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Waste converting through by-product synergy: an insight from three-echelon supply chain

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Abstract

By-product synergy (BPS) is an innovative method to convert waste into valuable by-products effectively. Based on a three-echelon supply chain composed of an upstream manufacturer, a processing plant with limited processing capacity, and a downstream manufacturer, this study derives the production quantity and waste disposal decisions of the upstream and downstream manufacturers as well as the optimal transfer price decision of the processing plant. Moreover, we assess the environmental performance of BPS. Analytical results suggest that the upstream manufacturer’s production quantity and waste disposal decisions and the processing plant’s transfer price decision are threshold dependent on the processing plant’s capacity, whereas the downstream manufacturer’s production quantity decision is threshold dependent on the processing plant’s capacity and price of raw materials. BPS is beneficial for all members of the supply chain to increase profit. The production promotion and cost-saving effects ensure that the supply chain members maximize their profit. However, BPS does not always have a positive effect on the environment; when the processing plant’s capacity and price of raw materials are below the threshold, implementing BPS results in a win-win situation of economic and environmental benefits.

Keywords: by-product synergy; waste converting; three-echelon supply chain; environmental performance; sustainability; operational collaboration

1 Introduction

The manufacturing process inevitably generates fixed proportions of waste output. However, the waste is not worthless, it can be captured value through reuse or further processing (Yang et al., 2014; Zhang et al., 2018). Meanwhile, severe environmental pollution caused by waste has resulted in critical social and economic challenges (Fraccascia, 2019; Sun, 2017). For example, as the “factory of the world,” China produces at least 1.55 billion tons of industrial solid waste each year (MEE, 2020). If they are discarded or buried, not only economic benefits of resource reuse will lose, but also the ecological environment will be damaged (Kamarehie et al., 2020; Liu et al., 2020).

By processing waste stream into saleable by-products (such as raw material) that can be used in
industrial production, by-product synergy (BPS) is an innovative method to convert waste effectively, and it has been adopted in practice (Lee and Tongarlak, 2017; Suzanne et al., 2020; Zhu and Ruth, 2013). The Japanese (Van Berkel et al., 2009), British (Jensen et al., 2011) and China (MIIT, 2016) have issued policy to support the development of BPS. Some eco-industrial parks have also implemented BPS projects to achieve waste conversion and resource recycling (He et al., 2020; Li and Xiao, 2017).

Different from traditional operational decisions that focuses on main outputs, the application of BPS focuses on main outputs and secondary outputs (waste) of main production activities. It requires operational collaboration among different stakeholders, and the operational decisions are more complex (Fraccascia et al., 2020; Turken and Geda, 2020). Current research of the effect of BPS on operational decisions has only considered a monopoly manufacture’s (Lee, 2012; Choi et al., 2020), or focused on the two-echelon supply chain (Zhou et al., 2020). In fact, due to technological limitations, most manufacturers outsource their waste processing to third party (processing plant), which means a three-echelon supply chain collaboration among upstream manufacturers, processing plants, and downstream manufacturers is necessary (Herczeg et al., 2018; Wang et al., 2019). A typical example is bagasse as a substitute of wood in paper production. The bagasse (waste) from sugar refinery (upstream manufacturer) can be transferred to pulp plant (processing plant), the pulp plant can convert bagasse into pulp product (by-products), and the pulp product instead of wood (raw material) can be sent to paper mill (downstream manufacturer) to produce paper. A more complex three-echelon supply chain structure puts forward some new management problems on operational decisions and BPS coordination strategies. For example, how to arrange production decisions considering the cost of processing waste? Is it always better to use BPS and what effect may influence BPS (Tang et al., 2021)? Solving those problems are critical in enhancing BPS and improving the efficiency of resource utilization (Mathivathanan et al., 2018).

In the BPS implementation, we found that relative studies ignored the limitation of processing capacity (Lee, 2012; Lee and Tongarlak, 2017). However, due to high investment cost, the capacity (henceforth processing capacity) of the processing plant is usually built well in advance, which means the amount of waste converting and by-product supplying will be limited. The processing plant may not have enough capacity to process all the waste that transferred from upstream manufacturer, upstream manufacturer should consider how to deal with redundant waste (Zhou et al., 2020). For downstream manufacturer, the multiple raw materials purchasing channels should be considered because of the processing plant may not supply sufficient by-products (Cho and Tang, 2014; Yazan and Fraccascia, 2020). Therefore, capacity limitations can affect manufactures’ operational strategies and the supply chain members’ collaboration.

Moreover, the environmental performance of BPS is controversial. Generally, BPS is considered to be positive for the environment, but some studies shows that this is not always the case (Lee, 2012). Using waste stream to produce by-products avoids waste pollution and taking by-products into
downstream production reduces raw material consumption. But it cannot be neglected that converting
waste into by-products needs to input some material and energy, which could lead to a negative impact
on environment (Aigbedo, 2019). So we raise the questions, which situation will BPS protect the
environment?

Based on the practice of BPS, the main work of this paper is to investigate the interaction effect of
BPS on operations among different parties based on a three-echelon supply chain composed of an
upstream manufacturer, a downstream manufacturer, and a limited capacity processing plant.
Meanwhile, taking environmental issues into consideration, we assess the environmental performance
of BPS that incorporates the optimal operational decisions and further discuss the balance between
economic benefits and environmental protection. Specifically, we will answer the following questions:

(1) How are the production quantity, waste converting decision and optimal profit affected by BPS
in a three-echelon supply chain? How is the limited processing capacity affects the operational strategies?

(2) which situation will BPS positive for the environment? Can BPS achieve the balance between
economic benefits and environmental protection?

The main contributions of this study are as follows. First, considering the three-echelon supply
chain structure is in line with the practical situation, and the analysis of the effect of BPS on the
operational decisions in a three-echelon supply chain fills the research gap in this field. Second, by
considering the limitations of waste converting and the by-product supply, this study expands the
research on BPS supply chain with limited processing capacity. Finally, from the perspective of
productive use of waste stream, this study states whether BPS can achieve the win-win situation of
economic and environment. The conclusions of this paper can help enterprises to achieve sustainable
production.

