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Order or Collaborate? Manufacturers Utilize 3D-Printed Parts to Sustainably Facilitate Increased Product Variety

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Abstract: 3D printing (3DP) has garnered significant attention from industries, prompting traditional manufacturers to adopt 3DP to sustainably facilitate increased product variety. Observing manufacturers' two adoption strategies, ordering parts and collaboratively printing 3DP parts, in a real-world setting, we utilize a wholesale price contract and a Nash Bargaining contract to describe these two strategies and then develop a supply-chain model including a 3DP supplier (Supplier) and a traditional manufacturer (Manufacturer). Further, we employ backward induction to solve the subgame-perfect Nash equilibrium for the model to reveal differences between these two strategies and the impact of 3DP's improved resource efficiency. According to equilibrium outcomes, analytical results show that first, as long as the unit cost of each 3DP part is not overly high and 3DP's resource efficiency is not extremely low, the Manufacturer is willing to implement 3DP to increase product variety. Second, a rise in the resource efficiency can create a "win-win" scenario for the Manufacturer and the Supplier. Third, supply-chain collaboration can be achieved when the Manufacturer's and the Supplier's bargaining powers approach equality. Interestingly, a Nash bargaining contract can incentivize the manufacturer to substitute a base product with a variety of products, a change facilitated by an increase in the retail price of this base product. The managerial implication of this research is that enhanced resource efficiency can lead to less environmental pollution in the collaboration model by resulting in the sale of lower quantities of the base product, which would otherwise consume more resources and generate greater environmental pollution.

Keywords: 3D printing; resource efficiency; product variety; supply chain; Nash bargaining

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1. Introduction

In response to "Industry 4.0", manufacturing industries around the world are developing various advanced production technologies to achieve digitalization and sustainable production. 3D printing (3DP), also called additive manufacturing (AM), has been considered as one of the most flexible manufacturing technologies for use in improving production efficiency, drawing remarkable attention from different industries across the globe. According to the Wohlers Report 2023 [1], the growth rate of 3DP products and services reached 18.3% in 2022, continuing a double-digit growth trend seen in 25 of the last 34 years. Some high-tech firms, such as GE, Siemens, and HP, have invested in 3DP to ensure a strong future for industrial innovation. Unlike a traditional manufacturing process, 3DP utilizes 3D software to achieve digital and flexible designs for different products and then prints them in a layer-upon-layer manner without any need for tools or molds [2,3]. This flexibility of 3DP not only supports the production of integrated single-step designs, suggesting its potential as a sustainable manufacturing method [4], but also enhances custom manufacturing to increase product variety [5]. Thus, 3DP enables manufacturers to achieve greater product variety without cost penalties [6] while achieving improved resource efficiency, which contributes to reductions in energy consumption, carbon emissions [7], and materials wastes [8] and even leads to zero materials waste in some industries [9], although 3DP raw materials are more costly than traditional materials [10].

In light of 3DP's capability to enhance resource efficiency by printing products with integrated designs, some firms adopt 3DP to lower their energy and resource consumption and carbon emissions [7]. Specifically, some firms choose to order from suppliers of 3D-printed components to achieve sustainable transformation. For example, Airbus Aircraft orders on-demand complex parts from Stratasys (a leading 3D-printing service) to enhance its material utilization [11]. Conversely, some traditional manufacturers tend to collaborate with 3DP suppliers to develop and print more sustainable 3DP parts. A notable example is Boeing's partnership with Norsk, a Norwegian 3D-printing firm, to print different components involving fewer separate parts [12].

Further, benefiting from 3DP's ability to facilitate an increase in product variety, a group number of traditional manufacturers are embedding these sustainable 3DP parts in their base product (BP) to provide sustainable customization. For example, Nike has utilized 3DP to offer sustainable mass customization to allow consumers to tailor the shoes to better fit their feet and preferences, dramatically reducing lead time, eliminating production tools, and simplifying production processes [13]. Notice that most of the manufactures engaged in such customization also follow the ordering and collaboration approaches mentioned above to achieve their supply of sustainable 3DP parts. For instance, Avular (a forward-thinking robotics firm) designs new lightweight parts based on consumers' endogenous preferences and orders these 3DP parts from HP. Meanwhile, New Balance (a prominent athletic brand) prefers direct collaboration with Formlabs (a famous 3DP provider) to print footwear parts, such as more personalized spike plates, to better fit consumers' requirements.

The above-observed 3DP-adoption strategies that traditional manufacturers choose—to either order various parts from 3DP suppliers to sustainably increase product variety or collaborate with 3DP suppliers to jointly print 3DP parts to sustainably increase product variety—motivate us to establish a dynamic game model including an upstream 3DP supplier (Supplier) and a downstream traditional manufacturer (Manufacturer) to explore differences between these two strategies and examine the impact of 3DP's improved resource efficiency. Further, we use a wholesale price contract (the ordering model) and a Nash Bargaining contract (the collaboration model) to describe these two strategies. To more accurately develop the dynamic game model, we describe sequences of the ordering model and the collaboration model, respectively.

In the ordering model, under which the manufacturer and supplier may sign a wholesale price contract, the supplier first levies a uniform wholesale price across the variety of 3DP parts within its printing variety (stage 1), and in stage 2, having learned the supplier's wholesale price, the manufacturer determines whether to embed these sustainable 3DP parts in the base product to expand product variety. If this possibility is rejected, the manufacturer needs only to set a retail price for the base product, and if it is accepted, the manufacturer then determines retail prices for both the base product (BP) and a variety of products (VPs). In stage 3, consumers make their purchasing decisions based on retail prices and their preferences.

In the collaboration model, in which the manufacturer may collaborate with the supplier to print the sustainable newly designed parts according to a Nash bargaining contract, first, the supplier and manufacturer negotiate for the allocation of product profits given the manufacturer's bargaining power and decide whether to accept the contract (stage 1). Second, they jointly make decisions regarding retail prices for the BP and VPs (stage 2). In stage 3, consumers make their purchase decisions, which are conditional on retail prices and their preferences.

In both models, we employ the Hoteling line to capture the preferences of consumers in the final market and derive the demand functions of the manufacturer's BP and VPs. Thereafter, we employ backward induction (a manual-calculation method) and the concept of subgame-perfect Nash equilibrium to derive the equilibrium outcomes of the ordering model and the collaboration model. With the equilibrium outcomes of two supply-chain models, we aim to answer the following research questions:

(1) What conditions prompt the Manufacturer to adopt the Supplier's 3DP technology to increase product variety?
(2) If it is adopted, what is the better contract for the Manufacturer?
(3) How does the cost savings from 3DP's improved resource efficiency affect the equilibrium outcomes, and what management insights will it bring for sustainable production?

Based on equilibrium-outcomes analysis, we derive the following detailed results. First, if the unit cost of each 3DP part is not excessively high, the Manufacturer is willing to adopt 3DP technology to sustainably facilitate an increase in product variety. Second, when the Manufacturer's bargaining power is moderate, the collaboration can result in a "win-win" situation for both the Manufacturer and the Supplier. Third, with an increase in cost savings due to 3DP's enhanced resource efficiency, both the Manufacturer's and the Supplier's profits rise owing to the lower final unit production cost and higher demand for VPs. Furthermore, higher cost savings causes the collaboration model to pollute less by selling lower quantities of the BP, which otherwise consumes more resources and releases more environmental pollution. Accordingly, this paper contributes to the existing literature on several key points: first, our research enriches the existing work (such as [14–19]) by exploring how 3DP's cost savings influences the game equilibrium; second, we further consider collaboration with a Nash bargaining contract, which is ignored by existing papers (e.g., [17,20]) focusing on 3DP-based parts production.

The rest of this paper is organized as follows. Section 2 includes the literature review. In Section 3, we specifically describe two supply-chain models and consumers' preferences, as captured by the Hotelling line. We present the equilibrium and further show the impact of 3DP's improved resource efficiency on the equilibrium outcomes in Section 4. Section 5 reveals the differences between two models. Section 6 discusses the results and uncovers some contributions of the research. Finally, concluding remarks and plans for future research are presented in Section 7.

2. Literature Review

This paper is related to the following three main streams of research in the literature: (1) 3DP in business operations, (2) 3DP in supply-chain operations, and (3) supply-chain collaboration under a Nash bargaining contract. These literature streams are reviewed below.

The existing literature on 3DP in business operations serves as the initial focus of our review. Some researchers focus on how 3DP technology impacts the operations of a monopoly firm. Specifically, Chen et al. [21] establish a model to capture how a traditional manufacturer employs 3DP technology to print on-demand products within dual-channel contexts. Guo et al. [22] report that a traditional manufacturer can employ 3DP technology to achieve mass customization and capture the advantages of 3DP technology in light of the value of consumers' finding fun in designing their own products. Sethuraman et al. [23] demonstrate that 3DP technology can enable a traditional manufacturer to offer a personal fabrication strategy that benefits from personalization, postponement, and manufacturability services. Sun et al. [24] investigate how the 3DP online sharing platform chooses the optimal pricing strategy and the impacts of usage level and printer heterogeneity on consumers' owning and renting choices. Sun et al. [20] model that 3DP technology can enable traditional manufacturers to provide an after-sales service with higher consumer valuation and uncover the conditions under which traditional manufacturers choose pure 3DP technology, pure traditional technology or a hybrid strategy. Additionally, some scholars extend the issues to a duopoly model. Hartl and Kort [25] regard 3DP technology as a potential entrant that prints personalized products to compete with an incumbent producing multiple standard products and reveal the impact of 3DP technology on the incumbent. In detail, Kleer and Piller [26] model how 3DP technology brings locally based competition to central manufacturers to uncover the impact of 3DP technology on the central manufacturers. Further, Nie et al. [27]

consider the capacity limitations of 3DP technology and examine the impact of this limited capacity on competition with traditional technology.

Nevertheless, all the above papers ignore the supply chain's upstream–downstream interaction. Our research bridges this gap by considering a two-echelon supply chain involving both an upstream 3DP supplier and a downstream traditional manufacturer to reveal the impact of this interaction.

The second stream of literature situates 3DP within supply-chain operations, and some literature has shed light on the effects of 3DP adoption on supply-chain operations. Specifically, Jia et al. [14] and Arbabian and Wagner [15] built three models: traditional manufacturing, retailer-dominant 3DP manufacturing and manufacturer-dominant 3DP manufacturing, and point out their respective merits and drawbacks. Arbabian [16] further discovers that retailer-dominant 3DP manufacturing can eliminate the double marginalization and can be viewed as a new mechanism for the supply-chain collaboration. Sun et al. [3] establish a model comprising of an upstream 3DP platform and downstream designer and investigate how the 3DP platform and designer sell standard and customized products to maximize their profits under two pricing strategies. Xiong et al. [17] focus on a model that a downstream logistics supplier can employ 3DP technology to print parts in the aftersales market and reveal the impact of it on the supply chain. Tong and Li [18] establish a Stackelberg game model with an OEM and retailer to characterize the optimal decision under different modes and highlight that the OEM's chosen mode depends on the market size, 3DP investment cost and licensing fee. Li et al. [19] extend Chen et al. [21] to a retailer-manufacturer supply chain offline and online and discover the conditions under which a manufacturer or retailer offers 3DP customization.

