

## Article

# Green Cooperation Strategy of Prefabricated Building Supply Chain Based on Smart Construction Management Platform

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**Abstract:** Green technological innovation in the prefabricated building supply chain (PBSC) is an important way to realize the sustainable development of the construction industry. However, the competitive environment and the green input costs reduce the willingness of PBSC firms to improve the green technology level. This paper constructs a PBSC consisting of a smart construction management platform (SCMP), a contractor, and prefabricated-component manufacturers (PCMs) to explore green cooperation strategies in the PBSC. Stackelberg game models are constructed and the green technology level and PBSC profit under different cooperation strategies are examined. The study shows that the optimal service commission of the SCMP increases with the cost parameter of green technology and the intensity of competition between PCMs. However, the green technology level decreases with the competition. The integration strategy does not necessarily achieve the highest level of green technology. The horizontal cooperation among competing PCMs is not conducive to improving the green technology level, but PCMs always have incentives to form horizontal cooperative alliances to achieve Pareto improvement under certain conditions. For the SCMP, the vertical cooperation strategy with PCMs is the most favorable, but for the PBSC, the system profit under the integration strategy is the most profitable. This study enriches the theoretical foundation of the PBSC and provides theoretical guidance for green cooperation strategies in PBSCs.

**Keywords:** smart construction management platform; green technology; cooperation strategy; prefabricated building supply chain



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## 1. Introduction

The carbon peaking and carbon neutrality goals put forward higher requirements for carbon emission reduction, and the construction industry, as an industry with a large share of global carbon emissions, must have targeted measures to control carbon emission reduction [1,2]. Prefabricated buildings provide a feasible solution to reduce carbon emissions in the construction industry. Prefabricated buildings are different from the centralized construction of traditional buildings, which is divided into factory manufacturing and on-site assembly construction. Compared with the assembly construction process, in the factory manufacturing process, carbon emissions are greater [3], but carbon emissions are easier to control [4]. It has been shown that technical factors are the most influential factors affecting carbon emission reduction in the prefabricated building supply chain (PBSC) [5], so it is of great practical significance to control carbon emission reduction in the prefabricated component production process through green technology development and improvements in the factory manufacturing process. As a link firm in the factory stage of the PBSC [6], prefabricated-component manufacturers (PCMs) should endeavor to improve their green technology innovation level, which is an important path to realize carbon emission reduction in the construction industry [4,7].

With the development of information technology such as mobile Internet, big data, and cloud computing, smart construction management platforms (SCMPs), such as Bozhilin and Xiangjianyun, have emerged and continue to develop [8]. Firms in each segment of the

PBSC have their accounts and can log into the SCMP for operation. The functions provided by SCMPs include project management, prefabricated-component design, production management, transportation management, and assembly management [9,10]. In addition, SCMPs also provide knowledge management services. In the knowledge management module, the firms can maintain information through blockchain technology to empower the improvement of green technology [11]. SCMPs integrate the data of each participating unit through Internet technology [12,13], which can realize the collaborative management of multiple parties in the PBSC, thus promoting green cooperation and the technological innovation of upstream and downstream firms in the supply chain [8,11].

Many scholars have proposed the logic model of SCMPs based on information technology, such as IoT technology [12]. Contractors, designers, prefabricated-component manufacturers, and other related firms rely on SCMPs to form an outlet for integrated management. At the operation level, SCMPs strengthen communication and cooperation among firms, and in the construction of the underlying framework, SCMPs provide conditions for technical cooperation. In practical operation, SCMPs as a service platform provide information services and transaction guarantees for upstream and downstream firms, and upstream PCMs attract contractors to purchase more prefabricated components through green technology innovation [14]. On the other hand, as an integration platform, SCMPs can stimulate upstream PCMs to improve their green technology level through cooperation to promote transactions and further enhance the overall efficiency of the supply chain. Therefore, how to carry out green cooperation between SCMPs and PCMs is of great significance for environmental protection and the overall efficiency of the supply chain.

However, there is competition among PCMs providing alternative prefabricated components, and upgrading one's green technology level means facing higher cost investment while increasing purchase orders, so how upstream PCMs make decisions on the level of green technology to maintain competitive advantages in a competitive environment is an important research question. Moreover, from the perspective of SCMPs, empowerment through technology will promote the digital and intellectual transformation of upstream and downstream firms, but it will likewise increase their maintenance costs and reduce the motivation for cooperation. Although some scholars have noticed SCMPs, there are few studies analyzing the operational decisions of SCMPs from the perspective of the PBSC, and even fewer have considered the role of SCMPs in green cooperation in the PBSC. To fill this gap, we incorporate an SCMP into the decision-making system of the PBSC and analyze the green cooperation strategies of the PBSC. To better guide the practice of the PBSC, this paper focuses on the following two questions: (1) How does one make decisions on the green technology level in the PBSC under the empowerment of SCMPs? (2) How should SCMPs and PCMs cooperate to realize a win-win situation in terms of environmental benefits and economic benefits?

To address the research questions, this paper constructs a PBSC consisting of an SCMP, two competing PCMs, and a contractor. We examine four cooperation strategies between PCMs and the SCMP, i.e., the integration strategy, the non-cooperation strategy, the horizontal cooperation strategy, and the vertical cooperation strategy, and comparatively analyze the impacts of the competition intensity between PCMs, the cost parameter of the green technology enhancement, and the marginal cost on the decision-making of the PBSC. Moreover, the profits of firms and the PBSC system under different cooperation strategies are further compared and analyzed to guide the strategic decisions of the PBSC.

The rest of the paper is organized as follows. Section 2 reviews the related studies. Section 3 describes the problem and explores the decision models of four cooperation strategies. Section 4 analyzes the optimal decisions of cooperation strategies. Section 5 uses numerical examples to compare the cooperation strategies and uses a case to illustrate practical implications. Section 6 discusses the results, gives managerial insights and research limitations. Finally, Section 7 concludes the paper.

