Additive Manufacturing Thermoplastic Recycling: Profit-driven Planning and Optimization

Lei Di[1], Yiran Yang[1*], Shuo Wang[2]

[1] Department of Industrial, Manufacturing, and Systems Engineering, University of Texas at Arlington, Arlington, Texas, USA

[1] Department of Mechanical and Aerospace Engineering, University of Texas at Arlington, Arlington, Texas, USA

* Corresponding author. Email: yiran.yang@uta.edu

Abstract

Additive manufacturing (AM) technologies have been implemented in a wide range of industries owing to the unique capabilities in manufacturing complexity, design freedom, reduced material waste, and potential cost-savings. Thermoplastic is one of the most commonly used AM materials, and if not appropriately treated, its waste could cause potential environmental concerns. Hence, research studies have been conducted to recycle the AM thermoplastic wastes and reuse it back to AM production. The state-of-the-art suggests that while the feasibility has been demonstrated, the quality of recycling AM thermoplastic wastes shows degradation in multiple rounds of recycling. Therefore, to facilitate the application of high-quality AM thermoplastic waste recycling, it is important to develop and improve the recycling plans with the considerations of costs and profits. In this study, profit-driven recycling plans are developed for recycling AM thermoplastic wastes in multiple rounds based on developed cost models. Comparative case studies are performed to evaluate the expected profits using different recycling plans and different pricing strategies. Results suggest that the profit could be potentially increased by 31.02% when applying the optimized recycling plan. Results also show that profit optimization should be adjusted based on different order information with respect to order diversity among different types of wastes and filaments. This study aims to promote the sustainability of AM by generating more insights on how to recycle AM thermoplastic wastes with a high quality and a high profit.

Keywords

Additive manufacturing; Waste recycling; Sustainability

Notation List

Symbol	Definition
t	Index of workdays, $t \in \{Monday, Tuesday, \ldots Friday\}$
p	Index of the priority level, $p \in \{0,1,2\}$
i	Index of product type, $i \in \{F0, F1, F2, F3, W0, W1, W2, W3\}$
i	Index of order, $i \in \{1,2, \ldots, J\}$
J	Total number of orders of a workday
F	Filament type
W	Waste type
T	Total workdays (days)

T_{work}	Work time for each workday (min)
u	Filament manufacturing rate (kg/min)
μ	Material utilization rate (%)
P	Power of the system (W)
$CapIn$	Inventory capacity (kg)
CT	Maintenance time to change the material (min)
C	Unit cost ($/kg)
LS	The life span of a machine (years)
T_{Prep}	Setup time for fabrication (min)
MC	Material cost ($/kg)
MP	Market price ($/kg)

1. Introduction

Additive manufacturing (AM), also known as 3D printing, has revolutionized the manufacturing industry by enabling the creation of complex and customized objects on demand. Compared with traditional manufacturing, AM has several advantages of offering greater design flexibility, faster product development, and more sustainable manufacturing processes. With AM, there are fewer design constraints, as objects can be built layer by layer rather than requiring molds. AM produces less waste than traditional manufacturing, which reduces the environmental impact of manufacturing and can also lead to cost savings. In addition, AM allows for the creation of objects on demand, eliminating the need for large inventories or long lead times. It can be particularly useful in industries such as healthcare, where customized products may be needed quickly. AM can be more cost-effective than traditional manufacturing methods for small production runs because it eliminates tooling time and human interaction.

There are a variety of polymers that can be used in AM, depending on the specific application and desired properties of the final product, including polylactic acid (PLA) (Anderson, 2017; Cruz Sanchez et al., 2015), acrylonitrile butadiene styrene (ABS) (Mohammed et al., 2019, 2018). nylon, polycarbonate (PC) (Reich et al., 2019), polyethylene terephthalate (PET) (Shen et al., 2010; Woern et al., 2018), and other polymers (Woern and Pearce, 2017). Specifically, PLA is a biodegradable and compostable thermoplastic derived from renewable resources, such as corn starch. It is commonly used in 3D printing due to its ease of use, low toxicity, and ability to produce high-quality prints with good dimensional accuracy(Chen et al., 2020; Tang et al., 2016). ABS is a tough and durable thermoplastic that is widely used in AM. It is known for its high impact resistance, heat resistance, and versatility in terms of surface finish and color. Nylon is a strong and flexible thermoplastic that is commonly used in 3D printing. It is known for its high strength-to-weight ratio, durability, and ability to produce intricate and detailed prints. PC is a thermoplastic known for its high impact resistance, clarity, and heat resistance. It is commonly used in applications that require high toughness and transparency, such as automotive parts and medical equipment.

While AM has many advantages and wide applications, it still generates waste from various manufacturing stages. Several reasons may lead to waste in the thermoplastic AM process shown as follows. (1) Support structures: In some cases, support structures may need to be printed alongside the main object to ensure that it is stable and to prevent it from collapsing during printing. These support structures are removed after printing, resulting in waste. (2) Failed prints: When a print job fails or is not up to the required standard, the object may need to be discarded. This can result in the waste of the polymer material used to print the failed object. (3) Excess material: During the printing process, the excess thermoplastic material is often used to ensure that the object being printed adheres to the build platform and that there are no gaps or holes in the final product. This excess material is typically removed after printing, resulting in waste.

Without proper treatment, thermoplastic waste generated in AM process may cause serious environmental issues. According to the results of the global plastic outlook in 2022, it is estimated that the amount of plastic waste generated globally has doubled from 2000 to 2019 to 353 million tons, and 9% of plastic waste is recycled and 22% is mismanaged in the worldwide range (*Glob. Plast. Outlook*, 2022). Such a large amount of thermoplastic waste is landfilled, which leads to negative influences on terrestrial and aquatic ecosystems (Kumar et al., 2021). As a result, there has been a growing research interest in recycling the polymer used in AM process. Multiple approaches have been applied in recycling AM polymer waste including the mechanical approach, chemical approach, and thermal recycling. Based on the literature review, the opportunities of AM in the circular economy are feasible but beginning to be explored (Colorado et al., 2020; Cruz Sanchez et al., 2020; Fico et al., 2022; Mikula et al., 2021). Researchers discuss the mechanical, thermal, and chemical recycling methods that can be used to convert waste plastics into 3D printing filaments. A research study has developed a recycling solution that produces filament from PLA waste, indicating the feasibility of mechanical and chemical recycling (Shen et al., 2010). The study also compared the different recycling approaches, presenting that mechanical recycling provides better environmental impacts than chemical recycling by saving more energy consumption and causing less greenhouse gas emissions. A recycling system with a feed tube is designed and used to recycle the granulated polyethylene terephthalate (Little et al., 2020). The optimal process parameters are investigated based on the thermal properties of the fabricates manufactured by the recycled filament. Research studies have proved that it is feasible to recycle thermoplastics as AM filaments.

Research efforts have been made to investigate material properties degradation over the course of multiple recycling cycles. Tensile, compression, flexion, and microhardness test are performed to investigate the mechanical properties of recycled ABS in multiple recycling cycles (Vidakis et al., 2020). It is found that the mechanical properties increase by an average of 30% in the first third recycling courses and rapidly decrease after the fifth recycling cycle. The degradation of mechanical properties is also observed in other research studies (Chacón et al., 2019; Czyżewski et al., 2018; Hirayama and Saron, 2018; Mohammed et al., 2020; Woern et al., 2018). In addition, some solutions have been studied to avoid the issue caused by thermal degradation in AM thermoplastic recycling. In specific, continuous fiber is used to reinforce the thermoplastic composites (Chacón et al., 2019). The results show that carbon fiber-reinforced composites have higher values of strength and stiffness. Another study investigates the reinforcing effect of continuous fiber on different thermoplastics in AM recycling. It is shown that the recovery of PET fiber can reach 100% and the rate of PLA is 83%. The tensile strength increases by 117.8% when the fiber is added to the recycling process. Carbon fiber is used to reinforce the AM polymer filament during its recycling process (Huang et al., 2020). It is measured that the parts fabricated with 10 wt% carbon fiber have 10.18% higher flexural strength and 26.21% higher flexural modulus. Results from similar studies also indicate that carbon fiber-reinforced AM leads to an increase in conductivity and potential benefit in environmental impact and cost (Rahimizadeh et al., 2019; Tian et al., 2017b, 2017a). Although recycling may lead to material degradation, it is potentially worth exploring its economic benefits.

