air and 50% by water, plus 200 km local travel. Based on Table 7, the cost will be 1000 0.111 (7.3 + 0.156) + 100 0.111(1 + 0.225) = **$841.2/tonne**
- The distance of the recycling facilities and subsequent processing can be the other critical factor of cost saving. From the source (the collection site) to the sink (the waste processing site), direct transportation determines transportation costs, energy consumption and CO_2 emission.
- Under a well-controlled system, MRF-and AM-distributed manufacturing can bridge individual processes into one integrated approach. This integration eliminates supply chain, transportation distance, energy consumption and CO_2 emissions and can be why local recycling and manufacturing play a key role in cost saving.
- A generic equation is derived in the subsequent section to optimise the transportation distance.
- In the collection and recycling process, both the MRF number and transportation distance need optimisation to save costs. The Monte Carlo simulation technique is applied through extensive investigation to predict these values and support the optimisation process.

2.5.4 CO_2 emissions

CO_2 emission caused by Transportation applies raw data from EPA is illustrated in table 8 [26]

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 grams	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 in transportation

CO_2 emission caused by recycling and manufacturing are illustrated in tables 9 and 10.

Raw data source: [27]	Method: 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

Table 9. CO_2 emission in recycling

Raw data source: [17]	Method: CM (Injection Molding)		
Materials type	PET	PLA	PP
CO_2 emission (ton CO_2/ton plastic)	**1.4**	**4.16**	**4.98**

Table 10. CO2 emission in manufacturing

Greenhouse gases (GHG) are a vital contributor to climate change, which requires tracking in transportation or manufacturing processes [28]. Carbon footprint (CFP) can be an essential indicator of GHG measurement that needs control. CO_2 emission caused by transportation are estimated to be 0.11 tonnes per tonne of plastic per km. Therefore, reducing transportation means reducing energy and CO_2 emission.

According to Balogun [29], CO_2 emission in the manufacturing process is proportional to energy consumption and can be simplified by calculating a 0.5-tonne energy consumption (MWh/tonne). AM and CM consume around 10–20 MWh/tonne energy or CO_2 emission ranged at approximately 5–10 tonnes per tonne-plastic in both processes. However, as Oak Ridge [30] indicated, the AM process can be an equipped GHG resolver in reducing CO_2 emission up to 20%, which further makes AM a preferred method.

3. Method and Approaches

The objectives of materials recycling are to optimise the full performance of recycling facilities from cost saving, materials recovery, energy reduction and CO_2 elimination perspectives. The CRM model covers the entire life cycle between raw materials and products. The overview can be simplified into a generic form (Figure 5). The individual C, R and M sub-models can be independently constructed and integrated.

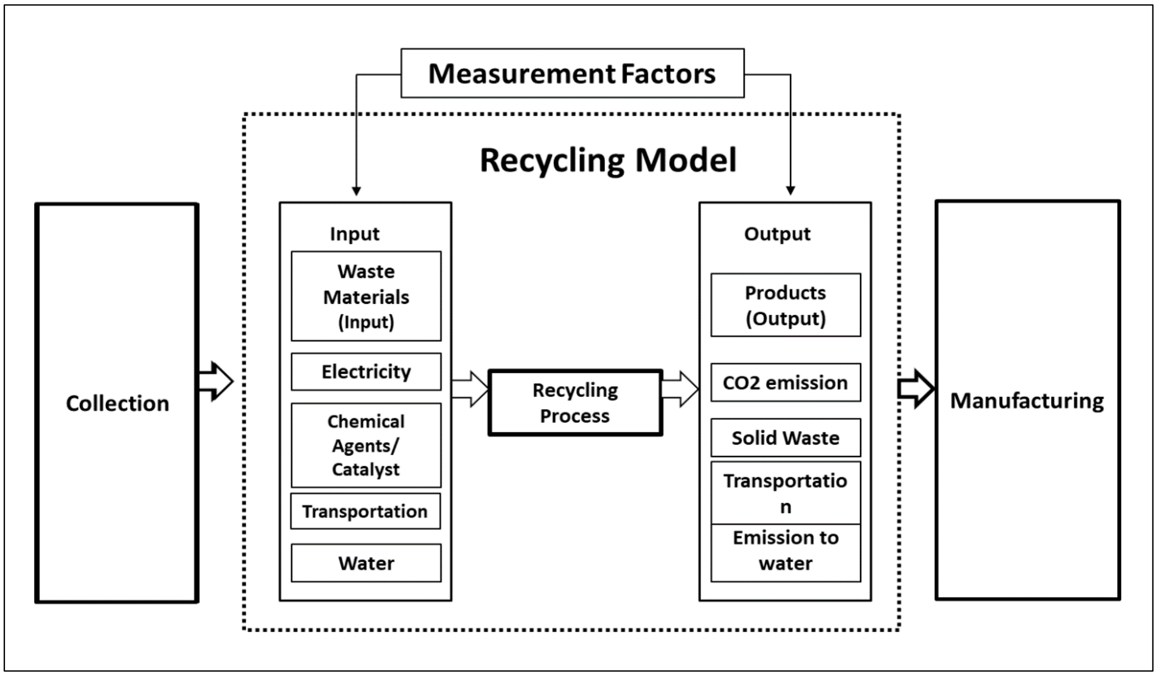


Figure 5. CRM model process overview

3.1 Optimization between MRF and Transportation

MRF topology and transportation distance have been two critical areas that impact recycling efficiency and cost savings and thus merit an investigation. This study investigates the optimised MRF number and transportation distance and derives a generic equation.

