JOINT DECISION ON PRICING AND WASTE EMISSION LEVEL IN INDUSTRIAL SYMBIOSIS CHAIN

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Abstract. Based on a monopoly model in industrial symbiosis chain including one upstream manufacturer and one downstream manufacturer, the price sensitive-environmental concern demand is introduced into the paper. The decision behaviors of the manufacturers in industrial symbiosis chain under environmental regulations imposed by the policy makers or the government in waste emission standard, waste emission tax and subsidy for waste usage are investigated. The results show the operational factors of the manufacturers must be taken into account in the right formulation of waste emission standard, and the simultaneous implementation of waste emission tax and subsidy for external environmental performance of the manufacturers is superior to a single policy. Environmental concerned consumers with stronger green attitude who are more willing to buy environmentally friendly products could pressurize the manufacturers into decreasing waste emission level, and the manufacturers will affirmatively involve in industrial symbiosis chain due to the intervention of environmental regulations. Especially, integrated industrial symbiosis becomes the optimal decision for the manufacturers to boost both economic benefit and environmental performance. Waste emission contract and quantity discount contract can be techniques to improve the performance of non-integrated industrial symbiosis chain.

1. Introduction. For the past decades, more and more consumers have been gradually concerned about the environmental performance of the products, which compels the firms to produce environmentally friendly products with low carbon or minimum emission [10, 14]. The policy makers or the government has become aware of a large and increasing amount of environmental risk existing in the supply chain, especially the usage of waste generated in the supply chain. Under increasing regulatory environmental pressure from different aspects, the firms have to respond to consumers’ concern on the environmental performance of the products and to address the environmental impacts of their operations [22, 26, 36, 25, 7, 40]. Environmental excellence could be the key to improving management and operations
of the firms [11]. Therefore, the firms have to involve environmental management into their supply chain management to achieve better environmental performance [4, 44].

However, there are many shortcomings and deficiencies in the traditional green solutions for the products, for example, an end-of-pipe approach cannot eliminate pollutants or waste, but what this approach can do is to transform them from one form to another [50], and traditional supply chains reduce waste within manufacturing processes and reuse end-of-life products [2]. As a more sustainable industry practice, industrial symbiosis reuses, recycles and reprocesses waste and intermediates within the system of organizations to reduce the usage of virgin raw materials [2, 5].

Implementing industrial symbiosis in the form of eco-industrial parks is seen as a model for more environmentally responsible production for almost 30 years. The success of industrial symbiosis at Kalundborg, Denmark is replicated all over the world, and this manufacturing mode has brought significant economic and environmental benefits. But a lot of academic questions need to be exposed: How do the firms make their decisions in a chain of industrial symbiosis under environmental regulations imposed by the government or the policy makers in waste emission standard, waste emission tax and subsidy for waste usage? How do environmental regulations and consumers’ price sensitive and environmental concern have effects on decision processes of industrial symbiosis chain and how do the policy makers formulate environmental regulations?

This paper develops industrial symbiosis chain models to address the questions mentioned above. The manufacturers from the upstream and downstream make production plans by taking into consideration environmental regulations, and then choose the optimal strategies for their economic benefits and environmental performances based on different structure of industrial symbiosis chain. Contract mechanisms are used to coordinate the performance of industrial symbiosis chain with different structure.

2. Literature review. Our work is related to the previous literatures about economic analysis on regulations, supply chain management with regulations and industrial symbiosis chain.

For the literatures about economic analysis on regulations, Baris and Richard [3] develop an economic analysis in order to examine the effects of consumer, regulatory, and competitive pressure on the firm’s investments in environmentally friendly production. Environmentally friendly behavior is not always compatible with the profit-seeking behavior of the firm, and the firm must balance the costs and benefits of environmental investments [33, 19]. Muthulingam et al. [31] find that managers might not always make rational environmental investment decisions due to personal biases. Policy measures, past environmental investments, the importance of environmental technologies for consumers and the firms’ performance have a positive effect on environmental investments [32]. These researchers have analyzed the decision behaviors of the firms under environment regulations. However, they only emphasize in an individual economic entity and are lacking of examining the firms along a supply chain.

In terms of supply chain management with regulations, Xie [51] first investigates the impact policy makers have when they set the standard of energy saving levels in a green supply chain. Hamza and Greenwood [17] point out that the major
impact of regulating energy consciousness and environmental sensibility would fall upon many parties. Tsoulfas and Pappis [46] deal with the problems of identifying environmental principles for the design and operation of supply chains. Seuring [42] addresses the importance of the various participants along the supply chain, as well as the interaction between those participants, all of which combine to make a contribution to the future development of industrial ecology. Ordinary green supply chain is often treated as research object with the regulation on the greening of products from various participants along the supply chain, which links with closed-loop or reverse supply chain. But few models have been designed to deal with trading waste in the supply chain, especially in an industrial symbiosis chain.

For industrial symbiosis chain, Bansal and McKnight [2] argue that coordination of supply chain organization and operations is an important part of managing industrial symbiosis. They compare two different forms of interorganizational relationships that deal with the production and movement of waste: industrial symbiosis and supply chain. The firms in an industrial symbiotic relationship benefit directly through reducing costs of raw materials on the input side and reducing costs for the treatment of waste streams on the output side [24]. The benefits of industrial symbiosis to the firms include lowering “raw” materials costs for the receiving firms and reducing waste disposal costs or increasing revenues (from by-product sale) for the providing firms [35]. The downstream firms in an industrial symbiosis chain reduce the consumption of raw material and natural resources instead of using the waste as raw material [15]. The existing researches on industrial symbiosis mainly take qualitative study as method and conclude from case study, while few quantitative models are employed to explore the trading behavior of waste between the firms in industrial symbiosis and there are no environmental regulations mentioned in industrial symbiosis chain. Therefore, it is extremely essential to combine operational management and environmental regulations into the management of waste based supply chain [28], e.g., industrial symbiosis chain.

This paper will discuss how the manufacturers in industrial symbiosis chain choose the way to exchange waste under environmental regulations, how the government or the policy makers formulate environmental regulations and how consumers’ price sensitive and environmental concern impact decision behaviors of the manufacturers. Numerical simulations are done for analyzing economic benefit and environmental performance of industrial symbiosis chain with different structure, and identifying the effect of consumers’ price sensitive and environmental concern on decision processes of the manufacturers.

The remainder of this paper is organised as follows. Three different models, i.e., base model, integrated model and non-integrated model, are presented in Section 3. Section 4 makes a comparative analysis between the three models. In Section 5, two contract mechanisms are proposed to coordinate the performance of non-integrated industrial symbiosis chain. Numerical simulations are introduced in Section 6. Finally, Section 7 concludes with a summary.

3. Model.

3.1. Description of the model. The government or the policy makers set waste emission standard for each product and waste emission level of each manufacturer is regulated to be less than waste emission standard, or the manufacturer’s business should be suspended due to noncompliance. The manufacturers must afford waste emission tax which is similar to disposal cost for the waste dumped into the
environment directly without any treatment. Total waste emission tax is dependent on the amount of the waste emitted by the products from the manufacturers. Meanwhile, the policy makers or the government must subsidize the downstream manufacturer for his/her usage of waste exchanged from the upstream manufacturer as raw material to produce his/her own product.

Therefore, the policy makers or the government will enforce environmental regulations on the manufacturers in industrial symbiosis chain from waste emission standard, waste emission tax and subsidy for waste usage.

The notations used in this paper are listed as follows:

- \( p_i \): prices per unit of the upstream manufacturer’s product \((i = A)\) and the downstream manufacturer’s product \((i = B)\).
- \( c_i \): costs per unit of the upstream manufacturer’s product \((i = A)\) and the downstream manufacturer’s product \((i = B)\), where the costs are defined as production costs generated by raw material, rather than waste flow.
- \( c_W \): cost per unit of the downstream manufacturer’s product produced by waste instead of raw material.
- \( a \) and \( b \): potential intrinsic demands of product A and product B separately.
- \( \alpha_1 \) and \( \beta_1 \): consumers’ price sensitive coefficients of product A and product B separately.
- \( \alpha_2 \) and \( \beta_2 \): consumers’ environmental concern coefficients of product A and product B separately.
- \( \gamma_i \): waste emission levels \((i = A, B)\) of product A and product B.
- \( \gamma_0^i \): initial waste emission levels \((i = A, B)\) of product A and product B.
- \( \bar{\gamma}_i \): waste emission standards \((i = A, B)\) of product A and product B, which are regulated by the policy makers or the government.
- \( c_i^P \): waste emission taxes or waste disposal costs for per unit of waste emitted by the upstream manufacturer’s product \((i = A)\) and the downstream manufacturer’s product \((i = B)\).
- \( m_i \): the cost factors of reducing waste emission involved in making an investment (e.g., environmental innovation investment or environmental equipment purchased) in lowering unit waste emission levels \((i = A, B)\) of product A and product B separately.
- \( p_W \): transaction price or transfer price of waste in industrial symbiosis chain, which is usually paid for by the downstream manufacturer to the upstream manufacturer.
\( \tau \): subsidy for waste usage of the downstream manufacturer, which is paid for by the government.

\( \Pi \): profits of the manufacturers or industrial symbiosis chain with different structure.

3.2. Assumption. Assumption 1. In equilibrium or optimum, the manufacturers have positive demands and non-negative profits [27].

Schumacher [41] shows environmental concerned consumers with stronger green attitude are generally more willing to buy environmentally friendly products, while price oriented consumers don’t prefer to purchasing environmentally friendly products because of the higher price compared with ordinary products. Windrum et al. [47] consider consumer classes with heterogeneous environmental preferences and heterogeneous price preferences, and investigate the consequences of heterogeneous consumer preferences to trade-offs between environmental performance, product quality, and price. They find the demand for environmentally friendly product increases with the consciousness of environmental concerned consumers but decreases with price sensitive of price-oriented consumers. Thus, price sensitive and environmental concern of the consumers need to be considered into the demand function simultaneously.

Deishin [12] studies how a firm can create and capture value by converting a waste stream into a useful and saleable by-product (i.e., implementing by-product synergy (BPS)). She considers a manufacturing firm that produces product A, which is called the original product. During the processing of the original product, waste is generated that can be further processed into a useful stream into by-product B, which obviously consists of a typical industrial symbiosis chain. Producing by-product by consuming the original product’s waste stream is a process innovation that avoids the waste disposal cost. However, there is no environmental regulation considered in her work.

