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Channel Selection and Pricing Decisions Considering Three Charging Modes of Production Capacity Sharing Platform: A Sustainable Operations Perspective

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Abstract: In the context of sharing economy, a manufacturer can source from two alternative channels: sharing and traditional, when facing production capacity constraints and sustainably conscious consumers. The aim of the paper is to analyze channel selection and pricing strategies of the manufacturer for achieving sustainable operations, to investigate the operations of the platform regarding charging modes, access requirements, and commission rates in different stages of development, and to discuss the interaction among all stakeholders for sustainability in the whole system. The game-theoretic approach is adopted. The results provide references for decisions of the manufacturer and surplus production capacity supplier to join in the sharing, as well as corresponding optimal pricing strategies, which guides platforms to keep a balance between profitability and attracting participants by relatively low access requirements and commission rates. Moreover, developing platforms prefer to charge suppliers and set low access requirements while relatively developed platforms tend to charge bilateral sides or manufacturers and set high access requirements. Charging the manufacturer encourages the bilateral participation of the platform most. In addition, as charging mode changes, the trend of changes in consumer surplus and social welfare is the same as that in the market share of products from the sharing channel.

Keywords: production capacity sharing; channel selection; pricing; charging mode; game theory; sustainable operations perspective

1. Introduction

Traditionally, the definition of supply chain management is the management of physical, logical, and financial flows in networks of intra- and inter-organizational relationships to add value and achieve consumer satisfaction [1,2]. However, the traditional supply chain management is conducted in the operation process that can be abstracted as “take-make-consume-disposal” or “extract-produce-use-dump material and energy flow”, which raises the sustainability problems [3]. The issues of sustainable operations expand the scope of traditional supply chain management and focus on the management of products, information, capital, and cooperation among members to achieve sustainable goals in society, economy, and ecology dimensions [4,5]. The practice of the “production capacity sharing” on production capacity sharing platforms (denoted by “platforms”) is used to foster sustainable operations in the context of sharing economy, such as the MindSphere platform (https://www.siemens.com/MindSphere), the General Electric Predix platform (https://www.ge.com/digital/iiot-platform), and the CASICloud platform (http://www.casicloud.com/) [6–8].
Production capacity sharing is also an important part of sustainable production and makes products have better performance on sustainability compared to that in a traditional manufacturing environment [9,10]. Firstly, the products can be produced from surplus production capacity, which is environmentally friendly and economical [11,12]. Figure 1 shows the process of production capacity sharing [11,13]. Platforms can integrate massive and fragmented surplus production capacity from owners of equipment that is underutilized and help manufacturers with capacity constraints share the surplus production capacity with surplus production capacity suppliers (denoted by “capacity suppliers”) through technologies such as the Industrial Internet of Things (IIOT). Besides, scholars believe that surplus production capacity sharing has a low-carbon attribute [14]. Secondly, technologies and services on the platforms improve the quality and delivery time of the orders, which is conducive to the sustainability of transactions. The emergence of the production capacity sharing shifts ownership transactions to transactions of usage rights and enables the nodes of supply chain operations to shift from enterprises to equipment, which is beneficial to equipment efficiency improvement and stability of the production [15]. Moreover, platforms facilitate efficient mutual searches and matching among manufacturers and capacity suppliers and provide supervision and control services for the whole process. For example, the platform of Alibaba (https://tgc.1688.com/) provides expert services for order tracking and the iSESOL platform (https://www.isesol.com/) transparentizes the capacity sharing process for both sides of the platform to monitor production and payment processes. Services on the platform reduce rework and improve production sustainability. Based on the description above, production capacity sharing as a new mode to produce breaks the balance and sustainability of original manufacturing systems, changes the traditional way of production capacity allocation, and raises new opportunities and challenges in sustainable operations for stakeholders including manufacturing enterprises with overcapacity or insufficient capacity, platforms, and sustainably conscious consumers. Therefore, it is an interesting topic in the sharing economy era to focus on the behaviors and interactions of production capacity sharing stakeholders from a sustainable operations perspective.

![Figure 1. The process of production capacity sharing.](image-url)
More specifically, from the perspective of actual operations, production capacity sharing brings new directions to sustainable supply chain management issues. For example, as consumers have become more sustainably concerned [16,17], production capacity sharing on the platforms is an effective alternative for manufacturing enterprises to ensure competitive advantage by meeting demands of the market, reduce their risk of wasting capacity, no longer face with the selection limitations, optimize business scheduling, and gain new revenue streams [13]. However, production capacity sharing mechanism design considering sharing features is challenging. For example, a capacity-constrained manufacturer or an overcapacity supplier needs to decide whether to join in the sharing considering the cost of the sharing and consumer’s consciousness of sustainability comprehensively. In addition, a platform operator needs to design appropriate operational mechanisms particularly the charging mechanisms to balance the relationship between attracting participants of the platform and gaining profits, considering its own development levels and operational goals. Therefore, with regards to production capacity sharing, how to make channel selection decisions and corresponding optimal pricing strategies for manufacturing enterprises and how to design operational mechanisms for platforms from a sustainable operations perspective is important, urgent, and promising. In other words, the aims of this paper are to explore the behaviors of the overcapacity manufacturer and capacity supplier in traditional and sharing manufacturing environments and the operational mechanisms of the platform regarding charging modes, access requirements, and commission rates. Furthermore, to discuss the internal mechanism of interactions among production capacity sharing stakeholders, including sustainably conscious consumers, the manufacturer, the platform, the capacity supplier, and the traditional supplier to promote sustainability of the whole supply chain.

In recent years, although the issues about the production capacity sharing have attracted some scholars, this topic is still in its infancy. Firstly, scholars are keen to study capacity sharing in the field of consumption such as transportation, space, and durable goods [18–20], where the system generally consists of three parties: suppliers, demanders and sharing platforms. However, there are four parties including suppliers, demanders, platforms, and downstream consumers that interact with each other with regards to the production capacity sharing in the manufacturing field. Consumer purchasing behavior is an important factor affecting the strategies of upstream decision-makers. However, there is a gap between a consumer’s actual actions and positive attitudes to sustainability, which means that sustainability consciousness does not always lead to purchasing behavior for products made via the platforms [17]. This raises an interesting question that how consumer’s consciousness of sustainability affects their purchasing behavior and then affects the decision-making of upstream supply chain members? Secondly, for the charging mechanism of the platforms, commissions or registration fees are considered in the previous literature on sharing platforms [21,22]. In addition to the choice of lump-sum fees or two-part tariffs, the platform also needs to decide which side to charge [23]. The impacts of different charging modes, namely different charging objects, on each stakeholder and the whole system are needed to be discussed. Thirdly, the achievement in the sustainable operations of supply chains considering production capacity sharing is limited. For example, what the conditions for manufacturing enterprises to join in the sharing from a sustainable operations perspective? How the production capacity sharing influences the relationship between short-term individual profitability and long-term development of the system? How does the platform balance the relationship between access requirements and commission rates for achieving sustainability? Fourthly, the research on production capacity sharing mainly includes related concepts, technology, services, and framework of the platforms using description, case study, and other empirical methods [24,25]. For analyzing conflict and cooperation among stakeholders in the process of production capacity sharing, using the game theory, which is a powerful theoretical tool, is important and interesting. From the economic attribute perspective of production capacity sharing, it is necessary to coordinate the interests of each participant and ensure the participation of the sharing can be profitable [26]. From the perspective of actual operations, game theory can model the characteristics of the research problem in terms of state (dynamic or static), cooperative attribute (cooperation or not), number of games (one-shot or
repeated), etc. Particularly, the Stackelberg game that used in this paper captures the characteristics of the decision-making sequence in operations \([27,28]\). In a word, there are four points of motivations for research questions in this paper, namely to enrich the research on: the impacts of differences between consumer’s consideration for sustainability and sustainable product purchasing decisions on upstream supply chain members, platform’s operational mechanisms particularly the charging mechanism design for sustainable operations, sustainable supply chain management such as channel selection and pricing strategies considering production capacity sharing, and production capacity sharing issues using game theory.

Motivated by the issues mentioned above, behavioral decisions of stakeholders regarding production capacity sharing in the supply chain are investigated. Particularly, the game-theoretic approach is adopted to analyze the following research questions:

- From the perspective of sustainable operations, what is the optimal channel selection for a manufacturer when faced with a traditional sourcing environment versus a production capacity sharing sourcing environment considering consumer’s consciousness of sustainability?
- From the perspective of sustainable operations, what are the optimal pricing strategies for suppliers and the manufacturer under corresponding channel selection strategies of the manufacturer?
- From the perspective of sustainable operations, what are the platform’s operational mechanisms regarding charging objects, access requirements, and commission rates in different stages of development considering the interactions among stakeholders in the whole supply chain?

To answer these questions, a supply chain including two sourcing channels is considered. Specifically, a sharing channel is composed of a platform and a capacity supplier linked on the platform. Another one is a traditional channel consisting of a traditional supplier. Product performance in terms of sustainability differentiates the two channels. From the perspective of sustainable operations, game theory is applied to study the pricing strategies of supply chain members based on three channel selection strategies of the manufacturer: sharing-channel only strategy, traditional-channel only strategy, and dual-channel strategy. The Stackelberg game model is developed and the equilibrium solutions can be obtained according to the backward induction. Demand of sustainably conscious consumers on the products from the two sourcing channels depends on consumer surplus, which is affected by the product performance in terms of sustainability. The consumer acceptance of the channel is used to capture different preferences of consumers for product sustainability characteristics. Three charging modes of the platform and capacity management costs of the capacity supplier, which reflects the access requirements of the platform are also considered. In order to achieve the sustainability of the production capacity sharing system, the interaction among the decision-making of the stakeholders and the balanced operations of the platform between profitability and sustainable development are analyzed.

The main contributions of this paper are as follows. Firstly, production capacity sharing problem with the concern of the gap between consumer’s actual actions and positive attitudes to sustainability is considered in a supply chain including four parties. They include suppliers (capacity supplier and traditional supplier), platform, manufacturer, and sustainably conscious consumers in the field of manufacturing, rather than only three parties (without downstream consumers) in the field of consumption. Besides, this paper focuses on the design of the production capacity sharing mechanism considering three charging modes, access requirements, and commission rates and its role in the platform’s different stages of development from a sustainable operations perspective. Secondly, a game-theoretic model is used to formulate the issues with the concern of optimal channel selection and pricing strategies under three charging modes of the platform and provide a reference framework for the behavioral decision-making of participants in a sustainable supply chain. Thirdly, this paper not only validates the proposed methodology concerning the production capacity sharing problem, but also calls for the urge of integrating the philosophies of sustainability into the channel selection, pricing strategies, and platform charging mechanism design in a supply chain.
The remainder of this paper is organized as follows. Section 2 presents a literature review. Problem statement and formulation are developed in Section 3. Section 4 depicts the pricing strategies for sustainable operations under three channel selections of the manufacturer considering the charging modes of the platform based on the impacts of capacity supplier’s capacity management costs and consumer acceptance of traditional channel. Section 5 discusses the interaction among stakeholders regarding production capacity sharing from the perspective of sustainable operations. Section 6 provides the numerical examples concerning the effects of interaction among participants in the supply chain on their profits and platform’s charging mode selection. Section 7 is the conclusion of the research including main findings, significance, limitations, and further work.