Limited studies have been made on the recycling plan of AM filament from the perspective of the manufacturer. A conceptual model of a closed-loop supply chain network to produce 3D printing filament is presented in the paper (Pavlo et al., 2018). The distributed plastic recycling network presented in the paper indicates the feasibility of model, optimization, or stochastic programming of the closed-loop supply chain that fabricates the AM filament. It is also indicated that there is a potential benefit to the economy and the environment. In another research study, numerical case studies are performed on the closed-loop circular supply chain that manufactures 3D printed products using both virgin and recycled material (Sun et al., 2020). The results show how 3D printing platforms and material suppliers in a circular supply chain should price their products and material based on real-life data. The pricing strategy derives the prices, demand, and profits of the platform as well as both the virgin and recycled material. In addition, the optimization of route design for a closed-loop supply chain network for plastic recycling is performed from a logistic perspective (Santander et al., 2020). The proposed model uses the real-world data of 3D printing wastes generated from local secondary schools in a specific area in France. Results indicate the huge potential benefit both economically and environmentally. However, there is a lack of research in the profit analysis of manufacturing the AM filament and collecting the waste from the customer simultaneously. Based on the literature review, no studies have been performed on the recycling planning for multiple cycles for AM thermoplastic filament.

Calculating the economic benefits of a recycling plan for multiple cycles of AM filament can be complicated. First, the cost of raw materials for recycled 3D printing filaments can vary significantly depending on the source and quality of the plastic waste. Additionally, the process of sorting and pre-processing the plastic waste can be time-consuming and labor-intensive, which can add to the overall cost. Second, multiple recycling rounds have different fabrication times, recycling ratios, and material recycling rates. It makes it difficult to predict the economic benefits of a recycling plan, especially over multiple cycles. Third, the price of recycled AM filament can be volatile and can fluctuate based on factors such as supply and demand, production capacity, and geopolitical events. In addition, the market demand for recycled filaments can be difficult to predict, which makes it challenging to calculate the potential benefits of recycling planning for recycling 3D printing filaments. Different pricing strategies may lead to a significant influence on the profit analysis of the recycling plan for AM filament. To address the knowledge gap and overcome the challenges, this paper aims to formulate the profit and the cost of a supply chain for fabricating AM filament with multiple recycling rounds. The inventory of the products and the raw materials is considered in this work. An optimization algorithm is applied to the model to manufacture the AM filament with the max profit. And different pricing strategies are considered in the case study. The comprehensive model established in this work gives realistic guidance to the manufacturer on how the recycling plan for AM filament is made.

The rest of the paper is organized as follows. The problem formulation and the optimization method are introduced in Section 2. Section 3 includes the case stud results. In addition, the conclusion and future research will be introduced in Section 4.

2. Problem Formulation

In this research, a mechanical recycling facility that processes 3D printing thermoplastic wastes is studied. The objective of this research is to obtain the optimum daily recycling plans (or sequences) for this facility to achieve maximum profit. To achieve this goal, the AM thermoplastic recycling process is first illustrated in Section 2.1, the recycling costs are modeled in Section 2.2, and the optimization problem is formulated in Section 2.3.

2.1 Illustration of AM Thermoplastic Recycling

The AM thermoplastic recycling process is illustrated in Figure 1. In Figure 1 (a), 3D printing wastes such as failed parts, support structures, wasted filaments, and abandoned parts are generated, possibly due to machine errors, inappropriate geometry designs, or improper process parameter settings. These wastes are collected, cleaned, and cut into uniform-sized pellets in Figure 1 (b). The waste pellets are then heated, extruded, and cooled to form filaments via the extruder in Figure 1 (c), the air path in Figure 1 (d), and the spool in Figure 1 (e). The recycled filament is then used back in AM for fabricating parts.

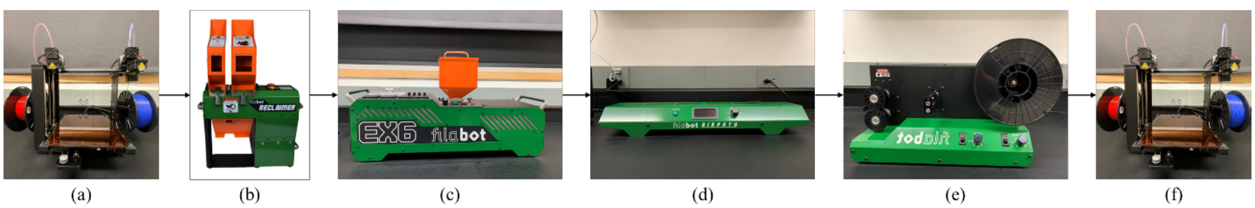

Figure 1. Illustration of AM thermoplastic recycling process

Existing research studies show a certain level of mechanical degradation in parts fabricated using recycled filament, in comparison with parts fabricated using new filament. Also, the mechanical degradation caused by recycling becomes worse with an increasing number of recycling times.

2.2 Recycling Cost Model Formulation

To model the recycling cost, a few assumptions are adopted in this research.

(1) The recycling facility offers the fabrication of new filament (using virgin material pellets) and the fabrication of recycled filament (using collected wastes). At the recycling facility, four types of filaments can be made, including new filament F0, first-time recycled filament F1, second-time recycled filament F2, and third-time recycled filament F3. Any recycling times that are greater than three are not considered in this research due to the unsatisfactory quality and consistency of the recycling and the 3D printing.

(2) The recycling facility accepts two types of orders. i.e., picking up waste from customers and delivering filaments to customers. When a customer places an order, this customer can choose to just place a pick-up order, a delivery order, or both.

(3) Customers are responsible for correctly labeling the 3D printing as "new waste" (waste generated from new filament), "first-time recycled waste", "second-time recycled waste", and "third-time recycled waste". The third-time recycled waste will not be recycled at the facility, but rather, it will be disposed of strictly following all relevant regulations.

(4) Customers pay the facility for filament purchase and delivery, depending on the order filament type and the delivery speed. Orders with different required delivery speeds will be assigned a different level of priority. On the other hand, customers receive incentives when they order waste pickup, depending on the waste type.

(5) For the utility, the material used to fabricate each type of filament is sufficient, assuming the manufacturer has run the service for a long time and the inventory is relatively steady.

(6) The study focuses on the fabrication plan at the manufacturer site. The delivery process is not considered because it is performed beyond the range of the manufacturer site.

Total cost in a time T of includes electricity cost EC, overhead cost OC, labor cost LC, and material cost MC.

$$TC(T) = EC(T) + OC(T) + LC(T) + MC(T) \tag{1}$$

Let $\boldsymbol{i} \in \{\boldsymbol{W0}, \boldsymbol{W1}, \boldsymbol{W2}, \boldsymbol{W3}, \boldsymbol{F0}, \boldsymbol{F1}, \boldsymbol{F2}, \boldsymbol{F3}\}$ is the index of the type of material or filament. Let $\boldsymbol{t} \in [\boldsymbol{1}, \boldsymbol{T}]$ be the index of the workday. $\boldsymbol{p} \in [\boldsymbol{1}, \boldsymbol{3}]$ is the index of the priority level. $\boldsymbol{j} \in [\boldsymbol{1}, \boldsymbol{J}]$ is the index of the order to be manufactured in a workday. $\boldsymbol{MT}$ is the index of the manufacturing date of the order.

2.2.1 Material Cost

The material cost MC includes the total cost of virgin material, the total cost of the first-time recycled waste, the total cost of the second-time recycled waste, and the total cost of the third-time recycled waste.

$$MC(T) = \sum_{MT(i_j^{t,p})=1}^{T} \sum_{j=1}^{J} \sum_{i\in\{W0,W1,W2,W3\}} W(j_i^{t,p}) \times MC_i \tag{2}$$

In this equation, MC_{W0} is the material unit cost for the pellets to fabricate the new material (USD/kg). MC_{W1} (USD/kg), MC_{W2} (USD/kg), and MC_{W3} (USD/kg) are the material cost of purchasing the waste from the customers. W is the weight of the corresponding material.