The difference of our work from this literature is that we further consider 3DP's environmentally sustainable feature, i.e., improved resource efficiency, and then explore how improved resource efficiency impacts supply-chain decisions. Meanwhile, we use a Nash bargaining contract to describe the issue observed in the real world, namely, some traditional manufacturers tend to collaborate with 3DP suppliers to print more personalized parts to facilitate an increase in product variety.

Finally, our paper discusses supply-chain collaboration frameworks utilizing Nash bargaining solutions. Numerous scholars utilize a Nash bargaining contract to solve supply-chain collaboration. Feng and Lu [28] demonstrate that a Nash bargaining contract can be appropriate for issues in supply-chain collaboration. Based on this, Zhang et al. [29] address the collaboration issues of a green supply chain composed of an upstream manufacturer and downstream retailer under a Nash bargaining contract and demonstrate that the green supply-chain collaboration under such contract yields higher profits and energy efficiency. Zhou et al. [30] and Guan et al. [31] demonstrate that supply-chain collaboration can result in a "win-win" situation when bargaining allocations are distributed equitably. Shi et al. [32] similarly construct a Nash bargaining model to compare two sustainability-investment patterns and reveal that the manufacturer and retailer are willing to accept the Nash bargaining contract under certain conditions. Du et al. [33] also build a Nash bargaining model and show that the Nash bargaining contract can improve investment in the supply chain.

As mentioned before, research on the impact of 3DP technology on the operations of a supply chain has commonly adopted the Stackelberg game. However, the Stackelberg game cannot solve the real-world issues related to collaboration between traditional manufacturers and 3DP suppliers, so we follow Feng and Lu [28] and Shi et al. [32] in considering the collaboration model under a Nash bargaining contract to further investigate the pragmatic reasons behind traditional manufacturers' preferences with regard to collaboration with 3DP suppliers.

3. Model

In this section, we build a supply chain involving an upstream 3DP supplier (Supplier) and a downstream traditional manufacturer (Manufacturer) under a wholesale-price-contract-based ordering model and a Nash Bargaining-contract-based collaboration model to answer the research questions. The supplier can print various parts, and the manufacturer originally produces a base product (BP) and can utilize the supplier's parts to newly produce a variety of products (VPs). Both BP and VPs are marketed to consumers. To further elaborate, we use the following subsections to provide a more detailed description.

3.1. Consumer Utility and Product Variety

The Manufacturer initially sells one base product (BP), i.e., product 0, at a price p_0 to consumers who are uniformly located on a Hotelling line from $\underline{x} = 0$ to $\overline{x} = 1$ and purchase at most one unit of BP. Without loss of generality, we assume product 0 is located at $x_0 = \underline{x} = 0$. The willingness of consumer x, who is located at $x \in [0, 1]$, is $v - |x - x_0|$. v is consumers' valuation for product 0, and $|x - x_0|$ can be viewed as a "transportation" cost that captures the preference difference that consumer x purchases one unit of product 0. For simplicity, we normalize v to 1 (i.e., $v = 1$). Hence, the net utility of consumer x' buying product 0 at a retail price p_0 is

$$u(x, x_0, p_0) = 1 - x - p_0 \tag{1}$$

while $u_0 = 0$ when the consumer buys nothing.

Similar to [15], once the Supplier decides to initiate 3DP plans, the Supplier owns limited capacity (i.e., printing variety n) and can print at most n horizontally differentiated types of 3DP parts. In addition, as 3DP technology is one of the most flexible manufacturing technologies, we assume $n > (1 + c_m)/(1 - c_m)$. These n types of 3DP parts can be used by the Manufacturer to produce n horizontally different types of products (labelled as product $1, \cdots, n$) based on product 0. Additionally, without loss of generality, we assume that the Manufacturer produces product l with the 3DP part l and product 0 in a one-to-one manner. Then, we denote the locations of the variety of products (VPs) on the Hotelling line by x_1, $x_2, \cdots$, and x_n respectively, where $x_l \in (0, 1]$ and $x_{l+1} > x_l$.

If the Manufacturer sets the price $p_l (\leq 1)$ for selling product l $(\in \{1, \cdots, n\})$ located at x_l, similarly, a consumer located at x's willingness to pay for one unit of the product l is $1 - |x - x_l|$, where $|x - x_l|$ also represents the preference difference that consumer x purchases one unit of product x_l. Then, the net utility to consumer x of consuming one unit of product l can be written as $u(x, x_l, p_l) = 1 - |x - x_l| - p_l$. Therefore, consumer x with $u(x, x_l, p_l) \geq 0$ buys product l $(\in \{0, 1, \cdots, n\})$ if and only if

$$u(x, x_l, p_l) \geq u\left(x, x_j, p_j\right) \text{ forall} j \in \{0, 1, \cdots, n\} \setminus \{l\} \tag{2}$$

Further, Ref. [34] introduces a general multi-product monopoly framework wherein a monopolist will prevent inter-product competition, suggesting that the demand for BP is irrelevant to whether VPs are introduced, i.e., $D_0(x_1, \cdots, x_n, p_0, p_1, \cdots, p_n) = 1 - p_0$ and each demand for VPs is irrelevant to the others. Together with some previous studies (e.g., [35,36]), the Manufacturer and Supplier (in the collaboration model) or the Manufacturer (in the ordering model) will opt to market all types of VPs to sell if VPs are profitable. Namely, the chosen variety of 3DP parts is equal to n, and VPs are located at

$$x_l = 1 - p_0 + \frac{(2l - 1)p_0}{2n} (l \in \{1, \ldots, n\}) \tag{3}$$

and priced uniformly, i.e.,

$$p_1 = p_2 = \cdots = p_n = p \tag{4}$$

Therefore, we can rewrite the demand for product 0 as

$$D_0(p_0, p) = 1 - p_0 \tag{5}$$

By observing the locations and prices of VPs, the demand for VPs can be summarized as follows:

$$D_l(p_0, p) = \begin{cases} 0, \ if \ p \geq 1 \\ 2(1-p), \ if \ p \in (1 - p_0/(2n), 1) \quad (l \in \{1, 2, \ldots, n\}) \\ p_0/n, if \ p = 1 - p_0/(2n) \end{cases} \tag{6}$$

where $p < 1 - p_0/(2n)$ obviously cannot be optimal and $p \geq 1 - p_0/(2n)$ ensures the inhibition of inter-product competition. Hence, the total demand for VPs can be presented as follows:

$$D(p_0, p) = nD_l(p_0, p) = \begin{cases} 0, \ if \ p \geq 1 \\ 2n(1-p), \ if \ p \in (1 - p_0/(2n), 1) \quad (l \in \{1, 2, \ldots, n\}) \\ p_0, if \ p = 1 - p_0/(2n) \end{cases} \tag{7}$$

For ease of understanding, the segment of the final market can be qualitatively illustrated in Figure 1 below.

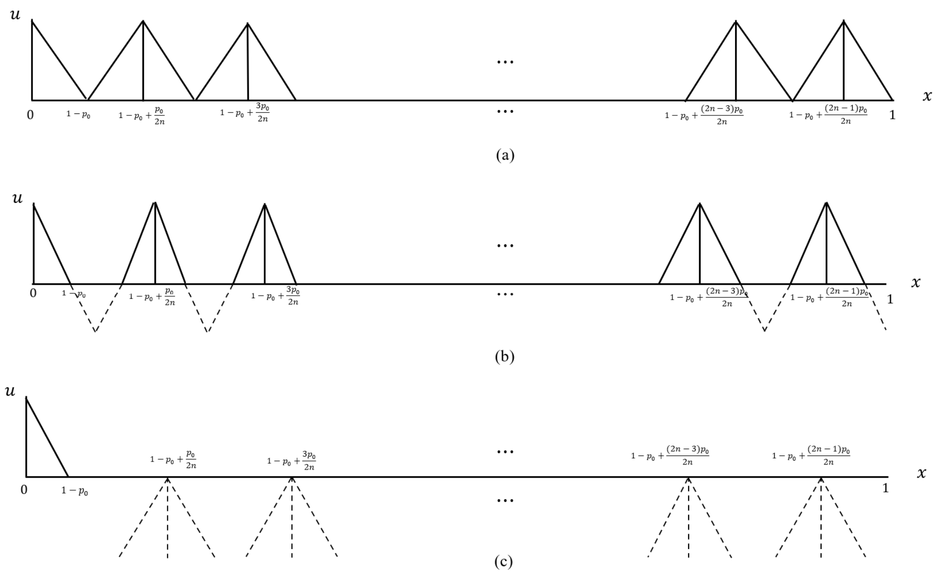


Figure 1. The segment of the final market. (**a**) $p = 1 - p_0/(2n)$; (**b**) $1 - p_0/(2n) < p < 1$; (**c**) $p \geq 1$.

3.2. In the Ordering Model

In the ordering model, the sequence of events is as follows (as illustrated in Figure 2): Firstly, the Supplier charges a uniform wholesale price w for all types of sustainable 3DP parts within its printing capacity, denoted by n; after observing the Supplier's wholesale price, the Manufacturer determines whether to embed these sustainable 3DP parts in the basic product (BP) to expand product variety. If this option is rejected, the Manufacturer needs only to set a retail price p_0 for BP, and if it is accepted, the Manufacturer then determines retail prices for both BP and VPs, i.e., p_0 for BP and p for VPs. Finally, consumers make their purchasing decisions conditional on retail prices and their positions.

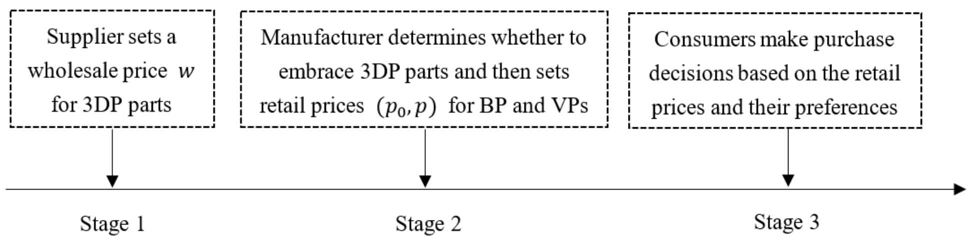


Figure 2. The sequence of events in the ordering model.

Then, in consideration of the enhanced resource efficiency associated with 3DP [7–9], its cost function is denoted by

$$C_s(D_1,\ D_2,\cdots,D_n) = Kc_s\sum_{l=1}^{n} D_l \tag{8}$$

where $c_s \geq 0$ is the unit cost of each 3DP part regardless of 3DP's better resource efficiency and $K \in [0,1]$ captures the nature of cost savings of each of the Supplier's 3DP parts [32,37] due to 3DP's environmentally friendly quality (i.e., enhanced resource efficiency). In detail, a higher K indicates small cost savings for the Supplier's individual 3DP part. Thus, the Supplier's optimal decision is captured by $\max_{w}\pi_s(w) = \sum_{l=1}^{n}(w - Kc_s)D_l - T$, where w is the Supplier's uniform wholesale price and T is a fixed cost for the Supplier to develop 3DP plans [15,16]. For simplicity, we normalize T to zero, i.e., $T = 0$, and thus, together with (7), the Supplier's decision can be rewritten as

$$\max_{w}\pi_s(w) = (w - Kc_s)D(p_0, p) \tag{9}$$

Given the Supplier's uniform wholesale price w, the Manufacturer's decision can be written as

$$\max_{p_0,p}\pi_m(p_0, p) = (p_0 - c_m)D_0 + (p - c_m - w)D(p_0, p) \tag{10}$$

where c_m is the unit cost of the Manufacturer's BP (note that the unit cost of BP's replaced parts is denoted by c_0 and that 3DP raw materials are more costly than traditional materials [10], i.e., $c_0 < c_s$ [25]. For simplicity, we normalize c_0 to 0 (i.e., $c_0 = 0$).).

