Process Improvement of Waste Collection, Materials Recycling and Sustainable Manufacturing

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Summary
With the advancement of technologies and sustainability awareness, sustainable manufacturing has formed a trend and transformation in manufacturing industry is becoming inevitable. In order to cope with the manufacturing transformation, this study proposes a collection-recycling-manufacturing (CRM) model to envision the process simulation as well as the process improvements.

In this transformation, reduction of materials, cost, transportation and energy, and elimination of CO₂ emission are the objectives, and innovation is the key to drive the solutions into a concrete foundation. By applying simulation techniques in the optimization of recycling facility management, this study produces generic formula in Materials Recycling Facilities (MRF) topology design and transportation distance calculation. The formula is expected to predict operation through an optimization of MRF counts at the cost of transportation, energy consumption, and CO₂ emission. This study also proposes solutions to fill-in the gap of Additive Manufacturing (AM) before becoming the industry mainstream.

This study suggests an expansion of materials recycling coverage, and take full advantages of AM to penetrate market. Meanwhile, it identifies AM limitations supported by enhancement plan to streamline the transformation and to support sustainable manufacturing.

Keywords: Sustainability, Materials Recycling, Plastic, Simulation, AM, CM, Cost-energy saving, CO₂

I. Background
Materials recovery and manufacturing efficiency are critical to prevent degrading of industrial ecosystems. Due to the nature of multi-disciplinary requirements, this research proposes a framework - the CRM model, to classify technical elements such as facilities, processes, and interfaces of materials recycling and manufacturing followed by an introduction of process simulation to derive generic formula in optimizing MRF counts and transportation distance.

A high efficiency materials recycling process significantly reduce materials waste, save cost, eliminate energy consumption and CO₂ emission. Furthermore, energy saving by using recycling materials and optimized transportation distance simulation can be an effective method to eliminate energy consumption and CO₂ emission. Rather than qualitative analysis, this study produces generic formula in MRF setup guidelines to support the fundamental transformation of plastic industry.
II. Plastic Materials for Recycling

Waste plastics are presented in a few basic formats such as packaging, bottles, and caps, and from the perspective of materials, plastic wastes are composed of different types of polymers.

II-1. Plastic Materials Categories

According to the definitions of Society of the Plastics Industry (SPI) (Hunta, E., et al, 2015); plastic materials are classified into 7 categories based on Resin Identification Code (RIC) shown in Table 1 (Sanchez, F., et al., 2020).

<table>
<thead>
<tr>
<th>Plastic category</th>
<th>Plastics Properties</th>
<th>Applications and usages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. PET (PET) Polyethylene Terephthalat</td>
<td>Good gas &amp; moisture barrier properties, High heat resistance, Clear, Hard, Tough, Microwave transparency, Solvent resistant</td>
<td>Soda bottles, water bottles, medicine jars, and salad dressing bottles, Mineral Water, fizzy drink and beer bottles, Pre-prepared food trays and roasting bags, Boil in the bag food pouches, Soft drink and water bottles, Fibre for clothing and carpets, Strapping, Shampoo, and mouthwash bottles</td>
</tr>
<tr>
<td>2. HDPE High Density Polyethylene</td>
<td>Excellent moisture barrier properties, Excellent chemical resistance, Hard to semi-flexible and strong, Soft waxy surface, Permeable to gas, HDPE films crinkle to the touch, Pigmented bottles stress resistant</td>
<td>Soap bottles, detergent and bleach containers, and trash bags, Detergent, bleach and fabric conditioner bottles, Snack food boxes and cereal box liners, Milk and non-carbonated drinks bottles, Toys, buckets, rigid pipes, crates, plant pots, Plastic wood, garden furniture, Wheeled refuse bins, compost containers</td>
</tr>
<tr>
<td>3. PVC Polyvinyl Chloride</td>
<td>Excellent transparency, Hard, rigid (flexible when plasticised), Good chemical resistance, Long term stability, Good weathering ability, Stable electrical properties, Low gas permeability</td>
<td>Plumbing pipes, cables, and fencing, Plumbing pipes, cables, and fencing, Credit cards, Carpet backing and other floor covering, Window and door frames, guttering, Pipes and fittings, wire and cable sheathing, Synthetic leather products</td>
</tr>
<tr>
<td>4. LDPE Low Density Polyethylene</td>
<td>Tough and flexible, Waxy surface, Soft – scratches easily, Good transparency, Low melting point, Stable electrical properties, Good moisture barrier properties</td>
<td>Cling wrap, sandwich bags, and grocery bags, Films, fertiliser bags, refuse sacks, Packaging films, bubble wrap, Flexible bottles, Irrigation pipes, Thick shopping bags (clothes and produce), Wire and cable applications, Some bottle tops</td>
</tr>
<tr>
<td>5. PP Polypropylene</td>
<td>Excellent chemical resistance, High melting point, Hard, but flexible, Waxy surface, Translucent, Strong</td>
<td>Reusable food containers, prescription bottles, and bottle caps, Most bottle tops, Ketchup and syrup bottles, Yoghurt and some margarine containers, Potato crisp bags, biscuit wrappers, Crates, plant pots, drinking Straws, Hinged lunch boxes, refrigerated containers, Fabric/carpet fibres, heavy duty bags/tarpaulins</td>
</tr>
<tr>
<td>6. PS Polystyrene</td>
<td>Clear to opaque, Glassy surface, Rigid or foamed, Hard, Brittle, High clarity, Affected by fats and solvents</td>
<td>Plastic utensils, packaging peanuts, and Styrofoam, Yoghurt containers, egg boxes, Fast food trays, Video cases, Vending cups and disposable cutlery, Seed trays, Coat hangers, Low cost brittle toys</td>
</tr>
<tr>
<td>7. Others</td>
<td>If not in the above 6 lists, then it is classified as others</td>
<td>Nylon (PA), Acrylonitrile butadiene styrene (ABS), Polycarbonate (PC), Layered or multi-material mixed polymers</td>
</tr>
</tbody>
</table>