## 2. Literature Review

This study is closely related to the PBSC and cooperation strategies of the supply chain.

### 2.1. Prefabricated Building Supply Chain

The PBSC provides a solution for carbon emission reduction during the processes of production, transportation, and assembly in the construction industry [15]. In terms of theoretical modeling, Zhang et al. studied the influencing factors affecting the risk resistance of prefabricated buildings and put forward suggestions to improve the risk resistance of the PBSC [16]. Zhang et al. showed that the degree of government promotion, the pressure of on-site construction, the quality of prefabricated components, load-bearing capacity, and the quality of molds are the main factors affecting the cost of prefabricated constructions, which provide theoretical guidance for the decision-making of the contractors [17]. In terms of strategic decisions, Han et al. analyzed the strategic decisions of contractors in self-making prefabricated components and outsourcing prefabricated components, indicating that when contractors are larger, self-making prefabricated components can be more profitable [18]. Liu and Li studied the use of IoT in the PBSC for promotional purposes and found that market penetration of IoT platforms in the market of primary commodities and services is a key factor influencing the decisions of key stakeholders [11]. In terms of operational decisions, Jiang et al. examined the optimal pricing and ordering decisions of PBSCs under different power structures and carbon trading policies, and analyzed the impact of two-part tariff contracts on the optimal decisions [19]. Zhai et al. explored the time coordination problem of PBSCs and proposed reducing the handling cost by reducing the time uncertainty and congestion probability through a spatial-temporal approach [20]. Du et al. analyzed the assembly rate of the PBSC under different government subsidy policies and designed a revenue distribution coordination contract based on the subsidy [21]. Yuan et al. explored the scheduling problem of the PBSC considering resource constraints under an uncertain environment based on fuzzy theory and proposed a multi-stage hybrid cooperative co-evolutionary algorithm to improve search efficiency [22].

Existing studies have extensively researched the logic model, influencing factors, carbon emission reduction, and other issues of prefabricated supply chains, but most of them do not consider the role of SCMPs. Existing research is limited to the construction of operation models by PCMs, contractors, transporters, and other firms, but is less involved in the functional characteristics of SCMPs to incorporate SCMPs into the decision-making system. The difference between this paper and the existing studies is that this paper takes the SCMP as an integrated platform to collaborate with prefabricated-component suppliers and contractors, and considers different cooperation strategies between PCMs and platforms to explore the green technology decision-making of the PBSC under different cooperation strategies.

### 2.2. Cooperation Strategy of Supply Chain

To improve the level of research and development, green inputs, or carbon emission reduction in the supply chain, inter-firms in the supply chain will cooperate to pursue technology spillover effects by sharing costs or benefits [23]. According to the cooperation between upstream and downstream firms in the supply chain, there are generally horizontal and vertical cooperation strategies [24]. Ge et al. showed that cooperation can only achieve a win-win situation when the contribution level of firms in the research and development alliances reaches a Pareto match [25]. Wei and Zhao studied the product pricing strategies under different channel power structures when manufacturers form horizontal alliances in fuzzy environments, which provides theoretical support for pricing decisions of substitute products [26]. Wei et al. investigated horizontal cooperative alliances for complementary products and showed that when retailers dominate the channel, it is optimal for consumers that two manufacturers adopt a cooperative strategy [27]. Ma et al. constructed a three-level closed-loop supply chain consisting of manufacturers, retailers, and recyclers and found that the cooperative strategy is conducive to increasing the recycling rate of used products

and that cooperative alliance strategies can achieve win–win situations [28]. Yang et al. explored carbon emission reduction strategies under horizontal and vertical cooperative strategies and showed that vertical cooperation strategies are beneficial to reduce carbon emissions and benefit consumers [29]. Chen et al. also verified that the vertical cooperation strategy is more favorable than the horizontal cooperation strategy in the prefabricated supply chain [3]. However, Sim et al. showed that although the vertical cooperation strategy can achieve higher social welfare, it cannot balance the environmental pollution caused by the production process [30]. Moreover, Fan et al. also found that a vertical cooperation strategy does not always improve the overall profitability of the supply chain [31].

Most of the abovementioned research focused on the cooperative strategies in the retail supply chain and examined the cooperative strategies between the two supply chains consisting of manufacturers and retailers [28,32,33]. However, there are fewer studies on the PBSC, which involves more firms and is highly susceptible to forming cooperative alliances. Although some studies have focused on the cooperative mode of the PBSC [3], the impact of SCMPs has not been considered. As an integrated platform, the operation mode of an SCMP is different from the price markup mechanism in product sales but focuses on the management service function. Moreover, the competition of PCMs cooperating with an SCMP focuses on the level of green technology, which affects the motivation and conditions of cooperation between SCMPs and the PCMs, leading to different preferences for cooperation strategies among PBSC firms.

### 2.3. Contributions to the Literature

This paper contributes to the existing studies in two aspects.

Firstly, this paper focuses on the cooperation strategy of the PBSC, and constructs a green cooperation game model between an SCMP, PCMs, and the contractor from the perspective of the supply chain to investigate the operation decision of green technology under different cooperation strategies. Most of the existing studies have been limited to theoretical logic models [16,17], and most of them have investigated decisions such as pricing, carbon emission reduction level, and assembly rate [19,21], while fewer studies have investigated green technology decisions. This paper constructs green cooperative operation decision models, analyzes the green technology level of the PBSC, and finds that the green technology level decreases with the increase in cost parameter, marginal cost, and the intensity of competition among component manufacturers, which is different from the conclusion that the green level increases with the increase in the intensity of competition among manufacturers [34,35].