3.3. In the Collaboration Model

In this subsection, we consider the collaboration between the Manufacturer and the Supplier regarding the sustainable 3DP parts as a Nash bargaining process. The decision-making sequence is outlined as follows: firstly, the Supplier and the Manufacturer engage in negotiations to distribute the product profits, employing a Nash bargaining solution given the Manufacturer's bargaining power. After the profit-sharing collaboration is agreed upon, the Manufacturer and the Supplier jointly make decisions regarding retail prices for both BP and VPs. Finally, consumers make their purchase decisions conditional on retail prices and their positions. For ease of understanding, we use the following Figure 3 for illustration.

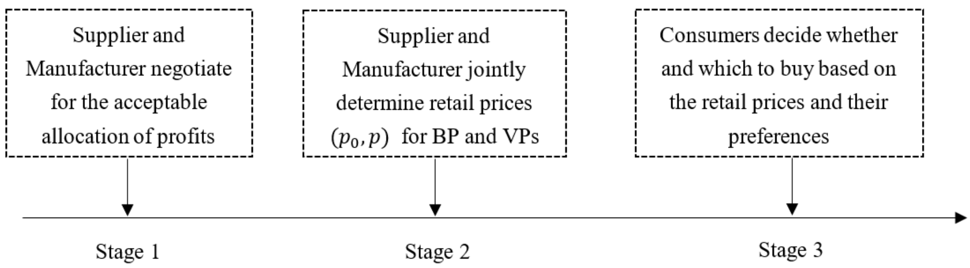


Figure 3. The sequence of events in the collaboration model.

Thus, drawing on the work of [28,32], given the Manufacturer's bargaining power θ, we firstly set the profit pair (π_m^B, π_s^B) to maximize the following Nash bargaining unit,

$$\Phi(\pi_m^B, \pi_s^B) = (\pi_m^B - \pi_m^N)^{\theta}(\pi_s^B - \pi_s^N)^{1-\theta}$$
$$s.t.\begin{cases} \pi_m^B + \pi_s^B \leq \pi^{B*} \\ \pi_m^B - \pi_m^N \geq 0 \\ \pi_s^B - \pi_s^N \geq 0 \end{cases} \tag{11}$$

where π_m^N and π_s^N are Supplier's and the Manufacturer's profits under the scene where the Manufacturer does not adopt 3DP technology to boost product variety, π^{B*} is the equilibrium profit under the collaboration model and the superscript B represents the Nash bargaining contract.

Similarly, considering the assumption of $T = 0$, the Manufacturer and the Supplier jointly make following decisions,

$$\max_{p_0,p} \pi^B(p_0, p) = (p_0 - c_m)D_0 + \sum_{l=1}^{n} (p_l - c_m - Kc_s)D_l \tag{12}$$

Finally, notations used in this paper are summarized in Table 1 below.

Table 1. Lists of notations.

Symbol	Description
x	Consumer product preference location, and $x \in [0, 1]$
v	Consumer's valuations for the base product and variety of products and normalized to 1
u	Consumer net utility from buy one unit product
n	Supplier's printing variety
K	Nature of cost savings of each 3DP part due to 3DP's enhanced resource efficiency
θ	Bargaining power of the Manufacturer
x_l, p_l, D_l	Location, price, and demand of product l, where $l \in \{0, 1, \cdots, n\}$
c, C	Unit cost and total costs
w	Wholesale price of 3DP parts
π	Profit function
m	This subscript represents the traditional manufacturer
s	This subscript represents the 3DP supplier
B	This superscript represents the Nash bargaining contract

4. Equilibrium and Analysis

In this section, we adopt the backward induction (a manual calculation method) to solve the game presented in Section 3 and use the concept of subgame-perfect Nash equilibrium to characterize the equilibrium of our model following the decision sequences previously outlined in both the ordering model and collaboration model. To elaborate, we first substitute the demands for BP and VPs into profit functions in the ordering model and collaboration model respectively and then, solve the maximization problems. Meanwhile, we further investigate the impact of cost savings on the equilibrium results.

4.1. Equilibrium in the Ordering Model

In this subsection, the Manufacturer implements ordering sustainable 3DP parts from Supplier to enhance product variety. Given that $D(p_0, p)$ in (7) is continuous in p, substituting (3)–(7) into (10), the Manufacturer's profit function can be rewritten as

$$\begin{aligned} &\max_{p_0,p} \pi_m(p_0, p; w) = (1 - p_0)(p_0 - c_m) + 2n(1 - p)(p - w - c_m) \\ &\text{s.t. } 1 - p_0/2n \le p \le 1 \\ &\qquad 0 \le p_0 \le 1 \end{aligned} \tag{13}$$

Subsequently, in line with the methods of [35,36], we relax the assumption of integrity of n to ease the calculation. Solving the optimization problem presented in Equation (13) yields the Manufacturer's optimal response to Supplier's uniform wholesale pricing strategy, which is summarized in Lemma 2.

Lemma 1. *In the ordering model, the Manufacturer's best price response $(p_0(w), p(w))$ is given by*

$$(p_0(w), p(w)) = \begin{cases} \left(\frac{1+c_m}{2}, 1\right), \ if\ w > 1 - c_m \\ \left(\frac{1+c_m}{2}, \frac{1+w+c_m}{2}\right), \ if\ w \in \left(1 - c_m - \frac{1+c_m}{2n}, 1 - c_m\right] \\ \left(\frac{n(2-w)}{2n+1}, \frac{4n+w}{4n+2}\right), \ if\ w \le 1 - c_m - \frac{1+c_m}{2n} \end{cases} \tag{14}$$

Proof. The proof of Lemma 1 is delegated to Appendix A. □

Lemma 1 reveals that in the ordering model, as long as the Supplier's wholesale price is high, i.e., $w > 1 - c_m$, none of VPs can be profitable for the Manufacturer as the sum of the wholesale price and the unit cost of BP exceeds consumers' valuations (i.e., $w + c_m > 1$). This results in that the Manufacturer is against adopting Supplier's sustainable 3DP parts to produce VPs. Then, if the wholesale price is set at a moderate level, i.e., $w \in \left(1 - c_m - \frac{1+c_m}{2n}, 1 - c_m\right]$, the Manufacturer adopts the Supplier's sustainable 3DP parts to partially cover the final market. Finally, when w is low, i.e., $w \leq 1 - c_m - \frac{1+c_m}{2n}$, the Manufacturer can produce VPs via Supplier's sustainable 3DP parts to fully cover the market.

Substituting the Manufacturer's best price response, the total demand for VPs in (7) can be rewritten as

$$D(w) = \begin{cases} 0, if\ w > 1 - c_m \\ n(1 - w - c_m),\ if\ w \in \left(1 - c_m - \frac{1+c_m}{2n}, 1 - c_m\right] \\ \frac{n(2-w)}{2n+1},\ if\ w \leq 1 - c_m - \frac{1+c_m}{2n} \end{cases} \tag{15}$$

Then, anticipating (15), the Supplier's profit in (9) can be presented as

$$\max_{w} \pi_s(w) = \begin{cases} 0, if\ w > 1 - c_m \\ n(1 - w - c_m)(w - Kc_s),\ if\ w \in \left(1 - c_m - \frac{1+c_m}{2n}, 1 - c_m\right] \\ \frac{n(2-w)}{2n+1}(w - Kc_s),\ if\ w \leq 1 - c_m - \frac{1+c_m}{2n} \end{cases} \tag{16}$$

Solving the maximization problem (16), we can obtain the Supplier's equilibrium wholesale price. Then, we summarize the equilibrium results in Proposition 1 as follows.

Proposition 1. *In the ordering model, the equilibrium results are given as follows.*

(i) *When* $c_s > c_{s2}$, $w^* = \begin{cases} 1 - c_m - \frac{1+c_m}{2n},\ if\ K \leq K_1 \\ w^{\#},\ if\ K \in (K_1, K_2] \\ 1 - c_m,\ if\ K > K_2 \end{cases}$;

(ii) *When* $c_s \in (c_{s1}, c_{s2}]$, $w^* = \begin{cases} 1 - c_m - \frac{1+c_m}{2n},\ if\ K \leq K_1 \\ w^{\#},\ if\ K > K_1 \end{cases}$;

(iii) *When* $c_s \leq c_{s1}$, $w^* = 1 - c_m - \frac{1+c_m}{2n}$ *for all* $K \in [0, 1]$,

where $c_{s1} = 1 - c_m - \frac{1+c_m}{n}$, $c_{s2} = 1 - c_m$, $K_1 = \frac{1 - c_m - \frac{1+c_m}{n}}{c_s}$, $K_2 = \frac{1-c_m}{c_s}$ *and* $w^{\#} = \frac{1-c_m+Kc_s}{2}$.

Proof. The proof of Proposition 1 is delegated to Appendix A. □

Proposition 1 presents the equilibrium strategy in the ordering model, which is also illustrated in Figure 4, where "N", "P" and "F" mean no implementation of 3DP technology and adopting 3DP technology to partially and fully covered markets respectively. As detailed in Proposition 1(i) and Figure 4, when the unit cost of each 3DP part is high, i.e., $c_s > c_{s2}$, if the cost savings of Supplier's each 3DP part is high, i.e., $K \leq K_1$, the Supplier's enhanced resource efficiency prompts the choice of a relatively low wholesale price which makes the Manufacturer can produce VPs via Supplier's sustainable 3DP parts to fully cover the market. As the cost savings diminishes to a relatively low level, i.e., $K \in (K_1, K_2]$, the Manufacturer can purchase Supplier's sustainable 3DP parts with a higher wholesale price to produce VPs to partially cover the final market. If the cost savings is extremely low, i.e., $K > K_2$, the combination of the extremely low cost savings and high unit costs, renders VPs unprofitable for the Manufacturer.

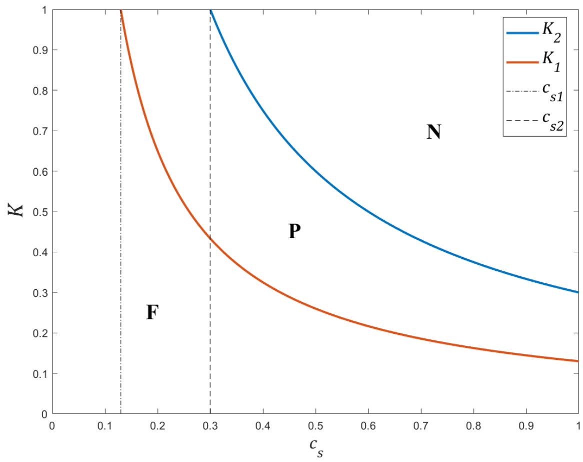


Figure 4. Equilibrium strategy in the ordering model setting $c_m = 0.7$ and $n = 10$.