The remainder of this paper is organized as follows. Section 2 provides a review of the literature
related to our study. Section 3 describes the assumption and model. In Section 4, the optimal decisions
of each stage are derived, and they are compared with the benchmark to discuss the economic and
environmental benefits of BPS. The numerical analysis is presented in Section 5, and Section 6 provides
the discussion and Section 7 is the conclusion. The proof of this study is attached to the appendix.

2 Literature review

Recent studies into waste reuse/recycling coordination strategies has investigated operational decisions
not only in the two-echelon supply chain, but also for more common structure of three-echelon supply
chain. However, studies of the effect of BPS on operational decisions have only considered a monopoly
manufacture or two-echelon supply chain. Lee (2012) firstly studied how a monopolist manufacturer
arrange production with BPS under different market conditions. Lee and Tongarlak (2017) explored
monopolist retail grocers arrange production with BPS under uncertainty. Choi et al. (2020) used the
Cournot competition model to discuss the production decision-making problem of multiple
manufacturers that have adopted BPS. Zhou et al. (2020) explored the effect of BPS on the operations of a two-echelon supply chain, consisting of two competing upstream manufacturers and a downstream processing plant. However, this study ignored the participation of downstream manufacturers. Unlike above studies, we consider a more complex three-echelon supply chain structure and investigate the effect of BPS on stakeholders’ operational decisions.

In a supply chain, capacity restriction affects the manufacturer’s operational decisions (Cannella et al., 2018; Fransoo and Lee, 2013). Many scholars investigated optimal decisions under limited supply capacity (Erkoc and Wu, 2005; Zheng et al., 2015; Shukla and Naim, 2017), limited distribution capacity (Qi et al., 2015; Yang et al., 2018) and limited inventory capacity (Boute et al., 2009). Moreover, a small number of studies focused on waste recycle supply chain with limited treatment capacity. Neto et al (2017) considered three levels of processing capability for recycling platform, assessed the economic profitability of construction and demolition waste recycling. Liu et al (2019) analyzed the influences of recycler’s waste treatment capacity on its recycling strategies and stakeholders' profit under different market scenarios. However, above studies did not pay attention to the innovation method of BPS. In other words, the operational decisions of a three-echelon supply chain with limited processing capacity has not been explored.

A smaller number of scholars concentrated on the environmental performance of BPS. Lee (2012) developed emissions framework under an optimal operational decision and proposed that the environmental performance of BPS is not always positive for manufacturers. However, using the enterprise input-output approach, Yazan (2016) investigated two empirical cases on bioenergy and cement production and concluded that there are significant environmental benefits in implementing BPS. Similarly, Sgarbossa and Russo (2017) claimed that although waste prevention is the best option in protecting the environment, BPS can also help to protect the environment. After analyzing the evolution of industrial symbiosis in Altamira-Tampico industrial corridor in Mexico, Morales et al. (2019) concluded that BPS enhances environmental protection development. However, research that explores the environmental performance of BPS that incorporates the optimal operational decisions is relatively rare, and whether or when BPS can achieve the win-win situation of economic benefits and environmental protection from a supply chain perspective is still unexplored, and that is the motivation for this study.

Different from previous studies, this paper analyzes the effect of BPS on the operational decisions of a more complex three-echelon supply chain structure by constructing a game model. Through assessing the environmental performance of BPS that incorporates the optimal operational decisions, this study states whether BPS can achieve the win-win situation of economic and environment.

3 Model description
A three-echelon supply chain, with an upstream manufacturer, a downstream manufacturer, and a
processing plant with limited capacity, is considered (in Fig. 1a). Table 1 summarizes the notations used in this paper. The upstream manufacturer produces product \( A \) and generates waste. According to environmental regulation, the upstream manufacturer must dispose of waste; it can choose to dispose of the waste itself or transfer the waste to the processing plant. Because of the limited processing capacity, the upstream manufacturer may need to dispose of part of the waste when it decides to transfer the waste to the processing plant. The processing plant converts the waste into by-products and then sells the them to the downstream manufacturer. The downstream manufacturer produces product \( B \). Since the by-products from the processing plant may not enough to meet the required input for production, the downstream manufacturer needs to buy some raw materials.

| Notations | Explanations |
|-----------|--------------|
| \( c_i \) | Unit production cost of product \( i \), \( i = A, B \) |
| \( c_d \) | Unit disposal cost of upstream manufacturer |
| \( c_b \) | The sale price of by-products |
| \( c_w \) | Unit cost of converting waste into by-products |
| \( c_r \) | The sale price of raw materials |
| \( K \) | The capacity of processing plant |
| \( r \) | The waste generated by unit of product |
| \( E_i \) | Unit production emissions of product \( i \), \( i = A, B \) |
| \( E_d \) | Unit disposal emissions of upstream manufacturer |
| \( E_r \) | Unit converting emissions of processing plant |
| \( P_i \) | The price of product \( i \), \( i = A, B \) (decision variables) |
| \( Q_i \) | Production quantity of product \( i \), \( i = A, B \) (decision variables) |
| \( w \) | Transfer price of processing plant (decision variables) |
| \( \Pi_i \) | The profit of upstream manufacturer, downstream manufacturer or processing plant, \( i = U, N, P \) |

Without losing generality, the following assumptions are proposed.

**Assumption 1:** To highlight the effect of BPS on the manufacturer’s operational decisions, we proposed linear downward sloping demand curves \( P_A = a - Q_A \) and \( P_B = b - Q_B \) (Lee, 2012), where \( a \) and \( b \) represent the initial market scale.

**Assumption 2:** High waste disposal cost is one of the first reasons for upstream manufacturer to adopt BPS (Herczeg et al., 2018), so we assume that the cost of the upstream manufacturer’s self-disposal of waste is higher than the transfer price paid to the processing plant (that is, \( w < c_d \)) (Zhou et al., 2020).

**Assumption 3:** Low price of by-products is the main reason for downstream manufacturer to adopt BPS (Tang et al., 2021), so we assume that the price of raw materials is higher than the price of by-products (that is, \( c_b < c_r \)) (Lee, 2012; Lee and Tongarlik, 2017).

**Assumption 4:** By-products and raw materials are homogeneous: a unit of waste produces a unit of by-
product, and a unit of product \( B \) contains a unit of raw material (He et al., 2020).

**Assumption 5:** We assume that the price of the product includes transportation costs and all the supply chain members are rational and produce based on the principle of maximizing profit. The available information is symmetrical among these members.