Table 1. Plastic Materials 7 categories

II-2. Plastic Waste Management

Recycling in developed countries rates at around 30% while in developing countries recycling rates close to 0% (d’Ambrières, W., 2019). Materials recycling are imperative, and the current status is still far away from the target – 100% recycling this study aims to achieve. Among all waste management methods, recycling is the most sustainable and efficient way (Lazarevic, D., et al., 2010) (Akinola, A., Adeyemi1, I., Adeyinka2, F., 2014). Although there is a continuous growing of recycling, more than half of plastic waste on earth end up discarded.
II. Plastic Materials Recycling Overview

Plastic materials recycling can be challenging but can be a great opportunity as well. Challenging means the threats to environment and resources if materials recycling process is not well-established. Opportunity stands for sustainability of circular economies, green ecology system and stable society.

Plastic materials have committed tremendous advantages such as light weight, low cost, non-fragile and durability that contribute economies and society however; its non-degradable nature poses threat to the environment. Eventually, it threatens global sustainability in economies, environment and society. The reason this study focuses on plastic polymer is based on the reality that plastics polymer have been commonly used. Main reasons are that they have some typical benefits such as durability and comparatively low-cost (Hopewell, J., Dvorak, R., and Kosior, E. 2009).

Plastic wastes can severely impact ecology system if they are mishandled. In the past, plastic polymers have caused tremendous problems as they can severely impact ecology systems. Micro-plastic, deriving from fibrous particles can travel long distances; and through the sea, they can travel across the earth, stay for hundreds of years to decompose, and potentially threat to all lives. According to “Our World in Data” (Ritchie, H., Roser, M., 2018), over 8 billion tons of plastic has been produced on planet earth so far which has been on an exponential growth since its debut in last decade. As indicated in Figure 1, it reached over 7 billion tons by 2015.

As predicted in Figure 2, global plastic recycling reached 20% in 2015 and is predicted to reach 44% in 2050. 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.

The facilities of materials recycling have different complexity in handling solid waste. They can be simple facility by receiving presorted streams of recyclables for baling and shipping to other facilities. Instead, they can be complex that actually performs separation of recyclables from a single stream for further processing.
II-1 Collection and Materials Recycling Processes

From solid waste collection to materials recycling; the recycling facilities consist of collection station (CS), transfer station (TS) and MRF as illustrated in Figure 3 and 4. The objective is to achieve:

\[
\text{max (Product-Recovery-Ratio – non-Materials-Cost – CO}_2\text{ emission)}
\]

This implies; the objectives of materials recycling is to optimize the full performance of recycling facilities from cost saving, materials recovery, energy reduction and CO\(_2\) elimination perspectives. Based on the objective, a generic form is derived as followed which covers processes of collection (\(C_{CS}\)), transfer (\(C_{TS}\)), and MRF (\(R_h\)).

\[
\begin{align*}
\sum_{g=1}^{m_1} f_g \times C_{CS} \sum_{g=2}^{m_2} f_g \times C_{TS} \sum_{h=1}^{n} f_h \times R_h + & \sum_{i=1}^{p} s_i \times M0_i + \sum_{j=1}^{q} r_j \times M1_j + \sum_{k=1}^{r} r_k \times M2_k
\end{align*}
\]

Plastic sorting capability plays critical role in subsequent processing. Sorting of different plastic categories depends on the characteristics of materials and sorting capacity. According to Yeo, et al; the main plastic sources, the PP and PET, contributing over 45% of global production and over 60% of them is used in packaging industry (Yeo, J., et al, 2018).

Such type of plastic wastes is popular and easy recovery. For instance, PET, the most prevailing plastic in daily life being used in water bottles, is the most common plastic being recycled. In addition, HDPE is usually used in bleach type bottles can be sorted without any difficulty.
II-2 Semi-products and Recycling Methods

Semi-plastics

Plastic recycling involved in complex processes and semi-products. It usually covers several steps to produce semi-products before the recycled materials can be manufactured to the final products, and the process can be standardized with slight variations depending on the form.

1) Flakes: Usually made of mixed materials from bottles which are shredded into small pieces.
2) Pellets: The flakes are washed at high temperature and dried, and are melted in mold to produce pellets.
3) Yarn: The melted pellets are extruded through small holes into yarn, and then be spun and woven into fabrics.
4) Fabric: Fabric can be produced by shortcut or long process depending on the purity and sorting techniques.

Among all, sorting of plastic waste can be the first step of recycling due to the fact that the wastes come from different form, shape and materials. Instead, unsorted and mixed-up materials of different plastic types may lead to fragility and quality degrades.

According to Karayannidis and Achilias (Karayannidis, G., Achilias, D., 2007), there are four methods of plastic recycling. These four methods consist of; In-Plant recycling, Mechanical recycling, Chemical recycling and Incineration. Among all, primary and secondary methods are recommended in this research.