We now turn to Proposition 1(ii) where the unit cost of each 3DP part is modest, i.e., $c_s \in (c_{s1}, c_{s2}]$ (see Figure 4). As the unit cost of each 3DP part decreases, it remains consistently profitable for the Manufacturer to produce VPs by ordering Supplier's sustainable 3DP parts. Specifically, the unit cost of each 3DP part is low enough to avoid the situation where the sum of the wholesale price and the unit cost of BP exceeds consumers' valuations (i.e., $w + c_m > 1$, see Lemma 1). Additionally, there also exists a threshold of the cost savings of Supplier's each 3DP part, i.e., K_1, below which the Manufacturer can produce VPs to fully cover the market.

According to Proposition 1(iii) and Figure 4, as the unit cost for each 3DP part further decreases to an extremely low level, i.e., $c_s \leq c_{s1}$, the Supplier invariably opts for a relatively low wholesale price which makes the Manufacturer can produce VPs by purchasing Supplier's sustainable 3DP parts and sell them to all consumers regardless of the value of K.

Finally, according to Proposition 1, we can derive the equilibrium retail prices and demands for BP and VPs, i.e., (p_0^*, p^*) and (D_0^*, D^*), and profits of the Manufacturer and the Supplier (π_m^*, π_s^*) in the ordering model. These results can provide clearer expressions for us to complete subsequent research. More specifically, we summarize the above equilibrium decisions and profits in following Table 2.

Table 2. Equilibrium results in the ordering model.

Conditions		$\left(p_0^*, p^*, D_0^*, D^*, \pi_m^*, \pi_s^*\right)$
(i) $c_s > c_{s2}$	$K \leq K_1$	$\left(\frac{1+c_m}{2}, \frac{4n-(1+c_m)}{4n}, \frac{1-c_m}{2}, \frac{1+c_m}{2}, \pi_m^{\#1}, \pi_s^{\#1}\right)$
	$K \in (K_1, K_2]$	$\left(\frac{1+c_m}{2}, \frac{3+c_m+Kc_s}{4}, \frac{1-c_m}{2}, \frac{n(1-c_m-Kc_s)}{2}, \pi_m^{\#2}, \pi_s^{\#2}\right)$
	$K > K_2$	$\left(\frac{1+c_m}{2}, 1, \frac{1-c_m}{2}, 0, \frac{(1-c_m)^2}{4}, 0\right)$
(ii) $c_s \in (c_{s1}, c_{s2}]$	$K \leq K_1$	$\left(\frac{1+c_m}{2}, \frac{4n-(1+c_m)}{4n}, \frac{1-c_m}{2}, \frac{1+c_m}{2}, \pi_m^{\#1}, \pi_s^{\#1}\right)$
	$K > K_1$	$\left(\frac{1+c_m}{2}, \frac{3+c_m+Kc_s}{4}, \frac{1-c_m}{2}, \frac{n(1-c_m-Kc_s)}{2}, \pi_m^{\#2}, \pi_s^{\#2}\right)$
(iii) $c_s \leq c_{s1}$	$K \in [0, 1]$	$\left(\frac{1+c_m}{2}, \frac{4n-(1+c_m)}{4n}, \frac{1-c_m}{2}, \frac{1+c_m}{2}, \pi_m^{\#1}, \pi_s^{\#1}\right)$

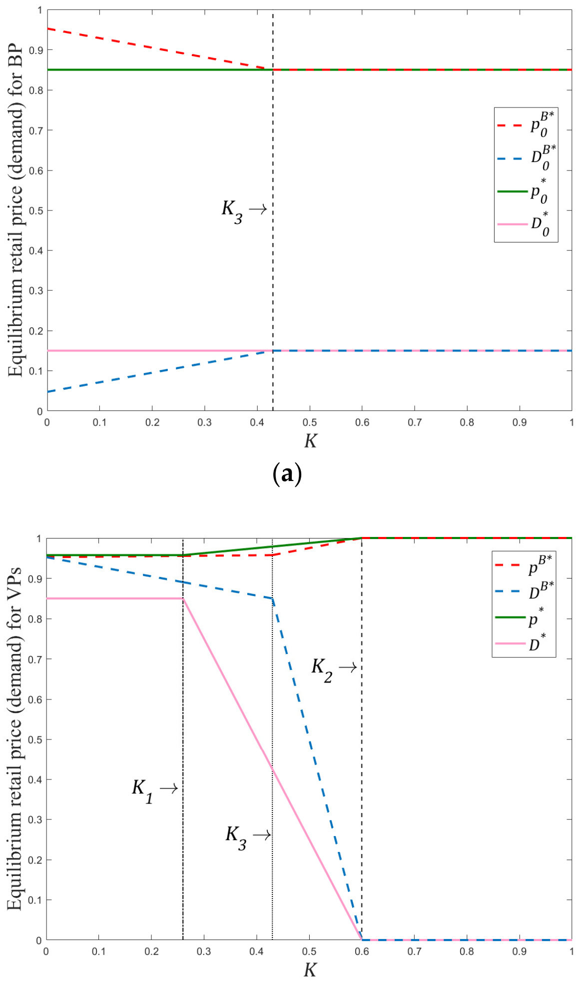
where $\pi_m^{\#1} = \frac{(1-c_m)^2}{4} + \frac{(1+c_m)^2}{8n}$, $\pi_s^{\#1} = \frac{1+c_m}{2}\left(1 - c_m - \frac{1+c_m}{2n} - Kc_s\right)$, $\pi_m^{\#2} = \frac{(1-c_m)^2}{4} + \frac{n(1-c_m-Kc_s)^2}{8}$ and $\pi_s^{\#2} = \frac{n(1-c_m-Kc_s)^2}{4}$.

Then, we further investigate how the nature of 3DP's enhanced resource efficiency impacts, i.e., K, on the equilibrium results in the ordering model shown in Proposition 2 below.

Proposition 2. *In the ordering model, p_0^* and D_0^* remain constant in K, w^* and p^* are non-decreasing in K, but D^*, π_m^* and π_s^* are non-increasing in K.*

Proof. The proof of Proposition 2 is delegated to Appendix A. □

Proposition 2 suggests that in scenarios where the Manufacturer and the Supplier do not engage in a collaborative effort to enhance product variety, the equilibrium retail price and demand for BP are not affected by the cost saving, as illustrated in Figure 5a (setting $c_m = 0.7$, $n = 10$ and $c_s = 0.5$). This is because BP's higher marginal revenue makes the Manufacturer tend to ensure BP's profit in the ordering model. Then, the stronger cost saving, i.e., lower K, can (weakly) lead to lower equilibrium wholesale price and retail price for VPs as a lower K means lower unit cost of VPs that can result in a lower price. Finally, the cost savings has a positive effect on the equilibrium demand for VPs, as illustrated in Figure 5b and profits of the Manufacturer and the Supplier. The mechanism behind this is that a lower price, due to a lower K, encourages consumers purchase more VPs. Therefore, the Manufacturer and the Supplier can catch more profits from more demands for VPs, culminating in a "win-win" scenario for both parties.



(**a**)

(**b**)

Figure 5. Comparison of equilibrium retail prices (demands) for BP and VPs setting $c_m = 0.7$, $n = 10$ and $c_s = 0.5$. (**a**) BP; (**b**) VPs.

4.2. Equilibrium in the Collaboration Model

In the collaboration model, the Supplier and the Manufacturer negotiate on the allocation of product profits via a Nash bargaining solution and then collaboratively make decisions. Similarly, substituting (3)–(7) into (12), the collaborative supply chain's profit function can be rewritten as

$$\begin{aligned} &\max_{p_0,p} \pi^B(p_0,p) = (1-p_0)(p_0-c_m) + 2n(1-p)(p-c_m-Kc_s) \\ &\text{s.t. } 1-\frac{p_0}{2n} \le p \le 1 \\ &\quad\; 0 \le p_0 \le 1 \end{aligned} \tag{17}$$

By solving the maximization problem (17), we can derive the equilibrium decisions of the collaboration model and we summarize them in following Proposition 3.

Proposition 3. *In the collaboration model, the best price response of BP and VPs* $\left(p_0^{B*}, p^{B*}\right)$ *is given as follows.*

(1) *When* $c_s > c_{s2}$, $\left(p_0^{B*}, p^{B*}\right) = \begin{cases} \left(\frac{n(2-Kc_s)}{2n+1}, \frac{4n+Kc_s}{4n+2}\right), if\ K \le K_3 \\ \left(\frac{1+c_m}{2}, \frac{1+c_m+Kc_s}{2}\right),\ if\ K \in (K_3, K_2] \\ \left(\frac{1+c_m}{2}, 1\right),\ if\ K > K_2 \end{cases}$;

(2) *When* $c_s \in (c_{s0},\ c_{s2}]$, $\left(p_0^{B*}, p^{B*}\right) = \begin{cases} \left(\frac{n(2-Kc_s)}{2n+1}, \frac{4n+Kc_s}{4n+2}\right),\ if\ K \le K_3 \\ \left(\frac{1+c_m}{2}, \frac{1+c_m+Kc_s}{2}\right),\ if\ K > K_3 \end{cases}$;

(3) *When* $c_s \le c_{s0}$, $\left(p_0^{B*}, p^{B*}\right) = \left(\frac{n(2-Kc_s)}{2n+1}, \frac{4n+Kc_s}{4n+2}\right)$ *for all* $K \in [0,1]$,

where $c_{s0} = 1 - c_m - \frac{1+c_m}{2n}$ *and* $K_3 = \frac{1-c_m-\frac{1+c_m}{2n}}{c_s}$.

Proof. The proof of Proposition 3 is delegated to Appendix A. □

The outcomes of Proposition 3 echo those of Proposition 1, indicating that when the unit cost of each 3DP part is high but the cost savings of Supplier's each 3DP part is extremely low, VPs are unprofitable for the Manufacturer. Conversely, if the unit cost remains high but the cost savings is not negligible, the Manufacturer may find it advantageous to order Supplier's sustainable 3DP parts to produce VPs. In such case, the final market can be even fully covered if the cost savings of Supplier's each 3DP part is high enough. Finally, as the unit cost of each 3DP part further decreases to an extremely low level, the Manufacturer is positioned to leverage Supplier's sustainable 3DP parts to produce VPs to fully cover the final market no matter what the cost savings of Supplier's each 3DP part is.

Upon resolving the Nash bargaining unit, we derive following the equilibrium profits of the Manufacturer and the Supplier in the collaboration model under a Nash bargaining contract, as shown in Corollary 1 as follows.

Corollary 1. *In the collaboration model under a Nash bargaining contract, the profit allocation of the Manufacturer and the Supplier* $\left(\pi_m^{B*}, \pi_s^{B*}\right)$ *are given by* $\left(\theta\left(\pi^{B*} - \pi_s^N\right) + (1-\theta)\pi_m^N, \theta\pi_s^N + (1-\theta)\left(\pi^{B*} - \pi_m^N\right)\right)$.

Proof. The proof of Corollary 1 is delegated to Appendix A. □

Corollary 1 illustrates the distribution of profits in the collaboration model under a Nash bargaining contract between the Manufacturer and the Supplier based on the Manufacturer's bargaining power θ. Necessarily, this goal of the bargaining is to achieve the collaboration and the achievement of bargaining means the Manufacturer and the Supplier jointly make decisions facing consumers and obtain their respective profits from the collaboration. Meanwhile, Corollary 1 also highlights that Manufacturer's and the Supplier's profits are also influenced by their non-collaborative profits, denoted by $\left(\pi_m^N, \pi_s^N\right)$ when the Manufacturer does not adopt 3DP technology to diversify its product offerings.