According to these assumptions, the upstream manufacturer determines the disposal decisions and the quantity of product \( A \). The processing plant determines the transfer price based on the amount of waste transferred by the upstream manufacturer. The downstream manufacturer considers the amount of by-products provided by the processing plant in determining the quantity of product \( B \). Hence, the following demonstrates the sequence of events in the Stackelberg model. In stage 1, the downstream manufacturer makes production quantity decision \( (Q_b) \). In stage 2, the processing plant is relatively strong in the supply chain. When the plant determines the transfer price \( (w) \), it will take the manufacturer’s production decisions, the price of by-products into consideration (Zhou et al., 2020). In stage 3, the upstream manufacturer makes the production quantity decision \( (Q_a) \) and the waste disposal decision based on the capacity of the processing plant.

![Fig.1](image)

Based on the operational decisions about the production quantity, transfer price, waste conversion and waste disposal, the environmental performance of BPS is further explored. Emissions are used to measure the environmental performance of BPS; this is a common method in measuring environmental footprint (Subramanian et al., 2007; Yenipazarli, 2016). Using the framework constructed by Lee (2012) and Lee and Park (2020) as a reference, the emissions structure is shown in Fig 1b. The emissions of the upstream manufacturer include production emissions and waste disposal emissions. For processing plant, converting waste into by-products will generate emission. Due to the advanced technology of the processing plant, converting waste generates less emission than dispose of waste, that is \( E_b < E_d \). The emissions of the downstream manufacturer include production and raw materials emissions. Compared with using raw materials to produce, using by-products to produce
requires fewer resources and have better low-carbon characteristics (Lee, 2012); therefore, \( E_s < E_r \). Combined with profit, we explore circumstances under which BPS can increase profit and reduce emissions to achieve the win-win situation of economic and environmental benefits.

4 Model analysis

4.1 Benchmark

To evaluate the economic and environmental benefits of BPS, we set up a benchmark, that is, when BPS has not been implemented. The upstream manufacturer disposes of all waste by itself, whereas the downstream manufacturer purchases raw materials needed for production. Therefore, their profit functions are:

\[
\begin{align*}
\Pi_U &= P_A Q_A - c_A Q_A - c_d r Q_A \\
\Pi_D &= P_B Q_B - c_B Q_B - c_r Q_B
\end{align*}
\] (1)

Lemma 1. Without BPS, the equilibrium production quantity and profit of the upstream and downstream manufacturers can be expressed as:

\[
Q^N = \begin{cases} 
Q^N_A = \frac{a - c_a - r c_d}{2} \\
Q^N_B = \frac{b - c_B - c_r}{2}
\end{cases} \quad \Pi^N = \begin{cases} 
\Pi^N_U = \frac{(a - c_a - r c_d)^2}{4} \\
\Pi^N_D = \frac{(b - c_B - c_r)^2}{4}
\end{cases}
\] (2)

In the benchmark, the upstream manufacturer disposes of all waste by itself, so its emissions function is \( E^N_U = (E_A + r E_d)Q^N_A \). The downstream manufacturer purchases raw materials, so its emissions function is \( E^N_D = (E_B + E_r)Q^N_B \).

4.2 Interactive production decision under BPS

In this part, we investigate the equilibrium solution of each stage, then the optimal operational decisions of the upstream and downstream manufacturers, as well as the processing plant, is obtained. Based on the benchmark, the effect of BPS on operational decisions is explored.

4.2.1 Stage 3: the production quantity decision of the upstream manufacturer

Given the processing capacity and transfer price, the upstream manufacturer’s profit function is as follows:

\[
\Pi_U(Q_A, K, w) = (P_A - c_A)Q_A - w \min (r Q_A, K) - c_r (r Q_A - K)^+
\] (3)

In Equation (3), the first term is the profit from the market, the second represents the transfer cost that should be paid to the processing plant, and the last represents the upstream manufacturer’s cost of self-disposal of waste. Because \( w < c_d \), the manufacturer prefers to use BPS. However, when the amount of waste is higher than the processing capacity, part of the waste must be disposed by the manufacturer, so the third term is always positive. Based on the concavity of the objective function, we obtain the upstream manufacturer’s optimal production quantity decision in Proposition 1.
**Proposition 1.** The upstream manufacturer’s optimal production quantity is given as:

\[ Q^*_A = \begin{cases} 
\frac{a - c_A - rc_d}{2} & K < \frac{r(a - c_A - rc_d)}{2} \\
\frac{K}{r} & K \in \left[ \frac{r(a - c_A - rc_d)}{2}, \frac{r(a - c_A - rw)}{2} \right] \\
\frac{a - c_A - rw}{2} & K > \frac{r(a - c_A - rw)}{2}
\end{cases} \]  

(4)

and the corresponding profit is given as:

\[ \Pi^*_U = \begin{cases} 
\frac{(a - c_A - rc_d)^2}{4} + K(c_d - w) & K < \frac{r(a - c_A - rc_d)}{2} \\
\frac{-K^2 + rK(a - c_A - rw)}{r^2} & K \in \left[ \frac{r(a - c_A - rc_d)}{2}, \frac{r(a - c_A - rw)}{2} \right] \\
\frac{(a - c_A - rw)^2}{4} & K > \frac{r(a - c_A - rw)}{2}
\end{cases} \]  

(5)

When the processing capacity is low, the upstream manufacture disposes of some of waste itself. Although the upstream manufacturer's production quantity is consistent with the benchmark, the profit premium is the cost saving \( K(c_d - w) \) from the processing plant replaces the manufacturer to dispose of part of the waste at a lower cost, which demonstrates the cost-saving effect of BPS. When the processing plant operates at a medium capacity, it just disposes of the waste transferred by the upstream manufacturer; hence, the production quantity of the upstream manufacturer increases due to fully utilize BPS. Thus, utilizing BPS enhances the production promotion effect. When the processing plant operates at a high capacity, it can handle all the waste transferred by the upstream manufacturer, so the manufacturer does not consider the cost of waste disposal when making production decisions, and the production quantity and profit of the manufacturer increase. In this case, both effects are high.