The context which turns the waste generated from the product A into by-product B in Deishin’s work [12] is a representative industrial symbiosis chain, which is similar to our work where the waste generated from the upstream manufacturer A is used to produce by-product by the downstream manufacturer B. To present the results clearly, Deishin uses linear demand functions and continues to use linear demand functions throughout the rest of her analysis in order to simplify the mathematical model of her work. Deishin assumes the consumers’ demand price sensitive coefficient of products as 1. The demand function assumed in our work is more general in terms of treating price sensitive coefficient as \( \alpha_1 \) and \( \beta_1 \) respectively. Many scholars consider the more general demand function in their work [3, 51, 1, 6, 52, 53, 55]. Therefore, the demand function can be assumed as Assumption 2.

\begin{itemize}
  \item **Assumption 2.** The demand function of product A is \( q_A = a - \alpha_1 p_A - \alpha_2 \gamma_A \), and product B’s demand function is \( q_B = b - \beta_1 p_B - \beta_2 \gamma_B \), which is different from the assumption in Deishin’s work [12] where setting \( \alpha_1 \) and \( \beta_1 \) to be 1.
  \item **Assumption 3.** If initial waste emission levels are such low that they comply with environmental regulations and emission standards originally, it implies the manufacturers have non-negative profits under this circumstance even with null investment in environmental innovation, which is in line with the reality.
\end{itemize}

The difference value between initial waste emission levels \( \gamma^0_i \) and waste emission levels \( \gamma_i \), \( \gamma^0_i - \gamma_i \) is waste emission reduction. (1) When initial waste emission levels are not compliant with waste emission standards regulated by the government, i.e.,

\[ \gamma^0_i > \gamma_i \]
initial waste emission levels are larger than waste emission standards, it is necessary for the manufacturers to invest in environmental innovation or make some efforts on emission reduction in order to let their waste emission levels be compliant with waste emission standards, i.e., making waste emission levels less than or equal to waste emission standards at least, which means waste emission levels must be less than initial waste emission levels under this circumstance. (2) When initial waste emission levels meet expected standards, it is not necessary for the manufacturers to invest in environmental innovation or make efforts to decrease emission. Thus the manufacturers whose waste emission levels are commensurate with waste emission standards (i.e., initial waste emission level), need not to do anything on emission reduction, which indicates that the cost of reducing per-unit waste emission to a level $\gamma_i$, will be zero. (3) When initial waste emission levels are below the required standards, it is an indication that waste emission levels already conform to waste emission standards. This illustrates that the manufacturers have no investment in emission reduction because of their conformity to waste emission standards. Consequently, waste emission levels will be set as initial waste emission levels and always below the standards.

Generally speaking, waste emission levels should remain within initial waste emission levels for any rational manufacturers to be compliant with waste emission standards, i.e., $0 < \gamma_i \leq \gamma_0^i$.

We have learnt about the better environmental performance of the product, the larger market demand of the product, i.e., the lower emission level of the product, the larger the market demand of the product. Therefore, the manufacturers will try their best to decrease waste emission levels to attract more consumers and obtain more market demand. From the perspective of product demand function, the manufacturers will always hold lower waste emission levels comparable to initial waste emission levels, and benefit from the increasing product demand.

In additional, Baris and Richard [3] assume “the firm currently has per-unit emission of $E_0$ and the firm can invest in reducing these emissions; perhaps through innovations in its production technologies, investment in cleaner technologies, or education of its employees. To be specific, the cost of reducing per-unit emissions to a level $E_1$ will cost $t(E_0 - E_1)^2$, where $t$ determines the magnitude of the cost involved in making an investment”. Alok et al. [1] have also adopted the same investment function of emission reduction as Baris and Richard [3].

In the early stage, it might be relatively inexpensive for the firms to reduce waste emission. As the firms’ environmental performance improves, it requires more significant changes in technologies and processes for further reduction in emission, which makes it more expensive and costly to achieve levels of improvements with comparison to the initial reduction [18, 37].

Similar investment function with quadratic form for emission reduction has been also recommended by Xie [51], John and Moffitt [23], Yu and Mindy [49], etc. Therefore, the cost related to waste emission reduction or the investment function of lowering waste emission level is assumed as Assumption 4.

**Assumption 4.** In order to meet waste emission standards, the manufacturers have to decrease their waste emission levels by environmental innovation and must pay for a certain investment or make some efforts on emission reduction. To be specific, the cost of reducing per-unit waste emission to a level $\gamma_i$ will be $m_i(\gamma_0^i - \gamma_i)^2$.

Based on the above assumptions, this paper will build three different models, i.e., base model (no waste exchanged), integrated model (integrated industrial symbiosis
chain model), and non-integrated model (non-integrated industrial symbiosis chain model) to explore the decision processes of trading waste between the manufacturers.

3.3. Base model. In base model, the upstream and downstream manufacturers make decisions separately, without exchanging waste.

Profits of the upstream and downstream manufacturers are

\[ \Pi_A = (p_A - c_A - \gamma_A c_A^D)q_A - m_A(\gamma_A^0 - \gamma_A)^2, \]

\[ \Pi_B = (p_B - c_B - \gamma_B c_B^D)q_B - m_B(\gamma_B^0 - \gamma_B)^2. \]

**Proposition 1.** In base model without exchanging waste, the optimal solutions for the prices of product A and product B and waste emission levels for the two products under the non-constraint of regulation on waste emission standard are

\[
\begin{align*}
    p_A^* &= \frac{2m_A[a + \alpha_1 c_A + \gamma_A^0(\alpha_1 c_A^D - \alpha_2)] - (\alpha_2 + \alpha_1 c_A^D)(\alpha c_A^D + \alpha_2 c_A)}{4\alpha_1 m_A - (\alpha_2 + \alpha_1 c_A^D)^2}, \\
    \gamma_A^* &= \frac{4\alpha_1 m_A \gamma_A^0 - (a - \alpha_1 c_A)(\alpha_2 + \alpha_1 c_A^D)}{4\alpha_1 m_A - (\alpha_2 + \alpha_1 c_A^D)^2}, \\
    p_B^* &= \frac{2m_B[b + \beta_1 c_B + \gamma_B^0(\beta_1 c_B^D - \beta_2)] - (\beta_2 + \beta_1 c_B^D)(\beta c_B^D + \beta_2 c_B)}{4\beta_1 m_B - (\beta_2 + \beta_1 c_B^D)^2}, \\
    \gamma_B^* &= \frac{4\beta_1 m_B \gamma_B^0 - (b - \beta_1 c_B)(\beta_2 + \beta_1 c_B^D)}{4\beta_1 m_B - (\beta_2 + \beta_1 c_B^D)^2}.
\end{align*}
\]

**Proof.** To ensure \( \Pi_A \) is concave in \( p_A \) and \( \gamma_A \), the Hessian matrix of the expression (1) is

\[
\begin{bmatrix}
    \frac{\partial^2 \Pi_A}{\partial p_A^2} & \frac{\partial^2 \Pi_A}{\partial p_A \partial \gamma_A} \\
    \frac{\partial^2 \Pi_A}{\partial \gamma_A \partial p_A} & \frac{\partial^2 \Pi_A}{\partial \gamma_A^2}
\end{bmatrix} =
\begin{bmatrix}
    -2\alpha_1 & \alpha_1 c_A^D - \alpha_2 \\
    \alpha_1 c_A^D - \alpha_2 & 2(\alpha_2 c_A^D - m_A)
\end{bmatrix}.
\]

The Hessian matrix has been employed in many joint decision-making problems and adopted by many scholars in their works [14, 51, 52, 16, 43, 45, 21, 54, 20, 48, 38].

Because both the upstream manufacturer and downstream manufacturer seek to maximize their profits, i.e., a joint decision problem with solvable maximum value, the profit function of the upstream manufacturer must be concave in \( p_A \) and \( \gamma_A \). Therefore, the Hessian matrix of the profit function must be negative definite to guarantee there will be a maximum value on the profit function, which results in \(-4\alpha_1(\alpha_2 c_A^D - m_A) - (\alpha_1 c_A^D - \alpha_2)^2 > 0\), i.e., \( \alpha_2 < 2\sqrt{\alpha_1 m_A - \alpha_1 c_A^D} \), and there exist unique optimal solutions for product price and waste emission level. Of course, \( \alpha_2 c_A^D - m_A < 0 \) holds.

From the first order condition of the expression (1) with respect to product price and waste emission level, i.e., \( \frac{\partial \Pi_A}{\partial p_A} = 0 \) and \( \frac{\partial \Pi_A}{\partial \gamma_A} = 0 \), we get

\[
p_A = \frac{2m_A[a + \alpha_1 c_A + \gamma_A^0(\alpha_1 c_A^D - \alpha_2)] - (\alpha_2 + \alpha_1 c_A^D)(\alpha c_A^D + \alpha_2 c_A)}{4\alpha_1 m_A - (\alpha_2 + \alpha_1 c_A^D)^2},
\]

\[
\gamma_A = \frac{4\alpha_1 m_A \gamma_A^0 - (a - \alpha_1 c_A)(\alpha_2 + \alpha_1 c_A^D)}{4\alpha_1 m_A - (\alpha_2 + \alpha_1 c_A^D)^2}.
\]
From the boundary condition explained in the Assumption 3 of Section 3.2, $0 < \gamma_i \leq 1$, we have $0 < \gamma_A = \frac{4a_1c_A - (a - a_1c_A)(a_2 + a_1c_A)}{4a_1m_A - (a + a_1c_A)^2} \leq 1$. Solving this equality, we get $\gamma_A^0 = \frac{a - a_1c_A}{a_2 + a_1c_A}$ and $\gamma_A^0 \leq \frac{a - a_1c_A}{a_2 + a_1c_A}$.

Because $\frac{a - a_1c_A}{a_2 + a_1c_A} = \frac{(a - a_1c_A)(a_2 + a_1c_A)}{4a_1m_A - (a + a_1c_A)^2} > 0$, the lower and upper bound of $\gamma_A^0$ is $\frac{(a - a_1c_A)(a_2 + a_1c_A)}{4a_1m_A - (a + a_1c_A)^2} < \gamma_A^0 \leq \frac{a - a_1c_A}{a_2 + a_1c_A}$.