Similarly, based on Proposition 3, we can obtain the equilibrium demands for BP and VPs $\left(D_0^{B*}, D^{B*}\right)$, along with the total profit of the collaboration model under a Nash bargaining contract, i.e., π^{B*}. Further, it is straightforward that $\pi_m^N = \frac{(1-c_m)^2}{4}$ and $\pi_s^N = 0$ when the Manufacturer does not adopt 3DP technology to facilitate an increase in product variety. Consequently, these results allow us to obtain the equilibrium profits of the Manufacturer and the Supplier in under a Nash bargaining contract, as detailed in Corollary 1. The full array of equilibrium outcomes for the collaboration model are presented in Table 3 as follows.

Table 3. Equilibrium results in the collaboration model.

Conditions		$(D_0^{B*}, D^{B*}, \pi^{B*}, \pi_m^{B*}, \pi_s^{B*})$
$(i)\ c_s > c_{s2}$	$K \le K_3$	$\left(\frac{1+nKc_s}{2n+1}, \frac{n(2-Kc_s)}{2n+1}, \frac{n(2-Kc_s)^2}{4n+2} - c_m, \pi_m^{B1}, \pi_s^{B1}\right)$
	$K \in (K_3, K_2]$	$\left(\frac{1-c_m}{2}, n(1-c_m-Kc_s), \frac{(1-c_m)^2}{4} + \frac{n(1-c_m-Kc_s)^2}{2}, \pi_m^{B2}, \pi_s^{B2}\right)$
	$K > K_2$	$\left(\frac{1-c_m}{2}, 0, \frac{(1-c_m)^2}{4}, \frac{(1-c_m)^2}{4}, 0\right)$
$(ii)\ c_s \in (c_{s0}, c_{s2}]$	$K \le K_3$	$\left(\frac{1+nKc_s}{2n+1}, \frac{n(2-Kc_s)}{2n+1}, \frac{n(2-Kc_s)^2}{4n+2} - c_m, \pi_m^{B1}, \pi_s^{B1}\right)$
	$K > K_3$	$\left(\frac{1-c_m}{2}, n(1-c_m-Kc_s), \frac{(1-c_m)^2}{4} + \frac{n(1-c_m-Kc_s)^2}{2}, \pi_m^{B2}, \pi_s^{B2}\right)$
$(iii)\ c_s \le c_{s0}$	$K \in [0,1]$	$\left(\frac{1+nKc_s}{2n+1}, \frac{n(2-Kc_s)}{2n+1}, \frac{n(2-Kc_s)^2}{4n+2} - c_m, \pi_m^{B1}, \pi_s^{B1}\right)$

where $\pi_m^{B1} = \theta\left(\frac{n(2-Kc_s)^2}{4n+2} - c_m\right) + (1-\theta)\frac{(1-c_m)^2}{4}$, $\pi_s^{B1} = (1-\theta)\left(\frac{n(2-Kc_s)^2}{4n+2} - c_m\right)$, $\pi_m^{B2} = \frac{(1-c_m)^2}{4} + \frac{\theta n(1-c_m-Kc_s)^2}{2}$ and $\pi_s^{B2} = (1-\theta)\left(\frac{(1-c_m)^2}{4} + \frac{n(1-c_m-Kc_s)^2}{2}\right)$.

Accordingly, we further investigate how the nature of cost saving, i.e., K, impacts the equilibrium results in the collaboration model shown in Proposition 4 below.

Proposition 4. *In the collaboration model, p_0^{B*}, p^{B*}, π^{B*}, π_m^{B*} and π_s^{B*} are non-increasing in K, but D_0^{B*} and D^{B*} are non-decreasing in K.*

Proof. The proof of Proposition 4 is delegated to Appendix A. □

Echoing Proposition 2, the impact of the nature of cost saving, i.e., K, on the equilibrium demand for VPs is (weakly) positive and on the equilibrium retail price for VPs (see Figure 5b) and profits of the Manufacturer and the Supplier are (weakly) negative. Intuitively, the total profit of the collaboration model is also non-increasing in K. However, the impact of the nature of cost savings on the equilibrium retail price and demand for BP differs from Proposition 2. Namely, an increase in cost savings, or resource efficiency, usually results in a reduction of the retail price for BP, leading to a rise in demand. These differences stem from collaboration. In such collaboration model, the Manufacturer and the Supplier need to trade off marginal revenues of BP and VPs and then choose a higher BP's retail price which is positively correlated with K when the final market is fully covered. When the final market is partially covered, p_0^{B*} and D_0^{B*} remain constant in K (see Figure 5a).

5. Comparison

In this section, our analysis delves into the distinctions between the ordering model and collaboration model. In detail, the comparison of equilibrium retail prices for BP and VPs and demands for BP and VPs are explored first, then we compare equilibrium profits of the Manufacturer and the Supplier, and finally, we compare the environmental impact.

Proposition 5. *Comparing the equilibrium retail prices and demands for BP and VPs between the ordering model and collaboration model, we gain following properties: $p_0^* - p_0^{B*} \le 0$, $p^* - p_B^* \ge 0$, $D_0^* - D_0^{B*} \ge 0$ and $D^* - D^{B*} \le 0$.*

Proof. The proof of Proposition 5 is delegated to Appendix A. □

Proposition 5 and Figure 5 reveal that the equilibrium retail price for BP is lower in the ordering model than in the collaboration model, which in turn results in a higher demand for BP in the ordering model. Specifically, when the final market is fully covered, facing 3DP's sufficiently strong cost savings ($K \leq \min\{K_3, 1\}$), the Manufacturer and the Supplier jointly choose to raise the retail price of BP to substitute BP with VPs to maximize the total profit of the collaboration model. Meanwhile, the BP's retail price remains stable despite the introduction of 3DP technology when the final market is partially covered. All the above results imply that the collaboration model is more likely motivated to raise (decline) the retail price (demand) of BP. Stemming from this insight, in the collaborative supply chain, it is straightforward that VPs can capture a larger market share, i.e., $D^* \leq D^{B*}$, thereby leading to a lower retail price for VPs, i.e., $p^* \geq p_B^*$.

Proposition 6. *(i) When VPs are unprofitable,* $\pi_m^* = \pi_m^{B*}$ *and* $\pi_s^* = \pi_s^{B*}$*; (ii) When VPs are profitable, there exist two thresholds, i.e.,* θ_m *and* θ_s*, making both Manufacturer and the Supplier can benefit from the supply-chain collaboration, i.e.,* $\pi_m^* - \pi_m^{B*} < 0$ and $\pi_s^* - \pi_s^{B*} < 0$*, if* $\theta \in (\theta_m, \theta_s)$.

Proof. The proof of Proposition 6 is delegated to Appendix A. □

When VPs are unprofitable (Proposition 6(i)), the Manufacturer will not adopt 3DP technology to produce VPs to sell, and it is obvious that Supplier's profit is equal to zero while Manufacturer retains the equilibrium profit π_m^N. Conversely, when VPs are profitable for Manufacturer (Proposition 6(ii)), if the Manufacturer's bargaining power falls in a moderate range, i.e., $\theta \in (\theta_m, \theta_s)$, both Manufacturer and the Supplier have the potential to boost their profits via the supply-chain collaboration. Hence, if the Manufacturer's bargaining power is high (low), i.e., $\theta \leq \theta_m$ ($\theta \geq \theta_s$), the Nash bargaining contract fails to enhance the profitability for Manufacturer (Supplier). This result aligns with the research of [32,38] and reveals that the Nash bargaining contract is mutually advantageous for Manufacturer and the Supplier only if the Manufacturer's and the Supplier's bargaining powers are approaching. This intuitively uncovers a significant managerial insight: For a supply chain to reach a Pareto optimal state via a collaboration strategy, it is preferable to select a 3DP supplier and a traditional manufacturer with comparable bargaining powers.

Finally, following [38], we denote the environmental pollution per unit BP by I. As 3DP technology owns improved resource efficiency that leads to lower materials wastes [8], energy consumption and carbon emissions [7], the environmental pollution per unit VP can be represented by KI. For simplicity, we normalize I equal to 1, i.e., $I = 1$. Hence, the total environmental pollution, i.e., TP, in the ordering model and collaboration model are $TP^* = D_0^* + D^*K$ and $TP^{B*} = D_0^{B*} + D^{B*}K$ respectively. We compare TP^* and TP^{B*} to obtain following Proposition 7.

Proposition 7. *(i) When VPs are unprofitable,* $TP^* = TP^{B*}$*; (ii) When VPs are profitable, there exists a threshold, i.e.,* $K^\#$*, making* $TP^* - TP^{B*} \geq 0$ *if* $K \leq K^\#$.

Proof. The proof of Proposition 7 is delegated to Appendix A. □

Proposition 7 shows that when VPs are unprofitable (see Figure 6, $K > K_2$) leading that Manufacturer is against implementing 3DP technology to enhance product variety, the total environmental pollution in the ordering model is equal to the one in the collaboration model since Manufacturer exclusively sells BP and cannot capitalize on the superior resource efficiency of 3DP. Conversely, when VPs are profitable (see Figure 6, $K \leq K_2$), if the cost savings from improved resource efficiency are significant, i.e., $K \leq K^\#$, the collaboration model releases lower environmental pollution. Otherwise, i.e., $K > K^\#$, the collaboration model causes more environmental pollution. It is because, together with Proposition 5, the collaboration model pollutes less from producing VPs but more due to producing

BP. Essentially, more pronounced cost savings, i.e., $K \leq K^{\#}$, can significantly reduce the environmental pollution per unit VP and thus, leading to less overall pollution in the collaboration model. In contrast, the collaboration model incurs greater pollution due to both higher environmental pollution per unit VP and demands for VPs. This result motivates the manager of supply chain to pivot towards the collaboration in response to environmental regulations, especially when 3DP technology offers substantial resource efficiency.

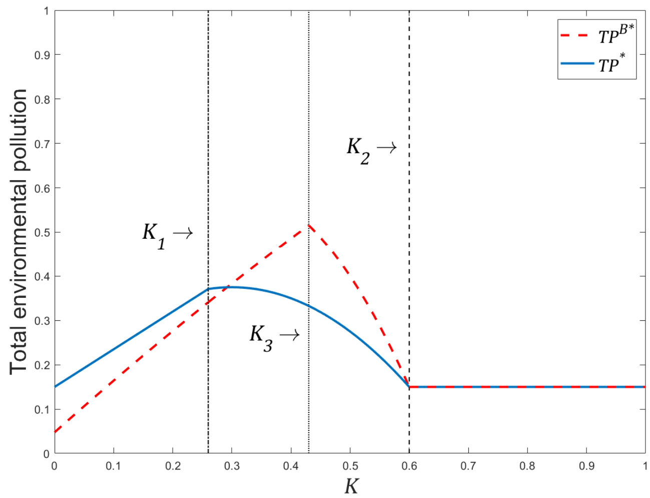


Figure 6. Comparison of equilibrium (*) total environmental pollutions setting $c_m = 0.7$, $n = 10$ and $c_s = 0.5$.

6. Discussion

In this section, we discuss our main findings, practical implications and contributions to literature, respectively.

6.1. Main Findings

Based on equilibrium outcomes analysis, we obtain the following main results.