1. Primary recycling of the scrap of plastic waste refers to direct use of a product without changing or altering the product itself. It only deals with the recycling of clean waste.
   
   Given the facts of its In-plant recycling simplicity and low cost, the method is limited to the single-type of waste that is uncontaminated. The method is deemed as reuse or recovery, which can be the most efficient way to keep product staying in a closed loop.

2. Mechanical recycling (Secondary recycling) first filters polymer out, from the contaminants, followed by conventional melt extrusion. The method first sort, separate, reduce size, and then proceed to melt filtration that do not involve in chemical process.
   
   Despite the method degrades polymer quality due to 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. Chemical recycling (Feedstock recycling) has been recognized as effective method of de-polymerization of PET to the monomers and then re-polymerize back to the original polymer.
   
   The method changes chemical structure as it turns polymers back to monomer. It costs higher than mechanical recycling though it maintains a certain level of quality and is being widely used.

4. Incineration (Combustion) is a type of energy recovery usually applied to the waste mixed with organic materials and the above 3 methods are hard to be applied.
   
   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 concern that can affect public health. Hence, incineration method shall not be a prioritized option.
II-3 Evaluation Criteria

From the viewpoints of sustainability; efficiency, and cost and materials saving are the criteria need evaluation. As recycling methods and materials varied hence, the evaluation envisions the prerequisites and aligns the genuine method to the appropriate materials.

Basically, evaluation of recycling assesses the scenarios based on “Recycle” and “New resin” 2 major criteria. It benchmarks the process metrics according to the status of the materials – recycled materials or new resin. The process metrics covers; 1) Energy consumption, 2) Materials recovery, 3) Transportation distance, and 4) CO₂ emission. The evaluation also produces metrics of unit cost to support the assessment. In addition, unit cost of transportation and energy consumption are applied in deriving generic equation of optimization.

1. Energy consumptions

Raw data shown in Table 1 (Roxanne et al., 2019) is for an energy benchmarking between recycled and new resin.

<table>
<thead>
<tr>
<th>Materials type : Energy consumption</th>
<th>PET (mWh/ton)</th>
<th>HDPE</th>
<th>PP</th>
</tr>
</thead>
<tbody>
<tr>
<td>New resin</td>
<td>19.4</td>
<td>20.9</td>
<td>20.7</td>
</tr>
<tr>
<td>Recycle</td>
<td>4.1</td>
<td>2.4</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Table 1. Energy consumption benchmark – Recycled materials vs. new resin

Raw data shown in Table 2 is for energy benchmarking between AM and CM.

<table>
<thead>
<tr>
<th>AM/CM method</th>
<th>Materials</th>
<th>Energy consumption (mWh/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM</td>
<td>SLS</td>
<td>29.9</td>
</tr>
<tr>
<td>FDM</td>
<td>ABS</td>
<td>23.1</td>
</tr>
<tr>
<td>FDM</td>
<td>polymer plaster</td>
<td>14.7</td>
</tr>
<tr>
<td>3DP</td>
<td>SLS</td>
<td>14.5</td>
</tr>
<tr>
<td>CM</td>
<td>Injection Molding</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 2. Energy consumption in AM and CM cases

Energy cost from different sources is indicated in Table 3 (Community choice energy, 2017).

<table>
<thead>
<tr>
<th>Sources</th>
<th>Wind (cent/kWh)</th>
<th>Solar (cent/kWh)</th>
<th>Natural gas (cent/kWh)</th>
<th>Micro-turbine (cent/kWh)</th>
<th>Biomass (cent/kWh)</th>
<th>Coal (cent/kWh)</th>
<th>Geo-thermal (cent/kWh)</th>
<th>Hydropower (cent/kWh)</th>
<th>Fuel cell (cent/kWh)</th>
<th>Diesel (cent/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>4.5</td>
<td>4.5</td>
<td>6</td>
<td>7.5</td>
<td>8.5</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>13.5</td>
<td>24</td>
</tr>
</tbody>
</table>

Table 3. Energy cost from different energy sources
Energy benchmarking leads to the following results;

- Compared to new resin, recycled materials saves energy up to 88%.
- Compared to conventional hydropower energy, solar and wind energy save 60% energy cost. Power sources for manufacturing varied which can be a factor impacts cost in energy consumption. For instance, wind, solar, and electrical actuation can be good substitutes of hydropower (Fredbloom, M., 2021) effectively reduce energy cost.
- By taking scenario of PET and wind energy into unit cost calculation, energy consumption in recycling process can be derived; 4.1 mWh/ton × 4.5 cent/kWh = $184.5/ton which is the energy unit cost during recycling process.
- Energy consumption of AM and CM varied depending on machines. The data indicated in Table 3 shows that both AM and CM are competitive and AM may not be a better option in energy saving need other factors in energy evaluation.
- CM, as a substantive method, can cause significant materials lose and the “buy-to-fly” (BTF) is the measurement of the ratio of the weight of product over materials being processed (Cotteleer, M., 2014) (Digital Alloys, 2019). In fact, BTF ratio averaged at around 11:1, which means 91% of CM materials become waste. BTF effeteness makes AM the better option in energy saving, materials yield, and CO₂ elimination.
- Energy consumption involves in 2 different parts: facility-based and transportation-based consumption. Analysis is limited to facility-based consumption, and transportation-based consumption is discussed in transportation session.

2. Materials recovery (yield)

Table 4 demonstrates materials recovery at around 85% (Roxanne et al., 2019). Mechanical recycling is the method.