In base model with satisfying the boundary condition of $\gamma_A^0$, the optimal solutions for the price and waste emission level of product A under the non-constraint of environmental regulation on waste emission standard are as follows:

$$
\begin{align*}
\left\{ \begin{array}{ll}
p_A^* = & \frac{2m_A[a + \alpha_1c_A + \gamma_A^0(a_1c_A^D - a_2)]}{4a_1m_A - (a + a_1c_A)^2} - (a_2 + a_1c_A^D)(ac_A^D + \alpha_2c_A), \\
\gamma_A^* = & \frac{4a_1m_A\gamma_A^0 - (a - a_1c_A)(a_2 + a_1c_A^D)}{4a_1m_A - (a + a_1c_A)^2},
\end{array} \right.
\end{align*}
$$

when $0 < \gamma_A^0 < 1$. Solving method for $p_B^*$ and $\gamma_B^*$ is similar to $p_A^*$ and $\gamma_A^*$. The optimal solutions for the price and waste emission level of product B under the non-constraint of environmental regulation on waste emission standard are as follows:

$$
\begin{align*}
\left\{ \begin{array}{ll}
p_B^* = & \frac{2m_B[b + \beta_1c_B + \gamma_B^0(\beta_1c_B^D - \beta_2)]}{4\beta_1m_B - (\beta_2 + \beta_1c_B)^2} - (\beta_2 + \beta_1c_B^D)(bc_B^D + \beta_2c_B), \\
\gamma_B^* = & \frac{4\beta_1m_B\gamma_B^0 - (b - \beta_1c_B)(\beta_2 + \beta_1c_B^D)}{4\beta_1m_B - (\beta_2 + \beta_1c_B)^2},
\end{array} \right.
\end{align*}
$$

when $0 < \gamma_B^0 < 1$.

From the optimal price and waste emission level, we have the maximum profits of two manufacturers, respectively,

$$
\Pi_A^* = \frac{m_A[a_1c_A - a + \gamma_A^0(a_1c_A^D + a_2)]}{4a_1m_A - (a + a_1c_A)^2}, \quad \Pi_B^* = \frac{m_B[b_1c_B - b + \gamma_B^0(\beta_1c_B^D + \beta_2)]}{4\beta_1m_B - (\beta_2 + \beta_1c_B^D)^2}.
$$

**Corollary 1.** If $\alpha_1c_A^D - a < 0$, $p_A^*$ will be greater than zero definitely, i.e., the sufficient condition for $p_A^* > 0$ is $\frac{\alpha_1c_A^D - a}{\alpha_1} < \frac{1}{\gamma_A^0}$.

**Proof.** Because $2m_A > \frac{(a_2 + a_1c_A)^2}{2a_1}$, we have

$$
\begin{align*}
2m_A[a + \alpha_1c_A + \gamma_A^0(a_1c_A^D - a_2)] - (a_2 + a_1c_A^D)(ac_A^D + \alpha_2c_A) \\
> \frac{(a_2 + a_1c_A^D)^2[a + \alpha_1c_A + \gamma_A^0(a_1c_A^D - a_2)]}{2a_1} - (a_2 + a_1c_A^D)(ac_A^D + \alpha_2c_A) \\
= \frac{(a_2 + a_1c_A^D)(a_1c_A^D - a_2)[\gamma_A^0(a_1c_A^D + a_2) + \alpha_1c_A - a]}{2a_1}.
\end{align*}
$$

We obtain the optimal demand $q_A^* = \frac{2m_A[a_1c_A^D(a_1c_A^D + a_2) + \alpha_1c_A + a]}{(a_2 + a_1c_A^D)^2 - 4a_1m_A}$ through substituting $p_A^*$ and $\gamma_A^*$ into the demand function and we have $\gamma_A^0(a_1c_A^D + a_2) + \alpha_1c_A - a < 0$ in accordance with Assumption 1. Thus $\alpha_1c_A^D - a < 0$, $p_A^*$ will be greater than zero definitely. \(\square\)
The following properties can be derived from Corollary 1.

1) From the first order condition of the expression (1) with respect to $p_A$, we obtain $p^*_A = \frac{\alpha_1 c_A - \gamma_A \alpha_2 + \alpha_1 c_A + a}{2m_A}$. This is similar to the work of Baris and Richard [3]. As established, waste emission tax has a positive influence on the price of a product with a given emission level, which connotes the regulation imposed on the manufacturers is shifted to the product price adopted by the consumers. Meanwhile, there is a negative relationship between the price and consumers’ concern on emission level. That is to say the consumers attach prominence to consuming environmentally friendly products, and it pressurizes the manufacturers into lowering the prices to attract more consumers to buy their products. As the price increases with decreasing waste emission level, it alludes to the previous literatures about the consumers’ willingness to pay for high price to the products with environmentally friendliness or higher green degree [27].

2) Taking the first derivative of $p^*_A$ with respect to $\gamma_0$, we know

$$\frac{\partial p^*_A}{\partial \gamma_0} = \frac{2m_A (\alpha_1 c_A - \alpha_2)}{4\alpha_1 m_A - (\alpha_2 + \alpha_1 c_A)^2} < 0.$$  

For the manufacturers initially access to green product market, they have to reduce product prices to lure attention from the consumers due to such high emission levels [30]. Especially in an environmentally friendly society, the potential entrant should keep an eagle eye on consumers’ environmental awareness to determine a reasonable product price.

3) Taking the first derivative of $p^*_A$ with respect to $m_A$, we know

$$\frac{\partial p^*_A}{\partial m_A} = \frac{-2(\alpha_1^2 c_A^D - \alpha_2^2)[\gamma_0 (\alpha_1 c_A^D + \alpha_2) + \alpha_1 c_A - a]}{[4\alpha_1 m_A - (\alpha_2 + \alpha_1 c_A^D)^2]^2} < 0.$$  

It indicates product price will be low when the cost factor of reducing waste emission is high. If product price is low, initial emission level ($\gamma_0$) or waste emission level ($\gamma_A$) is high. The manufacturers want to make progress in the uncharted field for them about emission reduction through both their own technological innovation of environment protection and purchasing the patents or equipments from external environment, while both of them need huge amount of investment.

If product price is high, initial emission level ($\gamma_0$) or waste emission level ($\gamma_A$) is low and has probably satisfied emission standard. At this point, emission reduction by technical means can cut capitalized cost because of the learning curve effect on manufacturers’ emission reduction technology, which also reflects the technological innovation of environmental emission reduction bringing huge long-term economic benefit to the manufacturers.

4) Taking the first derivative of $\gamma_A^*$ with respect to $\gamma_0$, we know

$$\frac{\partial \gamma_A^*}{\partial \gamma_0} = \frac{4\alpha_1 m_A}{4\alpha_1 m_A - (\alpha_2 + \alpha_1 c_A^D)^2} > 0.$$  

For a startup firm or a new entrant into the green product market, its emission reduction path will be limited to some extent on account of the high initial emission level. Therefore, the manufacturers who initially ignore product environmental performance must give special attention to this problem.

Corollary 2. When the cost factor of reducing waste emission involved in making an investment in lowering unit waste emission level, $m_A$ decreases, $\gamma_A^*$ will
also decrease, and the cost related to waste emission reduction, $m_A(\gamma_A^0 - \gamma_A^2)$ will increase.

**Proof.** Taking the first derivative of $\gamma_A^*$ with respect to $m_A$, we obtain

$$\frac{\partial \gamma_A^*}{\partial m_A} = -\frac{4\alpha_1(\alpha_1 c_A^0 + \alpha_2)(\gamma_A^0 - \gamma_A^2)}{4\alpha_1 m_A - (\alpha_2 + \alpha_1 c_A^0)^2} > 0.$$

It indicates that a decrease in the cost factor of reducing waste emission is beneficial to ameliorate waste emission level, while a high cost of reducing emission makes the firms inefficient to contribute to enhancing environmental quality. The fact that decreasing emission level can lead to the decrease in its investment is better for the manufacturers to innovate and improve protection of the environment. The adoption and employment of more advanced innovative environmental technologies engender a slash in environmental investment resulting in an increase in the profit of manufacturers and developing much greener product simultaneously.

Because the cost related to waste emission reduction or the investment function of lowering waste emission level is $m_A(\gamma_A^0 - \gamma_A^2)^2$, taking the first derivative of $m_A(\gamma_A^0 - \gamma_A^2)^2$ with respect to $m_A$, and then we have

$$\frac{\partial (m_A(\gamma_A^0 - \gamma_A^2)^2)}{\partial m_A} = -\frac{(\alpha_1 c_A^0 + \alpha_2)^2(\gamma_A^0 - \gamma_A^2) + \alpha_1 c_A - a}{4\alpha_1 m_A - (\alpha_2 + \alpha_1 c_A^0)^2} < 0.$$

The cost related to waste emission reduction, $m_A(\gamma_A^0 - \gamma_A^2)^2$ will increase with the decreasing of $m_A$ due to the fact that environmental improvement (i.e., a much lower waste emission level) has increased marginal cost. 

**Corollary 3.** The fraction $(\frac{\omega}{\alpha_2})$ that captures the demand characteristic of price sensitive compared with environmental concern have piecewise impact on waste emission level, i.e., $\gamma_A^*$ will increase with increasing $\frac{\omega}{\alpha_2}$ if $\frac{\omega}{\alpha_2}$ is less than $\omega'$, while decreasing with increasing $\frac{\omega}{\alpha_2}$ if $\frac{\omega}{\alpha_2}$ is greater than $\omega'$, where $\omega = \frac{a(4m_A \alpha_2 + c_A^0) - 4m_A \gamma_A^0 - \alpha_1 c_A^0}{4m_A \omega + 2\alpha_1 c_A - \alpha_2}$.