(1) When the unit cost of each 3DP part is sufficiently high, a low cost savings (improved resource efficiency) of per unit 3DP part leads the manufacturer not to adopt 3DP technology to sustainably facilitate an increase in product variety, but a high cost savings motivates the manufacturer to implement 3DP technology to sell VPs from the partially covered final market to the fully covered final market. Further, when the unit cost is not sufficiently high, the manufacturer will always accept to use 3DP technology to sustainably enhance product variety. Specifically, a high 3DP's cost savings leads to the fully covered final market and a low 3DP's cost savings results in the partially covered final market. Finally, when the unit cost is sufficiently low, no matter how 3DP's cost savings is, the final market can be always fully covered. All the above results hold in both the ordering model and the collaboration model.

(2) When the manufacturer's bargaining power is weak, the manufacturer tends to order sustainable 3DP parts from the supplier to produce VPs, and when the manufacturer's bargaining power is stronger, a stronger bargaining power incentivizes the manufacturer to collaborate with the supplier in printing sustainable 3DP parts to promote product variety. Intuitively, a weaker bargaining power of the manufacturer leads that it is less possible for the manufacturer to catch more profits from the collaboration between the manufacturer and supplier, thereby reducing the manufacturer's desire for working with the supplier. Further, if the manufacturer's bargaining power is strong enough, the Nash bargaining contract cannot raise the supplier's profit leading the supplier to forgo the collaboration.

(3) In the ordering model, a change in 3DP's cost savings does not affect the equilibrium retail price or demand for BP. Then, with an increase in the cost savings due to 3DP's enhanced resource efficiency, the equilibrium wholesale price for 3DP parts and retail

price for VPs will weakly decrease due to lower final unit production cost, resulting in an immediate increase in demand for VPs. Further, combined with the effects of the lower final unit production cost and higher demand for VPs, it eventually presents a "win-win" situation for both the manufacturer and supplier. As for the collaboration model, similarly, the cost savings has weakly negative impact on the equilibrium retail price for VPs and profits of the manufacturer and supplier, and the demand for VPs rises in the cost saving. Differing from the ordering model, the equilibrium retail price (demand) for BP is non-increasing (non-decreasing) in the cost saving. This is because when the final market is fully covered, such collaboration encourages the manufacturer and supplier to raise BP's retail price to substitute BP with VPs, boosting profits. Finally, as our equilibrium analysis emphasizes that if the supplier enables a low cost of unit 3DP parts, the manufacturer is willing to introduce these sustainable 3DP parts to enhance product variety, a higher cost savings renders the collaboration model pollutes less by selling less quantities of BP which consumes more resources and releases more environmental pollution.

6.2. Practical Implications

Our theoretical findings have several clear practical implications below.

Firstly, the Manufacturer is willing to embrace 3DP technology, provided that the unit cost is not sufficiently high or the improved resource efficiency is not extremely low. In reality, Nike's choice to utilize 3DP technology to offer sustainable mass customization is driven by the fact that 3DP technology at that time could provide approximately 10% cost efficiency for Nike's product innovation [39]. Therefore, 3DP's unit cost and improved resource efficiency constitute pivotal determinants in the Manufacturer's deliberation on adopting 3DP technology to promote sustainable product variety. Namely, the supply-chain manager, who wishes to facilitate the part transactions, needs to consider Manufacturer's acceptance regarding 3DP's unit cost and improved resource efficiency.

Then, our findings emphasize that the supply-chain manager should adjudicate the suitable approach to promote the part transactions upon the Manufacturer's bargaining power. Specifically, if the Manufacturer's bargaining power is weak, the supply-chain manager should lead the Manufacturer to directly purchase 3DP parts rather than collaborate with Supplier. This implication is consistent with the practical observations that Avular, as a nascent company, chooses to order sustainable 3DP parts from HP, while New Balance, as a listed company, prefers to collaborate with Formlabs.

Furthermore, with an increase in 3DP's improved resource efficiency, the lower final unit production cost can bring lower retail prices for new designed products. This conclusion is consistent with Adidas's experience in embracing 3DP technology. Specifically, when Adidas amateurishly implemented 3DP technology for shoe production, the retail price was as high as $20,000 in 2020 [40]. However, with the comprehensive application of 3DP, stronger improved resource efficiency (e.g., more space-efficient design) brought rapid reductions in retail prices, and new shoes were priced only $200 in 2021 [41]. Therefore, the supply-chain manager, while enhancing Supplier's 3DP technology, should also focus on training Manufacturer to utilize 3DP more efficiently. Both methods can bring stronger improved resource efficiency.

Finally, our study analyzes the differences of environmental impact between the ordering model and the collaboration model. The findings underscore an essential managerial insight that the manager of the supply chain should promote the manufacturer and supplier's collaboration to comply with government environmental regulations when 3DP's cost savings enabled by the improved resource efficiency is strong.

6.3. Contributions to Literature

This paper contributes to the existing literature in several key points.

The reviewed theoretical literature in Section 2 (such as [14–19]) have investigated the impact of 3DP technology on the operation of the supply chain, they usually ignore 3DP's environmental-friendly futures (i.e., improved resource efficiency) that lead to the cost savings of each 3DP part. Our research enriches the existing works by exploring how 3DP's cost savings influences the game equilibrium.

Then, we further enrich existing studies (i.e., [14–19]) focusing on the adoption of 3DP technology in supply-chain operations by analyzing the differences in environmental impact between the ordering model and the collaboration model. Our findings bridge the gap in research regarding which model should be implemented in light of government regulatory environments.

Finally, few of existing papers (e.g., [17,20]) pay attention to 3DP parts production and reveal whether 3DP technology is the game changer or threat. However, they mainly concentrate on the ordering model where traditional manufacturers order 3DP parts from 3DP suppliers to promote product variety while ignoring the realistic observation that some traditional manufactures tend to collaborate with 3DP providers. We further consider the collaboration in our model to uncover the mechanisms under which model the manufacturer can benefit more through a comparative analysis of equilibrium outcomes in both the ordering model and the collaboration model.

7. Conclusions and Future Research

7.1. Conclusions

3DP as one of the most flexible manufacturing technologies has attracted dramatical attention from different industries and many well-known firms such as GE, Siemens and HP have started 3DP plans. Considering 3DP's innovative attributes, especially its ability to print differentiated parts with substantial resource efficiency, some traditional manufacturers opt to order sustainable 3DP parts from 3DP suppliers, while some others collaborate with 3DP suppliers to print these sustainable parts. To uncover the mechanism of two different strategies, we develop a supply chain involving a 3DP supplier (S) and a traditional manufacturer in two models, i.e., the ordering model under a wholesale price contract and the collaboration mode under Nash bargaining contract.

Firstly, given 3DP's printing variety, the equilibrium outcomes of two supply chains depend on the unit cost of each 3DP part and the cost savings per unit 3DP part due to 3DP's enhanced resource efficiency. Our findings indicate that as long as the unit cost of each 3DP part is not sufficiently high and the cost savings is extremely small, VPs are profitable leading Manufacturer is willing to implement 3DP technology to enhance product variety. In contrast, VPs are unprofitable for the traditional manufacturer, and the Manufacturer rejects to boost product variety via sustainable 3DP parts. Secondly, as long as VPs are profitable for the traditional manufacturer, a rise in the cost savings can bring "win-win" to the traditional manufacturer and 3DP supplier. Thirdly, when the Manufacturer's and the Supplier's bargaining powers are approaching, the collaboration model under a Nash Bargaining contract becomes beneficial to both Manufacturer and the Supplier. Interestingly, the Nash bargaining contract incentives the Manufacturer to raise the retail price for BP to substitute BP with VPs to gain more profits. At last, the results emphasizes that if Supplier enables a lower cost of unit 3DP parts, the Manufacturer is willing to introduce these sustainable 3DP parts to enhance product variety, a higher cost savings renders the collaboration model pollutes less by selling less quantities of BP which consumes more resources and releases more environmental pollution.

Finally, we enrich existing literature by exploring how the cost savings due to 3DP's enhanced resource efficiency affects the game equilibrium, examining the impact of the supply-chain collaboration under a Nash bargaining contract on 3DP technology in supply-chain management, and uncovering how the supply-chain manager implements lower environmental pollution in response to government environmental regulations.

7.2. Future Research

However, there still exist some limitations in this paper. First, we normalize consumer's valuations for products to 1. In future research, this assumption can be relaxed, and we can further analyze how consumer's valuations for products affect consumers' purchase decisions and the price decisions of the Manufacturer and the Supplier. Second, this paper ignores endogenous decision of the 3DP's printing variety level investment. We can further follow [22] to endogenously characterize variety level investment and examine the impact of investment cost coefficient. Third, information sharing can improve supply-chain performance [42] and this paper does not consider information sharing issues in a supply chain. Accordingly, we can further follow [43] to investigate the benefits of sharing information. Finally, we neglect the competition situation where there may exist a competitor located at point 1. Considering the competition situation, we can comprehensively how the competitor's behavior impacts the Supplier's decisions.

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Appendix A

Proof of Lemma 1. We first consider $w > 1 - c_m$. Clearly, for any given $p_0 \in [0,1]$, $\pi_m(p_0, p; w)$ is continuous and concave in p and its stationary point is $p^\#(w) = \frac{1+w+c_m}{2}$. As $w > 1 - c_m$ implies $p^\#(w) > 1$, we know that the optimal p is $p(p_0; w) = 1$. Substituting $p(p_0; w) = 1$ into Manufacturer's profit $\pi_m(p_0, p; w)$, we have $\pi_m(p_0, p(p_0; w); w) = (1 - p_0)(p_0 - c_m)$ which immediately implies that the optimal p_0 is $p_0(w) = \frac{1+c_m}{2}$. Thus, when $w > 1 - c_m$, the Manufacturer's best price response is $(p_0(w), p(w)) = \left(\frac{1+c_m}{2}, 1\right)$.

We now turn to the case of $w \in \left(1 - c_m - \frac{1+c_m}{2n}, 1 - c_m\right]$. In this case, $p^\#(w) \leq 1$. Together with $p^\#(w) \geq (<) 1 - \frac{p_0}{2n}$ for $p_0 \geq (<) n(1 - c_m - w)$, the optimal p is

$$p(p_0; w) = \begin{cases} p^\#(w) = \frac{1+w+c_m}{2}, \; if \; p_0 \geq n(1 - c_m - w) \\ 1 - \frac{p_0}{2n}, \qquad\qquad otherwsie \end{cases} \tag{A1}$$

Substituting (A1) into Manufacturer's profit $\pi_m(p_0, p; w)$, we have

$$\pi_m(p_0, p(p_0; w); w) = \begin{cases} (1 - p_0)(p_0 - c_m) + \frac{n(1-w-c_m)^2}{2}, \; if \; p_0 \geq n(1 - c_m - w) \\ (1 - p_0)(p_0 - c_m) + p_0\left(1 - \frac{p_0}{2n} - w - c_m\right), \; otherwise \end{cases} \tag{A2}$$

It is clear that (A2) is continuous and piecewise concave in p_0 and its two stationary points are $p^\#_{01}(w) = \frac{1+c_m}{2}$ and $p^\#_{02}(w) = \frac{n(2-w)}{2n+1}$. Note that $w \in \left(1 - c_m - \frac{1+c_m}{2n}, 1 - c_m\right]$ implies $p^\#_{01}(w) = \frac{1+c_m}{2} > n(1 - c_m - w)$ and $p^\#_{02}(w) = \frac{n(2-w)}{2n+1} > n(1 - c_m - w)$. Thus, the optimal p_0 is $p_0(w) = p^\#_{01}(w) = \frac{1+c_m}{2}$. Substituting this result into $(A1)$, we know that Manufacturer's best price response is $(p_0(w), p(w)) = \left(\frac{1+c_m}{2}, \frac{1+w+c_m}{2}\right)$.