Secondly, this paper analyzes the motivation and conditions of cooperation between SCMPs and PCMs and provides theoretical guidance for green cooperation strategies in actual operation. Existing studies have shown that the integration strategy is effective in improving green technology levels and supply chain profitability [36,37], but this paper shows that the horizontal cooperation among competing PCMs is not conducive to the improvement of green technology levels. It is shown that horizontal cooperation among PCMs is more favorable when the market is highly competitive, which is different from the conclusion that horizontal cooperation among retailers is more favorable when the competition is strong [38].

## 3. Model Description and Development

### 3.1. Model Description

Based on an SCMP, a PBSC composed of PCMs and the contractor is constructed, as shown in Figure 1. The SCMP provides technical support for information interaction and charges service commission  $\rho$ . Competitive PCMs  $i$  ( $i = 1, 2$ ) provide alternative prefabricated components to the contractor, and the green technology level of PCMs is  $g_i$  ( $0 < g_i < 1$ ). (The green technology level of prefabricated-component manufacturers is reflected by green manufacturing technology, environmental research capability, information technology level, green culture, etc.) PCMs need to bear costs to improve the green

technology level, and part of it is the input cost of improving the level of green technology, denoted as  $t_i g_i^2 / 2$  [30,39], where  $t_i$  represents the cost parameter of green technology. In addition, PCMs need to conduct technology testing to prove that their green technology level is in line with the relevant information displayed on the SCMP. Examples include recognition by environmental organizations, proof of resource efficiency per unit of product, and carbon emissions, and this part of the cost is denoted as  $c g_i q_i$ , where  $c$  represents the marginal cost of green technology upgrading.

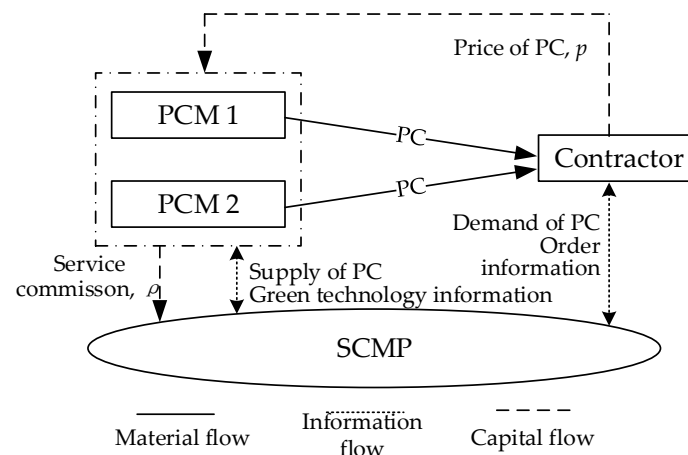


Figure 1. Operational model of PBSC based on SCMP.

The contractor is concerned about the green technology level of PCMs, and the purchasing decisions are influenced by the green technology level. In this paper, the market potential demand of PCM  $i$  is normalized to one. It is assumed that the market demand for PCM  $i$  is as follows,

$$q_i = 1 + g_i - \beta g_{3-i} \quad (1)$$

where  $i = 1, 2$ ,  $\beta (0 < \beta < 1)$  denotes the intensity of competition between PCMs, implying that the marginal impact of the green technology level on the market demand is more significant than that of the competitor's green technology level.

The assumptions are as follows.

- (1) The SCMP is the dominant player in the Stackelberg game and the PCMs are the subordinate players.
- (2) The SCMP charges the same service commission  $\rho$  to the PCMs.
- (3) Since competition in the same category tends to result in little difference in sales prices, this paper assumes that PCMs adopt indifference pricing  $p$ , which is an exogenous variable, and  $p > c$ .
- (4) The PCMs simultaneously decide on the green technology level and disclose the relevant information on the platform.
- (5) After the completion of the transaction between the PCMs and the contractor, the PCM, SCMP, and the supply chain system obtain profits  $\pi_i$ ,  $\pi_p$ , and  $\pi$ , respectively, where  $i = 1, 2$ .

$$\pi_i = (p - \rho - c g_i)(1 + g_i - \beta g_{3-i}) - t_i g_i^2 / 2 \quad (2)$$

$$\pi_p = \sum_{i=1}^2 \rho(1 + g_i - \beta g_{3-i}) \quad (3)$$

$$\pi_s = \sum_{i=1}^2 (p - c g_i)(1 + g_i - \beta g_{3-i}) - t_i g_i^2 / 2 \quad (4)$$

The symbols involved in this paper are shown in Table 1.