<table>
<thead>
<tr>
<th>Materials</th>
<th>PET recover rate</th>
<th>HDPE recover rate</th>
<th>PP recover rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovery rate</td>
<td>105/123.9 = 84.7%</td>
<td>47/55.9 = 84.1%</td>
<td>1.4/1.6 = 87.5</td>
</tr>
</tbody>
</table>

Table 4. 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 Roxann. Meanwhile, 10% of quality degrade is expected in each recycling, and the deterioration of product properties is due to chain scission reactions caused by the presence of water and trace acidic impurities. To maintain the polymer average molecular weight during recycling, this study proposes drying, vacuum, and the use of chain extender compounds.
- Both AM and CM have similar materials yield during the process however, by taking BTF into consideration, CM materials recovery can be lower than AM.
Transportation

Based on the raw data provided by Volvo (Volvo Truck Corporation, 2018) (Truck driver institute, 2013), trucking cost can be estimated as shown in Table 5.

<table>
<thead>
<tr>
<th>Transportation type</th>
<th>Payload in tons</th>
<th>liters/100 km</th>
<th>Fuel consume (liter/ton-km)</th>
<th>Fuel cost ($/ton-km)</th>
<th>Fuel cost/Total cost</th>
<th>Overall cost ($/ton-km freight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck, distribution traffic</td>
<td>8.5</td>
<td>30</td>
<td>30/(100×8.5) = 0.035</td>
<td>0.035 × (0.75 $/liter)</td>
<td>0.0263</td>
<td>39%*</td>
</tr>
</tbody>
</table>

Table 5. Transportation cost (by land: Fuel cost: 39% of total cost * $0.111 is the total cost per ton-km)

<table>
<thead>
<tr>
<th>Delivery method</th>
<th>Water</th>
<th>Rail</th>
<th>Truck</th>
<th>Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost ratio</td>
<td>0.156</td>
<td>0.225</td>
<td>1</td>
<td>7.30</td>
</tr>
</tbody>
</table>

(source data: Bureau of Transportation, 2018)

Table 6. Transportation cost (multi-options)

Transportation calculation leads to the following results;

- Waste transportation costs $0.111/ton-km by local trucking.
- Local recycling and manufacturing save significant transportation cost. Example is demonstrated as followed; In a scenario, both domestic and foreign use cases are considered. Assume domestic 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
  Assume foreign option is applied for 2000 km by 50% by air and 50% by water plus 200 km local travel. Based on Table 6, cost will be, 1000×0.111×(7.3+0.156)+100×0.111(1+0.225) = $841.2/ton
- The distance of the recycling facilities and subsequent processing can be the other critical factor of cost saving as direct transportation, from source (the collection site) to the sink (the waste processing site) determine transportation cost, energy consumption and CO₂ emission.
- Under a well-controlled system, MRF and AM distributed manufacturing can be bridged into one integrated process. This eliminates supply chain, transportation distance, energy consumption and CO₂ emission, and can be the reason the local recycling and manufacturing play key role in cost saving.
- In order to optimize the transportation distance, a generic equation is derived in the following session. In collection and recycling process, both MRF account and transportation distance need an optimization to save cost. Through extensive investigation, Monte Carlo simulation technique is applied to predict these values, and to support the optimization process.
4. CO2 emissions

CO₂ emission caused by Transportation applies raw data from EPA (EPA, Energy and the Environment, 2019)

<table>
<thead>
<tr>
<th>Energy consumption</th>
<th>CO₂ emission (per gallon of gasoline)</th>
<th>gallon of gasoline (per ton-km freight)</th>
<th>CO₂ emission (ton per ton-km plastic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck, regional traffic</td>
<td>8,887 grams</td>
<td>0.0214 (litter/ton-km) × 3.785 (gallon/litter) = 0.081 (gallon/ton-km)</td>
<td>0.008887/0.081 = 0.11 (ton of CO₂/ton-km plastic)</td>
</tr>
</tbody>
</table>

Table 7. CO₂ emission in transportation

CO₂ emission caused by recycling and manufacturing

<table>
<thead>
<tr>
<th>Raw data source: (Pavlo, 2019)</th>
<th>Method: Recycling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials type</td>
<td>PET</td>
</tr>
<tr>
<td>CO₂ emissions (ton CO₂/ton plastic)</td>
<td>new</td>
</tr>
<tr>
<td></td>
<td>2.78</td>
</tr>
<tr>
<td>Unit CO₂ handling fee ($/ton of CO₂)</td>
<td></td>
</tr>
<tr>
<td>CO₂ emission handling fee ($/ton plastic)</td>
<td>66.72</td>
</tr>
</tbody>
</table>

Table 8. CO₂ emission in recycling

<table>
<thead>
<tr>
<th>Raw data source: (World Centric, 2018)</th>
<th>Method: CM (Injection Molding)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials type</td>
<td>PET</td>
</tr>
<tr>
<td>CO₂ emission (ton CO₂/ton plastic)</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Table 9. CO₂ emission in manufacturing

CO₂ emission calculation leads to the following results;