Finally, $w \le 1 - c_m - \frac{1+c_m}{2n}$ with $n > \frac{1+c_m}{2(1-c_m)}$. In this case, one can follow the previous proof to reveal Manufacturer's best price response is $(p_0(w), p(w)) = \left(\frac{n(2-w)}{2n+1}, \frac{4n+w}{4n+2}\right)$.

Thus, the proof of Lemma 1 is thus finished. □

Proof of Proposition 1. According to (16), $\frac{\partial \pi_s(w)}{\partial w} = \frac{n(2-2w+Kc_s)}{2n+1} > 0$ for all $w \le 1 - c_m - \frac{1+c_m}{2n}$ and $\frac{\partial \pi_s(w)}{\partial w} = 0$ for all $w > 1 - c_m$, so we gain the stationary point $w^\# = \frac{1-c_m+Kc_s}{2}$ for $w \in \left(1 - c_m - \frac{1+c_m}{2n}, 1 - c_m\right]$.

We first prove Proposition 1(i), i.e., $c_s > c_{s2} = 1 - c_m$. Given $K \le K_1 = \frac{1-c_m-\frac{1+c_m}{n}}{c_s}$, $w^\# \le 1 - c_m - \frac{1+c_m}{2n}$ indicates $w^* = 1 - c_m - \frac{1+c_m}{2n}$. As for $K \in \left(K_1, K_2 = \frac{1-c_m}{c_s}\right]$, $w^\# \in \left(1 - c_m - \frac{1+c_m}{2n}, 1 - c_m\right]$ implies $w^* = w^\# = \frac{1-c_m+Kc_s}{2}$. Finally, if $K > K_2$, $w^\# > 1 - c_m$, and hence, the equilibrium wholesale price is $w^* = 1 - c_m$.

As for Proposition 1(ii), i.e., $c_s \in \left(c_{s1} = 1 - c_m - \frac{1+c_m}{n}, c_{s2}\right]$ and Proposition 1(iii) where $c_s \le c_{s1}$, one can follow the proof of Proposition 1(i).

Thus, the proof of Proposition 1 is thus completed. □

Proof of Proposition 2. According to Proposition 1 and Table 2, for the case of $c_s > 1 - c_m$, if $K \le K_1$, $\frac{\partial p_0^*}{\partial K} = 0$, $\frac{\partial p^*}{\partial K} = 0$, $\frac{\partial D_0^*}{\partial K} = 0$, $\frac{\partial D^*}{\partial K} = 0$, $\frac{\partial w^*}{\partial K} = 0$, $\frac{\partial \pi_m^*}{\partial K} = \frac{\partial \pi_m^{\#1}}{\partial K} = 0$ and $\frac{\partial \pi_s^*}{\partial K} = \frac{\partial \pi_s^{\#1}}{\partial K} = -\frac{(1+c_m)c_s}{2} < 0$; if $K \in (K_1, K_2]$, $\frac{\partial p_0^*}{\partial K} = 0$, $\frac{\partial p^*}{\partial K} = \frac{c_s}{4} > 0$, $\frac{\partial D_0^*}{\partial K} = 0$, $\frac{\partial D^*}{\partial K} = -\frac{nc_s}{2} < 0$, $\frac{\partial w^*}{\partial K} = \frac{c_s}{2} > 0$, $\frac{\partial \pi_m^*}{\partial K} = \frac{\partial \pi_m^{\#2}}{\partial K} = -\frac{n(1-c_m-Kc_s)c_s}{4} < 0$ and $\frac{\partial \pi_s^*}{\partial K} = \frac{\partial \pi_s^{\#2}}{\partial K} = -\frac{n(1-c_m-Kc_s)c_s}{2} < 0$, if $K > K_2$, $\frac{\partial p_0^*}{\partial K} = 0$, $\frac{\partial p^*}{\partial K} = 0$, $\frac{\partial D_0^*}{\partial K} = 0$, $\frac{\partial D^*}{\partial K} = 0$, $\frac{\partial w^*}{\partial K} = 0$, $\frac{\partial \pi_m^*}{\partial K} = 0$ and $\frac{\partial \pi_s^*}{\partial K} = 0$. For the cases of $c_s \in \left(1 - c_m - \frac{1+c_m}{n}, 1 - c_m\right]$ and $c_s \le 1 - c_m - \frac{1+c_m}{n}$, one can follow the proof of $c_s > 1 - c_m$. Thus, the proof of Proposition 2 is thus finished. □

Proof of Proposition 3. According to (17), for any given $p_0 \in [0, 1]$, $\pi^B(p_0, p)$ is continuous and concave in p and its stationary point is $p^{\#\#} = \frac{1+c_m+Kc_s}{2}$. Considering $p^{\#\#} > (\le) 1 - \frac{p_0}{2n}$, we have $p_0 > (\le) n(1 - c_m - Kc_s)$, so we rewrite the profit function as

$$\pi^B(p_0, p(p_0)) = \begin{cases} (1-p_0)(p_0-c_m) + \frac{n(1-c_m-Kc_s)^2}{2}, \ if \ p_0 > n(1-c_m-Kc_s) \\ (1-p_0)(p_0-c_m) + p_0\left(1-\frac{p_0}{2n}-c_m-Kc_s\right), \ if \ p_0 \le n(1-c_m-Kc_s) \end{cases}$$

Also, $\pi^B(p_0, p(p_0))$ is continuous and concave in p_0. Then, we calculate its two stationary points $p_{01}^\#(w) = \frac{1+c_m}{2}$ and $p_0^{\#\#} = \frac{n(2-Kc_s)}{2n+1}$.

We first prove Proposition 3(i), i.e., $c_s > c_{s2} = 1 - c_m$. Given $K \le K_3 = \frac{1-c_m-\frac{1+c_m}{2n}}{c_s}$, $p_{01}^\#(w) = \frac{1+c_m}{2} \le n(1 - c_m - Kc_s)$ and $p_0^{\#\#} = \frac{n(2-Kc_s)}{2n+1} \le n(1 - c_m - Kc_s)$ imply the optimal retail price for BP is $p_0^{B*} = p_0^{\#\#} = \frac{n(2-Kc_s)}{2n+1}$. Substituting $p_0^{B*} = p_0^{\#\#}$ into $p(p_0) = 1 - \frac{p_0}{2n}$, we have $p^{B*} = \frac{4n+Kc_s}{4n+2}$. If $K \in (K_3, K_2]$, $p_{01}^\#(w) = \frac{1+c_m}{2} > n(1 - c_m - Kc_s)$ and $p_0^{\#\#} = \frac{n(2-Kc_s)}{2n+1} > n(1 - c_m - Kc_s)$, so the optimal retail price for BP and VP are $p_0^{B*} = p_{01}^\#(w) = \frac{1+c_m}{2}$ and $p^{B*} = p^{\#\#} = \frac{1+c_m+Kc_s}{2}$ respectively. Finally, if $K > K_2$, $p^{\#\#} = \frac{1+c_m+Kc_s}{2} > 1$ implying the optimal retail price for BP and VP are $p_0^{B*} = p_{01}^\#(w) = \frac{1+c_m}{2}$ and $p^{B*} = 1$.

As for Proposition 3(ii) and (iii), one can follow the proof of Proposition 3(i).

Thus, the proof of Proposition 3 is thus completed. □

Proof of Corollary 1. Substituting $\pi_m^B + \pi_s^B = \pi^{B*}$ in $\Phi(\pi_m^B, \pi_s^B) = \left(\pi_m^B - \pi_m^N\right)^\theta \left(\pi_s^B - \pi_s^N\right)^{1-\theta}$ and after solving two first-order conditions of the Nash bargaining unit $\frac{\partial \left(\pi_m^B - \pi_m^N\right)^\theta \left(\pi^{B*} - \pi_m^B - \pi_s^N\right)^{1-\theta}}{\partial \pi_m^B}$

$= 0$ and $\frac{(\pi^{B*}-\pi_s^B-\pi_m^N)^\theta(\pi_s^B-\pi_s^N)^{1-\theta}}{\partial\pi_s^B} = 0$, we can derive $\pi_m^{B*} = \theta(\pi^{B*} - \pi_s^N) + (1-\theta)\pi_m^N$, and $\pi_s^{B*} = \theta\pi_s^N + (1-\theta)(\pi^{B*} - \pi_m^N)$. □

Proof of Proposition 4. According to Proposition 3 and Table 3, also, we mainly prove the case of $c_s > 1 - c_m$. If $K \le K_3$, $\frac{\partial p_0^{B*}}{\partial K} = -\frac{nc_s}{2n+1} < 0$, $\frac{\partial p^{B*}}{\partial K} = \frac{c_s}{4n+2} > 0$, $\frac{\partial D_0^{B*}}{\partial K} = \frac{nc_s}{2n+1} > 0$, $\frac{\partial D^{B*}}{\partial K} = -\frac{nc_s}{2n+1} < 0$, $\frac{\partial \pi^{B*}}{\partial K} = -\frac{2nc_s}{4n+2}(2-Kc_s) < 0$, $\frac{\partial \pi_m^{B*}}{\partial K} = \frac{\partial \pi_m^{B1}}{\partial K} = -\theta\frac{2nc_s}{4n+2}(2-Kc_s) < 0$ and $\frac{\partial \pi_s^{B*}}{\partial K} = \frac{\partial \pi_s^{B1}}{\partial K} = -(1-\theta)\frac{2nc_s}{4n+2}(2-Kc_s) < 0$.

If $K \in (K_3, K_2]$, $\frac{\partial p_0^{B*}}{\partial K} = 0$, $\frac{\partial p^{B*}}{\partial K} = \frac{c_s}{2} > 0$, $\frac{\partial D_0^{B*}}{\partial K} = 0$, $\frac{\partial D^{B*}}{\partial K} = -nc_s < 0$, and $\frac{\partial \pi^{B*}}{\partial K} = -nc_s(1-c_m-Kc_s) < 0$, $\frac{\partial \pi_m^{B*}}{\partial K} = \frac{\partial \pi_m^{B2}}{\partial K} = -\theta nc_s(1-c_m-Kc_s) < 0$ and $\frac{\partial \pi_s^{B*}}{\partial K} = \frac{\partial \pi_s^{B2}}{\partial K} = -(1-\theta)nc_s(1-c_m-Kc_s) < 0$.

If $K > K_2$, $\frac{\partial p_0^{B*}}{\partial K} = 0$, $\frac{\partial p^{B*}}{\partial K} = 0$, $\frac{\partial D_0^{B*}}{\partial K} = 0$, $\frac{\partial D^{B*}}{\partial K} = 0$, $\frac{\partial \pi^{B*}}{\partial K} = 0$, $\frac{\partial \pi_m^{B*}}{\partial K} = 0$ and $\frac{\partial \pi_s^{B*}}{\partial K} = 0$.

Similarly, the proofs of cases of $c_s \in \left(1 - c_m - \frac{1+c_m}{2n}, 1 - c_m\right]$ and $c_s \le 1 - c_m - \frac{1+c_m}{2n}$ can follow the case of $c_s > 1 - c_m$.