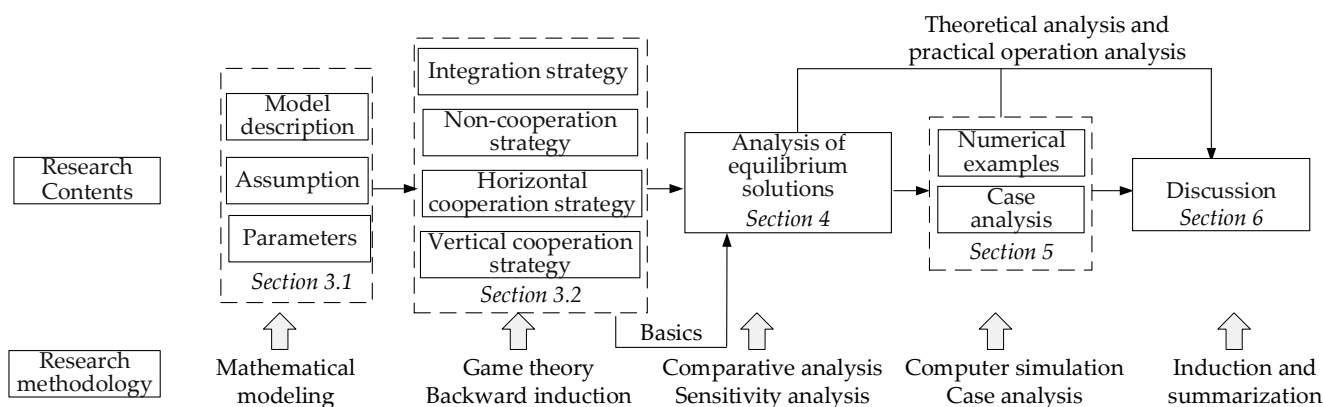


**Table 1.** Notations.

| Notations | Definitions                           | Notations | Definitions                            |
|-----------|---------------------------------------|-----------|--|
| $\rho$    | Service commission from SCMP          | $p$       | Sales price of prefabricated component |
| $g_i$     | Green technology level                | $\pi$     | System profit                          |
| $c$       | Marginal cost of green technology     | $\pi_i$   | Profit of PCM $i$                      |
| $t_i$     | Cost parameter of green technology    | $\pi_p$   | Profit of SCMP                         |
| $\beta$   | Intensity of competition between PCMs | $\pi_m$   | Profit of manufacturing alliance       |

To ensure that the research question is of practical significance, the parameters in Table 1 satisfy  $p(1 - \beta) > c$  and  $[2c(1 - \beta^2) + t_1][2(2c + t_1)(2c + t_2) + \beta^2 c^2] > \beta^2 t_2^2(2c + t_1)$ . The superscripts  $d$ ,  $h$ ,  $v$ , and  $c$  denote the non-cooperation strategy, the horizontal cooperation strategy, the vertical cooperation strategy, and the integration strategy model, respectively.

Based on the operation model and assumptions, four cooperation strategies are examined in the following subsection. The research contents and methodology are presented in Figure 2 to show the research process of this paper.

**Figure 2.** Research contents and methodology.

### 3.2. Model Development

This section first analyzes the integration strategy under a centralized decision-making model and then examines the non-cooperation strategy under a decentralized decision-making model, the horizontal cooperation strategy in which the PCMs cooperate, and the vertical cooperation strategy in which the SCMP cooperates with one PCM but not with another.

#### 3.2.1. Integration Strategy

Under the integration strategy, the SCMP and the PCMs fully cooperate to jointly optimize the green technology level to maximize the overall profit of the supply chain as the target decision. In this case, the decision function is the system profit of the PBSC.

From Equation (4), the Hessian matrix of  $\pi_s$  for  $g_1$  and  $g_2$  is  $H = \begin{bmatrix} \frac{\partial^2 \pi_s}{\partial g_1^2} & \frac{\partial^2 \pi_s}{\partial g_1 \partial g_2} \\ \frac{\partial^2 \pi_s}{\partial g_2 \partial g_1} & \frac{\partial^2 \pi_s}{\partial g_2^2} \end{bmatrix} = \begin{bmatrix} -2c - t_1 & 2c\beta \\ 2c\beta & -2c - t_2 \end{bmatrix}$ . When  $(2c + t_1)(2c + t_2) > 4c^2\beta^2$ ,  $H$  is a negative definite matrix. Therefore, solving  $\frac{\partial \pi_s}{\partial g_i} = 0$  can obtain the optimal value, the optimal green technology level under the integration strategy is  $g_i^c = \frac{[p(1-\beta)-c](2c(1+\beta)+t_3-i)}{4c^2(1-\beta^2)+2ct_2+t_1(2c+t_2)}$ , and the optimal system profit is  $\pi_s^c = \frac{4c(1+\beta)(c+p-p\beta)^2 + [c^2+p^2(1-\beta)^2+2cp(3+\beta)](t_2+t_1)+4pt_1t_2}{8c^2(1-\beta^2)+4ct_2+2t_1(2c+t_2)}$ .

### 3.2.2. Non-Cooperation Strategy

Under the non-cooperation strategy, the SCMP and the PCMs form a Stackelberg game. The SCMP first determines the service commission, and then the two PCMs determine their green technology level, respectively. According to backward induction, the optimal decision of the service commission and green technology level can be obtained.

From Equation (2), there is  $\frac{\partial^2 \pi_i}{\partial g_i^2} = -2c - t_i < 0$ , so solving  $\frac{\partial \pi_i}{\partial g_i} = 0$  obtains the green technology level, which is

$$g_i = \frac{(p - \rho - c)[c(2 + \beta) + t_{3-i}]}{c[c(4 - \beta^2) + 2t_{3-i}] + t_i(2c + t_{3-i})} \quad (5)$$

Bringing Equation (5) into Equation (3) can obtain  $\frac{\partial^2 \pi_p}{\partial \rho^2} = -\frac{2(1-\beta)[2c(2+\beta)+t_1+t_2]}{c[c(4-\beta^2)+2t_2]+t_1(2c+t_2)} < 0$ , so solving  $\frac{\partial \pi_p}{\partial \rho} = 0$  obtains the optimal service commission, which is

$$\rho^d = \frac{2c(2 + \beta)(c + p - p\beta) + [p - p\beta + c(3 + \beta)](t_2 + t_1) + 2t_1t_2}{2(1 - \beta)[2c(2 + \beta) + t_1 + t_2]} \quad (6)$$

Bring Equation (6) into Equation (5) to obtain the optimal green technology level, which is  $g_i^d = \frac{1}{2}[c(2 + \beta) + t_{3-i}] \left\{ \frac{p-c}{c[c(4-\beta^2)+2t_2]+t_1(2c+t_2)} - \frac{2}{(1-\beta)[2c(2+\beta)+t_1+t_2]} \right\}$ . The profit of the PCMs is  $\pi_i^d = (p - \rho^d - cg_i^d)(1 + g_i^d - \beta g_{3-i}^d) - t_i(g_i^d)^2/2$  and the profit of the SCMP is  $\pi_p^d = \frac{\{2c(2+\beta)(c+p-p\beta)+[p-p\beta+c(3+\beta)](t_1+t_2)+2t_1t_2\}^2}{4(1-\beta)[2c(2+\beta)+t_1+t_2]\{c[c(4-\beta^2)+2t_2]+t_1(2c+t_2)\}}$ .