**4.2.2 Stage 2: processing plant’s transfer price decision**

In this subsection, given \( Q_A \) and \( c_b \), the processing plant sets the transfer price that will maximize its profit. The profit function of the processing plant is given as:

\[ \Pi_p(w, K) = (c_b + w - c_m) \min(rQ_A, K) \]  

(6)

In Equation (6), the first term represents the marginal profit of the processing plant, and the second denotes the amount of waste that the processing plant can convert. Based on the concavity of the objective function, we obtain the processing plant’s optimal transfer price decision in **Proposition 2.**

**Proposition 2.** The processing plant’s optimal transfer price is given as:
and the corresponding profit is given as:

\[
\begin{align*}
\Pi^*_p &= \begin{cases} 
\Pi_{p1} & K < \frac{r(a-c_d - r\theta_d)}{2} \\
\Pi_{p2} & \frac{r(a-c_d - r\theta_d)}{2} \leq K \leq \frac{r(a-c_d + r\theta_d)}{2} \\
\Pi_{p3} & K \geq \frac{r(a-c_d + r^2\theta_d)}{4} 
\end{cases} \\
\Pi_{p1} &= (c_b + c_d - c_m)K \\
\Pi_{p2} &= -2K^2 + rK[(a-c_d) + Kc_b - c_m)] \\
\Pi_{p3} &= \left[\frac{a-c_d + r(c_b - c_m)}{2}\right]^2/8 \\
\end{align*}
\]

Proposition 2 shows that the processing plant’s optimal transfer price strategy is threshold dependent on capacity. When the processing capacity increases, the transfer price decreases. When the capacity is low, due to a small amount of waste conversion, the processing plant sets the highest transfer price to maximize its profit. When the processing capacity is medium, the transfer price will drop to \(w_1\). When the processing capacity is high, the transfer price is independent with capacity, and it will then decline due to the processing plant will have surplus capacity. In addition, it is only when the processing capacity is high that the transfer price is related to the price of by-products; it is negatively correlated to the price of by-products. When the price of by-products is high, the processing plant makes more profit from converting waste into by-products and has a higher willingness to convert waste. Thus, the transfer price charged by the upstream manufacturer will decrease accordingly.

We obtain the upstream manufacturer’s disposal decision and the processing plant’s production quantity of by-products (that is, the amount of by-products converted from waste) \(Q_b\); it is shown in Table 2. The upstream manufacturer’s disposal decision is based on its production quantity and processing capacity. The amount of waste disposed by the upstream manufacturer is not related to the transfer price. It is only when the processing capacity is high that the production quantity of by-products is related to transfer price.

Table 2: The disposal decision and production quantity of by-products.

| Capacity          | \(Q_b^*\) | Self-disposal | \(Q_b\) (BPS) |
|-------------------|-----------|---------------|----------------|
| \(K \in (0, \frac{r(a-c_d - r\theta_d)}{2})\) | \(\frac{a-c_d - r\theta_d}{2}\) | \(\frac{r(a-c_d - r\theta_d)}{2} - K\) | \(K\) |
| \(K \in \left[\frac{r(a-c_d - r\theta_d)}{2}, \frac{r(a-c_d - r\theta_d)}{2}\right]\) | \(\frac{K}{r}\) | 0 | \(K\) |
| \(K \in \left[\frac{r(a-c_d - r\theta_d)}{2}, \frac{r(a-c_d - r\theta_d)}{2}\right]\) | \(\frac{K}{r}\) | 0 | \(K\) |
\[ K \in \left( \frac{r(a-c_A-nw_A)}{2}, +\infty \right) \]

\[ \frac{a-c_A-nw_A}{2} \quad 0 \quad \frac{r(a-c_A-nw_A)}{2} \]

261 Plugging \( w \) into \( Q^*_A(w) \) and \( \Pi^*_U(w) \) in Proposition 2, we have

\[
Q_{A1} = \frac{a-c_A-rc_d}{2} \quad K < K_1
\]

\[
Q_{A2} = \frac{(a-c_A)+r(c_b-c_m)}{4} \quad K > K_2
\]

\[
\Pi_{U1} = \frac{(a-c_A-rc_d)^2}{4} \quad K < K_1
\]

\[
\Pi_{U2} = \frac{K^2}{2} \quad K \in [K_1, K_2]
\]

\[
\Pi_{U3} = \frac{[a-c_A+r(c_b-c_m)]^2}{16} \quad K > K_2
\]

264 Here, \( K_1 = \frac{r(a-c_A-rc_d)}{2} \), \( K_3 = \frac{r(a-c_A)+r^2(c_b-c_m)}{4} \)

265 Comparing with the benchmark, we have Corollary 1.

**Corollary 1.** When \( K \leq K_1 \), \( Q_A^* = Q_A^N \), \( \Pi_U^* = \Pi_U^N \); when \( K > K_1 \), \( Q_A^* > Q_A^N \), \( \Pi_U^* > \Pi_U^N \).

266 Corollary 1 shows that when the processing capacity is not low, the cost-saving effect helps upstream manufacturer decrease its disposal cost, the production promotion effect leads to more production quantity, thus BPS can improve the profit.

4.3.3 Stage 1: the production decision of the downstream manufacturer

In this subsection, given \( Q_A \), the downstream manufacturer decides the production quantity of product \( B \) to maximize profit. Due to the lower price of by-products, the downstream manufacturer prefers to buy by-products. Two scenarios of supplying by-products are presented, which are \( Q_b = K \), \( K \leq K_2 \) as scenario L, corresponding to a state of low and medium processing capacity; and \( Q_b = rQ_A \), \( K > K_2 \), as scenario H, corresponding to a state of high processing capacity. Therefore, the upstream manufacturer’s profit functions are given as:

\[
\Pi_U^L(Q_A) = (P_b-c_p)Q_b-c_bK-c_J(Q_b-K) \quad (11)
\]

\[
\Pi_U^H(Q_A) = (P_b-c_p)Q_b-c_brQ_A-c_J(Q_b-rQ_A) \quad (12)
\]

In Equations (11) and (12), the first term represents the profit from the market, the second represents the cost of purchasing by-products, and the last represents the cost of purchasing raw materials. Based on the concavity of the objective function, we obtain the upstream manufacturer’s optimal production quantity decision in Proposition 3.