- CO₂ emission caused by transportation is estimated at around 0.11 ton of CO₂/ton-km plastic.
- A reduction of energy can result in a reduction of CO₂.
- Carbon footprint (CFP) can be an important indicator of GHG measurement that needs a control.
- Greenhouse Gases (GHG) is a vital contributor of climate change which needs a tracking in either recycling or manufacturing processes (Khripko, D. et al, 2013).
- According to Balogun (Balogun, V., Kirkwood, N., Mativenga, P., 2015), CO₂ emission is in proportional to energy consumption, and can be simplified by a calculation of 0.5 ton × energy consumption (mWh/ton). Both AM and CM consume around 10-20 mWh/ton energy or CO₂ emission ranged at around 5-10 ton per ton-plastics in both process. By taking BTF into consideration, CO₂ emission of AM can be lower than CM.
- As indicated by Oak Ridge (Oak Ridge National Lab., 2020), AM can capture CO₂ emission up to 20%, and higher materials yield further reduce in CO₂ elimination, making AM a favorable method.
III. Plastic Materials Recycling Process Design

The objectives of materials recycling is to optimize the full performance of recycling facilities from cost saving, materials recovery, energy reduction and CO\textsubscript{2} elimination perspectives. The CRM model covers the full life cycle between raw materials and product. The overview as shown in Figure 5 can be broken down into a generic form. The individual C, R and M sub-models can be independently constructed and integrated, and the objectives can be represented by a simple formula: \[
\text{max} \ (\text{Product-Recovery-Ratio} - \text{non-Materials-Cost} - \text{CO}_2\text{ emission})
\]

MRF topology and transportation distance has been a critical area that impact recycling efficiency and cost saving need an investigation. This study investigates the optimized MRF number and transportation distance and derive generic equation.

III-1. Collection and Recycling Process Design

As stated in session V-1, the general equation of waste collection process can be represented by:

\[
- \sum_{i=1}^{n} f_i \times A_i - \sum_{i=1}^{n} (f_i \times M_i) \times (\sum_{j=1}^{m} f_j \times (t_{ij} \times d_{ij} + E_{IN}))
\]

Objectives: The optimized MRF number and distance between source and sink are the factors of evaluation.

Pre-assumption: In the collection system, there are branches between source and sink. Assume there are j units of CS/TS (waste collect station and transfer station) serving as source branch for the sink - the MRF at i\textsuperscript{th} site.

Collection Process covers 3 types of cost: 1) initial facility setup, 2) transportation and 3) MRF recycling energy cost.
In this evaluation, PET, as primary type of materials, is used as example of simulation. In addition, wind energy is used as primary energy in the MRF recycling at a cost of $184.5/ton which was derived from energy consumption.

**Initial setup cost**

Let $A_{MRF}$ ($/unit-day$) be the amortization breakdown of MRF initial setup cost on daily basis (Metro waste authority, 2018) (Creech, L., 2019). MRF capital cost is estimated at $15,000,000/MRF-unit for 10 years’ service at a capacity of 20,000 ton/year. After amortization breakdown, constants of $A_{MRF}$ and recycling daily capacity are derived as followed,

- **Initial Setup cost of n MRF amortized over 10 years** (including labor and other fixed costs)
  $$A_{MRF} = \frac{15,000,000}{10 \times 365} = \frac{4110}{n}$$
  for $n$ MRFs, this will be $\frac{4110}{n} \times n$ /day

- **Daily recycling capacity:**
  $$M_i = \frac{20,000}{365} = 54.8$$
  tons/day

**Operational cost**

- **Transportation distance:** In an arbitrary location $L_i$ with a circle whose radius = $r_0$ 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 $d_{ij}$ is the average distance in each MRF (Figure 7), we derive,
  $$n \times \pi r_n^2 = \pi r_0^2 \quad \text{or} \quad r_n = \frac{r_0}{\sqrt{n}}$$
  when $r_0 = 1000$, we derive $r_n = \frac{1000}{\sqrt{n}}$ or $d_{ij} = \frac{1000}{\sqrt{n}} (i=n)$

- **Transportation cost:** through the unit cost estimation derived from previous paragraph,
  $$t_{ij} : \text{through the unit cost estimation, the unit cost of transportation is estimated at} \quad 0.111/\text{ton-km}$$
  $$d_{ij} : \text{the distance of transportation, the dependent factor pending on the number of MRF being set up}$$
  $$n : \text{the number of MRF to be set up within a specific radius of circle}$$

  Assume the daily capacity of each MRF handle 54.8 tons at an average of $d_{ij}$ km transportation at a cost of $0.111/\text{ton-km}$. The transportation will cost $54.8 \times 0.111 \times d_{ij} \times n$

- **Energy consumption:** through the unit cost estimation, $184.5/\text{ton}$ (by wind energy) will be the energy consumption cost for one MRF unit with a capacity of 54.8 ton/day. This implies, the daily MRF energy consumption for $n$ MRFs will be: $54.8 \text{tons/day} \times 184.5/\text{ton} \times n$
\begin{itemize}
\item **Evaluation factors:** The objectives of this evaluation is 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). In previous paragraph, the unit costs are provided as followed,

\[ M_i = 54.8 \text{ tons/day} \quad t_{ij} = 0.111 \quad E_{IN} = 184.5 \quad d_{ij} = \frac{1000}{\sqrt{n}} \quad (n \text{ is the MRF count}) \quad A_{MRF} = \$4110 \times n \text{ /day} \]

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

\item **\( P_{balance} \):** denotes target profit per ton per MRF that balance all cost through: \( n \times M \) (ton/day) \times \( P_{balance} \).

This implies, the daily revenue of n MRFs that balance the total cost will be: \( n \times 54.8 \times (P_{balance}) \)

\item **Daily cost:** the daily operational cost of n MRFs in terms of transportation and energy.