**Proof.** Let $\omega = \frac{\omega}{\alpha_2}$, and the expression of $\gamma_A^*$ can be rewritten as

$$\gamma_A^* = \frac{4\alpha_1 m_A \gamma_A^0 - (a - \alpha_1 c_A)(\alpha_2 + \alpha_1 c_A^0)}{4\alpha_1 m_A - (\alpha_2 + \alpha_1 c_A^0)^2} = \frac{4m_A \gamma_A^0 + \alpha_1 c_A c_A^0 - 2\alpha_1 c_A - a}{4m_A - \alpha_1 c_A^0} \omega + \alpha_1 c_A - a.$$

Taking the first derivative of $\gamma_A^*$ with respect to $\omega$, we have

$$\frac{\partial \gamma_A^*}{\partial \omega} = \frac{(a - \alpha_1 c_A)(4m_A + \alpha_2 c_A^0 + \alpha_1 c_A^2) - 4m_A \gamma_A^0 (\alpha_2 + \alpha_1 c_A^0)}{(4m_A - \alpha_1 c_A^0) \omega - 2\alpha_1 c_A^0 - \alpha_2}.$$

The denominator of $\frac{\partial \gamma_A^*}{\partial \omega}$ is non-negative. If the numerator of $\frac{\partial \gamma_A^*}{\partial \omega}$ is larger than zero, then we have $\frac{\partial \gamma_A^*}{\partial \omega} > 0$, i.e., $\omega = \frac{\omega}{\alpha_2} < \frac{a(4m_A \alpha_2 + c_A^0) - 4m_A \gamma_A^0 - \alpha_1 c_A^0}{4m_A (\alpha_2 + \alpha_1 c_A^0) + \alpha_1 c_A - \alpha_2} = \omega'$. Therefore, $\gamma_A^*$ will increase with increasing $\frac{\omega}{\alpha_2}$ when $\frac{\omega}{\alpha_2}$ is less than $\omega'$, and $\gamma_A^*$ will decrease with increasing $\frac{\omega}{\alpha_2}$ when $\frac{\omega}{\alpha_2}$ is larger than $\omega'$.

If $\frac{\omega}{\alpha_2}$ could be controlled in a small range, i.e., $\frac{\omega}{\alpha_2}$ is less than $\omega'$, it’s indicative of the fact that consumers are sensitive enough to price or disregard to environment.
Proof. If there exists a threshold value of emission level, the optimal price and waste emission level of product A are of a higher waste emission level of the manufacturer. Due to the non-positive profit of product A, we find that makes \( \Pi_A \) be zero, we get \( \Pi_A = (p_A - c_A - \gamma_A c_A)q_A - m_A(\gamma_A - \gamma_A')^2 \). Thus from the first order condition of \( \Pi_A \) with respect to \( p_A \), i.e., \( \frac{\partial \Pi_A}{\partial p_A} = \gamma_A c_A - \gamma_A' \alpha_2 + \alpha_1 c_A + a - 2 \alpha_1 p_A = 0 \), we have \( p_A^* = \frac{\alpha_1 \gamma_A c_A - \gamma_A' \alpha_2 + \alpha_1 c_A + a}{2 \alpha_1} \). Substituting \( p_A^* \) into \( \Pi_A \), we find \( \Pi_A \) is a quadratic function of \( \gamma_A \), and zero of solutions for the quadratic function are \( \bar{\gamma}_A \) and \( \bar{\gamma}_A \). Also, we can obtain \( \bar{\gamma}_B, \bar{U}_B \) and \( \bar{U}_B \) for product B similar to product A.

In general, waste emission standard is set based on the characteristic of waste, such as waste storage and disposal site, and the damaging effects on its environment, people’s health, daily life and production activities, all of these considerations are from environmental perspective. However, the factors of production and operation in industrial symbiosis chain should be involved in formulating waste emission.
standard by the government from the point of view of economic benefit. Otherwise, the firms will go out of business due to lack of profitability.

In reality, there are a lot of companies with different cost and emission condition. Therefore, the policy makers should set waste emission standard based on average production condition of the industry, such as average production cost and average waste emission level of the industry.

**Corollary 4.** The more stringent environmental regulations don’t mean the higher profit of the manufacturer.

**Proof.** Substituting \( q_A = a - \alpha_1 p_A - \alpha_2 \gamma_A \) into the expression (1), and the profit function of upstream manufacturer can be rewritten as

\[
\Pi_A = \gamma_A^2 (\alpha_2 c_A^D - m_A) + \gamma_A (\alpha_1 p_A c_A^D + \alpha_2 c_A + 2 m_A \gamma_A^0 - ac_A^D - \alpha_2 p_A) + (a - \alpha_1 p_A)(p_A - c_A) - m_A \gamma_A^0.
\]

Because \( \alpha_2 c_A^D - m_A < 0 \), we have \( \frac{\partial^2 \Pi_A}{\partial \gamma_A^2} = 2(\alpha_2 c_A^D - m_A) < 0 \). It indicates that profit of upstream manufacturer, \( \Pi_A \) is concave in \( \gamma_A \). From \( \frac{\partial \Pi_A}{\partial \gamma_A} = 0 \), we can get the optimal waste emission level, \( \gamma_A^* \) and the maximal profit of upstream manufacturer, \( \Pi_A^* \).

When \( \bar{\gamma}_{A1} \in (\gamma_A^*, \bar{\gamma}_A) \), \( \frac{\partial \Pi_A}{\partial \gamma_A} > 0 \) and \( \Pi_A = \Pi_A(\bar{\gamma}_{A1}) \); when \( \bar{\gamma}_{A2} \in [\gamma_A^*, \bar{\gamma}_A) \), \( \frac{\partial \Pi_A}{\partial \gamma_A} \leq 0 \) and \( \Pi_A = \Pi_A(\gamma_A^*) \). Because \( \bar{\gamma}_{A1} < \gamma_A^* \), we have \( \Pi_A(\gamma_A) < \Pi_A^*(\gamma_A^*) \).

**Corollary 4** indicates a tougher waste emission standard doesn’t always make more profit. However, an appropriate emission standard will always meet larger profit aspiration of the manufacturer due to less investment cost in reducing waste emission level.

Thus, the policy makers should carefully choose waste emission standard and understand that more controlling tools or more stringent environmental regulations don’t always result in better environmental performance and might not necessarily benefit the environment [9, 8].

### 3.4. Integrated industrial symbiosis chain model

In integrated industrial symbiosis chain model, the upstream manufacturer is integrated with the downstream manufacturer to make decision together with exchanging waste, and there is no transaction price of waste (i.e., waste transfer price) in this model.

Profit of the whole industrial symbiosis chain is

\[
\Pi^I = (p_A - c_A)q_A - m_A(\gamma_A^0 - \gamma_A)^2 + (p_B - c_W - \gamma_B c_B^D)q_B - m_B(\gamma_B^0 - \gamma_B)^2 + \tau q_A \gamma_A.
\]

(3)

According to the solving process for base model, we obtain the optimal prices and waste emission levels of product A and product B in integrated model respectively, and the analytical solutions are shown as follows:

\[
\begin{align*}
p_A^* &= \frac{2 m_A [a + \alpha_1 c_A - \gamma_A^0 (\alpha_1 \tau + \alpha_2)] - (\alpha_2 - \alpha_1 \tau)(\alpha_2 c_A - a \tau)}{4 \alpha_1 m_A - (\alpha_2 - \alpha_1 \tau)^2}, \\
\gamma_A^* &= \frac{4 \alpha_1 m_A \gamma_A^0 - (a - \alpha_1 c_A)(\alpha_2 - \alpha_1 \tau)}{4 \alpha_1 m_A - (\alpha_2 - \alpha_1 \tau)^2},
\end{align*}
\]
when \( \alpha < 2\sqrt{\alpha_1 m_A} + \alpha_1 \tau \) and \( \frac{(a-a_1 c_A)(\alpha_2-\alpha_1 \tau)}{4\alpha_1 m_A} < \gamma_A^0 < \frac{a-a_1 c_A}{\alpha_2-\alpha_1 \tau} \),

\[
\begin{align*}
p_B^* &= \frac{2m_B[\beta + \beta_1 c_W + \gamma_B^0(\alpha_2 + \beta_1 c_B^D - \beta_2)] - (\beta_2 + \beta_1 c_B^D)(b_c B + \beta_2 c_W)}{4\beta_1 m_B - (\beta_2 + \beta_1 c_B^D)^2}, \\
\gamma_B^* &= \frac{4\beta_1 m_B \gamma_B^0 - (b - \beta_1 c_W)(\beta_2 + \beta_1 c_B^D)}{4\beta_1 m_B - (\beta_2 + \beta_1 c_B^D)^2}
\end{align*}
\]

when \( \beta_2 < 2\sqrt{\beta_1 m_B - \beta_1 c_B^D} \) and \( \frac{(b-\beta_1 c_W)/(\beta_2 + \beta_1 c_B^D)}{4\beta_1 m_B} < \gamma_B^0 < \frac{b-\beta_1 c_W}{\beta_2 + \beta_1 c_B^D} \).

Therefore, the optimal profit of integrated industrial symbiosis chain system is

\[
II^{NI*} = \frac{m_A[a_1 c_A - a + \gamma_A^0(\alpha_2 - \alpha_1 \tau)]}{4\alpha_1 m_A - (\alpha_2 - \alpha_1 \tau)^2} + \frac{m_B[\beta_1 c_W - b + \gamma_B^0(\beta_2 + \beta_1 c_B^D)]}{4\beta_1 m_B - (\beta_2 + \beta_1 c_B^D)^2}.
\]

Also, the optimal interval of waste emission standard for product A is similar to Proposition 2 as shown in Table 1.

3.5. Non-integrated industrial symbiosis chain model. In non-integrated industrial symbiosis chain model, the upstream and downstream manufacturers make decision separately with exchanging waste and transaction price of waste.