**Proposition 3.** (1) In scenario L, the downstream manufacturer’s optimal production quantity is given.
as:

\[
Q^*_b = \begin{cases} 
Q^L_b = \frac{b-c_b-c_r}{2}, & c_r < c_{i1} \\
Q^H_b = K, & c_{i1} \leq c_r < b-c_b 
\end{cases}
\]  

(13)

and the corresponding profit is given as:

\[
\Pi^*_b = \begin{cases} 
\Pi^L_b = \frac{(b-c_b-c_r)^2}{4} + K(c_r-c_b), & c_r < c_{i1} \\
\Pi^H_b = -K^2 + (b-c_b-c_r)K, & c_{i1} \leq c_r < b-c_b 
\end{cases}
\]  

(14)

(2) In scenario H, the downstream manufacturer’s optimal production quantity is given as:

\[
Q^*_b = \begin{cases} 
Q^H_{b1} = \frac{b-c_b-c_r}{2}, & c_r < c_{i2} \\
Q^H_{b2} = \frac{r(a-c_A)+r^2(c_r-c_m)}{4}, & c_{i2} \leq c_r < b-c_b 
\end{cases}
\]  

(15)

and the corresponding profit is given as:

\[
\Pi^*_b = \begin{cases} 
\Pi^H_{b1} = \frac{(b-c_b-c_r)^2}{4} + (c_r-c_b)\frac{r(a-c_A)+r^2(c_r-c_m)}{4}, & c_r < c_{i2} \\
\Pi^H_{b2} = -\frac{r(a-c_A)+r^2(c_r-c_m)}{4} + (b-c_b-c_r)\frac{r(a-c_A)+r^2(c_r-c_m)}{4}, & c_{i2} \leq c_r < b-c_b 
\end{cases}
\]  

(16)

Here, \( c_{i1} = b-c_b-2K \), \( c_{i2} = b-c_b-\frac{r(a-c_A)+r^2(c_r-c_m)}{2} \).

The production quantity and profit of the downstream manufacturer are negatively correlated to the price of raw materials. When the price of raw materials is lower than the threshold (i.e. \( c_r < c_{i1} \) or \( c_r < c_{i2} \)), the downstream manufacturer uses by-products and raw materials for production; however, when the price of raw materials is higher than the threshold, it only uses by-products for production.

Comparing the production quantity and profit under different scenarios, we obtain Corollary 2.

**Corollary 2.** (1) When \( c_r < c_{i2} \), the downstream manufacturer’s production quantity is the same in scenarios L and H; when \( c_r \in [c_{i2}, b-c_b) \), the production quantity will be higher in scenario H. (2) The downstream manufacturer gets more profit in scenario H.

When \( c_r < c_{i2} \), even though the supply of by-products can’t meet the production demand, the downstream manufacturer wouldn’t change production quantity decisions due to its can buy raw materials at low price, and the production cost wouldn’t increase too much. In scenario H, the manufacturer gets more low-cost by-products, and the marginal cost is lower than that of scenario L. When \( c_r \in [c_{i2}, b-c_b) \), a high price of raw materials makes it impossible for the manufacturer to expand production. In scenario H, more by-products are put into production, so the production quantity is larger, and the profit is higher.
Comparing with the benchmark, we have Corollary 3.

**Corollary 3.** (1) Under scenario L, when $c_r < c_{r1}$, $Q^*_b = Q^*_b^X$, $\Pi^*_b > \Pi^*_b^N$; when $c_r \geq c_{r1}$, $Q^*_b > Q^*_b^X$, $\Pi^*_b > \Pi^*_b^N$ . (2) Under scenario H, when $c_r < c_{r2}$, $Q^*_a = Q^*_a^X$, $\Pi^*_a > \Pi^*_a^N$; when $c_r \geq c_{r2}$, $Q^*_a > Q^*_a^X$, $\Pi^*_a > \Pi^*_a^N$.

Implementing BPS increases the downstream manufacturers’ profit in two ways. First, when the price of raw materials is lower than the threshold, the manufacturer’s production quantity will be the same as the benchmark, and the cost of $K(c_r - c_b)$ and $(c_r - c_b) r(a - c_x) + r^2(c_b - c_m)$ can be saved by replacing the raw materials with low price by-products, which shows the cost-saving effect of BPS.

Second, when the price of raw materials is higher than the threshold, compared with the benchmark, the by-products obtained at a lower price by the manufacturer is used as production input to stimulate production and increase profit. Therefore, BPS promotes production.

Then we discuss the effect of the technical factor $c_m$ on the production quantity and profit of the upstream and downstream manufacturers, as well as the transfer price and profit of the processing plant, shown in Proposition 4.

**Proposition 4.** When $c_m$ increases, the transfer price increases, production quantity of the upstream and downstream manufacturers decreases, and the profit of all the supply chain members decrease.

When the cost of converting waste into by-products increases, the processing plant increases the transfer price to offset the increase in the processing cost. However, the increase in transfer price leads to an increase in the upstream manufacturer’s marginal cost of production, which decreases its production quantity and profit. The decrease in the upstream manufacturer’s production quantity leads to a decline in the waste available for disposal, which decreases the production quantity of by-products and the profit of the processing plant. Furthermore, the decline in production quantity of by-products means that the downstream manufacturer will buy more raw materials at a high price, which increases the marginal cost of production and decreases production quantity and profit.

### 4.3 Environmental performance

In this section, we discuss the environmental performance of BPS from an emissions perspective. According to the analysis in the previous section, the operational decisions of the upstream manufacturer and the processing plant are affected by the processing capacity, whereas the downstream manufacturer’s operational decision is affected by the price of raw materials. Hence, the emissions from the upstream and downstream manufacturing activities in the supply chain are measured. The production quantity of by-products is closely related to the amount of waste generated by the upstream manufacturer. Therefore, we combined the upstream manufacturer and the processing plant as the upstream of the supply chain and classified their emissions as upstream emissions. However, the emissions of the...
downstream manufacturer do not include emissions from converting waste.