2. Literature Review

In recent years, to achieve the sustainability of supply chain, production capacity sharing has received considerable attention. This paper contributes to the literature on the following three aspects: production capacity sharing, channel selection and pricing strategies, and the charging modes of sharing platforms.

2.1. Literature on Production Capacity Sharing

The sharing economy, which is characterized by the sharing of usage rights, creates a great prospect about the potential sustainability benefits [29]. Current research on sharing economy focuses on collaborative consumption in the field of transportation [18], space [19], and durable goods [20]. Wu et al. [30] studied the sharing economy from an environmental perspective and found that the sharing economy could help to allocate resources and reduce greenhouse gas emissions. In the field of manufacturing, cloud manufacturing enabled the integration of surplus production capacity [31]. Manufacturing enterprises can publish or find surplus production capacity information in the cloud-based resource pool [32]. Ren et al. [33] defined the platform used for production capacity sharing as an entity that manages a shared pool of manufacturing resources and capacity over the Internet and the Internet of Things. Papers about the platform used for production capacity sharing have studied the theory [9,34] and services [24,35,36] of the platform using description, case study, survey, and other empirical methods. The game theory is an interesting and effective method to explore production capacity sharing issues [26].

From the perspective of the relationship between production capacity sharing related technologies and sustainability development, Xue et al. [37] and Ren et al. [38] found that the technologies for matching and control on platforms could render the process more efficient and secure. According to the previous research [39,40], products via platforms can be characterized by sustainability because the production process via the platform is guaranteed in terms of quality and delivery time and produced by surplus production capacity, using the related technologies. Furthermore, it is the emergence and diffusion of technologies such as cloud technology, the Internet of Things, and big data that implement related services and functions on the platform for production capacity sharing, which has played a positive role in sustainable manufacturing [25,40,41]. Makkonen and Inkinen proposed that enough support should be guaranteed for technology diffusion and to encourage consumers to use the new technologies rather than choosing other unsustainable alternatives [42]. Some other scholars researched the indicators of the technology diffusion process [43–46], and found that the indicators could drive sustainable development [45,47]. Therefore, if the platform considers the technology diffusion process indicators when applying or promoting related technologies, production capacity sharing and sustainable operations can be better promoted.

To sum up, the production capacity sharing has received a lot of attention in the context of sharing economy and is believed to be conducive to the sustainability of manufacturing systems. Researchers have mainly studied the theory (e.g., definition, technology, etc.) and services (matching, scheduling, etc.) of production capacity sharing in the field of manufacturing. However, research on the process of production capacity sharing from the decision making perspective using the game-theoretic
method is needed to be conducted. Thus, the Stackelberg game model is developed in this work to examine the interaction among behavioral decision-making of production capacity sharing stakeholders. Besides, preference and behavior of downstream sustainably conscious consumers are considered rather than just considering the demanders, the suppliers, and the sharing platform in the field of consumption.

2.2. Literature on Channel Selection and Pricing Strategies

Some scholars have studied the channel selection and pricing decisions affected by the characteristics of products from different channels. Guo et al. [16] analyzed the sourcing decisions of buyers choosing between a responsible supplier and a risky supplier. Socially conscious consumers would be more willing to pay a higher price for products sourced from a responsible supplier than products from a risky supplier. Xiao et al. [48] explored pricing strategies and the choice of two duopoly manufacturers with different delivery times and price characteristics considering consumer heterogeneity in delivery time. Li and Chen [49] studied a retailer’s sourcing channel selection and pricing strategies and found that the retailer would be always better off to integrate with a low-quality manufacturer when quality was endogenous.

Some scholars have focused on different sourcing channel structures. Some of the previous research on this subject was from the perspective of the difference between online and offline channels or the difference between online retailers and platforms [50–53]. The differences between channels in traditional environments and production capacity sharing environments have also been studied. Parker et al. [23] referred to the supply chain in traditional environments as a pipeline through which manufacturers could pass the value to consumers in the form of products and charge for product ownership. Parker et al. [23] also defined the production and transaction in a sharing-platform environment as a way to invite users to join and profit by creating value for users based on the services of the platform.

Above literature indicates that pricing and channel selection strategies of supply chain members can be influenced by different channel structures or consumer consciousness of product characteristics. However, the research on channel selection and pricing strategies considering both consumer consciousness of sustainability and the different channel structures in a traditional environment and a production capacity sharing environment is limited. Thus, the impacts of production capacity sharing on channel selection and pricing strategies of supply chain members, consumer surplus, and social welfare are analyzed in this paper to provide references for the sustainability of the entire system.

2.3. Literature on Charging Modes of Sharing Platforms

A set of papers has considered charging modes of sharing platforms. Kung and Zhong [22] studied membership-based pricing, transaction-based pricing, and cross-subsidization pricing to understand how to price sharing services. For different charging objects, Benjaafar et al. [20] proved that the platform would be beneficial by charging the owner when the cost of the ownership was low. Zhou et al. [21] found that charging both sides could be detrimental to the surplus of the demanders but improve the surplus of the suppliers compared to charging the supplier only.

According to the research above, the charging mechanism design of the production capacity sharing platform is still in its early stages. In addition, comparative studies on three charging modes in terms of different charging objectives and the research with comprehensive consideration of the charging modes, access requirements, and commission rates in different stages of the platform’s development are still limited. The differences between our work and the stated papers are that three charging modes according to different charging objects are compared in the platform’s different stages of development from the perspective of sustainable operations. Besides, the scenario of our paper is combined with the characteristics of the production capacity sharing process in the field of manufacturing. For example, the capacity supplier must consider capacity management costs to meet the access requirements of the platform for sharing surplus production capacity.
also discusses how to balance between the level of commission rates and access requirements of the platform to achieve sustainable operations.

3. Problem Statement and Formulation

3.1. Problem Description

This paper considered a supply chain composed of a single manufacturer ($M$), a production capacity sharing platform ($P$), a surplus production capacity supplier ($S$) linked to the platform, and a traditional supplier ($T$). The capacity supplier and the platform form the sharing channel ($SC$). The traditional channel ($TC$) is a traditional supplier. Suppliers produce a kind of core components with unit production cost $c_i$ and sell them to the manufacturer at unit wholesale price $w_i, i = (s,t)$. The manufacturer uses the components to produce product $i$ and then sells the product $i$ to sustainably conscious consumers ($V$) at price $p_i, i = (s,t)$. The profits of the participants are denoted as $\pi$.

The platform charges a commission with three charging modes based on different charging objects [10,23], which is indicated by $j$ where $j = 1, 2, 3$ denotes only charging the capacity supplier, only charging the manufacturer, and charging both the capacity supplier and the manufacturer, respectively. The platform charges the capacity supplier with commission rate $a$ and charges the manufacturer with commission rate $b$. When $j = 1$, $0 < a < 1$ and $b = 0$ are defined. When $j = 2$, $0 < b < 1$ and $a = 0$ are defined. When $j = 3$, $0 < a < 1$, $0 < b < 1$, and $0 < a + b < 1$ are defined. $a$ and $b$ are independent in each of the three charging modes. The platform has requirements for the capacity supplier to access to trading on the platform. For example, the Predix platform (https://www.ge.com/digital/iiot-platform) validates capacity supplier to reduce operational variability, risk, and rework. The access requirements cause the capacity supplier to undertake surplus production capacity management costs (denoted by “capacity management costs”) including the costs of production scheduling, controlling synchronization equipment, and certification to ensure the authenticity of information and the stability of production capacity supply, etc. Similar to access costs, some sharing platforms [21,54], the capacity supplier needs to undertake the capacity management cost $m$, where $m \in (0, 1)$, to meet the access requirements of the platform.

Consumer reservation price $\nu$ is modeled as uniformly distributed on the unit interval $[0, 1]$ within the consumer population from 0 to 1 with the density of 1, which captures the individual difference in product valuation [55]. The quantity of components required per unit of product is 1 and that the manufacturer’s sourcing strategy is optimal, which means that the quantity of components sourced for product $i$ (denoted as $q_i$) is equal to consumer demand for product $i$ [16]. The market share of the product is denoted as $\xi$. The total market demand is denoted as $Q$. The machining cost of the manufacturer and the basic operating cost of the platform are zero [22,23,56].

The manufacturer uses the same production process and time to produce the products after receiving the components from two channels. Products produced via sharing channel have superior performance with respect to sustainability than products from the traditional channel because the products from the sharing channel are produced from surplus production capacity and the quality and delivery time are supervised through the platform, as described in Section 1. Intuitively, an individual consumer has a higher reservation price for the product with the superior performance [57,58], so that a sustainably conscious consumer has a higher reservation price for the product with superior sustainability performance. The term “consumer acceptance” of the channel is adopted. Sustainably conscious consumers perceive product $s$ is perfect, which means that consumer acceptance of the sharing channel is 1 [58]. A parameter $\delta$, where $\delta \in [0, 1]$, is used to denote consumer acceptance of the traditional channel (denoted as consumer acceptance of $TC$). When the consumer’s level of sensitivity to sustainability (or the product’s characteristics of sustainability) increases, or the influence of services provided by the platform on the product’s characteristics of sustainability increases, $\delta$ decreases.
Figure 2 shows the model framework. The power of the manufacturer is weaker than the suppliers because the manufacturer is constrained by production capacity and eager to obtain the components to meet market demand. The suppliers decide the wholesale price for the components, and then the manufacturer determines the selling prices for the products, which is also compliance with actual production capacity sharing operations.