Profits of the upstream and downstream manufacturers are

\[
\begin{align*}
II_A^{NI} &= (p_A-c_A+\gamma_A p_W)q_A - m_A(\gamma_A^0-\gamma_A), \\
II_B^{NI} &= (p_B-c_W-\gamma_B c_B)q_B - m_B(\gamma_B^0-\gamma_B)^2 - p_W \gamma_A q_A + \tau q_A \gamma_A.
\end{align*}
\]

According to the solving process for base model, the optimal price and waste emission level of product A are

\[
\begin{align*}
p_A^{NI*} &= \frac{2m_A[a + a_1 c_A - \gamma_A^0(\alpha_1 p_W + \alpha_2)] - (\alpha_2 - \alpha_1 p_W)(a_2 c_A - a p_W)}{4\alpha_1 m_A - (\alpha_2 - \alpha_1 p_W)^2}, \\
\gamma_A^{NI*} &= \frac{4\alpha_1 m_A \gamma_A^0 - (a - a_1 c_A)(\alpha_2 - \alpha_1 p_W)}{4\alpha_1 m_A - (\alpha_2 - \alpha_1 p_W)^2}
\end{align*}
\]

when \( \alpha < 2\sqrt{\alpha_1 m_A} + \alpha_1 p_W \) and \( \frac{(a-a_1 c_A)(\alpha_2-\alpha_1 p_W)}{4\alpha_1 m_A} < \gamma_A^0 < \frac{a-a_1 c_A}{\alpha_2-\alpha_1 p_W} \).

The optimal price and waste emission level of product B are

\[
\begin{align*}
p_B^{NI*} &= p_B^* - \frac{(p_W-\tau)(\beta_2^2 + \beta_1 c_B^D - 2\beta_1 m_B)}{\delta[4\beta_1 m_B - (\beta_2 + \beta_1 c_B^D)^2]}, \\
\gamma_B^{NI*} &= \gamma_B^* + \frac{\beta_1 (p_W-\tau)(\beta_2 + \beta_1 c_B^D)}{\delta[4\beta_1 m_B - (\beta_2 + \beta_1 c_B^D)^2]}
\end{align*}
\]

when \( \beta_2 < 2\sqrt{\beta_1 m_B - \beta_1 c_B^D} \) and \( \frac{(b-\beta_1 c_W)/\beta_2 + \beta_1 c_B^D}{4\beta_1 m_B} < \gamma_B^0 < \frac{b-\beta_1 c_W}{\beta_2 + \beta_1 c_B^D} \).

It’s noted that \( \delta \) denotes one unit of waste can produce \( \delta \) unit of product B.

Therefore, the optimal profit of non-integrated industrial symbiosis chain system is

\[
II^{NI*} = \frac{m_A[a_1 c_A - a + \gamma_A^0(\alpha_2 - \alpha_1 p_W)]}{4\alpha_1 m_A - (\alpha_2 - \alpha_1 p_W)^2} + \frac{m_B[\beta_1 c_W - b + \gamma_B^0(\beta_2 + \beta_1 c_B^D)]}{4\beta_1 m_B - (\beta_2 + \beta_1 c_B^D)^2}.
\]

Also, the optimal interval of waste emission standard for product A is similar to Proposition 2 as shown in Table 1 below.

\[
p' = \frac{2m_A[a+\alpha_1 c_A-\gamma_A^0(\alpha_1 \tau+a_2)]-(\alpha_2-\alpha_1 \tau)(a_2 c_A-a \tau)}{4\alpha_1 m_A - (\alpha_2-\alpha_1 \tau)^2},
\]
Table 1. The optimal interval of waste emission standard (only for product A)

| Waste emission standard | Optimal waste emission level and price |
|-------------------------|---------------------------------------|
| $\frac{4\alpha_1 m_A 4^\alpha_1{(a-a_1 c_A)(a_2-a_1)}}{4\alpha_1 m_A - (a_2-a_1)^2} \leq \tilde{\gamma}_A < \tilde{U}_A$ | $\gamma^*_{A} = \frac{4\alpha_1 m_A 4^\alpha_1{(a-a_1 c_A)(a_2-a_1)}}{4\alpha_1 m_A - (a_2-a_1)^2}$ $p^*_A = p$ |
| $\tilde{U}_A \leq \gamma_A < \frac{4\alpha_1 m_A 4^\alpha_1{(a-a_1 c_A)(a_2-a_1)}}{4\alpha_1 m_A - (a_2-a_1)^2}$ | $\gamma^*_A = \gamma_A$ $p^*_A = -\alpha_1 a_1 \gamma^*_A + a_1 c_A + a$ |
| $\tilde{\gamma}_A \geq \tilde{U}_A$ or $\tilde{\gamma}_A \leq \tilde{U}_A$ | withdraw from the market |
| $\frac{4\alpha_1 m_A 4^\alpha_1{(a-a_1 c_A)(a_2-a_1 p_W)}}{4\alpha_1 m_A - (a_2-a_1 p_W)^2} \leq \tilde{\gamma}_A \leq \tilde{U}_A$ | $\gamma^*_A = \frac{4\alpha_1 m_A 4^\alpha_1{(a-a_1 c_A)(a_2-a_1 p_W)}}{4\alpha_1 m_A - (a_2-a_1 p_W)^2}$ $p^*_A = p^*_{NI}$ |
| $\tilde{U}_A < \tilde{\gamma}_A < \frac{4\alpha_1 m_A 4^\alpha_1{(a-a_1 c_A)(a_2-a_1 p_W)}}{4\alpha_1 m_A - (a_2-a_1 p_W)^2}$ | $\gamma^*_A = \frac{4\alpha_1 m_A 4^\alpha_1{(a-a_1 c_A)(a_2-a_1 p_W)}}{4\alpha_1 m_A - (a_2-a_1 p_W)^2}$ $p^*_A = -\alpha_1 a_1 \gamma^*_A + a_1 c_A + a$ |
| $\tilde{\gamma}_A \geq \tilde{U}_A$ or $\tilde{\gamma}_A < \tilde{U}_A$ | withdraw from the market |

$p^*_A = \frac{2m_A [a+a_1 c_A - \gamma^*_A (a_1 p_W + a_2)] - (a_2-a_1 p_W)(a_2 c_A - a p_W)}{4\alpha_1 m_A - (a_2-a_1 p_W)^2}$,
$\tilde{U}_A = \frac{4\alpha_1 m_A 4^\alpha_1{(a-a_1 c_A)(a_2-a_1)}}{4\alpha_1 m_A - (a_2-a_1)^2}$,
$\tilde{U}_A = \frac{4\alpha_1 m_A 4^\alpha_1{(a-a_1 c_A)(a_2-a_1)}}{4\alpha_1 m_A - (a_2-a_1)^2}$,
$\tilde{U}_A = \frac{4\alpha_1 m_A 4^\alpha_1{(a-a_1 c_A)(a_2-a_1 p_W)}}{4\alpha_1 m_A - (a_2-a_1 p_W)^2}$,
$\tilde{U}_A = \frac{4\alpha_1 m_A 4^\alpha_1{(a-a_1 c_A)(a_2-a_1 p_W)}}{4\alpha_1 m_A - (a_2-a_1 p_W)^2}$.

Also, we can obtain the optimal price and waste emission level constrained by the optimal interval of waste emission standard for product B similar to product A.

The results in Table 1 indicate that the firms should choose the appropriately optimal emission levels and prices according to different waste emission standards. For the government or the policy makers, waste emission standards should be formulated rationally in such a manner that will benefit the firms.

From a managerial perspective, the outcome partly explains the contribution of environmental concern of shifting heavy pollutant industries from developed nations to developing nations where environmental pressure is less due to the weak environmental awareness of the consumers and the loose environmental regulations in developing countries. Because of the stringent environmental regulations, i.e., the low standards of waste emission promulgated in developed countries, the firms have to make a large investment in technologies and environmental innovations to reduce their waste emission levels or green their products, which leads to an increasing cost on their products and compels the firms to stay out of the market in developed countries due to the low profitability of products.

While the high waste emission standards also render the firms no economic motivation to enter into the market, it can be explained by consumers’ environmental concern and high emission levels of the firms by the reason of less capital invested.
in environmental innovation, which results in a lower price and demand for the products and gives rise to the diseconomy for the firms.

**Proposition 3.** In integrated model, the subsidy, \( \tau \) for waste usage and waste emission tax, \( c_B^D \) can be set in the following intervals:

\[
\tau \in \begin{cases} 
\left( \frac{\alpha_2}{\alpha_1} - 2 \sqrt{\frac{m_A}{\alpha_1}}, \frac{\alpha_2}{\alpha_1} + 2 \sqrt{\frac{m_A}{\alpha_1}} \right), & \text{if } \alpha_1 < \alpha_1 < \bar{\alpha}_1 \\
\left( \frac{\alpha_2}{\alpha_1} - \frac{4m_A\gamma_A^0}{a - \alpha_1 c_A}, \frac{\alpha_2}{\alpha_1} + 2 \sqrt{\frac{m_A}{\alpha_1}} \right), & \text{otherwise}
\end{cases}.
\]

\[
c_B^D \in \begin{cases} 
\left( 0, 2 \sqrt{\frac{m_B}{\beta_1}} - \frac{\beta_2}{\beta_1} \right), & \text{if } \beta_1 < \beta_1 < \bar{\beta}_1 \\
\left( 0, \frac{4m_B\gamma_B^0}{b - \beta_1 c_W} - \frac{\beta_2}{\beta_1} \right), & \text{otherwise}
\end{cases}.
\]

Where

\[
\alpha_1 = \frac{a c_A + 2mA\gamma_A^0}{\gamma_A^0 + \gamma_A^0 \sqrt{m_A^2 + ac_A m_A}}, \quad \bar{\alpha}_1 = \frac{a c_A + 2mA\gamma_A^0}{\gamma_A^0 + \gamma_A^0 \sqrt{m_A^2 + ac_A m_A}}.
\]

\[
\beta_1 = \frac{b c_W + 2m_B \gamma_B^2}{\gamma_B^2 + \gamma_B^2 \sqrt{m_B^2 + b c_W m_B}}, \quad \bar{\beta}_1 = \frac{b c_W + 2m_B \gamma_B^2}{\gamma_B^2 + \gamma_B^2 \sqrt{m_B^2 + b c_W m_B}}.
\]