### 3.2.3. Horizontal Cooperation Strategy

When two PCMs cooperate to improve the level of green technology, the PCMs are considered to form a strategic alliance to sell prefabricated components through the SCMP. In this case, the profit of the manufacturing alliance is

$$\pi_m = \sum_{i=1}^2 (p - \rho - cg_i)(1 + g_i - \beta g_{3-i}) - t_i g_i^2/2 \quad (7)$$

The manufacturing alliance and the SCMP constitute a Stackelberg game, where the SCMP first determines the service commission and then the manufacturing alliance decides the green technology level. According to the backward induction method, the optimal decisions of the manufacturing alliance and the management platform can be obtained.

From Equation (7), the Hessian matrix of  $\pi_m$  for  $g_1$  and  $g_2$  is  $H = \begin{bmatrix} \frac{\partial^2 \pi_m}{\partial g_1^2} & \frac{\partial^2 \pi_m}{\partial g_1 \partial g_2} \\ \frac{\partial^2 \pi_m}{\partial g_2 \partial g_1} & \frac{\partial^2 \pi_m}{\partial g_2^2} \end{bmatrix} = \begin{bmatrix} -2c - t_1 & 2c\beta \\ 2c\beta & -2c - t_2 \end{bmatrix}$ . When  $(2c + t_1)(2c + t_2) > 4c^2\beta^2$ ,  $H$  is a negative definite matrix. Therefore, solving  $\frac{\partial \pi_m}{\partial g_i} = 0$  obtains the green technology level, which is

$$g_i = \frac{[(1 - \beta)(p - \rho) - c][2c(1 + \beta) + t_{3-i}]}{4c^2(1 - \beta^2) + 2ct_2 + t_1(2c + t_2)} \quad (8)$$

Bring Equation (8) into Equation (3) and obtain  $\frac{\partial^2 \pi_p}{\partial \rho^2} = -\frac{2(1-\beta)^2[4c(1+\beta)+t_1+t_2]}{4c^2(1-\beta^2)+2ct_2+t_1(2c+t_2)} < 0$ . Solving  $\frac{\partial \pi_p}{\partial \rho} = 0$  obtains the optimal service commission, which is

$$\rho^h = \frac{4c(c + p - p\beta)(1 - \beta^2) + (t_1 + t_2)[p(1 - \beta)^2 + c(3 + \beta)] + 2t_1t_2}{2(1 - \beta)^2[4c(1 + \beta) + t_1 + t_2]} \quad (9)$$

Bring Equation (9) into Equation (8) to obtain the optimal green technology level, which is  $g_i^h = \frac{1}{2}[c(2 + \beta) + t_{3-i}] \left\{ \frac{p(1-\beta)-c}{4c^2(1-\beta^2)+2ct_2+t_1(2c+t_2)} - \frac{2}{(1-\beta)[4c(2+\beta)+t_1+t_2]} \right\}$ . The profit of the manufacturing alliance is  $\pi_m^h = \sum_{i=1}^2 \left( p - \rho - cg_i^h \right) \left( 1 + g_i^h - \beta g_{3-i}^h \right) - t_i \left( g_i^h \right)^2 / 2$  and the profit of the SCMP is  $\pi_p^h = \frac{\{4c(1+\beta)[p(1-\beta)+c(1-2\beta)] + (3c+p-p\beta)t_2 + t_1(3c+p-p\beta+2t_2)\} \{4c(c+p-p\beta)(1-\beta^2) + [p(1-\beta)^2 + c(3+\beta)](t_2+t_1) + 2t_1t_2\}}{4(1-\beta)[4c(1+\beta)+t_1+t_2][4c^2(1-\beta^2)+2ct_2+t_1(2c+t_2)]}$ .

### 3.2.4. Vertical Cooperation Strategy

In this case, the SCMP cooperates with PCM 1 and does not cooperate with PCM 2. This scenario is considered the vertical cooperation strategy. In this case, the cooperating PCM 1 can be considered a subsidiary firm of the SCMP, but the non-cooperating PCM 2 is an ordinary firm. In this case, the profit of the SCMP is

$$\pi_p = (p - cg_1)(1 + g_1 - \beta g_2) - t_1 g_1^2 / 2 + \rho(1 + g_2 - \beta g_1) \quad (10)$$

The profit of the PCM 2 is

$$\pi_2 = (p - \rho - cg_2)(1 + g_2 - \beta g_1) - t_2 g_2^2 / 2 \quad (11)$$

The decision sequence is as follows. The SCMP first determines the service commission, and then the SCMP and the PCM 2 determine the green technology level, respectively. According to the backward induction method, the optimal decisions of the service commission and green technology level can be obtained.