3.2. Notation

Table 1 summarizes the notations used in this paper.

| Notation | Description |
|----------|-------------|
| M        | Manufacturer |
| S        | Surplus production capacity supplier |
| T        | Traditional supplier |
| SC       | Sharing channel |
| TC       | Traditional channel |
| V        | Sustainably conscious consumer |
| P        | Production capacity sharing platform |
| SN       | Sharing-channel only strategy |
| TN       | Traditional-channel only strategy |
| DS       | Dual-channel strategy |
| CS       | Consumer surplus |
| SW       | Social welfare |
| i        | The index of the product, $i = (s,t)$ |
| j        | The index of three charging modes of the production capacity sharing platform, $j = (1,2,3)$ |
| c        | Unit production cost of the core component |
| w        | Unit wholesale price of the core component |
| p        | Unit price of the product |
| q        | Demand for the product |
| π        | Profit of the participant |
| a        | Commission rate charged by the platform to the surplus production capacity supplier |
| b        | Commission rate charged by the platform to the manufacturer |
| m        | Unit surplus production capacity management cost |
| v        | Reservation price of the sustainably conscious consumer for the product |
| δ        | Consumer acceptance of traditional channel |
| ξ        | Market share of the product |
| Q        | Total market demand of the product |
3.3. Channel Selection of the Manufacturer and the Profit Functions for Each Player

$v, \delta,$ and $p_i$ are used to analyze the difference in the individual surplus: a sustainably conscious consumer chooses product $s$ when $v - p_s \geq \delta v - p_i$ and chooses product $t$ when $\delta v - p_i > v - p_s$ with nonnegative $v - p_s$ and $\delta v - p_i$. Three channel selection strategies of the manufacturer including sharing-channel only strategy (SN), traditional-channel only strategy (TN), and dual-channel strategy (DS) can be obtained according to the piecewise demand function of product $i$, which is shown as follows.

\[
q_s = \begin{cases} 
1 - \frac{p_s - p_t}{1 - \delta}, & \text{Channel Selection = DS} \iff \frac{p_t}{p_s} < \delta < 1 - p_s + p_t; \\
1 - p_s, & \text{Channel Selection = SN} \iff 0 \leq \delta \leq \frac{p_t}{p_s}; \\
0, & \text{Channel Selection = TN} \iff 1 - p_s + p_t \leq \delta < 1.
\end{cases}
\]

\[
q_t = \begin{cases} 
\frac{p_t - p_s}{1 - \delta} - \frac{p_t}{p_s}, & \text{Channel Selection = DS} \iff \frac{p_s}{p_t} < \delta < 1 - p_s + p_t; \\
0, & \text{Channel Selection = SN} \iff 0 \leq \delta \leq \frac{p_t}{p_s}; \\
1 - \frac{p_t}{p_s}, & \text{Channel Selection = TN} \iff 1 - p_s + p_t \leq \delta < 1.
\end{cases}
\]

Combining with channel selection strategies of the manufacturer, Table 2 shows the profit functions for each stakeholder based on three charging modes of the platform. Combining three charging modes of the platform and three channel selection strategies of the manufacturer, there are nine scenarios including $DS_j$, $SN_j$, and $TN_j$ where $j = 1, 2, 3$.

| $j=1$ | $j=2$ | $j=3$ |
|-------|-------|-------|
| $\pi_M = (p_s - w_s)q_s + (p_t - w_t)q_t$ | $\pi_M = (p_s - (1 + b)w_s)q_s + (p_t - w_t)q_t$ | $\pi_M = (p_s - (1 + b)w_s)q_s + (p_t - w_t)q_t$ |
| $\pi_S = (1 - a)w_s - c_s - m)q_s$ | $\pi_S = (w_s - c_s - m)q_s$ | $\pi_S = (1 - a)w_s - c_s - m)q_s$ |
| $\pi_P = aw_sq_s$ | $\pi_P = bw_sq_s$ | $\pi_P = (a + b)w_sq_s$ |
| $\pi_T = (w_t - c_t)q_t$ | $\pi_T = (w_t - c_t)q_t$ | $\pi_T = (w_t - c_t)q_t$ |

$c_s$ and $c_t$ are not defined to obtain generalized equilibrium solutions for nine scenarios. For simplicity, $c_s$ and $c_t$ is considered to be zero to further study the effects of consumer acceptance of TC, capacity management cost, commission rates, and charging modes on the interaction among the stakeholders in Corollary 1, 2, and 3 and Theorem 5, 6, 7, and 8 [59,60].

4. Pricing Analysis under Three Channel Selection Strategies from the Perspective of Sustainable Operations

In this section, the Stackelberg game model was built based on three channel selection strategies of the manufacturer under three charging modes of the platform. According to the sequence of the events that were described in Section 3 and using the backward induction (see Appendix A for details), the manufacturer’s equilibrium solutions could be obtained, and then the suppliers’ equilibrium solutions. In addition, the impacts of the capacity management cost, as well as consumer acceptance of TC, on the equilibrium solutions from the perspective of sustainable operations were also examined.

4.1. Dual-Channel Strategy (DS)

Combined with Equations (1), (2), and Table 1, specific model for $DS_j$ are as follows. The models for $SN_j$ and $TN_j$ can be obtained in the similar way.

\[
\pi_M(p_s, p_t) = \begin{cases} 
(p_s - w_s) \left(1 - \frac{p_t - p_s}{1 - \delta}\right) + (p_t - w_t) \left(\frac{p_t - p_s}{1 - \delta} - \frac{p_t}{p_s}\right), & j = 1; \\
(p_s - (1 + b)w_s) \left(1 - \frac{p_t - p_s}{1 - \delta}\right) + (p_t - w_t) \left(\frac{p_s - p_t}{1 - \delta} - \frac{p_t}{p_s}\right), & j = 2; \\
(p_s - (1 + b)w_s) \left(1 - \frac{p_t - p_s}{1 - \delta}\right) + (p_t - w_t) \left(\frac{p_s - p_t}{1 - \delta} - \frac{p_t}{p_s}\right), & j = 3.
\end{cases}
\]
Theorem 1. Under DSj scenarios, the strategies of two suppliers (S and T) and the manufacturer are given as follows. (summarized in Table 3).

Based on Table 3, the strategies of each player under DSj scenarios can be obtained in Theorem 1.

Table 3. Strategies of each player under DSj scenarios.

| Case | DS1 | DS2 | DS3 |
|------|-----|-----|-----|
| w_s  | 2 - 6a/(-a+c) 2m | 2(1+b)c_t + c_s + 2m | 2(1+b)c_t + c_s + 2m + 2m(-2c_s - 2c_t - 2d) |
| w_f  | (1+a)(4-b) 2m | (1+b)(4-b) | (1+a)(4-b) 2m |
| p_s  | 3 - 6a/(-a+c) 2m | 6(1+b)c_t + c_s + 2m | 6(1+b)c_t + c_s + 2m + (6c_s - 3c_t - 2d) |
| p_f  | 2(1-a)c_t + 6(5c_s + c_t + 2m - 21-a) | 2(1-a)(1-b) | 2(1-a)(1-b) |
| q_s  | (2a + m)(-a - 2c_t + 2m + 2m - 1 - a) 2m | (c_t - 2c_t - 2d) | (c_t - 2c_t - 2d) + 2(1 - m - b) |
| q_f  | (1+a)(4-b)(1-b) | (1+c_t - b_c + m - b_m - 1 - a)(2 - b) | (1+c_t - b_c + m - b_m - 1 - a)(2 - b) |

The proof of Theorem 1 appears in Appendix A.

Based on Theorem 1, the profits of each participant can be obtained as follows. For simplicity, \( A = 1 - a, B = 1 + b, \) and \( C = c_s + m \) are defined.

When the platform charges the capacity supplier, the profit of each participant under the DS1 scenario is as follows.

\[
\pi_{DS1} = \frac{A^2(4 - 3c_t)}{4(4 - d)^2(1 - b)}, \quad \pi_{DS1}^* = \frac{A^2(4 - 3c_t)}{4(4 - d)^2(1 - b)}, \quad \pi_{DS1}^{**} = \frac{A^2(4 - d)(1 - b)}{4(4 - d)^2(1 - b)}, \quad \pi_{DS1}^{***} = \frac{A^2(4 - 3c_t)}{4(4 - d)^2(1 - b)}.
\]

When the platform charges the manufacturer, the profit of each participant under the DS2 scenario is as follows.

\[
\pi_{DS2} = \frac{c_t(4 - 3c_t - 2c_t(4 - 4BC) - 4(1 - BC)^2 + (1 + 1 + 2d)(5 - 2BC)C)^2}{4(4 - d)^2(1 - b)}, \quad \pi_{DS2}^* = \frac{c_t(4 - 3c_t)}{4(4 - d)^2(1 - b)}, \quad \pi_{DS2}^{**} = \frac{c_t(4 - 3c_t)}{4(4 - d)^2(1 - b)}, \quad \pi_{DS2}^{***} = \frac{c_t(4 - 3c_t)}{2(4 - d)^2(1 - b)}.
\]
When the platform charges the both sides, the profit of each participant under the DS3 scenario is as follows.

\[
\begin{align*}
\pi_{DS'}^3 &= \frac{\alpha^2(4-3\delta-2c(4A(1-\delta)+BC))}{4A^2(1-\delta)(\delta)} + \frac{4(A-BC)^2 + (A^2 + 6C(1-6\delta)-3C(2B(1-A)+BC)A^2-(A-2BC)\delta^2)}{4A^2(1-\delta)}, \\
\pi_{DS'}^2 &= \frac{(2+c_2(2+c_2-2BC(1-\delta)-2BC(1-\delta))^2)}{2A^2(1-\delta)^2(1-\delta)}, \\
\pi_{DS'}^1 &= \frac{(A_2(2-\delta)-b(BC-w(1-\delta))^2)}{2A^2(1-\delta)^2(1-\delta)}, \\
\pi_{PS} &= \frac{(a+b)^2(2A+2BC+B(1-\delta)+2c(A_2-2aBC-BC(1-2\delta))}{2A^2B(1-\delta)^2(1-\delta)}.
\end{align*}
\]

(9)

To obtain channel selection strategies of the manufacturer, \( \delta^3 = p_t^{DS^3} / p_s^{DS^3} \) and \( \delta^3 = 1 - p_s^{DS^3} + p_t^{DS^3} \) are defined. The generalized thresholds of consumer acceptance of TC for the manufacturer to make channel selection decisions can be obtained according to Theorem 1. Solving for the specific results based on the different relationship between \( c_s \) and \( c_t \) is complex and analytically challenging. The manufacturer uses the components sourced from two channels to produce the same products. To highlight the production capacity sharing related parameters, the production costs of two suppliers are assumed to be equal without the consideration of complicated factors such as capacity scheduling and staff coordination in actual operations and then Theorem 2 can be obtained. For simplicity, \( A = 1 - a, B = 1 + b, \) and \( C = c_s + m \) are defined.

**Theorem 2.** The manufacturer chooses SN when \( 0 \leq \delta < \delta^3 \). The manufacturer chooses TN when \( \delta^3 \leq \delta < 1 \). The manufacturer chooses DS when \( \delta^1 < \delta < \delta^2 \). \( \delta^3 \) and \( \delta^3 \) under three charging modes of the platform are as follows.

\[
\begin{align*}
\delta^1 &= \frac{1}{2} \left( 1 + c + \frac{C}{A} - \sqrt{1 + 2C - 6c_2 + 2(1-6c_2)c_2 + (C+c_2)^2 - 2a(1+C+c_2-c_2(6-c_2))} \right), \\
\delta^2 &= \frac{1}{2} \left( 1 + c + BC - \sqrt{1 - 6c_1 + 2BC + (BC+c_2)^2} \right), \\
\delta^3 &= \frac{1}{2} \left( 1 + c + BC - \sqrt{1 + 2C - 6c_1 + 2(1-6c_1)c_1 + (C+c_2)^2 + 2BC(1+C+c_2) - 2a(1+C+c_2-c_2(6-c_2))} \right).
\end{align*}
\]

(10)

\[
\begin{align*}
\delta^1 &= \frac{2A-2C+A_2}{2A-C}, \\
\delta^2 &= \frac{2-2BC+c_2}{2-BC}, \\
\delta^3 &= \frac{2A-2BC+A_2}{2A-2BC}.
\end{align*}
\]

(11)

The proof of Theorem 2 appears in Appendix A.