After implementing BPS, the upstream emissions will be related to the processing capacity, and there are three scenarios:

\[
E_{U1} = E_A Q_{A1} + E_n K + E_a (rQ_{A1} - K) \quad K < K_1
\]

(17)

\[
E_{U2} = E_A Q_{A2} + E_n K \quad K \in [K_1, K_2]
\]

(18)

\[
E_{U3} = E_A Q_{A3} + E_n rQ_{A3} \quad K > K_2
\]

(19)

In Equations (17), (18) and (19), the first term refers to the upstream manufacturer’s production emissions; the second term represents emissions from converting waste into by-products, the last term denotes the upstream manufacturer’s emissions of waste disposal. Comparing with the benchmark, we obtain Corollary 4

**Corollary 4.** There exists a threshold \( K = \frac{E_a + rE_n}{E_A + rE_n} \), when \( K < K_E \), \( E_u < E_u^N \) and when \( K \geq K_E \), \( E_u \geq E_u^N \).

When the processing capacity is lower than the threshold, BPS reduces upstream emissions. Especially when \( K_E > K_1 \), BPS has a significant effect on reducing emissions. This is due to the processing plant converts part of the waste with low emission, instead of the upstream manufacturer disposes waste with lower emission. At the same time, upstream manufacturer’s production quantity remained unchanged and production emissions doesn’t increase. When the processing capacity is higher than the threshold, BPS increases upstream emissions. The increase in emissions is mainly due to two reasons: the increase in production emissions caused by the expansion of the upstream manufacturer’s production quantity, and the increase in converting emissions caused by converting more waste into by-products. The higher the advantage of waste conversion to the processing plant (that is, the smaller value of \( E_n \)), the higher the value of \( K_E \), which means that the upstream manufacturer can produce more products, and the processing plant can convert more waste into by-products without increasing emissions.

Based on scenarios L and H, the downstream emissions’ functions are:

\[
E_{D_{L}} = E_s Q_{B_i}^{L} + E_i [Q_{B_i}^{L} - \min(K, rQ_A)] \quad i = 1, 2
\]

(20)

\[
E_{D_{H}} = E_s Q_{B_i}^{H} + E_i [Q_{B_i}^{H} - \min(K, rQ_A)] \quad i = 1, 2
\]

(21)

In Equations (20) and (21), the first term denotes the downstream manufacturer’s production emissions, and the second denotes raw materials emissions. Comparing the production quantity with the benchmark, we obtain Corollary 5

**Corollary 5.** (1) Under scenario L, there exists a threshold \( c_{i_{L}} = \frac{E_s}{E_s + E_r} \), when \( c_{i_{L}} < c_{i_{L}} \), \( E_D < E_D^N \), and when \( c_{i_{L}} \geq c_{i_{L}} \), \( E_D \geq E_D^N \). (2) Under scenario H, there exists a threshold
When the price of raw materials is lower than the threshold (i.e. \( c_r < c_{1E} \) or \( c_r < c_{2E} \)), implementing BPS can reduce emissions, especially when \( c_r < c_{1E} \). Due to the downstream manufacturer’s production quantity being the same as the benchmark, BPS has significant emissions reduction effect by replacing the high emission raw materials to low emission by-products. When the price of raw materials is higher than the threshold, due to BPS stimulating production, the substantial increase in production quantity increases total emissions, and BPS loses the effect of emissions reduction. In this case, production promotion effect expands the profit, but also increases emissions, which is not conducive to win-win situation. This may be caused by the rebound effect, that is, although technological advancement improves the rate of resource utilization, that same advancement leads to an increase in resources used, leading to an increase in emissions (Raz et al., 2013; Zhang et al., 2020).

The upstream in the supply chain reduces emissions and increases profit when \( K_1 < K < K_E \); for the downstream, it reduces emissions and increases profit when \( c_r < c_{1E} \) or \( c_r < c_{2E} \). However, as shown in Table 3, the case of the entire supply chain is more complex. Under the condition of \( K < K_E \), if \( K_1 < K_E \leq K_2 \), it is only when \( c_r < c_{1E} \), that implementing BPS increases profit and decreases the entire supply chain’s emissions. In contrast, an emission reduction cannot be achieved in scenario H. If \( K_2 < K_E \), implementing BPS leads to a win-win situation of economic and environmental benefits when \( c_r < c_{1E} \) or \( c_r < c_{2E} \).

### Table 3: The upstream and downstream profit and emissions in the supply chain

| \( K \) | \( K_1 < K_E \leq K_2 \) | \( K_2 < K_E \) |
|---|---|---|
| \( K < K_1 \) | \( K \in [K_1, K_E) \) | \( K \in [K_E, K_2] \) | \( K > K_2 \) |
| \( c_r < c_{1E} \) | \( \Pi_U > \Pi^N_U \) | \( \Pi_U > \Pi^N_U \) | \( \Pi_U > \Pi^N_U \) | \( \Pi_U > \Pi^N_U \) |
| \( \Pi_r > 0 \) | \( \Pi_r > 0 \) | \( \Pi_r > 0 \) | \( \Pi_r > 0 \) | \( \Pi_r > 0 \) |
| \( \Pi_D > \Pi^N_D \) | \( \Pi_D > \Pi^N_D \) | \( \Pi_D > \Pi^N_D \) | \( \Pi_D > \Pi^N_D \) | \( \Pi_D > \Pi^N_D \) |
| \( E_r < E^N_r \) | \( E_r < E^N_r \) | \( E_r < E^N_r \) | \( E_r < E^N_r \) | \( E_r < E^N_r \) |
| \( E_d < E^N_d \) | \( E_d < E^N_d \) | \( E_d < E^N_d \) | \( E_d < E^N_d \) | \( E_d < E^N_d \) |

| \( c_r \geq c_{1E} \) | \( \Pi_U > \Pi^N_U \) | \( \Pi_U > \Pi^N_U \) | \( \Pi_U = \Pi^N_U \) | \( \Pi_U = \Pi^N_U \) |
| \( \Pi_r > 0 \) | \( \Pi_r > 0 \) | \( \Pi_r > 0 \) | \( \Pi_r > 0 \) | \( \Pi_r > 0 \) |
| \( \Pi_D > \Pi^N_D \) | \( \Pi_D > \Pi^N_D \) | \( \Pi_D > \Pi^N_D \) | \( \Pi_D > \Pi^N_D \) | \( \Pi_D > \Pi^N_D \) |
| \( E_r < E^N_r \) | \( E_r < E^N_r \) | \( E_r < E^N_r \) | \( E_r < E^N_r \) | \( E_r < E^N_r \) |
| \( E_d < E^N_d \) | \( E_d < E^N_d \) | \( E_d < E^N_d \) | \( E_d < E^N_d \) | \( E_d < E^N_d \) |