**Proof.** 1) Because \( \gamma_A^* = \frac{4\alpha_1 m_A \alpha_1}{4\alpha_1 m_A - (a - \alpha_1 c_A)(\alpha_2 - \alpha_1 \tau)} \), \( 4\alpha_1 m_A \alpha_1 - (a - \alpha_1 c_A)(\alpha_2 - \alpha_1 \tau) \geq 0 \) holds, then we obtain \( \tau \geq \frac{\alpha_2}{\alpha_1} - \frac{4m_A\gamma_A^0}{a - \alpha_1 c_A} \). From \( 4\alpha_1 m_A - (\alpha_2 - \alpha_1 \tau)^2 > 0 \), another intervals of \( \tau \) can be calculated as \( \alpha_1 - 2 \sqrt{\frac{m_A}{\alpha_1}} < \tau < \frac{\alpha_2}{\alpha_1} + 2 \sqrt{\frac{m_A}{\alpha_1}} \). Finally, we obtain

\[
\tau \in \begin{cases} 
\left( \frac{\alpha_2}{\alpha_1} - 2 \sqrt{\frac{m_A}{\alpha_1}}, \frac{\alpha_2}{\alpha_1} + 2 \sqrt{\frac{m_A}{\alpha_1}} \right), & \text{if } \alpha_1 < \alpha_1 < \bar{\alpha}_1 \\
\left( \frac{\alpha_2}{\alpha_1} - \frac{4m_A\gamma_A^0}{a - \alpha_1 c_A}, \frac{\alpha_2}{\alpha_1} + 2 \sqrt{\frac{m_A}{\alpha_1}} \right), & \text{otherwise}
\end{cases}.
\]

where \( \alpha_1 = \frac{a c_A + 2mA\gamma_A^0}{\gamma_A^0 + \gamma_A^0 \sqrt{m_A^2 + ac_A m_A}}, \bar{\alpha}_1 = \frac{a c_A + 2mA\gamma_A^0}{\gamma_A^0 + \gamma_A^0 \sqrt{m_A^2 + ac_A m_A}}. \)

The optimal emission level of product A in integrated model is zero when \( \tau = \frac{\alpha_2}{\alpha_1} - \frac{4m_A\gamma_A^0}{a - \alpha_1 c_A} \) and it’s \( \gamma_A^0 \) when \( \tau = \frac{\alpha_2}{\alpha_1} \), which indicates that the higher subsidy for waste usage doesn’t result in a better environmental performance. Therefore, the government should figure out the various factors influencing production and operational management of the firms, and crystallize consumers’ price sensitive and environmental concern for the characteristic of products as well as the unit investment for innovation in environmental technologies before giving a reasonable subsidy.

2) Because \( \gamma_B^* = \frac{4\beta_1 m_B \beta_1 -(b - \beta_1 c_W)(\beta_2 + \beta_1 c_B^D)}{4\beta_1 m_B -(\beta_2 + \beta_1 c_B^D)^2} \), \( 4\beta_1 m_B - (\beta_2 + \beta_1 c_B^D)^2 \geq 0 \) holds, then we obtain \( c_B^D \leq \frac{4m_B\gamma_B^0}{b - \beta_1 c_W} - \frac{\beta_2}{\beta_1} \). While \( 4\beta_1 m_B - (\beta_2 + \beta_1 c_B^D)^2 > 0 \) holds, we get \( 0 \leq c_B^D < 2 \sqrt{\frac{m_B}{\beta_1}} - \frac{\beta_2}{\beta_1} \). Finally, we obtain

\[
c_B^D \in \begin{cases} 
\left( 0, 2 \sqrt{\frac{m_B}{\beta_1}} - \frac{\beta_2}{\beta_1} \right), & \text{if } \beta_1 < \beta_1 < \bar{\beta}_1 \\
\left( 0, \frac{4m_B\gamma_B^0}{b - \beta_1 c_W} - \frac{\beta_2}{\beta_1} \right), & \text{otherwise}
\end{cases}.
\]
where \( \beta_1 = \frac{bc_w + 2m_A \gamma_B^2 - 2b \gamma_B \sqrt{m_B^2 \gamma_B^2 + b c_w m_B}}{c_w} \), \( \beta_4 = \frac{bc_w + 2m_A \gamma_B^2 + 2b \gamma_B \sqrt{m_B^2 \gamma_B^2 + b c_w m_B}}{c_w} \).

The optimal emission level of product B in integrated model is zero when \( c_B^D = \frac{4m_B \gamma_B^2 - \beta_2}{\beta_1} \), and it’s \( \frac{4b_1 m_B \gamma_B^0 - \beta_2 (b - \beta_1 c_w)}{4b_1 m_B - \beta_2^2} \) when \( c_B^D = 0 \), which implies the setting of waste emission tax has an immediate effect on improving product environmental performance.

From the social welfare point of view, the subsidy and emission tax can curb the manufacturers’ waste emission and enhance product environmental performance. A single policy, i.e., only subsidy or only emission tax, can’t restrain the behavior of upstream and downstream manufacturers’ waste disposal. However, the combination of carrot and stick, i.e., subsidy and emission tax implemented simultaneously for external environmental benefit is superior to a single policy, and guarantee all the manufacturers to engage in exchanging waste in order to minimize the waste discharged in industrial symbiosis chain.

4. Comparative analysis of the three models. In this section, by comparison of these three models in terms of waste emission level and marginal profit, the manufacturers decide the best industrial symbiosis chain structure for their decision-making about the optimal emission level and product price.

**Proposition 4.** For base model and integrated model, the optimal emission level of downstream manufacturer in base model is always larger compared with integrated model, while the upstream manufacturer’s optimal emission level in base model is less than that in integrated model with the sufficient condition, \( \gamma_A^0 < \frac{4 - \alpha_1 c_A}{2 \sqrt{\alpha_1 m_A}} \).

**Proof.** Because \( c_w < c_B \), we get \( b - \beta_1 c_w > b - \beta_1 c_B \), then there will be \( \gamma_B^0 > \gamma_B^I \) obviously.

For \( \gamma_A^0 \) and \( \gamma_A^I \), we build a function \( f(x) = \frac{4 \alpha_1 m_A \gamma_A^2 - (a - \alpha_1 c_A)x}{4 \alpha_1 m_A - x^2} \). Taking the first derivative of \( f(x) \) with respect to \( x \) and we get

\[
f'(x) = \frac{-(a - \alpha_1 c_A)x^2 + 8 \alpha_1 m_A \gamma_A^0 x - 4 \alpha_1 m_A (a - \alpha_1 c_A)}{(4 \alpha_1 m_A - x^2)^2},
\]

and \( \Delta = 16 \alpha_1 m_A [4 \alpha_1 m_A \gamma_A^2 - (a - \alpha_1 c_A)^2] \). When \( \Delta < 0 \), i.e., \( \gamma_A^0 < \frac{4 - \alpha_1 c_A}{2 \sqrt{\alpha_1 m_A}} \), the function \( f(x) \) has no real roots and there will be \( f'(x) < 0 \). Because \( \alpha_2 + \alpha_1 c_A^D > \alpha_2 - \alpha_1 \), there must be \( \gamma_A^0 < \gamma_A^I \). Then the proof is established.

Proposition 4 implies environmental performance contributed by industrial symbiosis for the downstream manufacturer is superior to that for the upstream manufacturer. In contrast to base model, the reason why the downstream manufacturer in integrated decision has low emission level is that, he/she not only saves production cost from exchanging waste, but also benefits from subsidy provided by the government and reinvests the additional profit into innovating technologies of environment protection.

**Proposition 5.** In terms of economic benefit, (1) If \( \gamma_A^0 < \frac{4 - \alpha_1 c_A}{2 \sqrt{\alpha_1 m_A}} \), when \( \tau < c_A^D \), the upstream manufacturer will definitely participate in integrated industrial symbiosis chain to exchange waste. (2) When \( \frac{b - \beta_1 c_w}{\beta_1} \leq c_B^D < \frac{b - \beta_1 c_w}{\beta_1} \), the downstream manufacturer will definitely join integrated industrial symbiosis chain to exchange waste.
Proposition 6. (i) When \( \gamma_A^0 < \frac{a_0 - a_1 c_A^*}{a_0 + a_1} \), \( \gamma_A^{N^*} \geq \gamma_A^r \) if \( p_W \geq \tau \); \( \gamma_A^{N^*} < \gamma_A^r \) if \( p_W < \tau \). (ii) \( \gamma_B^{N^*} \geq \gamma_B^r \) if \( p_W \geq \tau \); \( \gamma_B^{N^*} < \gamma_B^r \) if \( p_W < \tau \).

Proof. (1) From the first order condition of the expression (1) with respect to \( p_A \), we get 
\[
p_A^* = \frac{2a_2 \gamma_A c_A^2 - a_2 \gamma_A^2 + a_1 a_2}{2 a_1}.
\]
Due to the positive marginal profit of product A [51, 27], i.e., \( p_A - c_A - \gamma_A c_A^2 > 0 \), we obtain 
\[
c_A^* = \frac{a_0 - a_1 c_A^*}{a_1 + a_2}.
\]
If \( c_A^* = \frac{a_0 - a_1 c_A^*}{a_1 + a_2} \), the higher waste disposal cost for the upstream manufacturer in base model provides an opportunity to participate in exchanging waste for profit, and the upstream manufacturer in base model should slam the door without exchanging waste, then change the production mode from no waste recycled to industrial symbiosis.

From the first order condition of the expression (2) with respect to \( p_B^T \), we get 
\[
p_B^T = \frac{\partial \Pi}{\partial p_B} = -a_1 \gamma_A^* \tau - \gamma_A^T \alpha_2 + a_1 c_A + a - 2a_1 p_A^T = 0
\]
and based on the positive marginal profit of product A, i.e., \( p_A^T - c_A > 0 \), we obtain 
\[
p_A^T < \frac{a_0 - a_1 c_A^*}{a_1 + a_2}.
\]
When \( \gamma_A^0 < \frac{a_0 - a_1 c_A^*}{a_1 + a_2} \), we have 
\[
c_A^* = \frac{a_0 - a_1 c_A^*}{a_1 + a_2} > \frac{a_0 - a_1 c_A^*}{a_1 + a_2}.
\]
Thus \( c_A^* = \frac{a_0 - a_1 c_A^*}{a_1 + a_2} > \frac{a_0 - a_1 c_A^*}{a_1 + a_2} \tau \), i.e., \( \tau < c_A^* \), then the upstream manufacturer will intentionally trade waste with the downstream manufacturer and profit from waste disposal cost saving and subsidy.

Considering economic benefit, Proposition 5 shows how the policy makers balance the relationship between the manufacturers’ economic benefit and the improvement of emission level. The tradeoff between economic benefit and environmental performance turns into a common concern for the firms involved in industrial symbiosis. The firms are motivated by the intervention of government environmental regulations to get involved in industrial symbiosis from their own economic benefit and external environmental performance (The upstream manufacturer in base model doesn’t trade waste, and yet, the upstream manufacturer in integrated model remains at zero emission to the external natural environment).