According to Theorem 2, \( \delta^3 \) and \( \delta^3 \) depend on \( a, b, c_s, c_t, \) and \( m \). The platform provides information on commission rates and charging modes. The production costs of suppliers and capacity management costs, which reflects the platform’s access requirements for the capacity supplier can be estimated based on the business report of suppliers, the communication during the transactions, the professional knowledge of the manufacturer, etc. This Theorem provides a reference for the manufacturer to make channel selection decisions to achieve profitability and sustainable operational goals and meet the needs of sustainably conscious consumers.

**Corollary 1.** \( p_s^{DS^3} > p_t^{DS^3} \) and \( w_t^{DS^3} > w_t^{DS^3} \).

Corollary 1 shows that the price of product \( s \) is higher than the price of product \( t \) and that the wholesale price, as determined by the capacity supplier, is higher than that determined by the traditional supplier since the sustainability characteristics of the products enable sustainably conscious consumers to have higher reservation prices for product \( s \) than that for product \( t \).
Corollary 2. The sensitivities of strategies to parameter $m$ under $DS_j$ scenarios are as follows:

1. $\frac{\partial q^{DS_j}_i}{\partial m} > 0$, $\frac{\partial p^{DS_j}_i}{\partial m} > 0$, $\frac{\partial q^{DS_j}_j}{\partial m} > 0$, $\frac{\partial p^{DS_j}_j}{\partial m} > 0$, $\frac{\partial \delta^{DS_j}_i}{\partial m} < 0$, $\frac{\partial \delta^{DS_j}_j}{\partial m} < 0$, and $\frac{\partial \pi^{DS_j}}{\partial m} < 0$.

2. $\frac{\partial w^{DS_j}_s}{\partial m} < 0$, $\frac{\partial \delta^{DS_j}_i}{\partial m} < 0$, $\frac{\partial \delta^{DS_j}_j}{\partial m} > 0$ when $0 < m < m^{E_j}$ and $\frac{\partial \pi^{DS_j}}{\partial p} < 0$ when $m^{E_j} < m < \bar{m}^j$.

The values of $m^{E_j}$ appear in Appendix B.

$\bar{m}^j$ denotes the upper thresholds of capacity management costs. The capacity supplier will not join in the sharing when the capacity management cost is above $\bar{m}^j$. Theorem 5 explores $\bar{m}^j$ in detail. According to Corollary 2, the wholesale price of components and the price of products are positively related to capacity management costs. A higher price for product $s$ makes some sustainably conscious consumers who originally choose product $s$ switch to product $t$ or leave the market, which leads to a reduction in profit of the capacity supplier. Meanwhile, demand for product $t$ is rising in $m$ as the profit of the traditional supplier, which means that the traditional supplier benefits from an increase in the capacity management costs. The profit of the platform is affected by both $w^{DS_j}_s$ and $q^{DS_j}_s$.

Intuitively, the capacity management costs of the capacity supplier are positively correlated with the level of platform’s access requirements. From a sustainable perspective, the platform will reap the optimal profits and both sides of the platform can have profitable space by joining the platform when the platform’s access requirements cause the capacity supplier to undertake the capacity management costs with $m^{E_j}$. If the platform set higher access requirements and the capacity supplier undertake capacity management costs over $m^{E_j}$, there will be a decrease in the profit of the platform and fewer sustainably conscious consumers to choose product $s$, which is not conducive to the sustainability of $sc$ and the entire system.

Corollary 3. The sensitivities of strategies to parameter $\delta$ under $DS_j$ scenarios are as follows:

1. $\frac{\partial \delta^{DS_j}_s}{\partial \delta} < 0$, $\frac{\partial \delta^{DS_j}_i}{\partial \delta} < 0$, $\frac{\partial \delta^{DS_j}_j}{\partial \delta} > 0$. $\frac{\partial \delta^{DS_j}_s}{\partial \delta} > 0$ when $\{1\} 0 < \delta \leq 4 - 2 \sqrt{3}$ or $\{2\} 4 - 2 \sqrt{3} < \delta < 3 - \sqrt{5}$ and $m^{E_j} < m < \bar{m}^j$. $\frac{\partial \delta^{DS_j}_s}{\partial \delta} < 0$ when $\{1\} 3 - \sqrt{5} < \delta < \bar{m}^j$ or $\{2\} 4 - 2 \sqrt{3} < \delta < 3 - \sqrt{5}$ and $0 < m < m^{E_j}$.

2. $\frac{\partial \delta^{DS_j}_s}{\partial \delta} > 0$, $\frac{\partial \delta^{DS_j}_i}{\partial \delta} > 0$, $\frac{\partial \delta^{DS_j}_j}{\partial \delta} > 0$. $\frac{\partial \delta^{DS_j}_s}{\partial \delta} > 0$ when $0 < m < m^{G_j}$ and $\frac{\partial \delta^{DS_j}_s}{\partial \delta} < 0$ when $m^{G_j} < m < \bar{m}^j$.

3. $\frac{\partial \delta^{DS_j}_s}{\partial \delta} < 0$, $\frac{\partial \delta^{DS_j}_i}{\partial \delta} < 0$, $\frac{\partial \delta^{DS_j}_j}{\partial \delta} > 0$. $\frac{\partial \delta^{DS_j}_s}{\partial \delta} > 0$ when $\{1\} 0 < \delta \leq \frac{3}{4}$ or $\{2\} \frac{3}{4} < \delta < \bar{m}^j$ and $m^{H_j} < m < \bar{m}^j$.

The values of $m^{E_j}$, $m^{G_j}$, and $m^{H_j}$ appear in Appendix B.

$w^{DS_j}_s$ and $p^{DS_j}_s$, as well as the profit of the capacity supplier will be high when the consumers are sensitive to product’s characteristic of sustainability. Conversely, the more consumers are careless about sustainability characteristics of products, the more upside space is provided to $p^{DS_j}_t$. $w^{DS_j}_i$ and the profit of the traditional supplier are not always increasing in $\delta$. As $\delta$ increases, the capacity supplier continues to reduce $w^{DS_j}_s$. The traditional supplier raises its wholesale price as $\delta$ increases until it reaches a certain level because $w^{DS_j}_i > w^{DS_j}_j$ is always established according to Corollary 1. Similarly, the demand for product $s$ is not always decreasing in $\delta$. Low capacity management costs give the capacity supplier space to reduce the wholesale price and indirectly encourage the manufacturer to reduce the price of product $s$, which causes the manufacturer to obtain more demand for product $s$. The manufacturer will increase the proportion of product $t$ and decrease the proportion of product $s$ as $\delta$ increases.

Overall, the manufacturer can encourage the traditional supplier to manage delivery time and quality for improving performance of product sustainability characteristics and reducing the difference between consumer acceptances of the two channels. In addition, the platform should enhance the
services to make the sustainability characteristics of the products more prominent. Such benign mutual incentive promotes the sustainable development of the entire supply chain.

4.2. Sharing-Channel Only Strategy (SN)

The manufacturer adopts SN when $0 \leq \delta \leq \delta^1$. Whether the traditional supplier joins the game affects the decision making of the supply chain members. When $\delta = \delta^1$, the traditional supplier is involved in decision making even if $q_t = 0$. When $0 \leq \delta < \delta^1$, only the capacity supplier and the manufacturer make decisions. The strategies of participants under $SNj$ scenarios can be obtained in Theorem 3.

**Theorem 3.** Under $SNj$ scenarios, the strategies of two suppliers ($S$ and $T$) and the manufacturer and the profit of each participant are given as follows (summarized in Tables 4 and 5).

| Case | $\delta = \delta^1$ (SN1) | $\delta = \delta^2$ (SN2) | $\delta = \delta^3$ (SN3) |
|------|--------------------------|--------------------------|--------------------------|
| $w^S_{SNj}$ | $\frac{1 - a + \gamma + m + c - a}{2}$ | $\frac{1}{1 + b} \frac{1 - a + c + \gamma + m + b}{1 + b}$ | $\frac{1}{1 + b} \frac{1 - a + b + c + m + b}{1 + b}$ |
| $\delta^S_{SNj}$ | $\frac{3 - a - c - \gamma - m - 2b}{2}$ | $\frac{3 - a - c + b}{1 + b}$ | $\frac{3 - a - c + b}{1 + b}$ |
| $p^S_{SNj}$ | $\frac{1}{1 + b} \frac{1 - a + c + \gamma + m + b}{1 + b}$ | $\frac{1}{1 + b} \frac{1 - a + c + \gamma + m + b}{1 + b}$ | $\frac{1}{1 + b} \frac{1 - a + c + \gamma + m + b}{1 + b}$ |
| $\pi^S_{SNj}$ | $\frac{1}{1 + b} \frac{1 - a + c + \gamma + m + b}{1 + b}$ | $\frac{1}{1 + b} \frac{1 - a + c + \gamma + m + b}{1 + b}$ | $\frac{1}{1 + b} \frac{1 - a + c + \gamma + m + b}{1 + b}$ |
| $\pi^T_{SNj}$ | $\frac{1}{1 + b} \frac{1 - a + c + \gamma + m + b}{1 + b}$ | $\frac{1}{1 + b} \frac{1 - a + c + \gamma + m + b}{1 + b}$ | $\frac{1}{1 + b} \frac{1 - a + c + \gamma + m + b}{1 + b}$ |

| Case | $0 \leq \delta < \delta^1$ (SN1) | $0 \leq \delta < \delta^2$ (SN2) | $0 \leq \delta < \delta^3$ (SN3) |
|------|--------------------------|--------------------------|--------------------------|
| $w^S_{SNj}$ | $\frac{1 - a + c + \gamma + m + b}{1 + b}$ | $\frac{1 - a + c + \gamma + m + b}{1 + b}$ | $\frac{1 - a + c + \gamma + m + b}{1 + b}$ |
| $\delta^S_{SNj}$ | $\frac{3 - a - c - \gamma - m - 2b}{2}$ | $\frac{3 - a - c + b}{1 + b}$ | $\frac{3 - a - c + b}{1 + b}$ |
| $p^S_{SNj}$ | $\frac{1}{1 + b} \frac{1 - a + c + \gamma + m + b}{1 + b}$ | $\frac{1}{1 + b} \frac{1 - a + c + \gamma + m + b}{1 + b}$ | $\frac{1}{1 + b} \frac{1 - a + c + \gamma + m + b}{1 + b}$ |
| $\pi^S_{SNj}$ | $\frac{1}{1 + b} \frac{1 - a + c + \gamma + m + b}{1 + b}$ | $\frac{1}{1 + b} \frac{1 - a + c + \gamma + m + b}{1 + b}$ | $\frac{1}{1 + b} \frac{1 - a + c + \gamma + m + b}{1 + b}$ |
| $\pi^T_{SNj}$ | $\frac{1}{1 + b} \frac{1 - a + c + \gamma + m + b}{1 + b}$ | $\frac{1}{1 + b} \frac{1 - a + c + \gamma + m + b}{1 + b}$ | $\frac{1}{1 + b} \frac{1 - a + c + \gamma + m + b}{1 + b}$ |

The proof of Theorem 3 appears in Appendix A.