| \( c_r < c_{2E} \) | \( \Pi_U > \Pi^N_U \) | \( \Pi_U > \Pi^N_U \) | \( \Pi_U > \Pi^N_U \) | \( \Pi_U > \Pi^N_U \) |
| \( \Pi_r > 0 \) | \( \Pi_r > 0 \) | \( \Pi_r > 0 \) | \( \Pi_r > 0 \) | \( \Pi_r > 0 \) |
| \( \Pi_D > \Pi^N_D \) | \( \Pi_D > \Pi^N_D \) | \( \Pi_D > \Pi^N_D \) | \( \Pi_D > \Pi^N_D \) | \( \Pi_D > \Pi^N_D \) |
To measure the environmental benefits of BPS from an economic perspective, we introduced the environmental damage cost. The environmental damage cost represents the economic loss caused by emissions in monetary terms. It is also a common indicator of to measure the social effect of industrial production (Cao et al., 2017; Davidson et al., 2005). According to Cachon (2014), environmental damage cost can be expressed as $\nu E$, and $\nu(\nu > 0)$ is the environmental damage coefficient, indicating that emissions have a destructive effect on the environment. According to Yenipazarli (2016), the social welfare’s function is $SW = \Pi + CS - \nu E$, where $CS = Q^2 / 2$, representing the consumer surplus.

For upstream and downstream of the supply chain, their gap of social welfare is:

$$SW_U - SW_U^N = (\Pi_U - \Pi_U^N) + (CS_U - CS_U^N) - \nu (E_U - E_U^N)$$ (22)

$$SW_D - SW_D^N = \begin{cases} (\Pi_D^U - \Pi_D^N) + (CS_D^U - CS_D^N) - \nu (E_D^U - E_D^N) & \text{scenario L} \\ (\Pi_D - \Pi_D^N) + (CS_D^U - CS_D^N) - \nu (E_D^U - E_D^N) & \text{scenario H} \end{cases}$$ (23)

In Equations (22) and (23), the first terms, second terms and third terms are the gap of profit, consumer surplus and environmental damage cost. Above previous analysis, we can get Corollary 6

**Corollary 6.** (1) When $K < K_E$, $SW_U > SW_U^N$; when $c_{i1} < c_{i2E}$ or $c_{i2} < c_{i2E}$, $SW_D > SW_D^N$. (2) If $K > K_2$, the value of $SW_U - SW_U^N$ doesn’t change with the increase of $K$.

If the capacity is less than $K_E$, BPS will increase the social welfare of upstream supply chain due to the less emissions. The same case will occur in the social welfare of downstream supply chain when $c_{i1} < c_{i1E}$ or $c_{i2} < c_{i2E}$. However, when $K > K_2$, the welfare of upstream supply chain stays the same due to upstream manufacturer’s production quantity doesn’t increase. Furthermore, $K > K_2$ represents the redundancy in the processing capacity that cannot be utilized effectively.

However, when $K \geq K_E (c_{i1} \geq c_{i1E}$ or $c_{i2} \geq c_{i2E})$ the value of the gap changes with $K$ and $\nu (c_r$ and $\nu)$. It is hard to judge the positive and negative of the $SW_U - SW_U^N (SW_D - SW_D^N)$. Similarly, the threshold value and its function properties cannot be obtained by mathematical derivation. Therefore, we use numerical analysis to get relevant conclusions, which can be seen in Section 5.
5 Numerical analysis

5.1 Production output and profit

Setting $a = 20$, $b = 24$, $c_A = 4$, $c_B = 2$, $c_m = 10$, $c_b = 12$, and $r = 0.7$ represents the high level of waste generates, $r = 0.6$ represents the low level of waste generates. The production quantity and profit of the upstream manufacturer, as well as the production quantity of by-products increase with $K$ (as shown in Fig. 2a and 2c). When $K < K_1$, the upstream manufacturer must dispose of part of its waste ($rQ_A - Q_w$); when $K \geq K_1$, the processing plant converts all the waste transferred by the upstream manufacturer. The production quantity, profit of the upstream manufacturer, and production quantity of by-products are maximized when $K = K_2$. Fig. 2b and 2d show the changes in the transfer price and profit. When the processing capacity increases, the processing plant convert more waste into by-products, which decreases the transfer price and increases profit. However, the production quantity and profit of the processing plant are maximized when $K = K_2$, and then remains unchanged when $K$ increases.
Based on the numerical assumptions, $K_2 = 4.025$ ($K_1 = 3.3$). Hence, we let $K = 3.5$ ($K = 3.1$) in case of scenario L, and $K = 4.5$ ($K = 3.8$) in case of scenario H; $c_r$ fluctuates between 12 ($c_r > c_r$) and 22 ($c_r < b - c_r$). As the price of raw materials increases, the production quantity and profit of the downstream manufacturer decreases (as shown in Fig. 3). When $c_r < c_{r2}$, the downstream manufacturer's production quantity is the same in different scenarios. However, since it obtains more by-products in scenario H, the downstream manufacturer gets more profit, which reflects the cost-saving effect of BPS. When $c_r \geq c_{r2}$, in scenario H, the downstream manufacturer produces more and makes more profit, the production promotion effect of BPS is obvious. When $c_r \geq c_{r1}$, in both scenarios, the downstream manufacturer only uses by-products for production, and its profit reduces.
When $K \leq K_1$, due to the constant production quantity and the highest transfer price set by the processing plant, the profit of the upstream manufacturer is the same as the benchmark (as shown in Fig. 4a and 4c). When $K > K_1$, due to the increase in the production quantity and the decrease in the transfer price, the profit of the upstream manufacturer is higher than the benchmark. When the price of raw materials is lower than the threshold, the production quantity of the downstream manufacturer is the same as the benchmark, but the profit is higher than the benchmark. This is due to the cost-saving effect of BPS (as shown in Fig. 4b and 4d). When the price of raw materials is higher than the threshold, the production promotion effect of BPS is obvious. With an increase in the production quantity, the increase in profit is far higher than the benchmark.
Fig. 4: Effect of BPS on production quantity and profit