A simple formula of optimization can be represented as:

max (Product_Recovery_Ratio – non_Materials_Cost – CO_2 emission)

<u>Pre-assumption</u>: In the collection system, there are branches between the source and sink. Assume there are j units of CS/TS (waste collect station and transfer station) as source branch for the sink – the MRF at the i^{th} site. The collection process covers three types of costs: 1) initial facility setup, 2) transportation and 3) MRF recycling energy cost.

In this evaluation, PET, as the primary material, is used as an example of simulation. In addition, wind energy is used as the direct energy in the MRF recycling for **<u>$184.5/tonne</u>**, which was derived from energy consumption.

Initial setup cost

Let $\boldsymbol{A_{MRF}}$ (\$/unit-day) be the amortization breakdown of MRF initial setup cost daily [31] [32]. 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 $\boldsymbol{A_{MRF}}$ and daily recycling capacity are derived as followed,

- Initial Setup cost of n MRF amortized over 10 years (including labor and other fixed costs)

  $\boldsymbol{A_{MRF}}$ = \$15,000,000/(10 × 365) = \$**4110** × $\boldsymbol{n}$/day for n MRFs, this will derive $\boldsymbol{A_{MRF}}$ = \$**4110** × $\boldsymbol{n}$ **/day** (1)
- **Daily recycling capacity:** M_i = 20,000/365 or $\boldsymbol{M_i}$ **= 54.8 tons/day** (2)

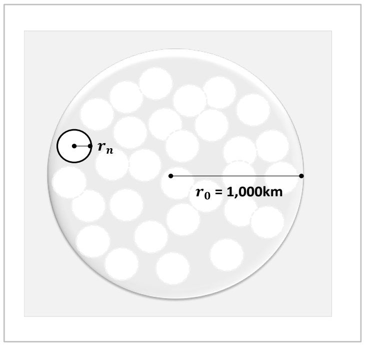


Figure 6. Radius of MRF service area (r_n)

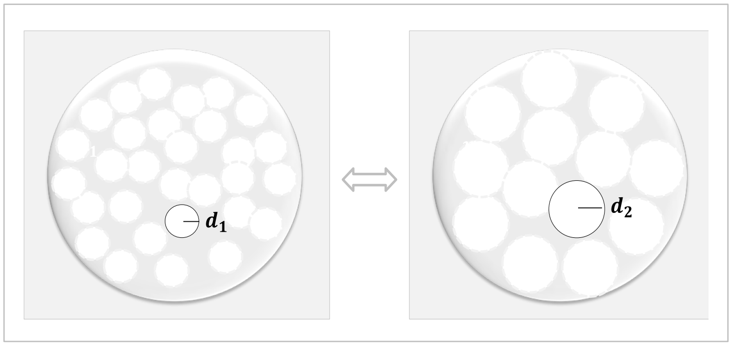


Figure 7. Optimization between MRF count and transportation distance

Operational cost

- **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 in location L_i, and let r_n be the radius of each small circle covered by each MRF. Theoretically, the addition of n small circles covered by n MRFs with radius r_n shall fully cover the total area of r_0. As r_n is the radius of a MRF's coverage (Figure 6) and $\boldsymbol{d_{i,j}}$ is the average distance in each MRF (Figure 7), we derive,

  $$n \times \pi {r_n}^2 = \pi {r_0}^2 \text{ or } r_n = \frac{r_0}{\sqrt{n}} \quad \text{when } r_0 = 1000, \text{ we derive } r_n = \frac{1000}{\sqrt{n}} \text{ or } \qquad \boldsymbol{d_{i,j} = \frac{1000}{\sqrt{n}}} \qquad (3)$$
- **Transportation cost:** through the unit cost estimation derived from previous paragraph,

  $\boldsymbol{t_{i,j}}$: the unit cost of transportation is estimated at \$ 0.111/ton-km $t_{i,j}$ = \$ 0.111/ton-km

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

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

  Assume the daily capacity of each MRF handle 54.8 tons (equation 2) at an average of $\boldsymbol{d_{i,j}}$ km transportation at a cost of \$0.111/ton-km. The daily transportation will cost: $\boldsymbol{T_{i,j} = 54.8 \times 0.111 \times d_{i,j} \times n}$ (4)
- **Energy consumption:** through the unit cost estimation, \$<u>184.5/ton</u> (by wind energy) will be the energy consumption cost for one MRF unit with a capacity of 54.8 ton/day (equation 2). This implies the daily MRF energy consumption for n MRFs will be: $\boldsymbol{E_{IN}}$ (per day) = **54.8 tons/day** × **\$184.5/ton** × $\boldsymbol{n}$ (5)
- **Evaluation factors:** The objectives of this evaluation are to derive the optimized MRF counts and transportation distance within a circle of radius = 1,000km, and the impact factors: amortization, transportation, and energy consumption are the dependent factors of n value (number of MRF to be built).

$\boldsymbol{M_i}$ = **54.8** tons/day $\boldsymbol{t_{i,j}} = \mathbf{0.111}$ $\boldsymbol{E_{IN}} = \mathbf{184.5}$ $\boldsymbol{d_{i,j}} = \frac{1000}{\sqrt{\mathrm{n}}}$ (n: MRF count) $\boldsymbol{A_{MRF}} = \mathbf{\$4110} \times \boldsymbol{n}$ /day

A profit balancer: $\boldsymbol{P_{balancer}}$ is introduced in the calculation, whose role is to keep: $\boldsymbol{P_{balancer}} - (\textbf{all costs}) \geq \mathbf{0}$

- $\boldsymbol{P_{balancer}}$: denotes target profit per ton per MRF that balance all cost through: n $\times \boldsymbol{M}$ (ton/day) $\times$ ($\boldsymbol{P_{balancer}}$) . This implies, the daily revenue of n MRFs that balance the total cost will be: n $\times$ **54.8** $\times$ ($\boldsymbol{P_{balancer}}$)
- **Daily cost**: the daily operational cost of n MRFs in terms of transportation and energy (sum of equation 4 and 5).