According to Equation (11), there are  $\frac{\partial^2 \pi_p}{\partial g_1^2} = -2c - t_1 < 0$  and  $\frac{\partial^2 \pi_2}{\partial g_2^2} = -2c - t_2 < 0$ . Therefore, solving  $\frac{\partial \pi_p}{\partial g_1} = 0$  and  $\frac{\partial \pi_2}{\partial g_2} = 0$  obtains the green technology level, which is

$$g_1 = \frac{c(p-c)(2+\beta) - 3c\beta\rho + (p-\beta\rho-c)t_2}{c[c(4-\beta^2) + 2t_2] + t_1(2c+t_2)} \quad (12)$$

$$g_2 = \frac{c(p-c)(2+\beta) - c(2+\beta^2)\rho + (p-\rho-c)t_1}{c[c(4-\beta^2) + 2t_2] + t_1(2c+t_2)} \quad (13)$$

Bringing Equations (12) and (13) into Equation (10) can obtain  $\frac{\partial^2 \pi_p}{\partial \rho^2} = -\frac{[2c(1-\beta^2)+t_1]\{c[c(8+\beta^2)+4t_1]+2(2c+t_1)t_2\}-\beta^2(2c+t_1)t_2^2}{\{c[c(4-\beta^2)+2t_2]+t_1(2c+t_2)\}^2} < 0$ , and solving  $\frac{\partial \pi_p}{\partial \rho} = 0$  obtains the optimal service commission, which is

$$\rho^v = \frac{c^3(c+p-p\beta)(8+8\beta+\beta^3+\beta^4) + ct_1\{4c^2(2+\beta) + pc[8+(2-\beta)^2\beta]\} + 2(c+p+p\beta)t_1}{t_2(2c+t_1)\{c\{c[6+(4-\beta)\beta] + p(1-\beta)(2-\beta^2)\} + (3c+p+p\beta)t_1\} + (2c+t_1)[c(2+\beta) + t_1 - p\beta]t_2^2}.$$

Bringing  $\rho^v$  into Equations (12) and (13) obtains  $g_1^v$  and  $g_2^v$ , and further calculations yield  $\pi_p^v$  and  $\pi_2^v$ .

## 4. Analysis of Equilibrium Solutions

We set  $t_1 = t_2 = t$  to better analyze the optimal decisions of different cooperative strategy models. Conclusions 1–3 show the changes and comparative results of the optimal decisions under four models.

**Conclusion 1:** (1)  $\rho^h > \rho^d > \rho^v$ . (2)  $\frac{\partial \rho^j}{\partial t} > 0, \frac{\partial \rho^j}{\partial c} > 0, \frac{\partial \rho^j}{\partial \beta} > 0$ .  $j = d, h, v$ .

**Proof of Conclusion 1.** See Appendix A.1. □

Conclusion 1 illustrates that the optimal service commission is the highest in the horizontal cooperation model, which is different from the conclusion that the price is lower in the horizontal cooperation alliance in product retailing [27]. The optimal service commis-



sion is the lowest in the vertical cooperation model, which is because the SCMP can plunder the market for more profit by cooperating with PCMs and does not rely on the service commission to maintain the platform operation. Compared with the non-cooperation strategy, under the horizontal cooperation strategy where PCMs ally, the SCMP will instead increase the service commission. This suggests that the strategic alliance formed by PCMs does not increase the bargaining power in cooperation with the platform, but instead leads to higher service commissions. The optimal service commission increases with the increase in the cost parameter and the marginal cost of green technology enhancement. The increase in cost parameters and marginal cost makes it more difficult to upgrade the green technology, which affects market demand and reduces the volume of transactions, and the platform will increase the service commission to maintain the operation of the platform. The increased competitive intensity of PCMs will cause platforms to take the opportunity to increase service commissions, thereby gaining more revenue through scale advantages.

**Conclusion 2:** (1) When  $\beta < 0.5$ , there is  $g_i^c > g_i^d > g_i^h$ ; when  $\beta > 0.5$ , if  $t < \frac{2c(1-\beta)^2}{2\beta-1}$ , there is  $g_i^c > g_i^d > g_i^h$ , but if  $t > \frac{2c(1-\beta)^2}{2\beta-1}$ ,  $g_i^c > g_i^d > g_i^h$  holds if  $p < p^*$ ;  $g_i^d > g_i^c > g_i^h$  holds if  $p > p^*$ .  $p^* = \frac{t^2+ct(3-2\beta)+2c^2(1-\beta)^2}{(1-\beta)[2t\beta-2c(1-\beta)^2-t]}$ . (2)  $\frac{\partial g_i^j}{\partial t} < 0$ ,  $\frac{\partial g_i^j}{\partial c} < 0$ ,  $\frac{\partial g_i^j}{\partial \beta} < 0$ ,  $i = 1, 2$ ,  $j = c, d, h, v$ .

**Proof of Conclusion 2.** See Appendix A.2.  $\square$

Conclusion 2 shows that when the competition coefficient between PCMs is small, the supply chain under the integration strategy makes decisions to maximize the profit of the system and can achieve the highest level of green technology. However, the green technology level under the horizontal cooperation strategy is the lowest, indicating that cooperation among PCMs does not effectively improve the green technology level. This is because the cooperation among PCMs leads to green technology not being able to realize technology spillover through market competition, which reduces the green technology level. Under the four cooperation strategies, the green technology level decreases with the increase in the cost parameter and the marginal cost of green technology enhancement as well as the intensity of competition among PCMs. The increase in the cost parameter and the marginal cost of green technology enhances the difficulty of PCMs to carry out green innovation, so the level of green technology decreases with the increase in the cost parameter and marginal cost, whereas the increase in competitive intensity indicates that when the substitutability between prefabricated components increases, PCMs tend to favor cost maintenance benefits since green technology enhancement leads to an increase in input costs and testing costs. Conclusion 2 suggests that it is necessary to guide the cooperation between PCMs and management platforms to enhance information exchange through the application of technologies, such as blockchain and informatization [40,41], to reduce the marginal cost and cost parameters. In addition, the differentiation of prefabricated components between different manufacturers should be enhanced to prevent the emergence of malicious competition.