2.2.2 Electricity Cost

Electricity cost includes the power used to extrude the filament and the power used to granulate the waste material. In this study, it is assumed that the extruding machine and the granulating machine work on the rated power. The time to fabricate a unit of each material is fixed but varies from each other. The time to granulate the same amount of each material is also the same but varies from each other. It is also assumed that the unit cost of the electricity is the same during the T days.

$$EC(T) = C_{Elec} \times \sum_{MT(j_i^{t,p})=1}^{T} \sum_{j=1}^{J} \sum_{i\in\{F0,F1,F2,F3\}} W(j_i^{t,p}) \times (P_{Extr} \times u_i + P_{Gran} \times T_{Gran,i}) \tag{3}$$

In this equation, C_{Elec} is the unit cost of electricity (USD/kWh). P_{Extr} is the power of the recycling machine. u_i is the time to recycle 1kg of material i (kW). P_{Gran} is the power of the granulating machine. $T_{Gran,i}$ is the time to granulate 1kg of material i (h). These parameters are defined to calculate the total fabricating time.

2.2.3 Labor Cost

Labor cost includes the workers' wages on the manufacturing site. In specific, labor cost is calculated by the workers' hourly pay multiplied by the total process time. As stated in section 2.2.2, the time to manufacture or granulate the same amount of one type of material is the same but varies depending on the material type.

$$LC(T) = C_{work} \times (\sum_{MT(j_i^{t,p})=1}^{T} \sum_{j=1}^{J} \sum_{i \in \{F0,F1,F2,F3\}} W(j_i^{t,p}) \times (u_i + T_{Gran,i}) + \sum_{MT(j_i^{t,p})=1}^{T} \sum_{j=1}^{J} \sum_{i \in \{W0,W1,W2,W3\}} W(j_i^{t,p}) \times T_{Prep}) \tag{4}$$

In this equation, C_{work} is the worker's hourly pay (USD/h). T_{Prep} is the preparation time for recycling 1kg of material, which includes cleaning the machine, setting up the machine, and pre-processing the materials (h).

2.2.4 Overheads

Overhead cost is the average facility cost per fabrication. It includes the average cost of the granulating machine and the extruding machine. Machines are assumed to have limited working lives. The facility cost is also included in the overhead cost. The overhead cost is summarized as follows.

$$OC(T) = \left(\frac{C_{Gran}}{LS_{Gran}} + \frac{C_{Extr}}{LS_{Extr}}\right) \times \sum_{MT(j_i^{t,p})=1}^{T} \sum_{j=1}^{J} \sum_{i \in \{F0,F1,F2,F3\}} W(j_i^{t,p}) \times (u_i + T_{Gran,i}) + C_{Faci} \times T \tag{5}$$

In this equation, C_{Gran} is the cost of the granulating machine (USD). LS_{Gran} is the life span of the granulating machine (min). C_{Extr} is the cost of the recycling machine (USD). LS_{Extr} is the life span of the recycling machine (min). C_{Faci} is the rent cost for the facility (USD/day).

2.2.5 Incentive

The incentive includes the incentive of the filament with each quality level and different order priority. It is assumed that the unit price for each type of filament is different. In addition, the price is higher for orders with higher priority.

$$I(T) = \sum_{MT(j_i^{t,2})=1}^{T} \sum_{j=1}^{J} \sum_{i \in \{F0,F1,F2,F3\}} W(j_i^{t,2}) \times MP_i \times Cr_2 + \sum_{MT(j_i^{t,1})=1}^{T} \sum_{j=1}^{J} \sum_{i \in \{F0,F1,F2,F3\}} W(j_i^{t,1}) \times MP_i \times Cr_1 + \sum_{MT(j_i^{t,0})=1}^{T} \sum_{j=1}^{J} \sum_{i \in \{F0,F1,F2,F3\}} W(j_i^{t,0}) \times MP_i \quad (6)$$

In the equation, MP_i is the price for the material i (USD/kg). Cr_p is the price change ratio for urgent orders that priority level is p. In this study, $Cr_p \in [1,2], for\ p = 1,2$.

2.3 Optimization Problem Formulation

The problem aims to find a recycling plan to maximize the profit during the period T. The mathematical model can be expressed as follows.

Objective: Max $P(T)$

$$P(T) = I(T) - TC(T) \quad (7)$$

The equation indicates the relationship between the profit in T days with the total cost and the incentive in T days. The aforementioned problem is modeled in the discrete-time control system perspective and further is formulated as an optimal control problem to obtain the best daily production strategy which will: (i) the plan keeps track of the daily inventory; (ii) it meets all customers' requests with different levels of emergency; and (iii) it maximizes the utility of the production line in terms of energy cost, producing time, etc.

The daily inventory is denoted as (i.e., $In_i(ct^t)$ for each category of material waste and filament, $i \in \{F_0, F_1, F_2, F_3, W_0, W_1, W_2, W_3\}$) as the state variable of interest, $x(t) \in \mathbb{R}^8$ with the first four for filament inventory and the rest for waste inventory, with $t = 0, 1, \dots, T$. Hence, the inventory can be expressed as follows.

$$x(t+1) = Ax(t) + Bu(t) + CO(t) \quad (8)$$

$$A = I_8 \quad (9)$$

$$B = \begin{bmatrix} \mu_1 & 0 & 0 & 0 \\ 0 & \mu_2 & 0 & 0 \\ 0 & 0 & \mu_3 & 0 \\ 0 & 0 & 0 & \mu_4 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \quad (10)$$

$$C=\begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{11}$$

These are constant matrices, $O(t) \in \mathbb{R}^8$ records the order information characterized for day t based on delivery time $DT(j^{t,p})$, and $u(t) \in \mathbb{R}^4$ denotes the daily resumption for each type of material due to daily production that will be determined optimally. In this study, the inventory is restricted due to practical needs, such as the capacity and actual demand of the customers' orders. The lower and upper bounds for the state variable $x(t)$ and targeted input $u(t)$ can be rewritten as (12) and (13).

$$x_{Lower} \le Dx(t) \le x_{upper} \tag{12}$$

$$u_{Lower} \le Eu(t) \le u_{upper} \tag{13}$$

In particular, equations (12) and (13) lead to $x_{Lower}\ equals\ to\ 0$ and $u_{Lower}\ equalts\ 0$, respectively. Equation (12) provides the upper-bound for the state, i.e., $D = [1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1]$ and $x_{upper} = CapIn.$. The production limit due to time can be calculated accordingly as follows.

$$E = [u_{F1}\mu_1 \quad u_{F2}\mu_2 \quad u_{F3}\mu_3 \quad u_{F4}\mu_4] \tag{14}$$

$$u_{upper} = T_{work} - 3CT \tag{15}$$

The goal is to come up with an optimal $u(t)$ such that the total profit is maximized, where the incentive $I(x,u,T)$ is determined by the order information $O(t)$ and the cost including electricity, overhead, labor, and material are considered.