  Operation cost: n $\times M$ (tons/day) $\times$ ($t_{i,j} \times d_{i,j} + E_{IN}$) C_{OP} = n $\times$ 54.8 $\times$ (0.111 x $d_{i,j}$ + 184.5)

  This derives: n $\times$54.8 tons/day $\times$ (0.111 $\times \frac{1000}{\sqrt{\mathrm{n}}}$ + 184.5) $\boldsymbol{C_{OP}} == \mathbf{n} \times \left(\frac{\mathbf{6083}}{\sqrt{\mathbf{n}}} + \mathbf{10111}\right)$ (6)

  A_{MRF} = n $\times$ \$4110/day (equation 1) **Daily cost =** $\boldsymbol{A_{MRF}} + \boldsymbol{C_{OP}} = \mathbf{n} \times \mathbf{4110} + \mathbf{n} \times \left(\frac{\mathbf{6083}}{\sqrt{\mathbf{n}}} + \mathbf{10111}\right)$ (7)
- **Profit balancer and Cost:** In a generic form, (Profit balancer – Costs) ≥ 0 is required to maintain the site. In the other words, the profit balancer is expected to balance revenue and cost, to achieve a positive profit.

  MRF number = n: $\mathbf{n} \times \mathbf{54.8} \times (\boldsymbol{P_{balancer}}) - (\boldsymbol{n} \times \mathbf{4110} + \boldsymbol{n} \times (\frac{\mathbf{6083}}{\sqrt{\mathbf{n}}} + \mathbf{10111})) \geq \mathbf{0}$ (8)

  MRF number = n+1: $(\mathbf{n+1}) \times \mathbf{54.8} \times (\boldsymbol{P_{balancer}}) - ((\boldsymbol{n}+\mathbf{1}) \times \mathbf{4110} + (\boldsymbol{n}+\mathbf{1}) \times (\frac{\mathbf{6083}}{\sqrt{\mathbf{n+1}}} + \mathbf{10111})) \geq \mathbf{0}$ (9)

  Equation 8 is the scenario that n MRFs are installed while Equation 9 is the scenario for (n+1) MRFs. Whether n+1th MRF is needed or not, the deviation "Δ" between Equation 8 and 9 can be indicator for decision.
- **Monte Carlo Simulation:** Monte Carlo simulation is used to derive optimized "n" for targeted $P_{balancer}$

  Let $\Delta = (n+1-n) \times 54.8 \times (\boldsymbol{P_{balancer}})$ - (n+1 – n) ×4110 - 6083 $\times \left(\frac{(n+1)}{\sqrt{\mathrm{n+1}}} - \frac{n}{\sqrt{\mathrm{n+1}}}\right)$ - (n+1 – n) ×10111

  $$\Delta = 54.8 \times (\boldsymbol{P_{balancer}}) - 4110 - 6083 \times \left(\frac{(\mathrm{n+1})}{\sqrt{\mathrm{n+1}}} - \frac{\mathrm{n}}{\sqrt{\mathrm{n}}}\right) - 10111$$

  $$\Delta = 54.8 \times (\boldsymbol{P_{balancer}}) - 14221 - 6083 \times \left(\frac{(\mathrm{n+1})}{\sqrt{\mathrm{n+1}}} - \frac{\mathrm{n}}{\sqrt{\mathrm{n}}}\right) \qquad (10)$$

  Δ /6083 = (54.8/6083) × $\boldsymbol{P_{balancer}}$ – (14221/6083) $-$ (6083/6083) × ($\sqrt{\mathrm{n}+1} - \sqrt{\mathrm{n}}$))

  Δ ≥ 0 means the (additive profit of n+1th MRF – additive profit of nth MRF) is positive, so n+1th MRF is feasible.

3.2 Results

Finally, a simple equation can be expressed as: 0.009 × $\boldsymbol{P_{balancer}}$ – 2.34 – ($\sqrt{\mathrm{n}+1} - \sqrt{\mathrm{n}}$)) ≥ 0 (11)

$\boldsymbol{P_{balancer}}$ serves as a profit balancer and performance indicator of each adding of MRF, and 'n' is the random value of the Monte Carlo simulation to test if n+1th MRF installation is feasible. After python computation, the optimised 'n' value for a pre-defined $P_{balancer}$ is derived. For example, when $P_{balancer}$ is set as \$265, n = 123 is the minimum number of MRF to keep the whole system optimised. This derives: $\boldsymbol{d_{i,j}} = \frac{1000}{\sqrt{\mathrm{n}}} = 90$ km (12)

$\boldsymbol{d_{i,j}} = 90$ km is the maximum distance between the source and the sink for 123 MRFs to operate in a circle with a radius of 1000 km, shall be 90 km. Since the 'n' value (123) is the entry threshold of optimisation, this method is a generic guideline and may need to be calculated for other factors such as population, the daily volume of waste and CO_2 emission. Overall, a maximum of 100 km transportation distance can be a guideline.

4. Discussion

The CRM model proposes the following criteria to achieve sustainable manufacturing: 1) reduce waste, 2) design for recycling, 3) facilitate design topology, 4) advocate localisation, 5) strengthen standardisation and 6) Applications and evaluations.