**Conclusion 3:** (1) When  $F(t) > \beta[c^4(1-\beta)^2\beta + 2c^3p\beta(1-\beta)^3 + \beta c^2p^2(1-\beta)^4]$ , there is  $\frac{\pi_m^h}{2} > \pi_i^d$ . (2) When  $G(t) > c^3(1-\beta)^2 + 2c^2p(1-\beta)^3 + cp^2(1-\beta)^4$ , there is  $\pi_p^h > \pi_p^d$ .  

$$F(t) = -2t^4\beta - t^3\beta[2c(5-3\beta) + 2p(1-\beta)] - t\beta[4c^3(2-\beta)(1-\beta) - 2cp^2\beta(1-\beta)^3 + 2c^2p(1-\beta)^2(4-3\beta)] + t^2\beta\{p^2(1-\beta)^2\beta - 2cp(1-\beta)(4-3\beta) - 2c^2[8-\beta(9-2\beta)]\}$$
 and  $G(t) = t^3 + ct^2(3-2\beta) + t[c^2(1-\beta) - p^2(1-\beta)^3]$ .

It can be seen that the green technology level under the horizontal cooperation model is the lowest from Conclusion 2, which also means that the input cost and marginal cost may be the lowest. Therefore, when the cost parameter of the green technology level enhancement meets certain conditions, if the PCMs share the alliance profit equally, it may motivate the PCMs to form a cooperative alliance. Further analysis of  $F(t)$  shows that as  $t$  increases, the change of  $F(t)$  is uncertain. This indicates that the cost parameter of

green technology enhancement affects PCMs' choice of whether to form a manufacturing alliance, which further affects the profitability of the platform and stimulates the platform to cooperate with PCMs to form a vertical cooperative alliance which undermines the manufacturing alliance and leads to the instability of the cooperation strategy.

## 5. Numerical Examples and Case Analysis

### 5.1. Numerical Examples

Since expressions of equilibrium solutions under vertical cooperation strategies are complicated and it is more difficult to obtain intuitive conclusions, this section analyzes different cooperation strategies comparatively with numerical examples. Let  $t_1 = 5$  and  $c = 1$ ,  $t_2$  and  $\beta$  be independent variables,  $t_2 \in [3, 8]$ , and  $\beta \in [0.2, 0.7]$ . The changes in equilibrium solutions with  $t_2$  and  $\beta$  are shown in Figures 3–9.

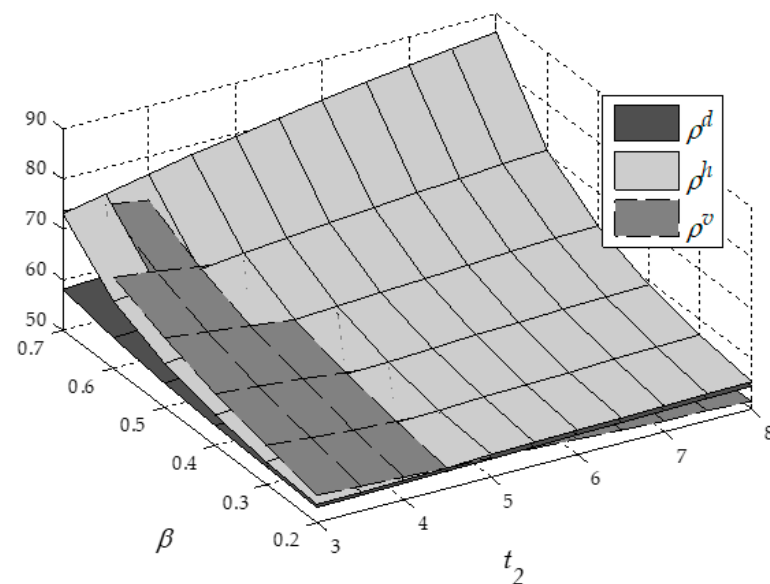


Figure 3. Changes in service commission.

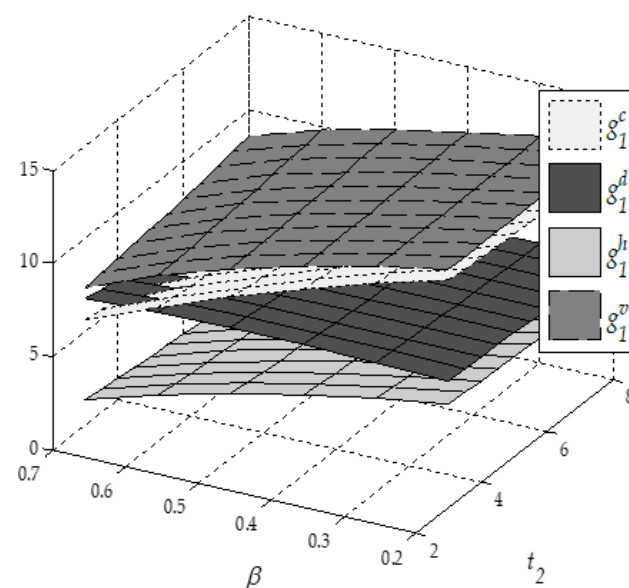


Figure 4. Changes in PCM 1's green technology level.

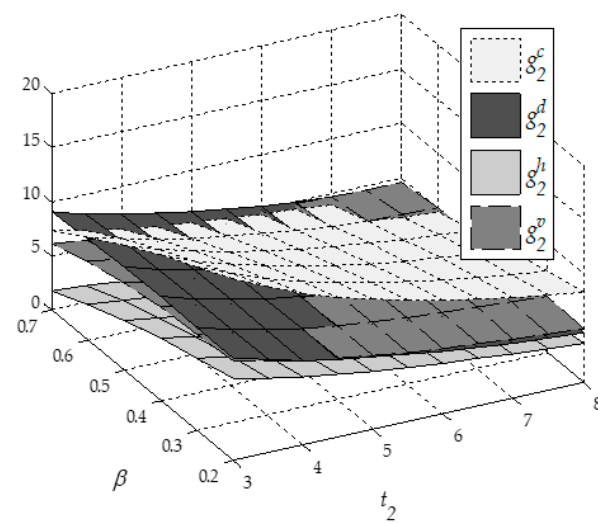


Figure 5. Changes in PCM 2's green technology level.