Now, the desired problem is transferred into the equations as follows.

$$\text{Objective: } \max_u P(x,u,T) = I(x,u,T) - TC(x,u,T)$$

$$= \sum_{t=0}^{T} \begin{bmatrix} \mu_1(MP_1 - MC_1 - u_{F1}C_{Elec}P_{Recy} - C_{Elec}P_{Gran}T_{Gran,1} - \frac{C_{Recy}}{LS_{Recy}}P_{Recy}u_{F1} - \frac{C_{Gran}}{LS_{Gran}}P_{Gran}T_{Gran,1}) \\ \mu_2(MP_2 - MC_2 - u_{F2}C_{Elec}P_{Recy} - C_{Elec}P_{Gran}T_{Gran,2} - \frac{C_{Recy}}{LS_{Recy}}P_{Recy}u_{F2} - \frac{C_{Gran}}{LS_{Gran}}P_{Gran}T_{Gran,2}) \\ \mu_3(MP_3 - MC_3 - u_{F3}C_{Elec}P_{Recy} - C_{Elec}P_{Gran}T_{Gran,3} - \frac{C_{Recy}}{LS_{Recy}}P_{Recy}u_{F3} - \frac{C_{Gran}}{LS_{Gran}}P_{Gran}T_{Gran,3}) \\ \mu_4(MP_4 - MC_4 - u_{F4}C_{Elec}P_{Recy} - C_{Elec}P_{Gran}T_{Gran,4} - \frac{C_{Recy}}{LS_{Recy}}P_{Recy}u_{F4} - \frac{C_{Gran}}{LS_{Gran}}P_{Gran}T_{Gran,4}) \end{bmatrix}^T u(t) \tag{16}$$

$$\text{s.t. } x(t+1) = Ax(t) + Bu(t) + CO(t) \tag{17}$$

$$x(t) \ge 0, u(t) \ge 0 \text{ and } Dx(t) \le x_{upper};\ Eu(t) \le u_{upper} \tag{18}$$

$$I(x,u,T) = [MP_1 \quad MP_2 \quad MP_3 \quad MP_4 \quad 0 \quad 0 \quad 0 \quad 0]^T x(t) \tag{19}$$

$$TC(x,u,T) = EC(x,u,T) + OC(x,u,T) + LC + MC\ (u) \tag{20}$$

$$EC(x,u,T) = C_{Elec} \cdot \begin{bmatrix} \mu_1(P_{Recy} \times u_{F1} + P_{Gran} \times T_{Gran,1}) \\ \mu_2(P_{Recy} \times u_{F2} + P_{Gran} \times T_{Gran,2}) \\ \mu_3(P_{Recy} \times u_{F3} + P_{Gran} \times T_{Gran,3}) \\ \mu_4(P_{Recy} \times u_{F4} + P_{Gran} \times T_{Gran,4}) \end{bmatrix}^T u(t) \tag{21}$$

$$OC(x,u,T) = \begin{bmatrix} \mu_1(\frac{C_{Recy}}{LS_{Recy}} \times P_{Recy} \times u_{F1} + \frac{C_{Gran}}{LS_{Gran}} \times P_{Gran} \times T_{Gran,1}) \\ \mu_2(\frac{C_{Recy}}{LS_{Recy}} \times P_{Recy} \times u_{F2} + \frac{C_{Gran}}{LS_{Gran}} \times P_{Gran} \times T_{Gran,2}) \\ \mu_3(\frac{C_{Recy}}{LS_{Recy}} \times P_{Recy} \times u_{F3} + \frac{C_{Gran}}{LS_{Gran}} \times P_{Gran} \times T_{Gran,3}) \\ \mu_4(\frac{C_{Recy}}{LS_{Recy}} \times P_{Recy} \times u_{F4} + \frac{C_{Gran}}{LS_{Gran}} \times P_{Gran} \times T_{Gran,4}) \end{bmatrix}^T u(t) \tag{22}$$

$$LC = C_{work} \times T \times T_{workday} \tag{23}$$

$$MC(x,u,T) = [\mu_1 MC_1 \quad \mu_2 MC_2 \quad \mu_3 MC_3 \quad \mu_4 MC_4] u(t) \tag{24}$$

Now, according to Pontryagon's Maximum Principle, the Hamiltonian associated with this system is defined as follows.

$$H(x,u,t) = lu + \lambda^T(Ax + Bu + Co) \tag{25}$$

In the equation, $\lambda(t) \in \mathbb{R}^8$ denotes the co-state that satisfies the following recursive law as shown in the equation.

$$\lambda(t) = A^T \lambda(t+1) \tag{26}$$

$$\lambda(T) = 0 \tag{27}$$

Hence, $\lambda(t) \equiv 0, \forall t = 0,1,\dots,T$, and then $H = lu$, which is linear with respect to the decision variable u. As a result, u is chosen as the largest possible value for each day, that is $u(t)$ must satisfy the equation as follows.

$$Dx(t) = x_{upper} \text{ and } Eu(t) = u_{upper} \tag{28}$$

2.3.1 Inventory Constraints

The total inventory includes the spaces for both raw materials and different types of filaments. The constraint limits the storage spaces for production. The constraints can be expressed using the following equations.

$$\begin{aligned} In_i(Maxt^{MT(j_i^{t,p})}) \\ &= In_i(Maxt^{MT(j_i^{t,p})-1}) + Ma_i^{MT(j_i^{t,p})} \\ &- W(j_i^{t,p}), forMT(j_{ji}^t) \in \{2,3,\dots T\}, i \in \{F0, F1, F2, F3\} \end{aligned} \tag{29}$$

The equation expresses the relationship between the inventory of the filament between two adjunct days.

$$In_i(Maxt^{MT\left(j_i^{t,p}\right)}) = In_i(Maxt^{MT\left(j_i^{t,p}\right)-1}) - Ma_i^{MT(j_i^{t,p})} + W(j_i^{t,p}), for\ t \in \{2,3, \dots T\}, i \in \{W0, W1, W2, W3\} \tag{30}$$

The equation is the relationship of the inventory for waste between two adjunct days.

$$In_i(Maxt^{MT\left(j_i^{t,p}\right)-1}) \geq \sum_{MT(i_j^t)=1}^{J} W\left(j_i^{t,p}\right), for\ t \in \{2,3, \dots T\}, i \in \{F0, F1, F2, F3\} \tag{31}$$

The constraint indicates that the inventory for each type of filament is enough for the orders to be delivered the next day.

$$In_{Fn}(T_{work}{}^{t-1}) + \mu_n \times In_{Wn}(T_{work}{}^{t-1}) \geq Ma_{Fn}^t, n \in \{0,1,2,3\} \tag{32}$$

The constraint indicates that the waste inventory on day t is enough to manufacture the amount of respective filament in the plan on day t.

$$\sum_{i=F0,F1,F2,F3,W0,W1,W2,W3} In_i(ct^t) \leq CapIn \tag{33}$$

The constraint indicates that the inventory cannot exceed a capacity amount of inventory $CapIn$.

2.3.2 Time Constraints

Two-time constraints are considered in this study. The first one is that the total manufacturing time of each day has an upper bound. The constraint indicates that the total manufacturing time of the plant has a limit $Maxt$ for each day, which is expressed in (34).

$$\Omega(t1) \leq T_{work}, t1 \in \{1,2, \dots T\} \tag{34}$$

The second time constraint considered in this study is that there are three delivery priority levels, indicating the day to deliver an order cannot exceed a specific number of days depending on the delivery priority. Three priority levels are considered in this study.

$$DT(j^{t,p}) \leq \begin{cases} t+7, p=0 \\ t+2, p=1 \\ t, p=2 \end{cases} \tag{35}$$

The constraint indicates that an order should be delivered within several days after it is submitted depending on the priority. $\Omega(t1)$ is the total manufacturing time (min) in day $t1$.

$$\Omega(t1) = \sum_{MT(j_i^{t,p})=t1} \tau\left(j_i^{t,p}\right) + \sum_{k=2}^{K} \theta(k) \times CT, j_i^{t,p} \in Se(t1) \tag{36}$$

In the equation, CT is the time to process the machine when the material is changed. $\theta(k)$ is a binary value defined as follows.

$$\theta(k) = \begin{cases} 1, if\ i_k \neq i_{k-1} \\ 0, if\ i_k = i_{k-1} \end{cases}, j_{k\,i_k}^{\,t_k,p_k} \in Se(t1) \tag{37}$$

3. Results and Discussion

In this Section, three case studies are performed to investigate the optimized recycling plan for AM thermoplastics. The first case study presents the parameters and their values applied in this study. It compares the order-driven recycling plan and the optimization recycling plan with two methods. The second case study demonstrates the optimization results based on the different order information. In the third case study, the profits of the optimized recycling plan applying different pricing strategies are discussed. The sensitivity analysis is performed on the pricing strategies considered in this study.