The proof of Proposition 4 is completed. □

Proof of Proposition 5. According to Table 2, Proposition 3 and Table 3, similarly, we mainly prove the case of $c_s > 1 - c_m$, if $K \le K_1$, $p_0^* - p_0^{B*} = -\frac{2n(2-Kc_s)-(2n+1)(1+c_m)}{2(2n+1)} < 0$, $p^* - p_B^* = \frac{(4n+2)(4n-(1+c_m))-4n(4n+Kc_s)}{4n(4n+2)} > 0$, $D_0^* - D_0^{B*} = \frac{2n(1-c_m)-(1+c_m)-2nKc_s}{4n+2} > 0$, and $D^* - D^{B*} = -\frac{2n(1-c_m)-(1+c_m)-2nKc_s}{4n+2} < 0$. If $K \in (K_1, K_3]$, $p_0^* - p_0^{B*} < 0$ and $D_0^* - D_0^{B*} > 0$ too, and then, $p^* - p_B^* = \frac{1}{4}\left(3 + c_m + Kc_s - \frac{2(Kc_s+4n)}{2n+1}\right) > 0$, and $D^* - D^{B*} = -\frac{n(3+c_m-2n+2c_m n+Kc_s(2n-1))}{2+4n} < 0$. If $K \in (K_3, K_2]$, $p_0^* - p_0^{B*} = 0$, $p^* - p_B^* = \frac{1-c_m-Kc_s}{4} > 0$, $D_0^* - D_0^{B*} = 0$, and $D^* - D^{B*} = -\frac{n(1-c_m-Kc_s)}{2} < 0$. If $K > K_2$, $p_0^* - p_0^{B*} = 0$, $p^* - p_B^* = 0$, $D_0^* - D_0^{B*} = 0$, and $D^* - D^{B*} = 0$. Finally, the proofs of the rest of cases can follow the proof of the case of $c_s > 1 - c_m$. The proof of Proposition 5 is finished. □

Proof of Proposition 6. Similar to the proof of Proposition 5, we first prove the the case of $c_s > 1 - c_m$, if $K \le K_1$, $\pi_m^* - \pi_m^{B*} = \frac{(1-c_m)^2}{4} + \frac{(1+c_m)^2}{8n} - \left[\theta\left(\frac{n(2-Kc_s)^2}{4n+2} - c_m\right) + (1-\theta)\frac{(1-c_m)^2}{4}\right] = \frac{(1+c_m)^2}{8n} - \left[\left(\frac{n(2-Kc_s)^2}{4n+2} - c_m\right) - \frac{(1-c_m)^2}{4}\right]\theta$. Then, $(\pi_m^* - \pi_m^{B*})|_{\theta=1} = \frac{(1+c_m)^2}{8n} - \left[\left(\frac{n(2-Kc_s)^2}{4n+2} - c_m\right) - \frac{(1-c_m)^2}{4}\right]$ and further, $\frac{\partial[(\pi_m^* - \pi_m^{B*})|_{\theta=1}]}{\partial K} = \frac{n(2-Kc_s)c_s}{2n+1} > 0$ and $[(\pi_m^* - \pi_m^{B*})|_{\theta=1}]|_{K=K_1} = -\frac{(1+c_m)^2(3+4n)}{8n(1+2n)} < 0$ imply $(\pi_m^* - \pi_m^{B*})|_{\theta=1} < 0$ always holds. This result, together with that $(\pi_m^* - \pi_m^{B*})$ is obviously decreasing in θ and $(\pi_m^* - \pi_m^{B*})|_{\theta=0} = \frac{(1+c_m)^2}{8n} > 0$, indicates that there exists a threshold θ_1 making $\pi_m^* - \pi_m^{B*} \ge 0$ when $\theta \le \theta_1$ and otherwise, $\pi_m^* - \pi_m^{B*} < 0$. Then, $\pi_s^* - \pi_s^{B*} = \frac{1+c_m}{2}\left(1 - c_m - \frac{1+c_m}{2n} - Kc_s\right) - (1-\theta)\left(\frac{n(2-Kc_s)^2}{4n+2} - c_m\right)$ and $(\pi_s^* - \pi_s^{B*})|_{\theta=1} = \frac{1+c_m}{2}\left(1 - c_m - \frac{1+c_m}{2n} - Kc_s\right) > 0$ obviously. Then, we focus on $(\pi_s^* - \pi_s^{B*})|_{\theta=0} = \frac{1+c_m}{2}\left(1 - c_m - \frac{1+c_m}{2n} - Kc_s\right) - \left(\frac{n(2-Kc_s)^2}{4n+2} - c_m\right)$. Similarly, $\frac{\partial[(\pi_s^* - \pi_s^{B*})|_{\theta=0}]}{\partial K} > 0$ and $[(\pi_s^* - \pi_s^{B*})|_{\theta=0}]|_{K=K_1} = -\frac{1+2n+2n^2+c_m(2-4n^2)+c_m^2(1+2n+2n^2)}{4n(1+2n)} < 0$. This implies that there also exists a threshold θ_2 making $\pi_s^* - \pi_s^{B*} \ge 0$ when $\theta \ge \theta_2$ and otherwise, $\pi_s^* - \pi_s^{B*} < 0$. If $K \in (K_1, K_3]$, $\pi_m^* - \pi_m^{B*} = \frac{(1-c_m)^2}{4} + \frac{n(1-c_m-Kc_s)^2}{8} - \left[\theta\left(\frac{n(2-Kc_s)^2}{4n+2} - c_m\right) + (1-\theta)\frac{(1-c_m)^2}{4}\right] = \frac{n(1-c_m-Kc_s)^2}{8} - \left[\left(\frac{n(2-Kc_s)^2}{4n+2} - c_m\right) - \frac{(1-c_m)^2}{4}\right]\theta$

and $\pi_s^* - \pi_s^{B*} = \frac{n(1-c_m-Kc_s)^2}{4} - (1-\theta)\left(\frac{n(2-Kc_s)^2}{4n+2} - c_m\right)$. Also, $(\pi_m^* - \pi_m^{B*})$ is decreasing in θ, $(\pi_m^* - \pi_m^{B*})|_{\theta=0} > 0$, $\frac{\partial[(\pi_m^*-\pi_m^{B*})|_{\theta=1}]}{\partial K} > 0$, and $[(\pi_m^* - \pi_m^{B*})|_{\theta=1}]|_{K=K_3} = -\frac{3(1+c_m)^2}{32n} < 0$ mean that exists a threshold θ_3 making $\pi_m^* - \pi_m^{B*} \geq 0$ when $\theta \leq \theta_1$ and otherwise, $\pi_m^* - \pi_m^{B*} < 0$. Similarly, there also exists a threshold θ_4 making $\pi_s^* - \pi_s^{B*} \geq 0$ when $\theta \geq \theta_4$ and otherwise, $\pi_s^* - \pi_s^{B*} < 0$. If $K \in (K_3, K_2]$, $\pi_m^* - \pi_m^{B*} = \frac{(1-c_m)^2}{4} + \frac{n(1-c_m-Kc_s)^2}{8} - \left[\frac{(1-c_m)^2}{4} + \frac{\theta n(1-c_m-Kc_s)^2}{2}\right] = \frac{n(1-c_m-Kc_s)^2}{8}(1-4\theta)$. It is straightforward that we have $\pi_m^* - \pi_m^{B*} \geq 0$ when $\theta \leq 1/4$. Then, for $\pi_s^* - \pi_s^{B*} = \frac{n(1-c_m-Kc_s)^2}{4} - (1-\theta)\left(\frac{(1-c_m)^2}{4} + \frac{n(1-c_m-Kc_s)^2}{2}\right) = \frac{n(1-c_m-Kc_s)^2}{4}(2\theta-1) - (1-\theta)\frac{(1-c_m)^2}{4}$, obviously, $(\pi_m^* - \pi_m^{B*})|_{\theta=0} = -\frac{n(1-c_m-Kc_s)^2}{4} - \frac{(1-c_m)^2}{4} < 0$ and $(\pi_m^* - \pi_m^{B*})|_{\theta=1} = \frac{n(1-c_m-Kc_s)^2}{4} > 0$, so there exists a threshold too. If $K > K_2$, $\pi_m^* - \pi_m^{B*} = 0$ and $\pi_s^* - \pi_s^{B*} = 0$. As for the rest parts of Proposition 6, one can follow the proof of the case of $c_s > 1 - c_m$. Finally, we use θ_m and θ_s to present the thresholds for Manufacturer and the Supplier, i.e., $\pi_m^* - \pi_m^{B*} < 0$ and $\pi_s^* - \pi_s^{B*} < 0$ when $\theta \in (\theta_m, \theta_s)$. Therefore, the proof of Proposition 6 is completed. □

Proof of Proposition 7. For the case of $c_s > 1 - c_m$, if $K \leq K_1$, $TP^* - TP^{B*} = \frac{1-c_m}{2} + K\frac{1+c_m}{2} - \frac{1+nKc_s}{2n+1} - K\frac{n(2-Kc_s)}{2n+1}$. As $\frac{\partial^2(TP^*-TP^{B*})}{\partial K^2} = \frac{2nc_s}{2n+1} > 0$ and $\frac{\partial(TP^*-TP^{B*})}{\partial K}\Big|_{K=K_1} = -\frac{3+2(c_s-1)n+(3+2n)c_m}{2+4n} < 0$, we can deduce $\frac{\partial(TP^*-TP^{B*})}{\partial K} < 0$. Then, $(TP^* - TP^{B*})|_{K=K_1} = \frac{(1+c_m)(1+(c_s-1)n+c_m(1+n))}{2n(1+2n)c_s} > 0$ leads that $TP^* - TP^{B*} > 0$ holds for all $K \leq K_1$. If $K \in (K_1, K_3]$, $TP^* - TP^{B*} = \frac{1-c_m}{2} + K\frac{n(1-c_m-Kc_s)}{2} - \frac{1+nKc_s}{2n+1} - K\frac{n(2-Kc_s)}{2n+1}$. Similarly, $\frac{\partial^2(TP^*-TP^{B*})}{\partial K^2} = -\frac{(2n-1)nc_s}{1+2n} < 0$ and $\frac{\partial(TP^*-TP^{B*})}{\partial K}\Big|_{K=K_1} = -\frac{2+2n(n+c_s)-3n-(2n^2+n-2)c_m}{2+4n} < 0$ for all $n > \frac{1+c_m}{1-c_m}$ imply $\frac{\partial(TP^*-TP^{B*})}{\partial K} < 0$. As $(TP^* - TP^{B*})|_{K=K_1} > 0$ and $(TP^* - TP^{B*})|_{K=K_3} = -\frac{(1+c_m)(2n(1-c_m)-(1+c_m))}{8nc_s} < 0$, we can deduce there exists a threshold $K^\$ \in (K_1, K_3]$ making $TP^* - TP^{B*} \geq 0$ if $K \leq K^\$$. If $K \in (K_3, K_2]$, $TP^* - TP^{B*} = -K\frac{n(1-c_m-Kc_s)}{2} < 0$. If $K > K_2$, $TP^* - TP^{B*} = 0$ always holds. Finally, the proofs of the rest of cases can follow the proof of the case of $c_s > 1 - c_m$ and we use $K^\#$ to represent all the thresholds of K. Thus, the proof is completed. □

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