4.1 Reduce the source of waste

Consumer behaviour, combined with manufacturers' awareness, can be the key to reducing waste from the source. Before 'Recycle', there are 'Refuse' and 'Reduce' that can be implemented by customers, manufacturers and sellers. In some cases, consumers may have a high consciousness of waste reduction, but a limited chance of implementation since most goods sold in stores are packed with layers of plastic. 'Reduce' from the manufacturer's site provides an opportunity for customers to consume in more eco-friendly ways. Although recycling and a circular economy help reduce material waste significantly, refusing to purchase, create or sell unsustainable products and reducing unnecessary material usage can effectively solve the tactical problem. These deal with the source and is a latent solution to 'zero waste' and sustainability.

Culture can be a factor that affects environmental performance. For instance, in Japan, it is culturally polite and decent to pack items in many layers. From a societal perspective, this promotes hygiene and the 'omotenashi' service of proper care. However, from an economic and primarily environmental perspective, it produces unnecessary costs and single-use plastics. As a result, Japan ranks second in the world regarding plastic packaging waste per capita. In an extreme case, five pieces of packaging were used to 'safeguard' one strawberry. Customers' attitudes and responses may help shift manufacturers' awareness to creating and selling more eco-friendly products. Encouraging the 'reuse' of uncontaminated packages is also effective in reducing single-use wastes.

4.2 Concept of design for recycling

Sustainability and cost saving are vital to the recycling process. Hence, when products are designed to be recycled more easily, the subsequent processes take less effort and consume less energy once the products reach the end of life (EOL), which requires starting its new entry into the CRM model.

The Design for Recycle' (DFR) is a critical concept in AM due to its design flexibility and adaptability to local recycling and manufacturing. Localisation supports DFR, as all entities can be aligned and locally build a closed-loop cycle quickly. For instance, AM designers can easily collaborate with their local market to maximise each part's coverage and simplify assembly. On the other hand, producers can determine which parts need maintenance or recycling and improve the design through a completely controllable closed-loop cycle.

4.3 Generic formula and objectives of the sub-models

Figure 8 demonstrates the possible routes of the CRM model. There are nine routes in the model, and as routes 'i' (landfill) and 'h' (incineration) are not this study's interests, the other seven routes are concentrated on. To elaborate the coverage and constraints of the CRM model, the following paragraphs extend the discussion on applicability of objective functions and their mapping to the process routes.

Since this study proposes ‘zero waste’, landfill (route ‘i’) will not be an option, and incineration (route ‘h’) is only applicable to waste mixed with organic materials or when sorting is difficult. Besides these two, AM aims to prototype and produce high-complexity products, while CM focuses on a large batch volume. Both recycled materials and new resin can be the source materials of AM and CM. Theoretically, all the routes (from ‘a’ to ‘g’) are feasible, and any particular restriction may not be within this study’s scope and will require a separate investigation. However, based on the benchmarking of source materials in Section 3.4 and the ‘closed-loop’ approach proposed in this study, new resin shall not be the priority. Therefore, new resin for AM (routes ‘f’) and for CM (route ‘g’) will be eliminated or avoided. Both options (route ‘f’ or route ‘g’) will happen only when sourcing or properties of the recycled materials have difficulty to meet specific demands, then route ‘f’ or route ‘g’ can be applied.

From distributed and local manufacturing perspectives, CM usually sticks to centralised manufacturing (route ‘e’ if recycled materials are applied), which relies on multi-plants to fabricate components and the final plant to assemble the parts. In contrast, AM can print the products or parts in fewer steps without much supply chain and logistics engagement. These characteristics give AM advantages in lead time and cost-saving, and a transformation of route ‘d’ to ‘b’, ‘c’ and finally to ‘a’ can be expected, which is the ultimate AM advantages. This concept will be discussed further in the next section.

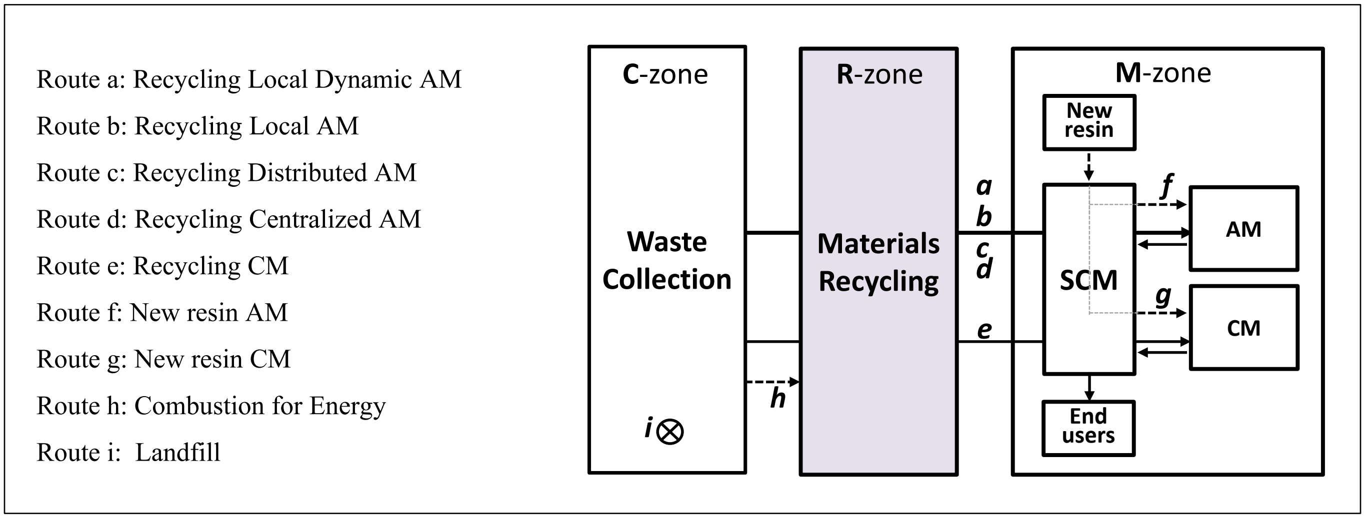

Route a: Recycling Local Dynamic AM
Route b: Recycling Local AM
Route c: Recycling Distributed AM
Route d: Recycling Centralized AM
Route e: Recycling CM
Route f: New resin AM
Route g: New resin CM
Route h: Combustion for Energy
Route i: Landfill