**Operation cost:** \( C_{OP} = n \times M \) (tons/day) \times \((t_{ij} \times d_{ij} + E_{IN}) = n \times 54.8 \times (0.111 \times d_{ij} + 184.5) \)

This derives: \( C_{OP} = n \times 54.8 \text{ tons/day} \times (0.111 \times \frac{1000}{\sqrt{n}} + 184.5) = n \times (\frac{6083}{\sqrt{n}} + 10111) \)

\( A_{MRF} = n \times \$4110 / \text{day} \) The sum of daily cost (in 3 items) = \( A_{MRF} + C_{OP} = n \times 4110 + n \times (\frac{6083}{\sqrt{n}} + 10111) \)

\item **Profit balancer and Cost:** In a generic form, (Profit balancer – Costs) \( \geq 0 \) 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.

\[ n \times 54.8 \times (P_{balance}) - (n \times 4110 + n \times (\frac{6083}{\sqrt{n}} + 10111)) \geq 0 \]

\( (n+1) \times 54.8 \times (P_{balance}) - ((n+1) \times 4110 + (n+1) \times (\frac{6083}{\sqrt{n+1}} + 10111)) \geq 0 \)

\( \text{Formula 1: MRF count} = n \)

\( \text{Formula 2: MRF count} = n+1 \)

Formula 1 is the scenario that n MRFs are installed while Formula 2 is the scenario for (n+1) MRFs.

Whether \( n+1 \text{th} \) MRF is needed or not, the deviation “\( \Delta \)” between Formula 1 and Formula 2 can be indicator for decision.

\item **Monte Carlo Simulation:** Monte Carlo simulation is used to derive optimized “n” for targeted \( P_{balance} \) and random “n”

Let \( \Delta = (n+1 - n) \times 54.8 \times (P_{balance}) - (n+1 - n) \times 4110 - 6083 \times \left( \frac{n+1}{\sqrt{n+1}} - \frac{n}{\sqrt{n+1}} \right) - (n+1 - n) \times 10111 \)

\[ = 54.8 \times (P_{balance}) - 4110 - 6083 \times \left( \frac{n+1}{\sqrt{n+1}} - \frac{n}{\sqrt{n}} \right) - 10111 \]

\[ = 54.8 \times (P_{balance}) - 14221 - 6083 \times \left( \frac{n+1}{\sqrt{n+1}} - \frac{n}{\sqrt{n}} \right) \]

\( \Delta /6083 = (54.8/6083) \times P_{balance} - (14221/6083) - (6083/6083) \times (\sqrt{n+1} - \sqrt{n}) \)

\( \Delta \geq 0 \) means the (additive profit of \( n+1 \text{th} \) MRF – additive profit of \( n \text{th} \) MRF) is positive, so \( n+1 \text{th} \) MRF is feasible.

Finally a simple formula for simulation can be expressed as: \( 0.009 \times P_{balance} - 2.34 - (\sqrt{n+1} - \sqrt{n}) \geq 0 \)

\( P_{balance} \) is the targeted and “n” is the random value of Monte Carlo simulation to test if \( n+1 \text{th} \) MRF installation is feasible. After python computation, the optimized “n” value for a pre-defined \( P_{balance} \) is derived, and example is as followed, When \( P_{balance} \) is set as \$265, \( n = 123 \) is the minimum number of MRF to keep the whole system optimized.

This derives, \( d_{ij} = \frac{1000}{\sqrt{n}} = 90 \text{ km} \) which is the maximum distance between the source and the sink for 123 MRFs to operate in a circle with a radius of 1000km, shall be 90 km. Since the “n” value (123) is the entry threshold of optimization, this method is a generic guideline and may need to take other factors into calculation such as population, waste daily volume, and CO\textsubscript{2} emission. In general, a maximum of 100 km transportation distance can be a guideline.
\end{itemize}
IV Evaluations of CRM model

IV-1 Generic formula and objectives of sub-models

Figure 8 demonstrates the possible routes of CRM model. There are nine routes in the model and as route i (landfill) and route h (incineration) are not this study’s interest, the focus is concentrated in other seven routes. Instead of going through collection and recycling, “new resin” is feed directly through route ‘f’ (AM) and ‘g’ (CM). Among the rest five routes, route ‘a’, ‘b’, ‘c’ and ‘d’ are based on recycled materials and AM process. From route ‘d’ to route ‘a’ is the AM transformation process that makes the whole process more agile with less dependencies from supply chain processes.

CRM model widely cover collection, recycling and manufacturing processes. Each of C, R, and M sub-model is evaluated against key factors, and the objectives can be represented as followed;

**C-zone - Collection sub-Model**

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

\[
- \sum_{i=1}^{n} f_i \times (M_i + A_i) - \sum_{i=1}^{n} (f_i \times M_i) \times (\sum_{j=1}^{m} f_j \times (t_{ij} + e_{ij}) \times d_{ij})
\]

("-" sign denotes profit loss)

- \(M_i\): Materials at \(i^{th}\) site MRF ready for Recycling

- \(A_i\): Amortization cost at \(i^{th}\) site MRF facility setup fee including land cost

- \(t_{ij}\): unit cost of transportation ($/ton-km) for the original waste site \(i\) to travel from facility \(j-1\) to \(j\) at \(i^{th}\) site

- \(e_{ij}\): CO2 emission (ton of CO2/ton of materials) caused by transportation for the \(i^{th}\) site to travel from facility \(j-1\) to \(j\)