5.2 Environmental performance

Based on the previous section, setting $E_A = 5$, $E_B = 4$, $E_d = 4$, $E_h = 3$, $E_r = 4$, $v = 0.5$. Fig. 5a and 5c show the environmental performance of BPS in the upstream of the supply chain. When $K < K_1$, the upstream emissions are lower than the benchmark. When $K$ increases, the amount of waste that the upstream manufacturer disposes of reduces, and the emission reduction effect of BPS will be significant. When $K \geq K_E$, with an increase in $K$, on the one hand, the production promotion effect of BPS is dominant, and the growth in emissions caused by the expansion of the production quantity of the upstream manufacturer offsets the emissions reduction caused by the improvement in the resource utilized per unit produced. On the other hand, the processing plant converts more waste into by-products, which leads to an increase in by-products production emissions. Therefore, BPS stimulates emissions. BPS expands social welfare in the upstream of the supply chain, which is due to the expansion of the profit of the upstream manufacturer and processing plant. However, the increase in profit conceals the environmental damage caused by the increase in emissions, especially when $K \geq K_E$. 
When \( c_i < c_{i1} \) (scenario L) or \( c_i < c_{i2} \) (scenario H), the downstream emissions are lower than the benchmark, and the reduction in emissions is due to the use of by-products instead of raw materials for production (as shown in Fig. 5b and 5d). However, when \( c_i \) increases, the production promotion effect of BPS is obvious, and the emissions increase caused by the expansion in production exceeds the reduction in emissions from using by-products instead of raw materials. When \( c_i \geq c_{i1E} \) or \( c_i \geq c_{i2E} \), implementing BPS leads to an increase in emissions. BPS expands social welfare in the downstream of the supply chain, but the marginal social welfare increases and then decreases. The increase in emissions leads to an increase in environmental damage cost and reduces the growth rate of social welfare.

Due to the different parameters that affect the operational strategies of the upstream and downstream manufacturers and the processing plant, the environmental performance of BPS of the entire supply chain is more complex (as shown in Fig. 6a and 6b). When the processing capacity is
medium, and the price of raw materials is low, the emissions reduction effect of BPS is significant (that is, the value of $E - E^N$ is the lowest). When the processing capacity is high, and the price of raw materials is higher than the threshold, BPS increases the supply chain’s emissions. Combined with the profit, when the processing capacity and price of raw materials are lower than the threshold, implementing BPS reduces emissions and increases profit.

Fig. 6: Effect of BPS on supply chain emissions

6 Discussion

In this part, we provide some insights into new findings. First, the production quantity of product and by-products, profit, and transfer price are threshold dependent on the processing capacity. Higher processing capacity leads to higher profit for all members of the supply chain. However, this requires a
high cost of investment, which is a huge burden for most processing plants (Krishnan and Zhu, 2006). Therefore, there should be favorable financing measures to reduce the investment burden of processing plants. In addition, processing plants must consider the efficiency of their capacity and avoid redundant capacity.

Second, production promotion and cost-saving effects are the main effects of BPS. The former is embodied since BPS stimulates upstream and downstream manufacturers’ productions, whereas the processing plant also converts more waste into by-products to expand profit. The latter is embodied in the cost-saving of the upstream manufacturer’s waste disposal and raw materials of the downstream manufacturer (since it uses by-products instead of raw materials). In operational process practice, when the processing plant sets a lower capacity, the manufacturer should focus on how to reduce other costs, such as energy consumption, in the production process to take advantage of the cost-saving effect of BPS. When the processing plant sets a higher capacity, the manufacturer should pay more attention to its own capacity construction to maximize the production promotion effect of BPS.

Third, when the processing capacity is lower than $K_e$ and the price of raw materials is lower than $c_{r1E}$ or $c_{r2E}$, implementing BPS increases profit and reduces emissions, in other cases, implementing BPS does not always have a positive effect on the environment. Our research results suggest that this may be due to the rebound effect, that is, during the implementation of BPS, the increase in emissions caused by expansion of production quantity of product and conversion of more waste into by-products may exceed the reduction in emissions caused by improving resource utilization efficiency. Therefore, manufacturers and processing plant must adopt cleaner production technology while implementing BPS (Liu et al., 2015; Shi et al., 2010). Moreover, the government should implement emissions control measures, such as carbon cap and trade, to influence the operational strategies of manufacturers and processing plants through emission monetization to achieve a win-win situation of environmental and economic benefits (Feng et al., 2019; Jian et al., 2019).

7 Conclusion

This study focuses on the effect of BPS on the operational decisions and environmental benefits of a three-echelon supply chain composed of an upstream manufacturer, a downstream manufacturer, and a limited capacity processing plant. Through game analysis, the optimal operational decisions of the upstream and downstream manufacturers and the processing plant are obtained. Comparing with the benchmark, we discussed the economic benefits of BPS. In addition, the environmental performance of BPS is discussed by considering production emissions and environmental damage cost. The following are the main conclusions of this study.

First, the upstream manufacturer's production quantity and waste disposal decisions and the processing plant’s transfer price decision are threshold dependent on processing capacity, whereas the downstream manufacturer's production quantity decision depends on the threshold of processing
capacity and price of raw materials. Second, for all members of the supply chain, BPS is beneficial to increase profit, the production promotion and cost-saving effects ensure their profit that are higher than the benchmark; in addition, a higher processing capacity brings in more profit. Third, BPS is not always conducive to the environment, and the implementation of BPS may increase emissions. When the processing capacity and price of raw materials are lower than the threshold, implementing BPS can result in a win-win situation of economic and environmental benefits.

The main practical significances of the conclusions are shown as follow. First, processing capacity is an important factor affecting the operation of BPS. Supply chain participations should negotiate to solve the capacity problem, so as to ensure that all parties can benefit from BPS. Second, the manufactures should adopt different operational strategies to fully utilize the production promotion and cost-saving effects of BPS. Third, when implementing BPS, emissions control measures or cleaner production technologies should be adopted to control the operational strategies of manufacturers and processing plants, so as to achieve a win-win situation for both emission reduction and profit increase.

This study has some limitations, which also point out the direction for future research. First, our work does not focus on the competition between manufacturers, considering multiple competitors may lead to more conclusions. Second, this paper does not discuss the investment decision of processing plant, future research can explore this area.

Declarations

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