3.1 Baseline Case

In this case study, the daily production amount and the inventory level change in 180 days are calculated. The results are set as a baseline case. In specific, one recycling system is considered in this case study. The price of each type of filament is based on the market price. The total profits in 180 days of three production plans are calculated in this case. The first plan is the optimized production plan for daily profit. The recycling plan maximizes the daily profit. The second plan is to manufacture based on the number of orders. The third plan is the optimized production plan for 10-day profit. The recycling plan maximizes the 10-day profit. Based on the results, production plans with optimization have higher profits than the plan that manufactures the number of orders. The reason is that the optimization offers a recycling plan that maximizes profit. The daily optimization plan has a similar profit to the 10-day optimization. The profit of filament 0 in daily optimization is less than the one in 10-day optimization. The reason is that in one-day optimization, all the idle time is used to produce filament 0, which makes the cost of manufacturing filament 0 high. In the 10-day optimization, idle time is used to manufacture the filament that has the highest profit in the previous 10 days. Filaments other than filament 0 are possible to be manufactured during idle time because of this mechanism. In this case, filament 1 in the 10-day optimization has less profit than in the daily optimization. The reason is that the idle time of some days in the 10-day optimization is used to fabricate filament 1. Profits of other filaments are similar in the two optimized recycling plans. The values of the parameters are presented in Table 1.

Table 1. Values of parameters used in case studies

Symbol	**Value**	**Data source**	**Symbol**	**Value**	**Data source**
T_{Recy}	30 (min)	(Mikula et al., 2021)	C_{Recy}	14,217.00 ($)	(Filabot, 2014)
u_{F1}	22 (min/kg)	(Cruz Sanchez et al., 2017)	LS_{Recy}	5 (yr)	
u_{F2}	20 (min/kg)		C_{work}	14.31 ($/hour)	(U.S. Bureau of Labor Statistics, 2020)
u_{F3}	18 (min/kg)		C_{Gran}	7979.00 ($)	(Filabot, n.d.)
u_{F4}	16 (min/kg)		LS_{Gran}	20 (yr)	
C_{Elec}	6.44 (cents/kWh)	(EIA, 2022)	T	180 (day)	Assumed in this study
MC_{w0}	3.31($/kg)	(Kauppila, 2022)	μ_1	0.98	

MC_{w1}	3.14($/kg)	μ_2	0.96
MC_{w2}	2.98($/kg)	μ_3	0.95
MC_{w3}	2.84($/kg)	μ_4	0.93
MP_{F0}	21.99($/kg)	$CapIn$	2000 (kg)
MP_{F1}	20.89($/kg)	CT	15 (min)
MP_{F2}	19.85($/kg)	T_{Prep}	20 (min)
MP_{F3}	18.85($/kg)	$T_{workday}$	8 (hour)

The production plan for 180 days is considered. The start inventory of each type of filament is 100 kg. The inventory capacity is 2000 kg in this case. The daily recycling plan is based on the order information. With fulfilling the number ordered by the customer, the idle time of the machine is used to manufacture the filament to optimize the total profit. It is assumed that 20 customers submit random orders. In each order, the maximum amount of each type of filament is 12, 10, 8, and 6 kg for filament 0, 1, 2, and 3, respectively. The filament suffers from less level of degradation with less recycling times. The maximum amounts are assumed because customers tend to select virgin filaments because they have a wider range of applications.

In Figure 2, compared with the other two recycling plans, order-driven manufacturing has less profit during the 180 days. The profit of the daily profit-driven recycling plan is 31.02% higher than the order-driven plan. And the profit of the 10-day profit-driven plan is 27.89% higher than the order-driven plan. The reason is that the latter two fabrication plans manufacture the filament in idle time, which leads to the potential inventory values. In this case, the profit of the daily profit-driven recycling plan is higher than it of the 10-day profit-driven plan. However, the different order amounts will lead to a change in profit, and this will be discussed in Section 3.2.

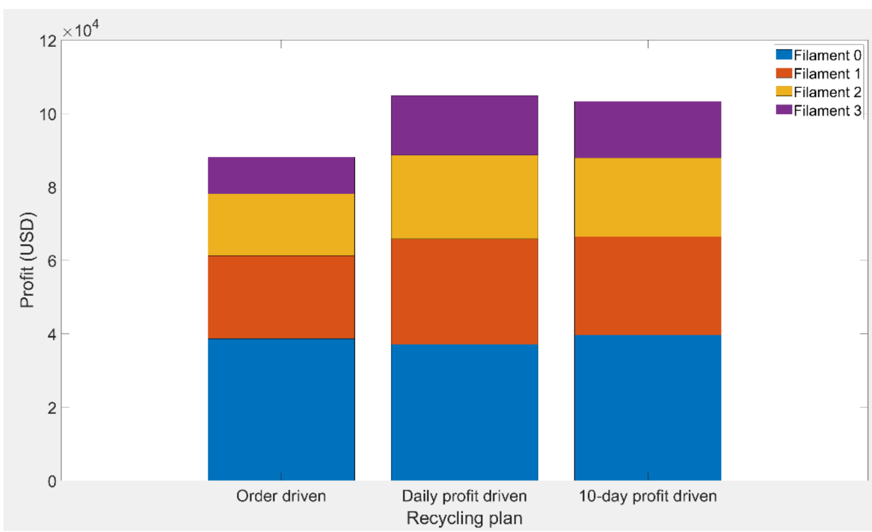

Figure 2. Profit of each recycling plant

To compare the daily profit driven and the 10-day profit-driven plan, the recycling plan for each day is presented in Figure 3. 60 days of the plan are presented in Figure *4*, It is noticed that in the daily profit-driven plan, the preference in the build-ahead production for filament 0 is higher than other types of the filament. The reason is that filament 0 has a higher unit profit than other types of filament. If the inventory capacity is not reached, making as much filament 0 as possible will maximize the daily profit. However, when the inventory capacity is almost reached, some types of other filaments are made during the left-over time. In the 10-day profit-driven plan, it is presented that the preference of the build-ahead production changes every 10 days. It is also noticed that the profit of filament 0 for the daily profit-driven recycling plan is less than the number in the 10-day profit-driven plan. The reason is that when the plan decides to fabricate more of a specific type of filament, the total cost of that type of filament increases, which decreases the average profit of the type. It is noticed that the product diversity of the 10-day profit plan is better than the daily profit-driven recycling plan because of the change of preference for build-ahead production every 10 days. Product diversity refers to the variety of products that a company offers. There are different ways to calculate product diversity, but one common approach is to use a measure called the Herfindahl-Hirschman Index (HHI). The HHI is a widely used measure of market concentration that is also applicable to measuring product diversity, which is calculated by the equation (38). The HHI of the daily profit-driven recycling plan is 0.27, and the number of the 10-day profit-driven recycling plan is 0.30, which indicates that the product diversity of the 10-day profit-driven recycling plan is better.