- \(d_{ij}\): distance (km) from facility \(j-1\) to \(j\) at \(i^{th}\) MRF site (source to sink)

**R-zone - Recycling sub-Model**
Objectives: Maximize Materials recovery ratio, and minimize Energy consumption and CO2 emission

\[ \sum_{i=1}^{n} f_i \times ((M_{OUT,i} - M_{IN,i}) + (E_{Combustion,i} - E_{IN,i} - \hat{e}_i)) \]

\( M_{IN,i} \): Materials input at i\(^{th}\) site MRF  \( M_{OUT,i} \): Materials output at i\(^{th}\) site MRF

\( \hat{e}_i \): CO2 emission (ton of CO2/ton of materials) caused by recycling process

\( E_{IN,i} \): Energy consumption in recycling process  \( E_{Combustion,i} \): Energy recovery in recycling through combustion

M-zone - Supply chain and Manufacturing sub-Model

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

\[-(\sum_{i=1}^{n} f_i \times (M_{inbound,i} + M_{outbound,i}) \times (t_{i,j} + e_{i,j}) \times d_{i,j})\]

(“-” sign denotes profit loss)

\( M_{inbound} \): Materials transfer from supplier to manufacture  \( M_{outbound} \): transfer from manufacture to supplier

\( t_{i,j} \): unit cost of transportation ($/ton-km) to travel from facility j-1 to j at i\(^{th}\) site

\( e_{i,j} \): CO2 emission (ton of CO2/ton of materials) caused by transportation to travel from facility j-1 to j

\( d_{i} \): distance (km) between supplier and manufacturer

M-zone - Additive Manufacturing sub-Model

Objectives: Maximize AM Product yield ratio and quality, and minimize Energy consumption and CO2 emission

\[ \sum_{i=1}^{n} f_i \times ((M_{OUT,i} - M_{IN,i} - M_{NEW,i}) - (E_{IN,i} + \hat{e}_i)) \]

\( M_{IN,i} \): Recycling Materials input at i\(^{th}\) site of AM  \( M_{OUT,i} \): output of AM  \( M_{NEW,i} \): New resin of AM

\( \hat{e}_i \): CO2 emission in AM process  \( E_{IN,i} \): Energy consumption (mWh/ton) in AM process

M-zone - Conventional Manufacturing sub-Model

Objectives: Maximize CM Product yield ratio and quality, and minimize Energy consumption and CO2 emission

\[ \sum_{i=1}^{n} f_i \times ((M_{OUT,i} - M_{IN,i} - M_{NEW,i}) - (E_{IN,i} + \hat{e}_i)) \]

\( M_{IN,i} \): Recycling Materials input at i\(^{th}\) site of CM  \( M_{OUT,i} \): output of CM  \( M_{NEW,i} \): New resin of CM

\( \hat{e}_i \): CO2 emission in CM process  \( E_{IN,i} \): Energy consumption (mWh/ton) in CM process
III-2 Concept of Design for Recycle

Sustainability and cost saving are vital to recycling process. Hence, when products are designed to be recycled easier, it takes less effort and consumes less energy for the subsequent processes once the products reach end of life (EOL) requires starting its new entry to CRM model.

The “Design For Recycle” (DFR) is a critical concept to AM due to the nature of its design flexibility and adaptability to local recycling and local manufacturing. Localization supports DFR as all entities can be aligned and locally build up a close-loop cycle easily. For instance; AM designers can easily collaborate with their local market for how to maximize each part’s coverage and simplify assembly. In the other hand, producers can determine which parts need maintenance or recycling, and improve the design through a completely controllable close-loop cycle.

III-3 Localization through Local Recycling and Manufacturing

A robust integration between materials recycling and AM enables AM’s capability in localization that CM hard to achieve. This seamless integration also eliminates the dependencies of supply chain from AM, and ultimate values AM has been bringing-in. Elimination of engagement and logistics through local recycling and manufacturing means saving transportation cost and CO₂ emission. Consequently, transportation cost, supply chain cost and delivery timeframe can be reduced.

Compared to domestic suppliers or domestic manufacturers, local manufacturing delivered by land (truck or rail) can save huge transportation cost. In the previous session, the simple example demonstrates local recycling/manufacturing of AM reduces product life cycle, saves 25 times of transportation cost and the associated CO₂ emission.

The transformation stages are demonstrated in Figure 9. The origin of transformation started with CM, relying inbound suppliers on materials and parts components. A centralized AM doesn’t demand parts supplier and reduce dependencies on manufacturers. Distributed AM further reduce centralized manufacturers and outbound distributors and finally, local AM minimizes the gap between suppliers, manufacturers and end-users, and build a concrete foundation of sustainable manufacturing through location.

![Figure 9. Transformation from central manufacturing to localization](image-url)
AM is one of the best assets for a wide coverage of functions, shapes and versatile of highly complex products. For instance, it is increasingly used in the medical industry that requires high degree of customization, such as dental molds or personalization in prosthetics. In the automotive and aerospace industry, the technology is widely used in those light-weighted parts to save energy, and to make replacement components or parts for different types of products. In sustainable manufacturing, AM can be the best choice for rapid prototyping as it offers flexibility to make necessary changes in a most rapid and cost-effective manner. Based on the requirements and materials applied, 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. These are the unique merits and differentiators that AM can easily take over the associated market.