The manufacturer only chooses SC if consumers highly value the sustainability characteristics of the products. Generalized equilibrium solutions can be obtained based on Theorem 3. Then, the production costs of two suppliers are assumed to be zero [59,60]. $w^S_{SNj}$ and $p^S_{SNj}$ are increasing in $m$. $d_S$, $\delta^S_{SNj}$, $\pi^S_{SNj}$, $\pi^S_{SNj}$, and $\pi^T_{SNj}$ are decreasing in $m$. For the sustainability of SC, the platform should set appropriate access requirements and give the capacity supplier pricing space, which will indirectly inspire the manufacturer and sustainably conscious consumers in $SNj$ scenarios.

4.3. Traditional-Channel Only Strategy (TN)

The manufacturer adopts TN when $\delta^1 \leq \delta < 1$. Whether the capacity supplier joins the game also affects the decision making of the supply chain members. When $\delta = \delta^1$, the capacity supplier is
involved in decision making even if \( q_s = 0 \). When \( 0 \leq \delta < \delta^* \), there is a two-player game between the traditional supplier and the manufacturer.

**Theorem 4.** Under TN\( j \) scenarios, the strategies of two suppliers (S and T) and manufacturer and the profit of each participant are given as follows.

\[
\begin{align*}
\text{(1)} & \quad \text{When } \delta = \frac{7j}{\delta} , w^T_{s1} = \frac{2c_j - 25j}{2 - \delta^*} , w^T_{s2} = \frac{2c_j - 25j}{(1 + b)(2 - \delta^*)} , w^T_{s3} = \frac{2c_j - 25j}{1 + b(2 - \delta^*)} , w^T_{t} = \frac{c_j + 25j - \delta^*}{2 - \delta^*}, \\
& \quad p^T_{s} = \frac{4 + c_j - 35j}{4 - 2\delta^*}, P^T_{T} = \frac{c_j + (3 - 25j)}{2 - \delta^*}, \eta^T_{T} = \frac{7j - c_j}{25j(2 - \delta)}, \eta^T_{M} = \frac{(7j - c_j)^2}{45j^2(2 - \delta^*)}, \text{ and } \pi^T_{T} = \frac{(7j - c_j)^2}{25j(2 - \delta^*)}.
\end{align*}
\]

(2) When \( \delta < \delta < 1 \), \( w^T_{s1} = \frac{c_j + \delta}{2}, w^T_{s2} = \frac{c_j + 3\delta}{4}, w^T_{s3} = \frac{\delta - c_j}{45}, \eta^T_{M} = \frac{(\delta - c_j)^2}{165}, \text{ and } \pi^T_{T} = \frac{(\delta - c_j)^2}{80}.
\]

The proof of Theorem 4 appears in Appendix A.

Small differences between consumer acceptance of TC and SC means that consumers are not sensitive to the sustainability characteristics of products that much, and that SC is eliminated from the market. According to Theorem 4, the traditional supplier and the manufacturer will set high prices if consumer acceptance of TC is high under TN\( j \) scenarios. The platform needs to improve its services and spread the significance of sustainable production in order to attract sustainably conscious consumers, increase the market share of the product \( s \), and promote the sustainability of the system.

5. Interaction Analysis Regarding Production Capacity Sharing for Sustainable Operations

In this section, the influence of production capacity sharing on supply chain members was investigated from a sustainable operations perspective, including the conditions for capacity supplier to join in the sharing under three charging modes of the platform, how the platform balances between the profitability and attracting participation considering the relationship between access requirements and commission rates and the relationship between charging modes and access requirements in different stages of the development, and how the charging modes of the platform influence consumer surplus and social welfare.

**Theorem 5.** The conditions for a capacity supplier to join in production capacity sharing are as follows:

\[
0 < m \leq \frac{2 - 2b + 2b^2}{2^n} \text{ for } j = 1, 0 < m \leq \frac{2 - 2b}{2 + 2b - 2 - \delta^*} \text{ for } j = 2, \text{ and } 0 < m \leq \frac{2 - 2b + 2b^2}{2 + 2b - 2 - \delta^*} \text{ for } j = 3.
\]

The proof of Theorem 5 appears in Appendix A.

Theorem 5 shows that the manufacturer will choose TC if the capacity management cost is high. Furthermore, the conditions also reflect the relationship among consumer acceptance of TC, the commission rates of the platform, and the capacity management costs of the capacity supplier. An excessive commission rate or high consumer acceptance of TC can lead to a decline in the thresholds of capacity management costs above which the capacity supplier will not choose to share surplus production capacity. Thus, the results provide recommendations for the platform to balance the relationship between access requirements and commission rates so as not to be eliminated from a given market with sustainably conscious consumers. \( \bar{m}^j \) denotes the upper thresholds of capacity management costs in Theorem 5.

In actual operations, the commission rate set by sharing platforms typically ranges from 10 to 30 percent. For example, commission rate on the Airbnb platform is 6 to 12 percent [21]. Uber charges 20 to 30 percent commission [61]. Lyft charges 25 percent on its platform [62]. Theorem 6 provides useful references for platform operators to set the level of commission rates and maintain a sustainable development.
Theorem 6. The sensitivities of strategies to commission rate for $0 \leq \delta < \delta^0$ are as follows:

1. $\frac{\partial \pi^{DS_i}}{\partial \delta} > 0$, $\frac{\partial \pi^{SN_i}}{\partial \delta} > 0$; $\frac{\partial \pi^{DS_i}}{\partial \delta} < 0$, $\frac{\partial \pi^{SN_i}}{\partial \delta} < 0$; $\frac{\partial \pi^{DS_i}}{\partial \delta} > 0$, $\frac{\partial \pi^{SN_i}}{\partial \delta} > 0$; $\frac{\partial \pi^{DS_i}}{\partial \delta} < 0$, $\frac{\partial \pi^{SN_i}}{\partial \delta} < 0$. $p^{DS_i}$ and $p^{SN_i}$ are positively related to commission rate $a$ or $b$. $q^{DS_i}$ and $q^{SN_i}$ are negatively related to commission rate $a$ or $b$.

2. $\tau^{DS_i}_M$, $\tau^{DS_i}_S$, $\tau^{SN_i}_M$, and $\tau^{SN_i}_S$ are negatively related to commission rate $a$ or $b$. $\tau^{SN_i}_T$ is positively related to the commission rate $a$ or $b$.

3. $\pi^{DS_i}_p$ is positively related to the commission rate $a$ or $b$ for $0 < m < m^{l_i}$ and negatively related to commission rate $a$ or $b$ for $m^{l_i} < m < m^i$. $\pi^{SN_i}_p$ is positively related to commission rate $a$ or $b$ for $0 < m < m^{l_i}$ and negatively related to commission rate $a$ or $b$ for $m^{l_i} < m < m^i$.

The proof of Theorem 6 appears in Appendix A. The values of $m^{l_i}$ and $m^{l_i}$ appear in Appendix B.

For Theorem 6, high commission rates result in a high price for product $s$, which removes the surplus of sustainably conscious consumers and decreases consumer demand for product $s$. Low capacity management costs provide space for the platform to increase commission rates to gain more profits. Conversely, an increase in commission rates can lead to a decline in the profit of the platform if the level of capacity management costs is high.

Only the platform and the traditional supplier can benefit from an increase in commission rates, which means that both sides of the platform have more incentive to find other platforms with lower commission rates for production capacity sharing. The results still hold when the traditional supplier is not involved in decision making. To maintain sustainable operations, the platform should not make transaction costs higher than the transaction value created by the platform services. Therefore, the platform needs to provide its participants with profitable space, which is conducive to attracting participation and increasing the market share of products from SC [23].

Theorems 7 investigates the impacts of the platform’s charging modes on the decision making of supply chain members in a given market. The total commission rate is denoted as $k$, where $0 < k < 1$. $a$ and $b$ are denoted as $a$ and $b$ when $j = 3$. Then, $a + b = a = b$ can be obtained. Since $0 < \delta < \delta^0$, the results in Theorem 7 are given when the manufacturer chooses $DS$ or $SN$ for $0 \leq \delta < \delta^1$. $X$ and $Y$ are defined as the indexes for $w$, $p$, $q$, $\xi$, and $\pi$.

Theorem 7. The optimal wholesale prices of the components, prices of the products, quantities, market share of the products, and the profit of each stakeholder under three platform’s charging modes in different orders for $0 < \delta < \delta^1$ are as follows.

1. $X^{1*} > X^{3*} > X^{2*}$ where $X \in \{w^{DS}_i, p^{DS}_i, q^{DS}_i, \tau^{DS}_M, \tau^{DS}_S, \tau^{SN}_M, \tau^{SN}_S\}$ and $Y^{2*} > Y^{3*} > Y^{1*}$ where $Y \in \{q^{DS}_M, \tau^{DS}_M, \tau^{DS}_S, \tau^{SN}_M, \tau^{SN}_S\}$.

2. As $m$ increases, the platform’s choice of charging mode for optimal profits exhibits a general trend of $j = 1 \rightarrow j = 3 \rightarrow j = 2$.

The proof of Theorem 7 appears in Appendix A.

The results show that the platform prefers to charge the manufacturer if the platform wants to increase the market share of products from SC. Specifically, the expense of the capacity supplier for commissions will be converted into the wholesale price of the capacity supplier. The traditional supplier has a similar pricing trend as the capacity supplier under three platform charging modes. The manufacturer follows suppliers when pricing product $s$ and $t$. The demand for product $t$ increases even if the price of product $s$ increases because sustainably conscious consumers who originally prefer product $s$ switch to product $t$ when the price of product $s$ increases.

From the perspective of sustainable operations, a low level of $m$ means the capacity supplier can trade on the platform with relatively low access requirements, which increases transaction risks.
The platform needs to rectify the supplier market to protect the rights of the manufacturer and its own reputation, thus choosing to charge the capacity supplier, which means to improve access requirements. From a macro perspective, charging the capacity supplier means eliminating the inferior capacity suppliers. The platform charges bilaterally when \( m \) is moderate, which reduces the cost pressure for the capacity suppliers so that they are not forced to leave the platform. A high level of \( m \) means a reliable supplier market based on which the platform charges the demand side. When consumer acceptance of \( TC \) is absolutely high in the range of \( 0 \leq \delta < \delta^1 \), charging the capacity supplier is always the best choice to get optimal profits for the platform. Since there is no space for the platform to increase the access requirements according to Theorem 5. The results hold when the traditional supplier is not involved in decision making. Similar results that have practical implications for sustainable operations of platforms have been confirmed by practices of many sharing platforms [23].