Figure 8. Possible routes in CRM model

The CRM model widely covers the collection, recycling and manufacturing processes. Each path in the C, R and M sub-models is evaluated against critical factors, and the objectives can be represented as follows.

C-zone - Collection sub-Model

$$\sum_{i=1}^{n} \boldsymbol{f_i} \times (\boldsymbol{M}_i - \boldsymbol{A_i}) - \sum_{i=1}^{n} (\boldsymbol{f_i} \times \boldsymbol{M}_i) \times \left(\sum_{j=1}^{m} \boldsymbol{f_j} \times (\boldsymbol{t_{i,j}} \times \boldsymbol{d_{i,j}}) + \boldsymbol{e_{i,j}}\right)$$ *(“-” sign denotes profit loss)*

$\boldsymbol{M}_i$: Materials at i^th^ site MRF ready for Recycling $\boldsymbol{f_i}$: Binary activator (1/0)

$\boldsymbol{A_i}$: Amortization cost at ith site MRF facility setup fee including land cost

$\boldsymbol{t}_{i,j}$: unit cost of transportation ($/ton-km) for the original waste site i to travel from facility j-1 to j at ith site

$\boldsymbol{e}_{i,j}$: CO_2 emission (ton of CO_2/ton of materials) caused by transportation for the ith site to travel from facility j-1 to j

$\boldsymbol{d}_{i,j}$: distance (km) from facility between I and j at ith MRF site (source to sink)

R-zone - Recycling sub-Model

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

$\boldsymbol{M}_{IN\_i}$: Materials input at ith site MRF $\boldsymbol{M}_{OUT\_i}$: Materials output at ith site MRF $\boldsymbol{f_i}$: Binary activator (1/0)

$\hat{e}_i$: CO_2 emission (ton of CO_2/ton of materials) caused by recycling process

$\boldsymbol{E}_{IN\_i}$: Energy consumption in recycling process $\boldsymbol{E}_{Combustion\_i}$: Energy recovery in recycling through combustion

M-zone - Supply chain and Manufacturing sub-Model

$$-\left(\sum_{i=1}^{\boldsymbol{n}} \boldsymbol{f_i} \times (\boldsymbol{M}inbound_i + \boldsymbol{M}outbound_i) \times (\boldsymbol{t}_{\boldsymbol{i,j}} + \boldsymbol{e}_{\boldsymbol{i,j}}) \times \boldsymbol{d}_{\boldsymbol{i,j}}\right)$$

("-" sign denotes profit loss)

$\boldsymbol{M}inbound_i$: Materials transfer from supplier to manufacture $\boldsymbol{M}outbound_i$: transfer from manufacture to supplier

$\boldsymbol{t}_{i,j}$: unit cost of transportation ($/ton-km) to travel from facility j-1 to j at ith site $\boldsymbol{f_i}$: Binary activator (1/0)

$\boldsymbol{e}_{i,j}$: CO_2 emission (ton of CO_2/ton of materials) caused by transportation to travel from facility j-1 to j

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

M-zone - Additive Manufacturing sub-Model

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

$\boldsymbol{M}_{IN\_i}$: Recycling Materials input at ith site of AM $\boldsymbol{M}_{OUT\_i}$: output of AM $\boldsymbol{M}_{NEW\_i}$: New resin of AM

$\hat{e}_i$: CO_2 emission in AM process $\boldsymbol{E}_{IN\_i}$: Energy consumption (mWh/ton) in AM process

M-zone - Conventional Manufacturing sub-Model

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

$\boldsymbol{M}_{IN\_i}$: Recycling Materials input at ith site of CM $\boldsymbol{M}_{OUT\_i}$: output of CM $\boldsymbol{M}_{NEW\_i}$: New resin of CM

$\hat{e}_i$: CO_2 emission in CM process $\boldsymbol{E}_{IN\_i}$: Energy consumption (mWh/ton) in CM process $\boldsymbol{f_i}$: Binary activator (1/0)

4.4 Local manufacturing and distributed manufacturing

A robust integration between materials recycling and AM enables AM's localisation capability, which is hard to achieve in CM. This seamless integration also eliminates the dependency of the supply chain on AM and the ultimate values AM has been bringing in.

The elimination of engagement and logistics through local recycling and manufacturing means saving transportation costs and CO_2 emissions. Consequently, it can reduce transportation, supply chain costs and delivery timeframes. Compared to domestic suppliers or manufacturers, local manufacturing delivered by land (truck or rail) can save substantial transportation costs. In the previous section, the example demonstrated that the local recycling/manufacturing of AM reduces products' life cycles, and transportation costs and the associated CO_2 emissions are reduced 25-fold.