AM applies computer-aided design (CAD) file and converted stereo-lithography (STL) file to hold the information of triangles and sliced shape of each to be printed (Wong, K., and Hernandez, A., 2012). It defines objects’ design, mathematics, and reverse engineering information to be embedded in 3D CAD model (Muthu, S., Savalani, M., 2016) to make it agile. Rapid development of AM enables capability to circular economies through the concept of “Distributed Recycling via Additive Manufacturing” (DRAM) (Little, H., et al, 2020), that turn vicious circle into virtuous circle. In summary; AM commits much less time to create product prototype once CAD and STL software are ready. Compared to CM, AM commits significant waste reduction based on additive method layer by layer that only consumes the exact materials the products require. This reduces energy consumption and CO₂ emission. In addition, AM can produce a piece of part that requires an assembly of many parts from CM and contributes to energy saving through reducing the weight of final products.

In terms of flexibility, part change becomes very flexible through AM and causes less impact to other parts. It has been widely applied to deal with products that demand high complexity, particularly those with complicated shapes or colors, which CM is difficult to achieve. Easy entry can be other advantage. AM overcomes the obstacle of initial cost as it only costs $3,500 for a professional AM machine which is affordable for home business to get entry. AM is well-positioned for its high potential to replace many CM-produced products. It can become a future trend that massive local production and home-based business can shorten end-to-end process from waste collection, recycling to manufacturing. This stremlines the entire recycling process, enabling waste management one step closer to consumers, to enhance green environment.

However, AM has some disadvantages to be resolved before it becomes industry mainstream. Unlike CM, fast in parts fabrication and assembly in mass production, AM prints products layer-by-layer with low speed due to slow speed caused by a long filament’s melting time. Hence, the products are limited to premium quality, smaller quantity and smaller size. Home-based business may take advantages of AM’s easy entry and inexpensive initial cost and partially solve scaling issue. However, an advanced AM machine may cost $0.5 – 1.5 million which can be a burden. In addition, most of AM machines are limited to one type of material even though they can produce many different types of products. A best-fit machine for one product may not be perfect for the other product.
VI. Conclusions

This study aims to evaluate plastics materials recycling as well as manufacturing, to further benchmark “recycled” and “new resin” plastics, and AM against CM through the viewpoints of sustainable manufacturing. The evaluation is based on quantitative analysis in terms of materials recovery, cost saving, energy consumption and CO₂ emission towards sustainability. In addition; innovation for process improvement and qualitative analysis are also covered in this evaluation.

Novelty of this assessment covers innovation and a generic formula is derived by using Monte Carlo simulation techniques. The equation enables predicting capability hence, number of MRF and transportation distance can be evaluated through quantitative methods. In general, in a 1000km radius circle, a maximum of 90km transportation distance can achieve optimization of cost saving and elimination of CO₂ emission.

The evaluation demonstrates feasibility of synthesis between materials recycling and AM process, and a robust integration between recycling and AM through localization can be future trend eliminates supply chain, and achieve objectives this study has been aiming. Materials recovery, cost saving, elimination of transportation, energy consumption and CO₂ emission are all the motivation bridging multi-entities such as authorities, stakeholders and consumers into a robust driving force. Such driving force can be tactical factors deciding AM’s future for how soon it will become manufacturing mainstream.

In term of materials recycling; compared to new resin, recycled materials save energy and CO₂ emission up to 88%. Materials yield averaged at around 85% and 10% of material properties degrade is inevitable due to chain scission reactions caused by the presence of water and trace acidic impurities. To maintain the polymer average molecular weight and to prevent degrade during recycling, this study proposes intensive drying, nitrogen injection, degassing vacuum, and the use of agents of chain extender compounds to minimize the impacts. Overall, materials recycling are crucial in achieving “Cradle-to-Cradle” and “Zero-Waste”. In terms of recycling method, both primary recovery and secondary (mechanical) recycling are recommended. In consideration of energy source, wind/solar energy save 60% compared to conventional hydropower, hence wind and solar energies are recommended in sustainable manufacturing.

In terms of manufacturing; AM commits higher materials yield in general based on layer by layer rather than CM’s subtractive method that produces high volume of waste. In terms of energy and CO₂ emission, given that AM and CM are in same level of energy consumption, AM significantly reduces energy as, 1) It simplifies process with less steps, and many parts of CM can be combined into one part; 2) Local recycling/ manufacturing minimize supply chain and save transportation; 3) Same reason for materials saving - AM stays with a 1:1 BTF that CM may not easily achieve. Simplicity with fewer parts can be another advantage as AM minimizes cost, time and risk, and print directly without “divide and conquer” strategy required by CM.

From qualitative perspectives, AM favors prototyping, flexibility and complexity as parts change of CM requires re-design and re-molding. For AM, any change causes less impact to other parts and can deal with the products demanding high complexity, which CM has difficulty to achieve. Flexibility also distinguishes AM from its unique characteristics in prototyping that consumes much less time to create product prototype upon the readiness
of CAD and STL software. Hence, AM can fully take advantages of sharable software through cloud computing to combine parts into whole.

Similar to those emerging technologies, AM has several bottlenecks to be resolved; among all weaknesses; speed, scale and size can be the drawbacks cause delay of AM becoming manufacturing mainstream. In addition, chain scission reactions can deteriorate materials properties that need improvement.

Overall, this study recommends a full adoption of materials recycling and suggests starting AM from best-fit technologies and products. Meanwhile, it identifies limitations of AM that require enhancements. This study further demonstrates feasibility and methods of process innovation, through the illustration of MRF-Distance generic equation, for how the bottleneck can be removed, so that sustainable manufacturing can be realized.

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