(2) From the first order condition of the expression (2) with respect to \( p_B \), we get 
\[
p_B = \frac{\partial \Pi}{\partial p_B} = \frac{\partial \Pi}{\partial p_B} = \frac{b_2 \gamma_B c_B^2 - b_2 \gamma_B^2 + b_2 c_B + b}{b_2 + b_3}.
\]
Due to the positive marginal profit of product B, i.e., \( p_B - c_B - \gamma_B c_B^2 > 0 \), we obtain 
\[
c_B^T < \frac{b_2 \gamma_B c_B^2 - b_2 \gamma_B^2}{b_2 + b_3}.
\]
From the first order condition of the expression (3) with respect to \( p_B^T \), we have 
\[
\frac{\partial \Pi}{\partial p_B^T} = \beta_1 \gamma_B c_B^T - \beta_2 \gamma_B^T + b_2 c_B + b - \beta_3 p_B^T = 0.
\]
Because of the positive marginal profit of product B, i.e., \( p_B^T - c_B - \gamma_B^T c_B^T > 0 \), we obtain 
\[
c_B^T < \frac{b_2 \gamma_B c_B^2 - b_2 \gamma_B^2}{b_2 + b_3}.
\]
We know that 
\[
\frac{b_2 \gamma_B c_B^2}{b_2 + b_3} - \frac{b_2 c_B}{b_2 + b_3} = \frac{b_2 \gamma_B c_B^2}{b_2 + b_3} - \frac{b_2 c_B}{b_2 + b_3} \leq \frac{b_2 \gamma_B c_B^2}{b_2 + b_3} - \frac{b_2 c_B}{b_2 + b_3} \leq \frac{b_2 \gamma_B c_B^2}{b_2 + b_3} - \frac{b_2 c_B}{b_2 + b_3} \leq \frac{b_2 \gamma_B c_B^2}{b_2 + b_3} - \frac{b_2 c_B}{b_2 + b_3}.
\]
When \( b_2 \gamma_B c_B^2 > b_2 \gamma_B^2 \), the marginal profit of product B in base model will be less than zero if the downstream manufacturer has no intention to recycle waste. But a proper interval of emission tax, e.g., \( b_2 \gamma_B c_B^2 < b_2 \gamma_B^2 \), drives the downstream manufacturer to automatically involve in integrated industrial symbiosis chain for making production plan based on economic interest and positive marginal profit at least.

\[
\text{Proposition 6. (i) When } \gamma_A^0 < \frac{a_0 - a_1 c_A^*}{a_0 + a_1}, \gamma_A^{N^*} \geq \gamma_A^r \text{ if } p_W \geq \tau; \gamma_A^{N^*} < \gamma_A^r \text{ if } p_W < \tau. \text{ (ii) } \gamma_B^{N^*} \geq \gamma_B^r \text{ if } p_W \geq \tau; \gamma_B^{N^*} < \gamma_B^r \text{ if } p_W < \tau.
\]

Proof. (1) Proposition 6 (i) can be proved by the optimal waste emission level and Proposition 4. Proposition 6 (i) indicates that waste tradable price of the upstream manufacturer should be dependent on the subsidy. When waste tradable price is higher than the subsidy, a better environmental performance will be induced by integrated decision. Because waste tradable price is too high, the downstream firm will not purchase waste from the upstream manufacturer as raw material to make production plan, which makes the downstream manufacturer procuring ordinary raw
material to produce and results in the upstream manufacturer to dump the waste into the environment immediately. In order to avoid the waste to be landfilled without any treatment, the upstream manufacturer has to collaborate with the downstream manufacturer to ensure a better environmental performance and reduce waste emission level.

(2) For Proposition 6 (ii), because \( \gamma_{WB}^{NI} = \gamma_{WB}^I + \frac{\beta_1 (pw - \tau)(\beta_2 + \beta_3 c_B^0)}{\beta_1 + \beta_2 + \beta_3 c_B^0} \), we obtain \( \gamma_{WB}^{NI} \geq \gamma_{WB}^I \) if \( pw \geq \tau \); \( \gamma_{WB}^{NI} < \gamma_{WB}^I \) if \( pw < \tau \). The proposition shows that a higher subsidy provided by the government may blindly not be able to encourage the downstream manufacturer to reduce emission level. Conversely, a lower subsidy flogs the downstream manufacturer to ponder over how to continue to profit on the premise of paying for the cost of trading waste, and the first choice for the downstream manufacturer is collaborating to integrate with the upstream manufacturer. The integration internalizes waste transaction cost and improves product environmental performance.

5. Contract design. From the above discussions, integrated decision is a better choice with respect to economic benefit and environmental performance for industrial symbiosis under partial constraints. While a contract coordination supports non-integrated decision in industrial symbiosis chain with the same performance as integrated decision, or achieves Pareto improvement at least, i.e., a better performance than original non-integrated decision. Supply chain contract is designed to ensure the coordination between the sellers and buyers’ profits and optimize the performance of the channel by providing appropriate information and incentives. Learning from ordinary revenue sharing contract and transaction amount of waste, a waste emission contract and a quantity discount contract are respectively proposed in this section to coordinate the performance of non-integrated industrial symbiosis chain.

5.1. Waste emission contract. The upstream and downstream manufacturers firstly agree to a waste emission contract with two parameters [51]: waste tradable price, \( p_{S-W} \) after coordinating non-integrated chain, and revenue sharing fraction, \( \phi \). Under waste emission contract, the upstream manufacturer keeps \( \phi (0 < \phi < 1) \) portion of the revenue that he/she generates, and shares the remaining portion, \( 1 - \phi \) of the revenue with the downstream manufacturer. This contract helps non-integrated chain with the same environmental performance as integrated chain, while economic benefit should be better than that in original non-integrated chain at least.

Profits of the upstream and downstream manufacturers under waste emission contract are

\[
\Pi_{SI-A}^{NI} = \phi (p_A^I + \gamma_A^I p_{S-W}^I - c_A q_A^I - m_A (\gamma_A^0 - \gamma_A^I)^2), \\
\Pi_{SI-B}^{NI} = (p_B^I - c_W - \gamma_B^I c_B^0) q_B^I - m_B (\gamma_B^0 - \gamma_B^I)^2 - p_{S-W} \gamma_A^I q_A^I \\
+ \tau \gamma_A^I q_A^I + (1 - \phi) (p_A^I + \gamma_A^I p_{S-W}^I) q_A^I. 
\]

If and only if \( \Pi_{SI-A}^{NI} \geq \Pi_A^{NI} \) and \( \Pi_{SI-B}^{NI} \geq \Pi_B^{NI} \) hold, Pareto improvement will be reached and the contract \( (p_{S-W}, \phi) \) presented by the upstream manufacturer will be accepted by the downstream manufacturer. Through contract coordination, environmental performance of non-integrated chain is the equivalent of that in integrated
chain. We obtain new waste tradable price \( p_{S-W} = \frac{a_2}{a_1} + \frac{4m_A}{4m_Aa_1^2(a_2-a_1)} \), and if \( \phi \leq \phi \leq \bar{\phi} \) can be derived from \( \Pi_{D-A}^{NI} \geq \Pi_{AI}^{NI} \) and \( \Pi_{D-B}^{NI} \geq \Pi_{B}^{NI} \).

Where
\[
\Phi = \frac{(p_A^{NI} + \gamma_A^{NI} + \frac{c_A}{w}q_A^{NI} + c_Aq_A^{NI} - m_A(\gamma_A^{NI} - \gamma_A^{I'})^2 - m_A(\gamma_A^{NI} - \gamma_A^{I'})^2)}{p_A^{NI} + \gamma_A^{NI} + \frac{c_A}{w}q_A^{NI}}.
\]
\[
\Phi = \frac{(p_B^{NI} - c_W - \gamma_B^{NI} - \gamma_B^{I'})q_B^{NI} + m_B(\gamma_B^{NI} - \gamma_B^{I'})^2 - m_B(\gamma_B^{NI} - \gamma_B^{I'})^2)}{p_A^{NI} + \gamma_A^{NI} + \frac{c_A}{w}q_A^{NI}}.
\]

When \( \phi \leq \phi \leq \bar{\phi} \), the upstream manufacturer employs waste emission contract mechanism and revises waste tradable price to coordinate non-integrated industrial symbiosis chain, which contributes to lower emission level and increase the profits of the manufacturers.

5.2. Quantity discount contract. The upstream manufacturer decides to discount transaction amount of waste if the downstream manufacturer uses waste as raw material to produce product B. The more waste consumed by the downstream manufacturer, the lower waste tradable price, i.e., the upstream manufacturer will consider a discount on waste tradable price based on the amount of exchanging waste.

This paper references the work of Ding et al. [13] introducing discount rate in quantity discount contract with two parameters: waste tradable price, \( p_{D-W} \) after coordinating non-integrated chain, and discount rate, \( \theta \). The linear quantity discount contract, \( p_{D-W} = p_{D-W} - \theta q_A \) is used to denote quantity discount, where \( 0 \leq \theta \leq \frac{p_{D-W}}{q_A} \). The upstream manufacturer doesn’t give any discount to the downstream manufacturer if \( \theta \) is equal to zero. Under quantity discount contract, the profits of the manufacturers are given by

\[
\Pi_{D-A}^{NI} = p_{D-A}^{NI} + \gamma_A^{NI} + \frac{c_A}{w}q_A^{NI} + m_A(\gamma_A^{NI} - \gamma_A^{I'})^2 - m_A(\gamma_A^{NI} - \gamma_A^{I'})^2,
\]
\[
\Pi_{D-B}^{NI} = (p_{D-B}^{NI} - c_W - \gamma_B^{NI} - \gamma_B^{I'})q_B^{NI} + m_B(\gamma_B^{NI} - \gamma_B^{I'})^2 - m_B(\gamma_B^{NI} - \gamma_B^{I'})^2.
\]

From \( \Pi_{D-A}^{NI} \), we have \( p_{D-A}^{NI} = \frac{2a_1\gamma_A^{NI} + \theta(a_2-a_1\gamma_a^{NI})}{2a_1\gamma_A^{NI} + \theta^2 + a_1\gamma_a^{NI} + \theta + 1} \) and based on quantity discount contract, \( p_{D-A}^{NI} = p_{D-A}^{NI} \) holds [13], and we can get discount rate \( \theta = \frac{(p_{D-W} - \theta q_A)^2 - 4m_A(a_2-a_1\gamma_A^{NI})}{4m_A(a_2-a_1\gamma_A^{NI}) + a_1\gamma_a^{NI} + \theta + 1} \). Then substituting \( \theta \) into \( \Pi_{D-A}^{NI} \) and \( \Pi_{D-B}^{NI} \), we obtain \( \Pi_{D-A}^{NI} = \Pi_{D-A}^{NI} + \Pi_{D-B}^{NI} \), which implies that the product will meet a superior environmental performance and the system profit will realize the level of integrated decision after the downstream manufacturer accepts quantity discount contract offered by the upstream manufacturer.