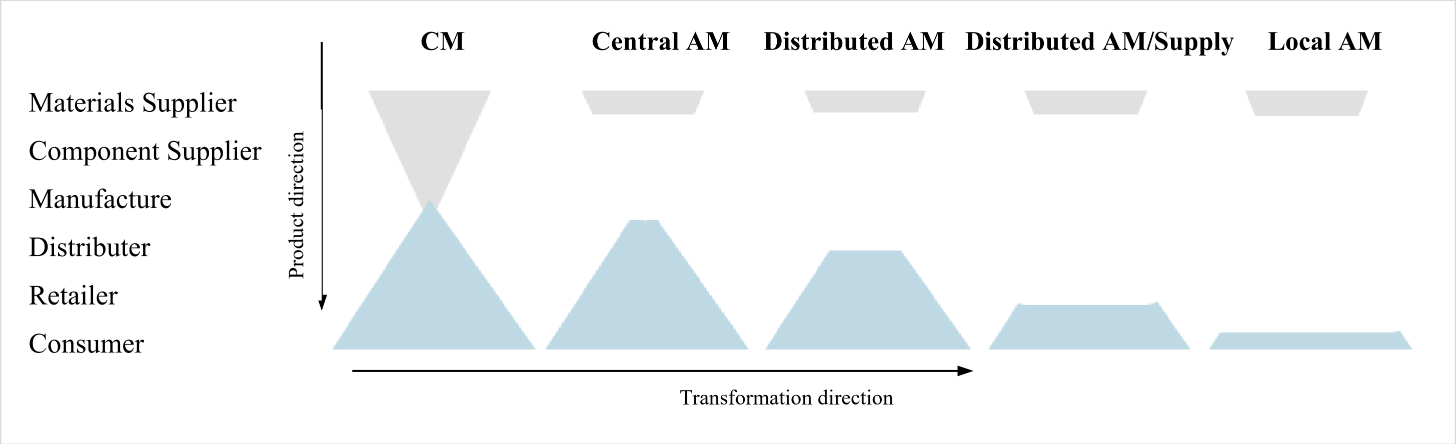


Figure 9. Transformation from central manufacturing to localization

The transformation stages are demonstrated in Figure 9. The origin of the transformation started with CM relying on inbound suppliers for materials and parts. A centralised AM does not demand a parts supplier and reduces dependency on manufacturers. Distributed AM further reduces centralised manufacturers and outbound distributors, and finally, local AM minimises the gap between suppliers, manufacturers and end-users and builds a concrete foundation of sustainable manufacturing through the location.

4.5 Standardisation

AM is rapidly growing in technologies; however, the AM standard can be a bottleneck, as the industry has been cautious about embracing AM due to the lack of reliable standards in moving from prototyping to production on a scale.

To introduce a brief history of AM standardisation, 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. Besides these two organisations, there were other Standard Development Organisations (SDOs) setting standards for specific domains of AM.

The standards include general feedstock materials, AM processes and equipment, finished parts and specific measures. The collaboration of ASTM and ISO has led to the publication of 25 standards as of 2020, with over 40 others under development. Furthermore, to amend the gap for industrial needs, the Additive Manufacturing Standardisation Collaborative (AMSC) developed a roadmap that identifies about 65 standardisation gaps that need additional R&D. There are several reasons behind the slow development of standards:

- It is voluntary and consensus-based.
- It requires experts to be involved in standards' development, but they often have no extra time outside their profession.
- Establishing standards consumes much time to reach an agreement on complex technical details.

As a solution, ASTM's AM Centre of Excellence (AM CoE) has initiated R&D projects that tie directly to standardisation gaps by collaborating with global leaders in AM research. By coupling standard development with R&D, it reduces the time to market for AM parts and materials.

As the above examples show, solutions to a shortage of standardisation include collaboration among SDOs, improving the working environment of experts and combining with R&D. Creating networks among SDOs, industries and influential organisations can also accelerate the standardisation process.

Since AM technology is still in the initial stage of development, the advancement requires robust and holistic study to fill in the gaps from multi-sectional perspectives. Another way to induce this process is through increasing community engagement. Usage and standardisation complement each other. Standardisation leads to more use, and increased community engagement also improves the speed and quality of standardisation.

4.6 Applications and evaluations

AM is one of the best assets for a wide coverage of functions, shapes and versatility of highly complex products. For instance, it is increasingly used in the medical industry, which requires a high degree of customisation, such as dental moulds or personalisation in prosthetics. The technology is extensively used in lightweight parts to save energy and replaces parts for different products in the automotive and aerospace industry. In sustainable manufacturing, AM can be the best choice for rapid prototyping, as it offers the flexibility to make necessary changes very rapidly and cost-effectively. Based on the requirements and materials applied, end users can choose the best-fit method to print the product using AM, and the materials being used in the processes can be liquid, powder or solid. These are the unique merits and differentiators AM can easily use to take over the associated market.

AM applies a computer-aided design (CAD) file and converted stereolithography (STL) file to hold the information of triangles and sliced shape of each product to be printed [33]. It defines the objects' design, mathematics and reverse-engineering information to be embedded in the 3D CAD model [34] to make it agile. The rapid development of AM enables circular economies through the concept of 'Distributed Recycling via Additive Manufacturing' (DRAM) [35], which turns a vicious circle into a virtuous circle.

Given the facts that AM has some advantages in scaling issues that can be a drawback to mass production and the speed, home-based businesses may take advantage of AM's easy entry and less expensive initial cost and solve the scaling issue.

AM can effectively overcome the obstacle of initial cost as the capital cost of 3D printers for plastic materials are 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.

5. Limitations

1. This study introduces the CRM model, focusing on the generic formula of the optimisation method between recycling facilities and transportation distance calculation. It covers the generic methods of different technologies and may not fully cover the details of the process steps, such as chemical recycling or supply chain management, which shall be amended in separate studies.