Since \( \delta^1 < \delta^3 < \delta^2 \), Table 6 summarizes the impacts of platform’s charging modes on the decision making of supply chain members for \( \delta^1 \leq \delta < 1 \).

| Case         | \( \delta^1 \) | \( \delta^3 \) | \( \delta^2 \) | \( \delta < 1 \) |
|--------------|-----------------|-----------------|-----------------|-----------------|
| \( \delta^1 \) | TN1             | DS2             | DS3             |                 |
| \( \delta^3 \) | TN1             | DS2             | TN3             |                 |
| \( \delta^2 \) | TN1             | TN2             | TN3             |                 |

Table 6. Scenarios of equilibrium solutions under three charging modes for \( \delta^1 \leq \delta < 1 \).

Consumer surplus refers to the difference between the final price and a consumer’s reservation price for a certain quantity of products [63,64]. In this paper, the consumer surplus, which is defined as \( CS \), is given by:

\[
CS = \int_{1-q_{s}}^{1-q_{t}} (\delta v - p_{1})dv + \int_{1-q_{t}}^{1} (v - p_{s})dv. \tag{12}
\]

Thus, the consumer surplus under three charging modes of the platform are given as follows.

\[
\begin{align*}
CS_1 &= \frac{4(1-a-m)^2 + (1-a)^2 + 6(1-a)m^2 - 3m^2 - (1-a)(5-5a-2m)^2}{8(1-a)^2(4-\delta)^2(1-\delta)}, \\
CS_2 &= \frac{(1+b)^2m^2(4-\delta) - 2(1+b)m(1-b)(4+b) + (1+b)(4+b)}{8(4-b)^2(1-b)}, \tag{13} \\
CS_3 &= \frac{4(1-a-m)^2 + (1-a)^2 + 6(1-a)(1+b)m - 3(1+b)m^2 - (1-a)(5-5a-2(1+b)m)^2}{8(1-a)^2(4-b)^2(1-\delta)}.
\end{align*}
\]

Theorem 8. The consumer surplus under platform’s three charging modes in descending order is \( CS_2 > CS_3 > CS_1 \).

The proof of Theorem 8 appears in Appendix A.

According to Theorem 8, charging the manufacturer is the most beneficial to consumer surplus among three charging modes. Meanwhile, as the charging mode changes, trend of changes in consumer surplus and social welfare are the same as that in the market share of products from the sharing channel according to Theorem 7. In other words, production capacity sharing helps drive consumer surplus improvement.

The social welfare is the sum of the entire supply chain’s surplus [63]. In this paper, social welfare, which is defined as \( SW \), is given by:

\[
SW = \int_{1-q_{s}}^{1-q_{t}} \delta v dv + \int_{1-q_{t}}^{1} (v - m)dv. \tag{14}
\]
The social welfare under three charging modes of the platform is given as follows.

\[
\begin{align*}
SW_1 &= \frac{4(1-a-m)(7-7m-a(7-8m)) - 25(1-a)^2 - 2(1-a)(37-20a)m + (3(7-8a)m^2)\delta - (1-a)\delta^2 + 4(1-a)^2\delta^3}{8(1-a)^2(4-\delta)^2(1-\delta)}, \\
SW_2 &= \frac{28-\delta(25+7-4\delta)+ (1+b)m(28-8\delta)(25-4\delta)-2m(1-\delta)(28-9\delta+b(12-50))}{8(4-\delta)^2(1-\delta)}, \\
SW_3 &= \frac{4(1-a-m-\beta m)(7-\delta)(7-\beta)m - \alpha(7-8m)) - (25(1-a)^2 - 2(1-a)(37-20\alpha + 17\beta)m + 3(1+\beta)(7-8\alpha-\beta)m^2)\delta - (1-a)(7-7m+8m) + 2m(9+5\beta-2(1+\beta)m))\delta^2 + 4(1-a)^2\delta^3}{8(1-a)^2(4-\delta)^2(1-\delta)}. 
\end{align*}
\]  

(15)

The social welfare, which is complex, would be analyzed in the form of numerical examples below. It should be noted that although the social welfare is studied in much research, the result of this part is limited to a certain degree due to the assumptions and the specificity of model selection. However, the results about social welfare can still provide references for actual operations, which was explained in detail in numerical examples.

6. Numerical Examples

The numerical examples were constructed to illustrate the effects of interaction among the capacity supplier, the traditional supplier, the manufacturer, the platform, and sustainably conscious consumers on the profit of each participant from the perspective of sustainable operations. Furthermore, the changes in the platform’s charging mode selection in different stages of sustainable development were analyzed. In addition, the impacts of charging modes on consumer surplus and social welfare were discussed.

6.1. Relationship Between Access Requirements and Commission Rates for Sustainable Operations

Scenario DS3 where all parameters were used was adopted to investigate the impacts of interaction between \(m\) and commission rates on the profit of each stakeholder, which is depicted in Figure 3a–h. In order to make the results more obvious, parameter values were set as: \(\delta = 0.1\) in Figure 3a–h; \(a = 0.2\) in Figure 3e–h; \(b = 0.2\) in Figure 3a–d; \(m = 0.05\) in Figure 3a, \(m = 0.1\) in Figure 3b,e, \(m = 0.4\) in Figure 3c,f, \(m = 0.5\) in Figure 3g, and \(m = 0.7\) in Figure 3d,h.

Comparing (b) and (e), or (c) and (f), or (d) and (h), the commission rates charged to the capacity supplier had stronger effects than the equal commission rates charged to the manufacturer on the profit of each participant. Specifically, take the profit of the platform as an example: \(\pi_P = 0.02243\) with \(a = 0.03\) and \(\pi_P = 0.02340\) with \(a = 0.04\) in Figure 3b; \(\pi_P = 0.02610\) with \(b = 0.03\) and \(\pi_P = 0.02697\) with \(b = 0.04\) in Figure 3e. When \(m\) was fixed, \(\pi_P\) with \(a = 0.2\) and \(b = 0.03\) was larger than \(\pi_P\) with \(b = 0.2\) and \(a = 0.03\). Furthermore, the difference between \(\pi_P\) with \(a = 0.03\) and \(\pi_P\) with \(a = 0.04\) in Figure 3b was larger than that between \(\pi_P\) with \(b = 0.03\) and \(\pi_P\) with \(b = 0.04\) in Figure 3e. In addition, the profits of the manufacturer and the capacity supplier were decreasing in commission rates. Traditional supplier benefits from an increase in commission rates. The results of numerical examples were consistent with actual situations where some sharing platforms that choose bilateral charging set the commission rates charged to the demand side higher than that charged to the suppliers in order to give each participant a more profitable space for sustainable operations [21].
Furthermore, the difference between commission rates led to three situations: Firstly, low capacity management costs, which reflect a low level of access requirements for the capacity supplier, set by the platform can result in that the platform benefits from an increase in commission rates such as Figure 3a,e. There were $m = 0.05$ in Figure 3a and $m = 0.1$ in Figure 3e because the commission rate $a$ had stronger effects than the equal commission rate $b$ on the profit of each participant and that there was a mutual relationship between $m$ and commission rates with a given $\delta$, which was found in Theorem 5. Secondly, with moderate capacity management costs, the profit of platform first increased and then decreased as the commission rates increase, which is shown in Figure 3b,c,f,g. Thirdly, a high level of access requirements set by the platform caused a decrease in profit of the platform as commission rates to increase such as Figure 3d,h. The results provided a reference for platform operators to balance access requirements and commission rates for sustainable operations when the manufacturer faces sustainably conscious consumers in a given market.

6.2. Relationship Between Access Requirements and Charging Modes for Sustainable Operations

Figure 4 integrates twelve curves about profits of the platform with different parameter values under three charging modes. As described in Section 5, the commission rates set by sharing platforms typically ranges from 10 to 30 percent. Thus, parameter values were set as: (1) $a = b = k = 0.15$, $\alpha = 0.05$, $\beta = 0.1$, and $\delta = 0.2$ or $\delta = 0.6$; (2) $a = b = k = 0.25$, $\alpha = 0.1$, $\beta = 0.15$, and $\delta = 0.2$ or $\delta = 0.6$ to examine the platform’s charging mode selection for optimal profits considering the level of $m$. Among the three charging modes: when $m$ was low, the platform obtained the most profits by charging the capacity supplier; when $m$ was moderate, the platform can collected the most profits by charging both sides; when $m$ was high, the platform obtained the most profits by charging the manufacturer. Additionally, combined with Corollary 2, the platform could obtain the most profits when it charges the capacity supplier and sets the access requirements that cause the capacity supplier to undertake the cost $mF_1$ to manage the surplus production capacity.
6.3. The Impacts of Charging Modes on Consumer Surplus and Social Welfare

In order for the results to be obviously displayed in figures and in line with reality, we set \( a = b = k = 0.3, \alpha = 0.1, \beta = 0.2, \) and \( \delta = 0.2 \). Figure 5a expresses the relationship among consumer surplus under three charging modes of the platform, which is \( CS2 > CS3 > CS1 \). Figure 5b expresses the relationship among social welfare under three charging modes of the platform, which is \( SW2 > SW3 > SW1 \). In addition, combined with the results above, charging the capacity supplier only may conflict with the profits of the participants, consumer surplus, and social welfare. Thus, developed platforms are more capable of sustainable operations and benefits for all stakeholders in production capacity sharing. The platform can choose bilateral charging, which is the option for many sharing platforms in actual operations while improving its own operational level.

![Graph showing impacts of charging modes on consumer surplus and social welfare](image)

**Figure 4.** The effects of \( m \) on the platform’s charging mode selection.

**Figure 5.** The effects of charging modes on consumer surplus and social welfare. (a) Consumer surplus changes with \( m \). (b) Social welfare changes with \( m \).

When the commission rates are quite high, the relationship of social welfare under three charging modes presents complexity. Due to the interrelationship between \( m \) and \( \delta \), when \( m \) is quite high, some specific \( \delta \) can also lead to different results. However, Theorem 6 and Corollary 2 indicate that high commission rates and high capacity management costs are not conducive to the sharing channel members’ profits and sustainability of the whole supply chain. Meanwhile, current sharing platforms do not set quite high commission rates or access requirements. Therefore, there is no need to discuss the relationship among social welfare under three charging modes with quite high commission rates or \( m \).