$$HHI = \sum_{i=F0,F1,F2,F3} {\frac{Profit(i)}{Totalprofit}}^{2} \quad (38)$$

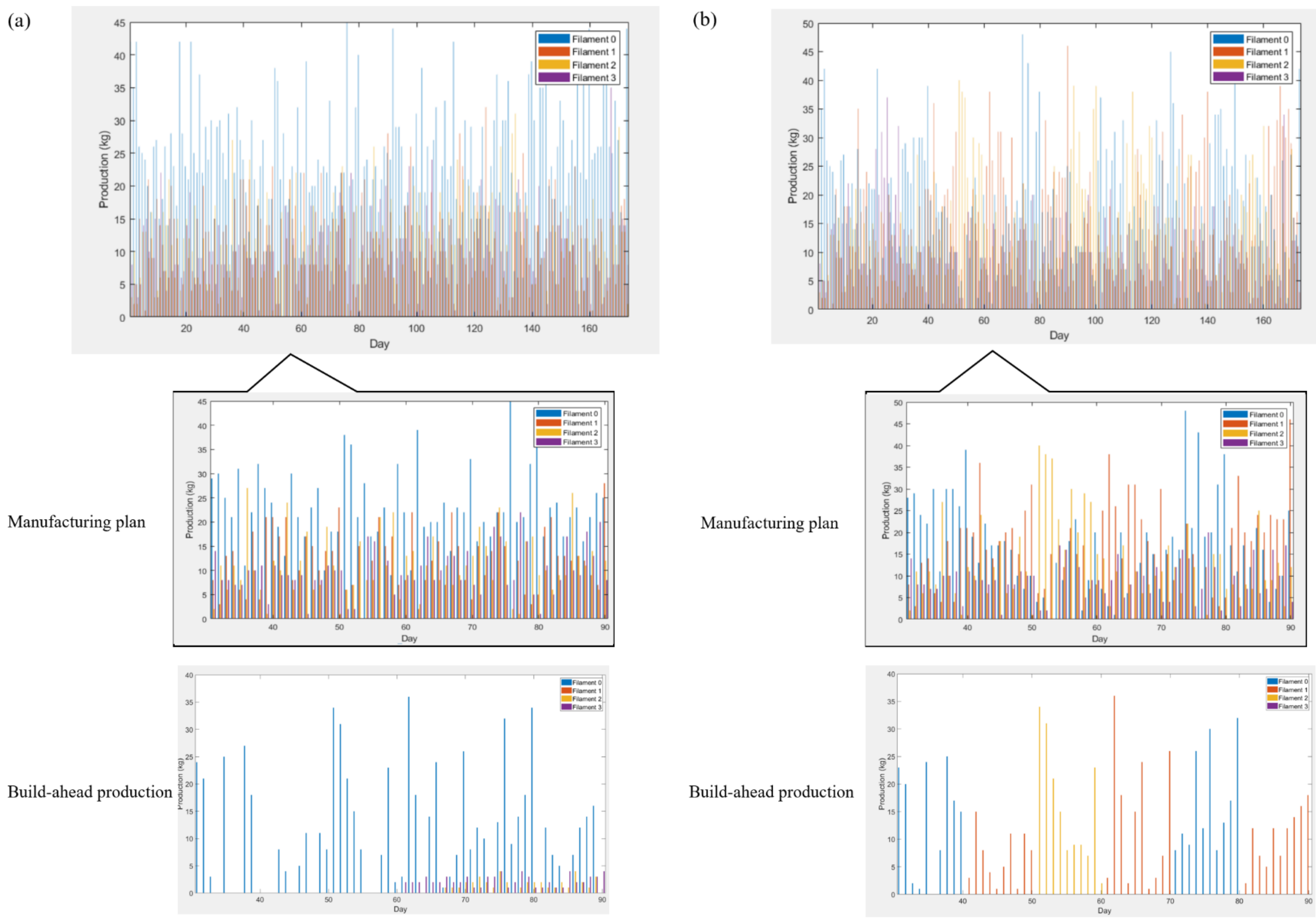

Figure 3. Production plan for each type of filament, (a) daily profit-driven recycling plan, (b) 10-day profit-driven recycling plan

3.2 Profit for Different Order Information

In this case, the influence of the order information pattern on the total profit is investigated. It is noticed that in some cases, the profit of a daily profit-driven recycling plan does not guarantee optimized profit over a period of days because it only considers the profit earned in each individual day, without taking into account any potential interdependencies or long-term effects such as inventory cost, customer preferences, and changes in the product quality, etc.

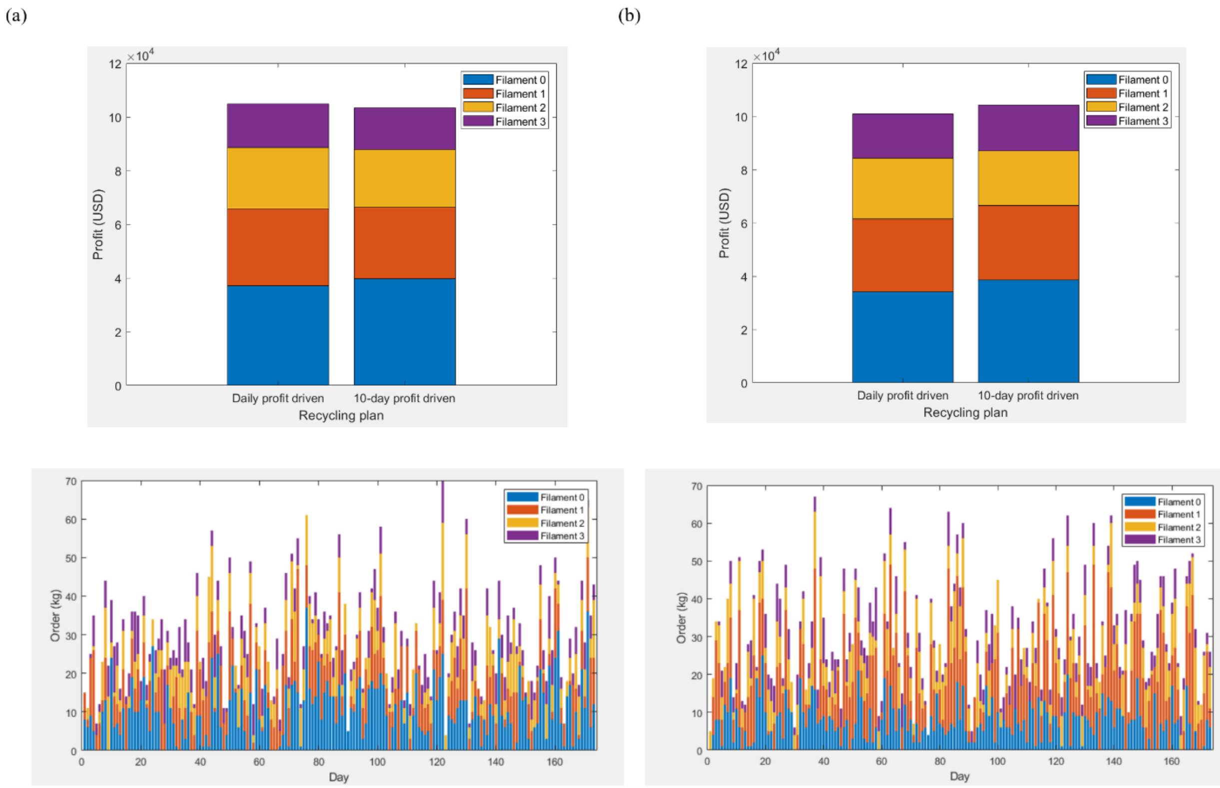

Figure 4. Profit for different order information

Figure 4 presents the profit comparison of the two methods based on two different order information. It is observed that in Figure 4 (a), the daily profit-driven recycling plan has a higher profit than the 10-day profit-driven. However, in Figure 4 (b), the 10-day profit-driven recycling plan has the higher profit. By comparing the order information, it is noticed that the order amount for filament 0 in Figure 4 (a) is higher than the number in Figure 4 (b). The increased order amount for filament 0 will lead to the generation of revenue for the build-ahead productions. As discussed in Section 3.2, the daily profit drive recycling plan has the preference of fabricating the filament 0. If in the order, the number of filament 0 dominates, it is recommended to select a daily profit-driven recycling plan. However, if customers prefer to order more recycled filaments, selecting 10-day profit-driven manufacturing will result in higher profit.

3.3 Profit for Different Pricing Strategies

In this case study, profit analyses are performed based on different pricing strategies. Four pricing strategies are considered in this case study. The first strategy is applying the market price. The price of the filaments is set based on the prevailing market conditions and the prices that competitors are charging for similar products or services. The second pricing strategy is using the profit margin price. It includes the cost of producing or acquiring the product, as well as any other expenses associated with delivering it to customers. The third pricing strategy is applying the bulk price. The strategy offers discounts to customers who purchase products or services in large quantities. The last strategy is the value-based pricing strategy. In this section, the transportation speed is selected as the value of the service. The strategy involves setting prices based on the perceived value that customers place on the speed of transportation. Some customers may be willing to pay more for faster shipping or transportation options. In this strategy, customers pay more if the order is delivered in less time. In this section, 10-day profit-driven recycling plan is considered for each pricing strategy.

Figure 5 presents the results of profit for each pricing strategy and the result where the number of orders increased by 40%. Specifically, with the amount of the order increasing by 40%: the profit in market price increases by 43.61%; the profit of the profit margin pricing strategy increases by 44.53%; the profit of the bulk price strategy increases by 36.59%; and the profit of value-based increases by 43.91%. The reason why the profit bulk pricing strategy increases less than other strategies is that more amount of orders leads to more discount for bulk pricing strategies.