6. Numerical simulation. In order to get the straight scene of the manufacturers’ decision-making during exchanging waste, a numerical simulation is used to explore the manufacturers’ production and operational decision processes. Some parameters of the manufacturers are assigned as \( a = 600, a_1 = 1, a_2 = 8, c_A = 4, c_B = 2, m_A = 30, \gamma_A^{NI} = 56, p_{D-W} = 1.5 \), and \( b = 300, \beta_1 = 1, \beta_2 = 4, c_B = 2, c_B = 1, m_B = 15, \gamma_B^{NI} = 35, c_W = 1, \tau = 1, \delta = 0.01 \). Numerical simulation is used to analyze the variation tendency of other unassigned parameters and the effects of consumers’ environmental concern and price sensitive on product price, emission level and the system profit.
6.1. **Result analysis of numerical simulation.** According to the above defined numerical value, the optimal price, waste emission level and the system profit are calculated and the results are shown in Table 2.

| Parameters                              | Base model | Integrated model | Non-integrated model |
|-----------------------------------------|------------|------------------|----------------------|
| Price of product A                      | 188        | 140.51           | 128.13               |
| Waste emission level of product A       | 38         | 35.89            | 36.60                |
| Price of product B                      | 124.86     | 124.57           | 138.86               |
| Waste emission level of product B       | 17.43      | 17.29            | 24.43                |
| System profit                           | 8427.86    | 24173.90         | 23115.00             |

From Table 2 above, the following observations and conclusions are drawn.

1. Waste exchanged activity can significantly increase the system profit of industrial symbiosis chain compared with base model, and the largest system profit is integrated industrial symbiosis chain under some constraints, i.e., integrated decision-making will make more profit. Apparently, industrial symbiosis could lower waste disposal cost and reduce procurement cost of raw material instead of using the waste as raw material due to waste exchanged activity, which decreases operation and production cost for industrial symbiosis chain and brings much more profit.

2. With the price and waste emission level for integrated model low, the product has a really dominant position on environmental performance and a comparative advantage of price. In terms of product environmental performance and external environmental effect of the whole industrial symbiosis chain, integrated model is the optimal policy for the manufacturers to make a strategic decision.

3. In non-integrated model, additional benefit of the upstream manufacturer with the competitive advantage of product price can compensate the loss of the downstream manufacturer with the inferior position on product price and waste emission level. However, the upstream and downstream manufacturers can design a coordination contract aforementioned in Section 5 to improve their performance at par with integrated model, or be better compared with original non-integrated model.

6.2. **The effect of consumers’ environmental concern on price and emission level.** The coefficients of consumers’ environmental concern are $\alpha_2 = 8$ and $\beta_2 = 4$ separately in above analysis. In order to ensure other variables with a positive value, we assume the value range of $\alpha_2$ and $\beta_2$ are $\alpha_2 \in [7.5, 8.5]$ and $\beta_2 \in [2, 4]$, respectively. The effects of consumers’ environmental concern on product price, emission level and system profit are illustrated in the following Figure 2-6.

In fact, it is essential for industrial symbiosis to achieve economic benefit [39], which motivates the manufacturers to involve in industrial symbiotic relationship. From the Figure 2-6, the following observations are made and concluded.

1. Figure 2 and Figure 4 indicate product price decreases with consumers’ environmental concern of the product, which is in accordance with the result of Section
Figure 2. Effect of $\alpha_2$ on price of product A

Figure 3. Effect of $\alpha_2$ on waste emission level of product A
Figure 4. Effect of $\beta_2$ on price of product B

Figure 5. Effect of $\beta_2$ on waste emission level of product B
3.3. Whether it is product A or product B, the product price in integrated model is lower than that in base model, i.e., joining integrated industrial symbiosis with centralized decision-making invariably makes the product more price competitive advantage comparable with dumping the waste into the environment directly without recycling it.

(2) Figure 3 and Figure 5 show emission level decreases with consumers’ environmental concern, which connotes that the manufacturers should attach importance to greening their products’ environmental characteristic and try to improve their environmental performance through reducing emission level in order to meet consumers’ preference of green products. This, from another aspect, confirms that consumers’ environmental concern plays an important role in improving environmental benefit.

However, waste emission level of product A in base model in Figure 3 has different trend. From the managerial perspective, there is no waste trading in base model, which leads to the upstream manufacturer and downstream manufacturer to make decision and take action independently. This turns the manufacturer to be a general manufacturer with emitting the waste into the environment directly [3]. Based on the monotone intervals, once a certain level of consumers’ concern on environmental performance is surpassed, the manufacturer increases his/her waste emission level, that is, the manufacturer invests less, not more (as might be expected) in environmental innovation, than it would if there were less pressure from consumers. Under some condition, the manufacturer in base model holds much less profit than the other two models because there is no waste trading in base model which increases operational cost of the manufacturer. Intuitively, the different trend and effect are observed in Figure 3 when $\alpha_2 \in [7.5, 8.5]$ because the less profit of the manufacturer is a disincentive to investing in environmental innovation at level where it would still be profitable, which seems to support an argument frequently used by those that argue against strong environmental regulation, for example, see Palmer and Oates [34].
(3) Figure 6 reflects the system profit decreases with consumers’ environmental concern. Consumers’ stringent requirement of product environmental characteristic weakens market supremacy of the manufacturers and induces a decrease in market share and profitability. However, waste exchanged activity invariably makes more profit; especially the integrated decision-making has higher profit than other two models.

6.3. The effect of consumers’ price sensitive on price and emission level. The coefficients of consumers’ price sensitive are $\alpha_1 = 1$ and $\beta_1 = 1$ separately in above analysis. In order to ensure other variables with a positive value, we assume the value range of $\alpha_1$ and $\beta_1$ are $\alpha_1 \in [1, 1.2]$ and $\beta_1 \in [1, 1.2]$ respectively. The effects of consumers’ price sensitive on product price, waste emission level and system profit are illustrated in the following Figure 7-11.

![Figure 7. Effect of $\alpha_1$ on price of product A](image)

Strong green attitude to the product is attached to environmental concerned consumers who are more willing to pay for environmentally friendly products, but price sensitive consumers hesitate to buy environmentally friendly products due to the higher price [41]. From Figure 7 & Figure 8, and Figure 9 & Figure 10, consumers with high price sensitive or price oriented consumers are inclined to buy the products with low price and high waste emission level (i.e., the products with low environmental performance, which is the same as ordinary products to some extent.). Additionally, Figure 7 and Figure 9 illustrate product price decreases with coefficient of price sensitive, which means that the manufacturers should price the products lowly to attract the consumers with high price sensitive and it’s in accordance with the traditional view. Figure 8 and Figure 10 present waste emission...
Figure 8. Effect of $\alpha_1$ on waste emission level of product A

Figure 9. Effect of $\beta_1$ on price of product B
Figure 10. Effect of $\beta_1$ on waste emission level of product B

Figure 11. Effect of $\alpha_1$ and $\beta_1$ on the system profit
level increases with coefficient of price sensitive. When the consumers pay more attention to the price of the products, the manufacturers have to sell the products with low environmental performance and high waste emission level, which could cut the investment cost of the products and put a low price on what price-oriented consumers demand. Figure 11 shows the system profit decreases with the coefficient of price sensitive, and it coincides with the fact that high price sensitive leads to reduce the product demand and increase waste emission level.

7. Conclusion. Considering environmental regulations exerted by the policy makers or the government in waste emission standard, waste emission tax and the subsidy for waste usage, the price sensitive-environmental concern demand is introduced into the paper. We analyzes decision processes of the manufacturers and the government from the perspective of environmental performance and economic benefit by establishing a monopoly model in industrial symbiosis chain including one upstream manufacturer and one downstream manufacturer. The motivation and decision-making processes of exchanging waste between the manufacturers are investigated.

Our results suggest that the government should take the factors of production and operation in industrial symbiosis chain into account when emission standard is formulated. Otherwise, the firms will go out of business due to lack of profitability, and the more stringent environmental regulations don’t mean the higher profit of the manufacturer. Environmental concerned consumers with stronger green attitude who are more willing to buy environmentally friendly products could pressurize the manufacturer into decreasing waste emission level. However, the manufacturer has to lower product price for price oriented or price sensitive consumers because they don’t prefer to purchasing environmentally friendly products, which results in a higher waste emission level of the manufacturer. The subsidy and emission tax are ambidextrous approaches for better external environmental benefit, however, the upper threshold of the high subsidy provided by the government for the downstream manufacturer lies on waste tradable price. We also find evidence advising the manufacturers to involve in industrial symbiosis with the intervention of environmental regulations, which is better for the improvement of economic benefit. Particularly integrated decision can bring about win-win situation for both economic benefit and environmental performance. For the manufacturers in non-integrated model, waste emission contract and quantity discount contract are strategies to ameliorate the performance of non-integrated chain.

Our work can be extended in several ways. In this paper, we assume there is only one firm in the upstream and downstream respectively, while in reality of symbiotic relationship, there exists several upstream firms providing waste for one downstream firm, and the competition between the firms in industrial symbiosis chain would be to add in the future work. Another way to expand this work is to treat the amount of waste emission generated by the production process as a random variable [29]. However, demand may change with the firms’ production process and market condition, and the uncertainty of demand adds an interesting aspect to the future model.

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