7. Conclusions

In general, sustainability can be measured by social, economic, and ecological dimensions [4,65]. In the context of sharing economy, production capacity sharing is considered to be environmentally friendly [14,30]. Meanwhile, the production capacity sharing platform makes it possible for
manufacturing enterprises to share surplus production capacity, which reduces waste and increases production efficiency. The services of the platform improve sustainability characteristics of the products, which facilitates sustainable supply chain management in terms of transactions and social welfare [12,13]. This paper focused on the design of production capacity sharing mechanism from the perspective of sustainable operations. Particularly, a supply chain where one manufacturer sources from two alternative channels: a sharing channel and a traditional one is considered. Three charging modes of the platform including charging the surplus production capacity supplier, the manufacturer, and both were analyzed and compared. Products from the sharing channel were superior to those from traditional channel in terms of sustainability performance. Sustainably conscious consumers in the market were segmented based on value and sustainability preference, namely consumer acceptance of traditional channel and consumer surplus for each channel. The game-theoretic model is formulated based on the piecewise demand function of the products from two channels and three channel selection strategies of the manufacturer: sharing-channel only strategy, traditional-channel only strategy, and dual-channel strategy under three charging modes of the platform. Corresponding to the specific research questions mentioned before, the main results are summarized as follows: optimal channel selection strategies of the manufacturer and the decisions about the participation of production capacity sharing of the capacity supplier, as well as corresponding optimal pricing strategies of the manufacturer and suppliers for sustainable operations; platform’s operational mechanism regarding charging modes, access requirements, and commission rates in different stages of development from a perspective of sustainable operations; the interaction among the stakeholders to achieve sustainability in the entire system.

7.1. Discussion and Significance

This paper further verified or expanded the conclusions of the relevant research. Main findings and the significance in theory and practice were summarized as follows.

This work provided several insights on theory for the design of the production capacity sharing mechanisms in academic research from a sustainable operations perspective. The theoretical link between production capacity sharing mechanisms and sustainable operations was proposed. For example, coordination and interaction among production capacity sharing stakeholders could facilitate sustainable operations based on the integrated decision-making framework in this paper. A theoretical reference for promoting the sustainability of the entire system in the platform’s different stages of development was provided. Moreover, studying the issues regarding production capacity sharing by game theory was conducive to the integration of economic and sustainable goals in the context of the sharing economy.

(1) The manufacturer can estimate consumer acceptance of the traditional channel based on the relationship among capacity management costs of a surplus production capacity supplier, commission rates and charging modes of the platform, and production costs of two suppliers to make channel selection decisions. Different from Luo et al. [58], product sustainability characteristics, sustainably conscious consumers, and features of production capacity sharing such as surplus production capacity management cost, platform’s commission rates, and charging modes were taken into account for obtaining channel selection strategies in this paper. The results provide a reference for the manufacturer to make a lean channel selection decision according to the thresholds of consumer acceptance of traditional channel from the perspective of sustainable operations considering the gap between consumer’s actual actions and positive attitudes to sustainability. Furthermore, according to the results, the platform could design and improve operational policies considering the characteristics of participants in the whole supply chain such as consumer acceptance of traditional channel to encourage manufacturers to choose the platform and promote the development of production capacity sharing.

(2) An optimal pricing decision framework for suppliers and the manufacturer was provided. The manufacturer will set the price of product $s$ higher than the price of product $t$ since
the sustainability characteristics of the products from sharing channel enable sustainably conscious consumers to have higher reservation prices for product \( s \) than that for product \( t \). When facing downstream heterogeneous consumers and two different upstream channels, similar manufacturer’s pricing rules, namely product with high performance deserved the high price, proposed by Guo et al. [16] and Luo et al. [58] were further validated here. Besides, the impacts of surplus production capacity management costs and consumer acceptance of the traditional channel were analyzed in detail under nine scenarios, where the manufacturer’s three channel selection strategies and platform’s three charging modes were crossly combined. However, different from Luo et al. [58], monotonous and non-monotonous impacts of the parameters that are on behalf of the consumer’s consideration for sustainability and the capacity supplier’s surplus production capacity management costs on the equilibrium solutions were both found under different channel selection strategies of the manufacturer in this paper. Since one more participant, the platform, was added, which increased the complexity of the interaction among supply chain members. Meanwhile, the players in the game were different under nine scenarios. In order to achieve sustainable operations, the manufacturer should encourage the traditional supplier to improve the product sustainability characteristics for reducing the difference between consumer acceptance of the two channels. The platform should enhance the services to make the sustainability characteristics of the products more prominent. Such mutual incentives promote the sustainability of the entire system. In addition, the results show that the platform not only needs to pay attention to operational policies but also should value science and technology development policies for improving the level of services to enhance the social impact of production capacity sharing in terms of sustainability.

(3) With regards to sustainable operations in production capacity sharing, the thresholds of production capacity management costs, which reflect the level of access requirements of the platform and integrate economic and sustainable goals under three charging modes, were provided. Cachon et al. [54] supposed that poor service version could be more prevalent when the joining cost is high on a service platform. Parker et al. [23] also discussed the access requirements for sharing platforms. Similarly and further, the conditions of the capacity supplier to join in the sharing were found in this paper and show that the platform needs to provide its participants with profitable space in case that the participants gave up production capacity sharing due to the high cost of joining in the sharing. The interaction among the participants suggested that excessive access requirements and commission rates were not conducive for the platform to the balance between profitability and attracting the participation. Furthermore, the platform could set the access requirements combined with the charging modes to seek the optimal profit based on the thresholds of production capacity management costs, which were also explored in this paper. The results show that setting reasonable access requirements and commission rates were critical to the healthy relationship between the platform and its users.

(4) In the platform’s different stages of sustainable development, from the perspective of bilateral market management, the platform’s decision concerning different charging objects experiences a general trend that is from charging the surplus production capacity supplier to charging both sides to charging the manufacturer as the access requirements increase. Zhou et al. [21] found that developing platforms preferred to charge the supplier and the developed platforms preferred to charge the bilateral users. Similar results were obtained in this paper. The difference was that this paper further provided a reference for platform operators to comprehensively consider setting access requirements and selecting the charging modes in different stages of development from a perspective of sustainable operations. Specifically, in the early stage of the platform development or when the platform enters an emerging market, it prefers to set low access requirements for attracting surplus production capacity suppliers and encourage the manufacturers to join in the sharing with no charge, which is also profitable for the platform. When the platform is relatively mature or in a saturated market, it will design relatively high access requirements
and change to charge bilateral sides or only the demand side to regulate the supply market and balance the relationship between its own profitability and bilateral participation for achieving sustainability. Furthermore, the results in this paper regarding operations of the platforms were consistent with actual situations where some sharing platforms that choose bilateral charging set the commission rates charged to the demand side higher than that charged to the suppliers in order to give each participant a more profitable space for sustainable operations [21]. Since the impact of commissions charged to the surplus production capacity suppliers on the profit of each participant is greater than that of commissions charged to the manufacturer, which is verified by numerical examples in this paper. Moreover, under three charging modes, the higher the market share of products from sharing channel, the greater the consumer surplus and social welfare. Therefore, the results show that advocating production capacity sharing is an effective measure to promote sustainable management of the supply chain. In addition to that, in the context of intelligent manufacturing or industrial 4.0, appropriate governmental and industry policy is important to support and drive sustainable practices [8,39]. Managemental departments of manufacturing industry or governments can design guiding policy referencing this result for production capacity sharing platforms that are in different stages to help them to achieve sustainable development. The results provide recommendations for the practice of production capacity sharing mechanism in sustainable operations.

7.2. Limitations and Future Research

This paper was not without its limitations. For simplicity, the production costs of suppliers were ignored, which is a common assumption in the research on supply chain management though [59,60]. In reality, the relationship between the production costs of two kinds of suppliers involves many complicated factors such as capacity scheduling and staff coordination due to the random and perishable properties of surplus production capacity. Besides, there are some special cases. For example, when the manufacturer is not subject to capacity constraints, the relationship of the manufacturer’s and the suppliers’ power may have multiple situations, which will affect the event sequence of the game. These limitations can be the directions of the future research below.

Valuable topics remain for future research. Firstly, the relationship between the production costs of suppliers considering the random and perishable properties of surplus production capacity is the follow-up work to extend the results of this paper. Secondly, the game with different event sequences and the game between multiple participants on both sides of the platform are promising research directions. Thirdly, the incentive mechanisms and penalty mechanisms of the production capacity sharing are useful topics for sustainable operations.

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Appendix A

Proof of Theorem 1. According to the backward induction and using Mathematica (Wolfram Research, Champaign, IL, USA) software, the Hessian matrix of $\pi^*_{DS}(p_s, p_t)$ is as follows.

$$H(\pi^*_{M}(p_s, p_t)) = \begin{bmatrix}
\frac{\partial^2 \pi^*_{M}(p_s, p_t)}{\partial p_s^2} & \frac{\partial^2 \pi^*_{M}(p_s, p_t)}{\partial p_s \partial p_t} \\
\frac{\partial^2 \pi^*_{M}(p_s, p_t)}{\partial p_t \partial p_s} & \frac{\partial^2 \pi^*_{M}(p_s, p_t)}{\partial p_t^2}
\end{bmatrix} = \begin{bmatrix}
-\frac{2}{\delta^2} & -\frac{2}{\delta^2} \\
-\frac{2}{\delta^2} & -\frac{2}{\delta^2} - \frac{2}{\delta}
\end{bmatrix}. \quad (A1)$$
The Hessian matrix is negative definite so that \( \pi_{DS}^{S1}(p_s, p_t) \) is joint concave in \( p_s \) and \( p_t \).