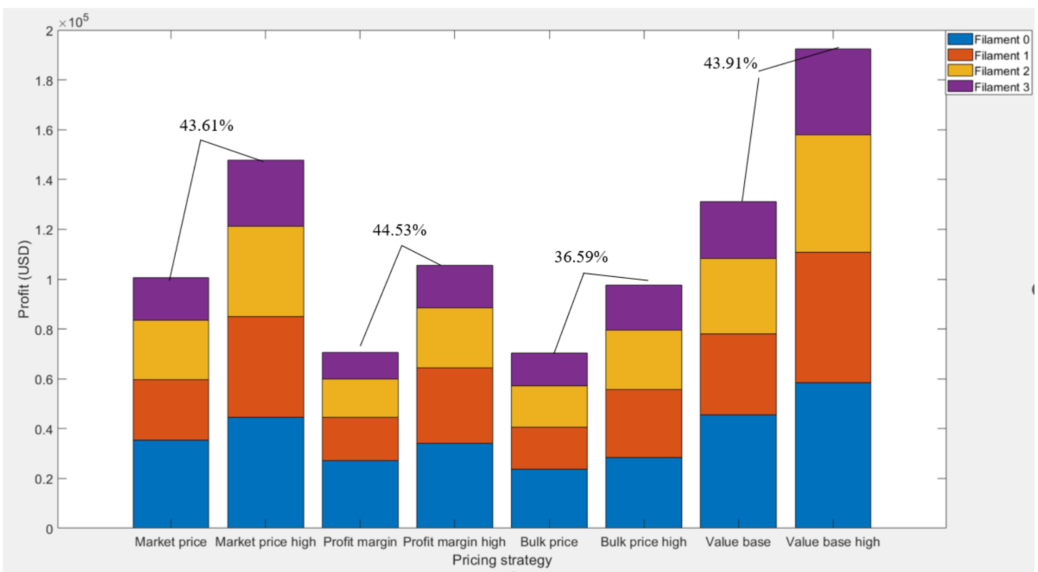

Figure 5. Profit from each pricing strategy

In addition, sensitivity analysis for material cost is performed for each pricing strategy. As shown in Figure 6, t is observed that by changing the material cost by 20%, the profit change for each pricing strategy is 3.62%, 9.19%, 12.79%, and 6.41%, correspondingly. The results indicate that the profit margin pricing strategy is more sensitive to the material price.

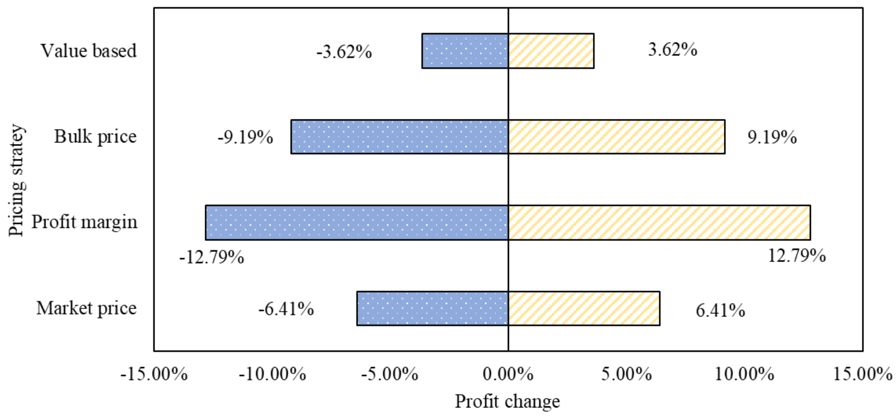

Figure 6. Sensitivity analysis on material cost

The sensitivity analysis on the electricity cost is presented in Figure *7*. It indicates that the profit changes for each pricing strategy by changing the electricity cost by 20%. The results show that the profit margin pricing strategy is still more sensitive to the energy cost compared with other pricing strategies, where a 20% change in electricity unit price results in a 5.58% change in the profit.

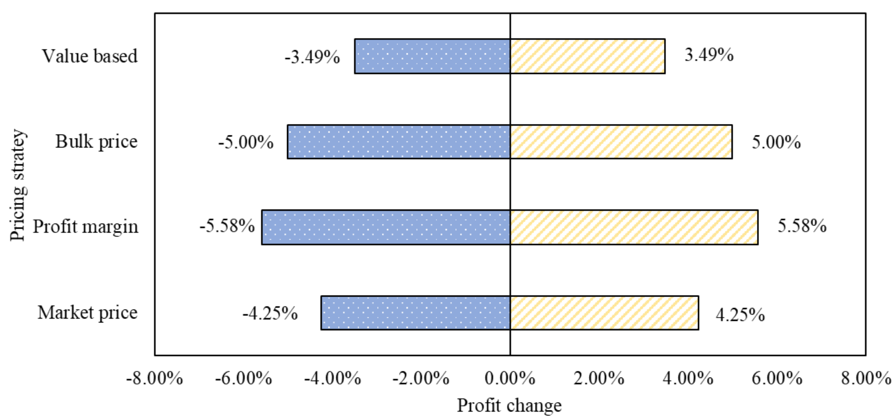

Figure 7. Sensitivity analysis on energy cost

4. Conclusions and Future Work

With the fast development of AM, investigating recycling plans for AM thermoplastics is a responsible and sustainable approach that can benefit both the environment and the industry. The goal of this paper is to develop a cost-effective supply chain for producing am filament using various types of waste materials. The paper proposes an optimization algorithm to maximize profits in the production process. Based on the results of the case studies, it is recommended to apply the recycling plan that contains the build-ahead productions. The profit of the daily profit-driven recycling plan can be is 31.02% higher than the order-driven recycling plan and the profit of the 10-day profit-driven can be 27.89% higher. It is noticed that if the amount order of filament is 0 dominants, selecting the daily profit-driven manufacturing will result in higher overall profit. If the demand for recycled filaments increases, selecting a 10-day profit-driven recycling plan may lead to higher profit. In addition, different pricing strategies are compared in the case study. Among the pricing strategies, the profit margin price is more sensitive to the material price. Results also indicate that the profit margin pricing strategy is more sensitive to the electricity price compared with other pricing strategies.

The results of this study can be used in multiple aspects. The profitability analysis identifies the key cost drivers in the manufacturing process, including the cost of raw materials, labor, equipment, and energy. This information can be used to optimize the production process and reduce costs. It helps to identify the key cost drivers in the manufacturing process, including the cost of raw materials, labor, equipment, and energy. The information can be used to optimize the production process and reduce costs. The results can be used to evaluate the performance of the recycling plan against established targets and benchmarks. It can help identify areas of improvement and optimize the production process for maximum profitability. By understanding the costs of production, the pricing strategy can be developed to ensure profitability while remaining competitive in the market. The cost-benefit analysis provides decision-makers with a clear understanding of the financial implications of different decisions related to the recycling plan. This can help ensure that decisions are based on sound financial considerations and can optimize profitability. Future work should be focused on the potential areas of research and development that can further enhance the effectiveness and sustainability of the production process. The cost model now has multiple assumptions to simplify the calculations. Future works can be applied to the model with more real-world data and nonlinear relationships to better simulate the situations.

References

Anderson, I., 2017. Mechanical Properties of Specimens 3D Printed with Virgin and Recycled Polylactic Acid. 3D Print. Addit. Manuf. https://doi.org/10.1089/3dp.2016.0054

Chacón, J.M., Caminero, M.A., Núñez, P.J., García-Plaza, E., García-Moreno, I., Reverte, J.M., 2019. Additive manufacturing of continuous fibre reinforced thermoplastic composites using fused deposition modelling: Effect of process parameters on mechanical properties. Compos. Sci. Technol. https://doi.org/10.1016/j.compscitech.2019.107688

Chen, X., Chen, G., Wang, G., Zhu, P., Gao, C., 2020. Recent Progress on 3D-Printed Polylactic Acid and Its Applications in Bone Repair. Adv. Eng. Mater. https://doi.org/10.1002/adem.201901065

Colorado, H.A., Velásquez, E.I.G., Monteiro, S.N., 2020. Sustainability of additive manufacturing: the circular economy of materials and environmental perspectives. J. Mater. Res. Technol. https://doi.org/10.1016/j.jmrt.2020.04.062

Cruz Sanchez, F.A., Boudaoud, H., Camargo, M., Pearce, J.M., 2020. Plastic recycling in additive manufacturing: A systematic literature review and opportunities for the circular economy. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2020.121602

Cruz Sanchez, F.A., Boudaoud, H., Hoppe, S., Camargo, M., 2017. Polymer recycling in an open-source additive manufacturing context: Mechanical issues. Addit. Manuf. https://doi.org/10.1016/j.addma.2017.05.013

Cruz Sanchez, F.A., Lanza, S., Boudaoud, H., Hoppe, S., Camargo, M., 2015. Polymer Recycling and Additive Manufacturing in an Open Source context : Optimization of processes and methods, in: Proceedings of Solid Freeform Fabrication Symposium.