   However, this will not affect the generic formula as a method of the CRM core area, as transportation cost, CO_2 emission and MRF amortisation are technology independent. The only dependency of the unit cost on recycling technology is the energy consumption of the recycling process. Eventually, the precise parameters of recycling energy consumption and the recycling steps require further investigation before a software package can be implemented.

2. Energy consumption, as illustrated in Table 3, varies depending on manufacturing technologies and plastic types. The illustration demonstrates that CM and AM consumed similar energy levels per unit weight of source materials. However, the CM method, such as CNC, can potentially consume higher energy (per unit weight of products) than AM.

   However, a lack of industry standards may mislead energy calculation in the manufacturing process, as the method in this table was well-optimised rather than randomly selected. Industry standard means optimised alignments between technologies (i.e. FDM, injection moulding), plastic types (i.e. PET, PLA), materials form (i.e. filament, powder and their density, etc.) and applications (i.e. product's form and mechanical properties). Since this is crucial to ultimate AM and CM in their applications, this study will extend its separate investigation into application standards.

6. Conclusions

This study aims to evaluate plastic materials recycling and manufacturing to further benchmark 'recycled' and 'new resin' plastics and AM against CM from the perspective of sustainable manufacturing. This evaluation is based on a quantitative analysis regarding materials recovery, cost saving, energy consumption and CO_2 emission towards sustainability. Furthermore, innovations for process improvement and qualitative research are also covered in this evaluation.

The novelty of this assessment covers innovation, and a generic formula is derived using Monte Carlo simulation techniques. Furthermore, the equation enables predicting capability. Hence, it can evaluate MRF number and transportation distances through quantitative methods. Overall, in a 1000 km radius circle, a maximum of 90 km transportation distance can optimise cost savings and eliminate CO_2 emissions.

The assessment further suggests integrating materials recycling and the AM process, which can eliminate supply chain engagement. Materials recovery, cost saving, elimination of transportation, energy consumption and CO_2 emission are all the motivations bridging multi-entities (such as authorities, stakeholders and consumers) into a robust driving force. Such driving forces can be tactical factors deciding AM's future regarding how soon it will become manufacturing mainstream.

Compared to new resin, recycling processes save up to 88% of energy and CO_2 emissions when recycled materials are used. However, the materials yield averaged at around 85%, and the degradation of 10% material properties is inevitable due to chain scission reactions caused by water and trace acidic impurities. This study proposes intensive drying, nitrogen injection, degassing vacuum and agents of chain extender compounds to minimise the impacts. It is expected to prevent the degradation of the polymer's average molecular weight.

Material recycling is crucial in achieving 'Cradle-to-Cradle' and 'Zero Waste'. Regarding recycling methods, both primary recovery and secondary (mechanical) recycling are recommended and the process of mechanical recycling is applied, as typical case, to demonstrate process flow of CRM model. Regarding energy sources, wind/solar energy saves 60% of energy costs compared to conventional hydropower. Hence, wind and solar energy are recommended for sustainable manufacturing.

In manufacturing, AM produces higher materials yield overall based on its layer-by-layer method, unlike CM's subtractive method, which produces a high volume of waste. Regarding energy and CO_2 emissions, given that AM and CM are at the same level of energy consumption, AM significantly reduces power, as:

- It simplifies the process with fewer steps, and CM can combine many parts into one component.
- Local recycling and manufacturing minimise the supply chain and save transportation.

Simplicity with fewer parts can be another advantage, as AM minimises cost, time and risk and prints directly without CM's 'divide and conquer' strategy. From a qualitative perspective, AM favours prototyping, flexibility and complexity as parts change, while CM requires re-design and re-moulding.

For AM, any change causes less impact on other parts and can handle the products demanding high complexity, which CM has difficulty achieving. Flexibility also distinguishes AM, given its unique characteristic in prototyping that consumes much less time to create a product prototype upon CAD and STL software readiness. Hence, AM can fully take advantage of shareable software through cloud computing to combine parts into the whole.

Like those emerging technologies, AM has several bottlenecks to be resolved. Particularly, weaknesses, speed, scale and size can be the drawbacks that cause a delay in AM becoming manufacturing mainstream. In addition, chain scission reactions can deteriorate materials' properties that need improvement.

Overall, this study recommends fully adopting materials recycling and suggests starting AM from best-fit technologies and products. However, it identifies the limitations of AM that require enhancement. Finally, this study further demonstrates the feasibility and methods of process innovation by illustrating the MRF-Distance generic equation for removing bottlenecks and realising sustainable manufacturing.

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

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

$\boldsymbol{e_i}$: 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

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

$\boldsymbol{f}$: 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

7. References

[1] Xin, X. et al., (2022), "Online Reinforcement Learning Multiplayer Non-Zero Sum Games of Continuous-Time Markov Jump Linear Systems", Applied Mathematics and Computation, vol 412, 1

[2] Fang, H. et al., (2021), "Adaptive Optimization Algorithm for Nonlinear Markov Jump Systems with Partial Unknown Dynamics", International Journal of Robust and Nonlinear Control, doi: 10.1002/rnc.5350Citations

[3] Hunta, E., et al, (2015), "Polymer recycling codes for distributed manufacturing with 3-D printers", Resources, Conservation and Recycling vol. 97, pp 24-30

[4] Sanchez, F., et al., (2020), "Plastic recycling in additive manufacturing: A systematic literature review and opportunities for the circular economy", Journal of Cleaner Production, vol. 264, 10 August 2020