Let \( \frac{\partial^2 \pi_{DS}(p_s, p_t)}{\partial p_s^2} = \frac{1}{1-\delta} (2 - 2c_s - 2c_t - 2m - 2\delta) \) and \( \frac{\partial^2 \pi_{DS}(p_s, p_t)}{\partial p_t^2} = \frac{1}{1-\delta} (2 - 2c_s - 2c_t - 2m - 2\delta) \). By substituting \( p_s \) and \( p_t \) into \( \pi_S(w_s) \) and \( \pi_T(w_t) \),

\[
\frac{\partial^2 \pi_S(w_s)}{\partial w_s^2} = -\frac{1}{1-\delta} < 0
\]

and \( \frac{\partial^2 \pi_T(w_t)}{\partial w_t^2} = -\frac{1}{1-\delta} < 0 \) are obtained. Therefore, \( \pi_S(w_s) \) and \( \pi_T(w_t) \) are concave in \( w_s \) and \( w_t \) respectively. The optimal wholesale prices are obtained by taking the partial derivatives

\[
\frac{\partial \pi_S(w_s)}{\partial w_s} = 0 \quad \text{and} \quad \frac{\partial \pi_T(w_t)}{\partial w_t} = 0.
\]

\( w_S^{DS1^*} = 2 - 6 - 2c_s - a(6 - c_t) + c_t + 2m \)

\[
(1-a)(4-\delta)
\]

\( w_T^{DS1^*} = \frac{(1 + c_s + m - a(1-\delta) - \delta) + 2(1-a)c_t}{(1-a)(4-\delta)}.
\]

By substituting Equations (A2) and (A3) into \( p_s = \frac{1+w}{2} \) and \( p_t = \frac{\delta+w}{2} \), the optimal prices are obtained.

\[
p_S^{DS1^*} = \frac{1}{2} \left( 3 - \frac{6 - 2c_s - a(6 - c_t) - c_t - 2m}{(1-a)(4-\delta)} \right),
\]

\[
p_T^{DS1^*} = \frac{2(1-a)c_t + \delta(2(1-a)c_t + 2m - 2(1-a)\delta)}{2(1-a)(4-\delta)}.
\]

Based on \( p_S^{DS1^*} \) and \( w_S^{DS1^*} \), \( q_S^{DS1^*}, \pi_S^{DS1^*}, \pi_T^{DS1^*} \), and \( \pi_P^{DS1^*} \) are obtained according to Equations (1)–(6). Similar to DS1 scenario, the equilibrium solutions for scenarios DS2 and DS3 can be obtained. \( \Box \)

**Proof of Theorem 2.** By substituting \( p_S^{DS^j} \) and \( p_T^{DS^j} \) in Table 3 into \( \delta^j = p_T^{DS^j}/p_S^{DS^j} \) and \( \delta^j = 1 - p_S^{DS^j} + p_T^{DS^j} \), \( \delta^j \) and \( \delta^j \) in Theorem 2 can be obtained, where \( j = (1, 2, 3) \). \( \Box \)

**Proof of Theorem 3.** When \( \delta = \frac{\delta^1}{2} \), traditional supplier is still involved in decision making. Similar to DS1 scenario, \( p_s = \frac{1+w}{2} \) and \( p_t = \frac{\delta+w}{2} \) are obtained. \( \delta = p_T/p_S \) or \( \delta = \frac{m}{w_S} \) makes three players game and positive demand for product s only. \( \pi_S^{SN1}(w_s) \) can be written as:

\[
\pi_S(w_s) = ((1-a)w_s - c_s - m)(1 - \frac{1+w}{2} \frac{(w_t + \delta)}{1-\delta}).
\]

According to Equation (A6), \( \frac{\partial^2 \pi_S(w_s)}{\partial w_s^2} = -\frac{1}{1-\delta} < 0 \) is obtained. By solving \( \frac{\partial \pi_S(w_s)}{\partial w_s} = 0 \), \( w_s = \frac{1+c_s+m+w_t-\delta-a(1+w_t-\delta)}{2(2-a)} \) is obtained. Combined with \( \delta = \frac{w}{w_S} \), the optimal pricing strategies are obtained.

\[
w_S^{SN1^*} = \frac{1 - a + c_s + m - \delta + a\delta}{(1-a)(2-\delta)},
\]

\[
w_t^{SN1^*} = \frac{\delta(1 - a + c_s + m - \delta + a\delta)}{(1-a)(2-\delta)}.
\]

\[
p_S^{SN1^*} = 1 - \frac{1 - a - c_s - m}{2(1-a)(2-\delta)},
\]

\[
p_t^{SN1^*} = \delta - \frac{(1-a-c_s-m)\delta}{2(1-a)(2-\delta)}.
\]

Based on \( p_S^{SN1^*} \) and \( w_S^{SN1^*} \), \( q_S^{SN1^*}, \pi_S^{SN1^*}, \pi_N^{SN1^*}, \) and \( \pi_P^{SN1^*} \) are obtained. When \( 0 < \delta < \frac{\delta^1}{2} \), there is a two players game. Similar to SN1 scenario, the equilibrium solutions for scenarios SN2 and SN3 can be obtained. \( \Box \)
Proof of Theorem 4. When \( \delta = \delta^1 \), \( p_s = \frac{1+w_0}{2} \), and \( p_l = \frac{\delta+\delta^0}{2} \) are obtained. \( \delta = 1 - p_s + p_l \) or \( \delta = 1 - w_2 + w_1 \) makes three players game and positive demand for product \( t \) only. \( \pi^{TN1}_T(w_t) \) can be written as:

\[
\pi^{TN1}_T(w_t) = (w_t - c_i) \left\{ \frac{1+w_0}{2} - \frac{1}{2} \left( w_t + \delta \right) \right\}.
\]  

(A11)

According to Equation (A11), \( \frac{\partial \pi_T(w_t)}{\partial w_t} = -\frac{1}{4} - \frac{1}{\delta} < 0 \) is obtained. By solving \( \frac{\partial \pi_T(w_t)}{\partial w_t} = 0 \), \( w_t = \frac{c_t + w_0}{2} \) is obtained. Combined with \( \delta = 1 - w_2 + w_1 \), the optimal pricing strategies are obtained.

\[
w^{TN1*}_s = \frac{2 + c_i - 2\delta}{2 - \delta}
\]  

(A12)

\[
w^{TN1*}_l = \frac{c_i + \delta - \delta^2}{2 - \delta}
\]  

(A13)

\[
p^{TN1*}_S = \frac{4 + c_i - 3\delta}{4 - 2\delta}
\]  

(A14)

\[
p^{TN1*}_T = \frac{c_i + (3 - 2\delta)\delta}{4 - 2\delta}
\]  

(A15)

Based on \( p^{TN1*}_S \) and \( w^{TN1*}_S, q^{TN1*}_S, \pi^{TN1*}_S \), and \( \pi^{TN1*}_M \) are obtained. When \( \delta^1 < \delta < 1 \), there is a two players game. Similar to TN1 scenario, the equilibrium solutions for scenarios TN2 and TN3 can be obtained. □

Proof of Theorem 5. A capacity supplier will choose to join in the production capacity sharing platform when it gets a new profit steam by sharing the surplus production capacity. By solving \( p^{DS^2}_S > w^{DS^2}_S > m \) and \( q^{DS^2}_S > 0 \) or \( p^{SN^2}_S > w^{SN^2}_S > m \) and \( q^{SN^2}_S > 0 \) for \( 0 < \delta < \delta^2 \), where \( j = (1, 2, 3) \), results in Theorem 5 can be obtained. □

Proof of Theorem 6. By taking partial derivatives of results in Equations (7)–(9), Table 3, Table 4, and Table 5 w.r.t. \( a \) or \( b \), results in Theorem 6 can be obtained. □

Proof of Theorem 7. Because \( w^{DS^2}_S - w^{DS^3}_S > 0 \), \( w^{DS^2}_S - w^{DS^3}_S > 0 \), \( p^{DS^2}_L - p^{DS^3}_L > 0 \), \( p^{DS^2}_L - p^{DS^3}_L > 0 \), \( q^{DS^2}_L - q^{DS^3}_L > 0 \), \( q^{DS^2}_L - q^{DS^3}_L > 0 \), \( \pi^{DS^2}_S - \pi^{DS^3}_S > 0 \), \( \pi^{DS^2}_S - \pi^{DS^3}_S > 0 \), \( \pi^{DS^2}_M - \pi^{DS^3}_M > 0 \), \( \pi^{DS^2}_M - \pi^{DS^3}_M > 0 \), \( \pi^{DS^2}_S - \pi^{DS^3}_S > 0 \), and \( \pi^{DS^2}_M - \pi^{DS^3}_M > 0 \), where \( i = (s, l) \), the results under DSj scenarios can be obtained in Theorem 7. By solving \( \pi^{DS^2}_S - \pi^{DS^3}_S \) and \( \pi^{DS^2}_M - \pi^{DS^3}_M \), and \( \pi^{DS^2}_S - \pi^{DS^3}_S < 0 \) hold in the most situations. Solving specific ranges in which the general trend of the platform’s profit does no hold is analytically challenging for Mathematica. But we can obtain the result by Mathematica that when consumer acceptance of TC is absolutely high in the range of \( 0 \leq \delta < \delta^1 \), charging the capacity supplier is always the best choice to get optimal profits for the platform because there is no space for the platform to increase the access requirements according to Theorem 5. Similarly, the results under SNj scenarios can be obtained. □

Proof of Theorem 8. By solving CS1–CS3 and CS2–CS3, CS1–CS3 < 0, and CS2–CS3 > 0 can be obtained. □
Appendix B

\[
\begin{align*}
m_{E1} & = \frac{\delta - ab - \delta^2 + ab^2}{4 + 2b}, \\
m_{E2} & = \frac{8b - \delta^2 - 4}{4 + 4b}, \\
m_{E3} & = \frac{8b - \delta^2 - 2b^2}{4 + 4b}. \\
m_{F1} & = \frac{4a + 8b - \delta^2 + ab^2}{4}, \\
m_{F2} & = \frac{8b - \delta^2 - 4}{4 + 4b}, \\
m_{F3} & = \frac{8b - \delta^2 + ab^2}{4 + 4b}.
\end{align*}
\]

\[
\begin{align*}
m_{G1} & = \frac{2 - 2a - 4b + 2b^2 - 2b^2}{2 - 4a + 2b}, \\
m_{G2} & = \frac{6 + 6b - 4b^2 + 2b^2}{2 - 4a + 2b}, \\
m_{G3} & = \frac{4 - 2b - 4b^2 + 2b^2}{2 - 4a + 2b}.
\end{align*}
\]

\[
\begin{align*}
m_{H1} & = \frac{4a + 11b - 11b^2 - 7a^2}{4 + 4b + 6b^2}, \\
m_{H2} & = \frac{11b - 7b^2 - 4}{4 + 4b + 6b^2}, \\
m_{H3} & = \frac{4a + 11b - 11b^2 - 7a^2}{4 + 4b + 6b^2}.
\end{align*}
\]

\[
\begin{align*}
m_{L1} & = \frac{\delta(1-a-b+ab)}{2(1+a)(2-b)} + \frac{1}{2} \sqrt{\frac{(1-a)^2((4-b)^2 - 8a^2(2-b))(1-b)^2}{(1+a)^2(2-b)^2}}, \\
m_{L2} & = \frac{(1-b)\delta}{2(1+2b)(2-b)} + \frac{1}{2} \sqrt{\frac{(1-b)^2((4-b)^2 + 2b(4-b)^2 + b^2)}{(1+b)^2(1+2b)^2(2-b)^2}}, \\
m_{L3} & = \frac{\delta(1-a-b+ab)}{2(1+a+2b)(2-b)} + \frac{1}{2} \sqrt{\frac{(1-a)^2(1-b)^2(16(1-a)(1+a+2b)-8(1-a)(1+a+2b)b+(1+b)^2b^2)}{(1+b)^2(1+a+2b)^2(2-b)^2}}.
\end{align*}
\]

\[
\begin{align*}
m_{O1} & = \sqrt{\frac{1-3a+3a^2-a^3}{1+a}}, \\
m_{O2} & = \sqrt{\frac{1}{1+4b+b^2+2b^3}}, \\
m_{O3} & = \sqrt{\frac{1-3a+3a^2-a^3}{1+a+2b}}.
\end{align*}
\]

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