Czyżewski, P., Bieliński, M., Sykutera, D., Jurek, M., Gronowski, M., Ryl, Ł., Hoppe, H., 2018. Secondary use of ABS co-polymer recyclates for the manufacture of structural elements using the FFF technology. Rapid Prototyp. J. https://doi.org/10.1108/RPJ-03-2017-0042

EIA, 2022. Electric Power Monthly [WWW Document]. URL https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

Fico, D., Rizzo, D., Casciaro, R., Corcione, C.E., 2022. A Review of Polymer-Based Materials for Fused Filament Fabrication (FFF): Focus on Sustainability and Recycled Materials. Polymers (Basel). https://doi.org/10.3390/polym14030465

Filabot, 2014. FILABOT EX6 FILAMENT EXTRUDER - STANDARD SERIES [WWW Document]. URL https://www.filabot.com/collections/filabot-core/products/filabot-ex6-filament-extruder?gclid=Cj0KCQjwhLKUBhDiARIsAMaTLnF63QQ0MfuaR9mR8K9iA2_nHCnk_we6NONoOUs4ZSgnHGqpmCAyiR0aAoQzEALw_wcB

Filabot, n.d. FILABOT RECLAIMER [WWW Document]. URL https://www.filabot.com/products/filabot-reclaimer-1?variant=33063213039691&currency=USD&utm_medium=product_sync&utm_source=google&utm_content=sag_organic&utm_campaign=sag_organic&gclid=CjwKCAjwrJ-hBhB7EiwAuyBVXVHYFUEQI2yKkKfezIDv6ja2QtZHmKS5yYABqvDaJDg0ftcGFgbI8RoC1yQQAvD_BwE

Global Plastics Outlook, 2022. , Global Plastics Outlook. https://doi.org/10.1787/de747aef-en

Hirayama, D., Saron, C., 2018. Morphologic and mechanical properties of blends from recycled acrylonitrile-butadiene-styrene and high-impact polystyrene. Polymer (Guildf). https://doi.org/10.1016/j.polymer.2017.12.038

Huang, H., Liu, W., Liu, Z., 2020. An additive manufacturing-based approach for carbon fiber reinforced polymer recycling. CIRP Ann. 69, 33–36. https://doi.org/10.1016/j.cirp.2020.04.085

Kauppila, I., 2022. The Best Pellet 3D Printers & Extruderse [WWW Document]. URL https://all3dp.com/1/cheaper-3d-printing-with-pellets/

Kumar, Rakesh, Verma, A., Shome, A., Sinha, R., Sinha, S., Jha, P.K., Kumar, Ritesh, Kumar, P., Shubham, Das, S., Sharma, P., Prasad, P.V.V., 2021. Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions. Sustain. https://doi.org/10.3390/su13179963

Little, H.A., Tanikella, N.G., Reich, M.J., Fiedler, M.J., Snabes, S.L., Pearce, J.M., 2020. Towards distributed recycling with additive manufacturing of PET flake feedstocks. Materials (Basel). https://doi.org/10.3390/MA13194273

Mikula, K., Skrzypczak, D., Izydorczyk, G., Warchoł, J., Moustakas, K., Chojnacka, K., Witek-Krowiak, A., 2021. 3D printing filament as a second life of waste plastics—a review. Environ. Sci. Pollut. Res. 28, 12321–12333. https://doi.org/10.1007/s11356-020-10657-8

Mohammed, M.I., Das, A., Gomez-Kervin, E., Wilson, D., Gibson, I., 2020. Ecoprinting: Investigating the use of 100% recycled Acrylonitrile Butadiene Styrene (ABS) for Additive Manufacturing, in: Solid Freeform Fabrication 2017: Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing

Conference, SFF 2017.

Mohammed, M.I., Wilson, D., Gomez-Kervin, E., Tang, B., Wang, J., 2019. Investigation of Closed-Loop Manufacturing with Acrylonitrile Butadiene Styrene over Multiple Generations Using Additive Manufacturing. ACS Sustain. Chem. Eng. https://doi.org/10.1021/acssuschemeng.9b02368

Mohammed, M.I., Wilson, D., Gomez-kervin, E., Vidler, C., Rosson, L., Long, J., 2018. The recycling of E-Waste ABS plastics by melt extrusion and 3D printing using solar powered devices as a transformative tool for humanitarian aid, in: Solid Freeform Fabrication Proceedings.

Pavlo, S., Fabio, C., Hakim, B., Mauricio, C., 2018. 3D-Printing Based Distributed Plastic Recycling: A Conceptual Model for Closed-Loop Supply Chain Design, in: 2018 IEEE International Conference on Engineering, Technology and Innovation, ICE/ITMC 2018 - Proceedings. https://doi.org/10.1109/ICE.2018.8436296

Rahimizadeh, A., Kalman, J., Fayazbakhsh, K., Lessard, L., 2019. Recycling of fiberglass wind turbine blades into reinforced filaments for use in Additive Manufacturing. Compos. Part B Eng. https://doi.org/10.1016/j.compositesb.2019.107101

Reich, M.J., Woern, A.L., Tanikella, N.G., Pearce, J.M., 2019. Mechanical properties and applications of recycled polycarbonate particle material extrusion-based additive manufacturing. Materials (Basel). https://doi.org/10.3390/ma12101642

Santander, P., Cruz Sanchez, F.A., Boudaoud, H., Camargo, M., 2020. Closed loop supply chain network for local and distributed plastic recycling for 3D printing: a MILP-based optimization approach. Resour. Conserv. Recycl. 154, 104531. https://doi.org/10.1016/j.resconrec.2019.104531

Shen, L., Worrell, E., Patel, M.K., 2010. Open-loop recycling: A LCA case study of PET bottle-to-fibre recycling. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2010.06.014

Sun, L., Wang, Y., Hua, G., Cheng, T.C.E., Dong, J., 2020. Virgin or recycled? Optimal pricing of 3D printing platform and material suppliers in a closed-loop competitive circular supply chain. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2020.105035

Tang, Y., Mak, K., Zhao, Y.F., 2016. A framework to reduce product environmental impact through design optimization for additive manufacturing. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2016.06.037

Tian, X., Liu, T., Wang, Q., 2017a. Manufacturing and recycling of 3D printed continuous carbon fiber reinforced pla composites, in: ICCM International Conferences on Composite Materials.

Tian, X., Liu, T., Wang, Q., Dilmurat, A., Li, D., Ziegmann, G., 2017b. Recycling and remanufacturing of 3D printed continuous carbon fiber reinforced PLA composites. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2016.11.139

U.S. Bureau of Labor Statistics, 2020. Occupational Employment and Wage Statistics [WWW Document]. URL https://www.bls.gov/oes/current/oes533032.htm

Vidakis, N., Petousis, M., Maniadi, A., Koudoumas, E., Vairis, A., Kechagias, J., 2020. Sustainable additive manufacturing: Mechanical response of acrylonitrile-butadiene-styrene over multiple recycling processes. Sustain. https://doi.org/10.3390/SU12093568

Woern, A., Pearce, J., 2017. Distributed Manufacturing of Flexible Products: Technical Feasibility and Economic Viability. Technologies. https://doi.org/10.3390/technologies5040071

Woern, A.L., Byard, D.J., Oakley, R.B., Fiedler, M.J., Snabes, S.L., Pearce, J.M., 2018. Fused particle fabrication 3-D printing: Recycled materials' optimization and mechanical properties. Materials (Basel). https://doi.org/10.3390/ma11081413