[5] d'Ambrières, W., (2019), "Plastics recycling worldwide: current overview and desirable changes", The journal of field actions Special Issue 19, 2019

[6] Bell, S., (2020), "The 5 R'S: Refuse, Reduce, Reuse, Repurpose, and Recycle", Roadrunner, can be accessed at: https://www.roadrunnerwm.com/blog/the-5-rs-of-waste-recycling

[7] Lazarevic, D., et al., (2010), "Plastic waste management in the context of a European recycling society: Comparing results and uncertainties in a life cycle perspective". Resources, Conservation and Recycling Vol. 55, Issue 2, pp. 246-259

[8] Wiesmeth, H., (2020), "Implementing the Circular Economy for Sustainable Development", Elsevier

[9] Hopewell, J., Dvorak, R., and Kosior, E. (2009). Plastics recycling: challenges and opportunities. Philosophical transactions of the Royal Society of London. Series B, Biological sciences, 364(1526), 2115–2126.

[10] Ritchie, H., Roser, N., (2018), "Plastic Pollution", Our World in Data, can be accessed at: https://ourworldindata.org

[11] Garmulewicz, A. et al., (2016), "Redistributing material supply chains for 3D printing", SAID Business School, University of Oxford press

[12] Yeo, J., et al, (2018), "Recent advances in the development of biodegradable PHB-based toughening materials: Approaches, advantages and applications, Materials Science and Engineering vol 92, pp 1092-1116

[13] Karayannidis, G., Achilias, D., (2007), "Chemical recycling of poly(ethylene terephthalate)", Macromol. Mater. Eng., 292(2), PP 128-146

[14] Roxanne, Z., et al., (2019), Energy Input and Processing Flow for Plastic Recycling, International Journal of Engineering Sciences &Research Technology, IJESRT: 8(7), July, 2019

[15] Huang, R., (2016), "Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components", Journal of Cleaner Production, vol 135, 1, pp 1559-1570

[16] Stefan Junk, S., Matt, R., (2015), "Investigation of Influencing Variables on Sustainability of 3D-Printing and Fused Deposition Modelling", Sustainable Design and Manufacturing 2015 : pp.365-376 : Paper sdm15-016

[17] World Centric, (2018), Eco-Profile of Compostable Plastic, can be assessed at: https://cc.bingj.com

[18] Franklin Associates, (2011), "Life Cycle Inventory of Plastic Fabrication Processes: Injection Molding and Thermoforming", can be accessed at: https://plastics.americanchemistry.com

[19] Community choice energy, (2017), "Levelized Cost of Energy from Fossil and Renewable Sources", can be assessed at: https://energyfreedomco.org/f3-LCOE.php

[20] Fredbloom, M., (2021), "Choosing Between Fluid Power and Electrical Actuation for a Mold-Handling System", Foundry Management and Technologies, can be accessed at: https://www.foundrymag.com

[21] Cotteleer, M., (2014), "3D opportunity for production: Additive manufacturing makes its (business) case", Deloitte Review Issue 15, assessable at: https://www2.deloitte.com/us/en

[22] Digital Alloys, (2019), "Comparison of Additive Manufacturing & CNC Machining". Can be assessed at: https://www.digitalalloys.com/blog/comparison-additive-manufacturing-cnc-machining

[23] Volvo Truck Corporation (2018), Emissions from Volvo's trucks https://www.volvotrucks.com/content/dam/volvo/volvo-trucks/markets/global/pdf/our-trucks/Emis_eng_10110_14001.pdf

[24] Truck driver institute, (2013), The real cost of trucking, can be accessed at: https://www.drivebigtrucks.com

[25] Bureau of Transportation Statistics, (2018), Average Freight Revenue per Ton-Mile, can be assessed at: https://www.bts.gov

[26] EPA, Energy and the Environment (2019), Greenhouse Gases Equivalencies Calculator - Calculations and References, https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

[27] Santander, P., Sanchez, F., Boudaoud, H., Camargo, M., (2020), "Closed loop supply chain network for local and distributed plastic recycling for 3D printing: a MILP-based optimization approach. Resources, Conservation and Recyclin", Elsevier, 2020, 154, pp.104531

[28] Khripko, D. et al, (2013), "Product carbon footprint in polymer processing – A practical application", 11th Global Conference on Sustainable Manufacturing, September 25, 2013, Berlin Germany

[29] Balogun, V., Kirkwood, N., Mativenga, P., (2015), "Energy consumption and carbon footprint analysis of Fused Deposition Modelling: A case study of RP Stratasys Dimension", Int'l Journal of Sc. & Eng. Research, vol 6, Issue 8

[30] Oak Ridge National Lab. (2020), "3D-Printed Device Enhances Capture of Carbon Dioxide Emissions", SciTechDaily

[31] Metro waste authority, (2018), "Materials Recovery Facility (MRF) Feasibility Study", can be accessed at: https://resource-recycling.com/resourcerecycling/wp-content/uploads/2020/06/December_2018_Board_Packet-23-94.pdf

[32] Creech, L., (2019), "MRFs look to the future", Resource sharing knowledge to promote waste as a resource, can be accessed at: https://cc.bingj.com/cache.aspx

[33] Wong, K., Hernandez, A., (2012), "A Review of Additive Manufacturing", ISRN Mechanical Engineering 2012 (4)

[34] Muthu, S., Savalani, M., (2016), Handbook of Sustainability in Additive Manufacturing Volume 1, Springer

[35] Little, H., et al, (2020), " Towards Distributed Recycling with Additive Manufacturing of PET Flake Feedstocks", Materials 2020, 13, 4273 DOI: 10.3390/ma13194273