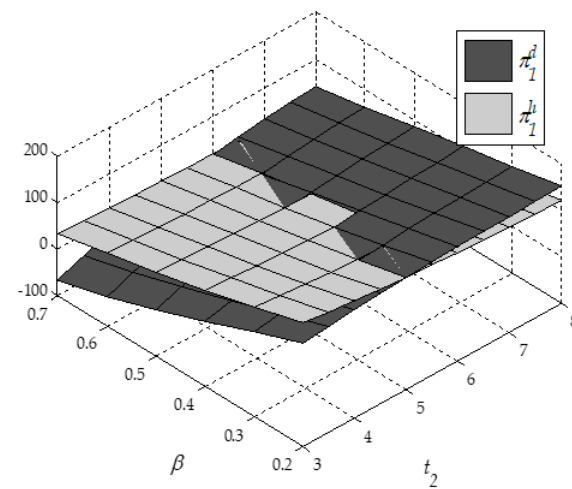


Figure 6. Changes in PCM 1's profits.

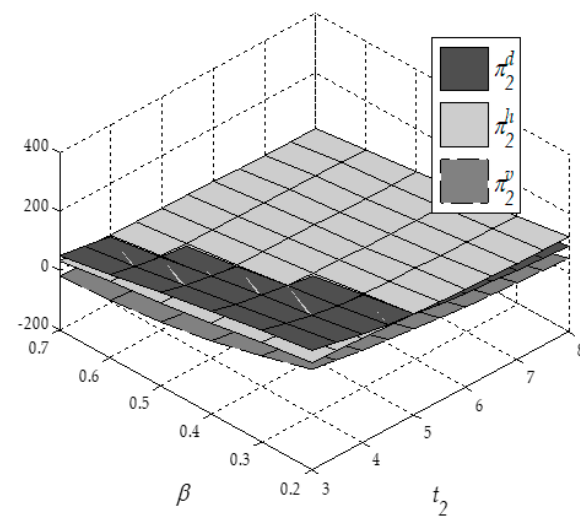


Figure 7. Changes in PCM 2's profits.

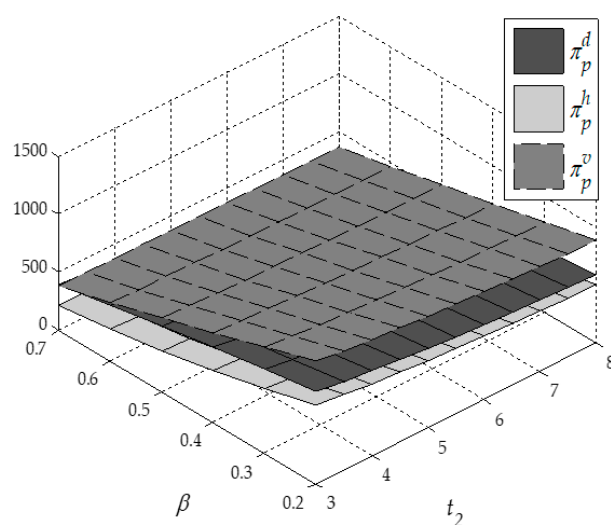


Figure 8. Changes in SCMP's profits.

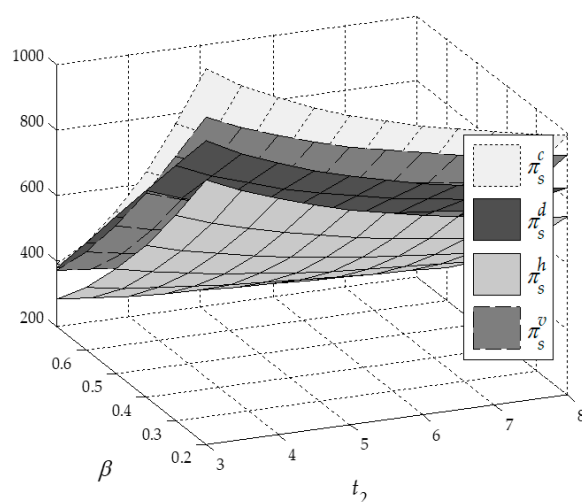


Figure 9. Changes in system profits.

Figure 3 illustrates that when the cost parameter of PCM 2 is large, the optimal service commission under the vertical cooperation strategy is the lowest, and the optimal service commission under the horizontal cooperation strategy is the highest, which is consistent with Conclusion 1. However, when the cost parameter of PCM 2 is small, the optimal service commission under the non-cooperative strategy is the lowest but is the highest under the vertical cooperative strategy. This is because PCM 2 has an advantage in upgrading green technology, and the management platform squeezes the profit margin of PCM 2 by setting higher service commissions under the vertical cooperation strategy.

From Figure 4, it can be seen that the green technology level of PCM 1 is the highest when PCM 1 cooperates with the platform and the competing PCM 2 does not participate in the cooperation. Moreover, when the competition coefficient is higher than a certain threshold ( $\beta > 0.6$ ), the green technology level of PCM 1 under the non-cooperation strategy will be higher than the green technology level under the integration strategy. Figure 5 shows that the green technology level of PCM 2 under the integration strategy is the highest when the intensity of competition is low, but when the competition is intense, the green technology level of PCM 2 under the vertical cooperation strategy is the highest if the cost parameter is large ( $t_2 > 6.5$ ); it is the highest under the non-cooperation strategy if the cost parameter is small ( $t_2 < 6.5$ ). In the case of fierce competition but a large cost parameter, PCM 2 still maintains the highest green technology level under the vertical

cooperation strategy, which is not favorable for the long-term development of PCM 2. Since the competition is fierce and improvement cost is high, the pursuit of improving the green technology level will lead to the inability to make profits, which affects the long-term development of the firm. Therefore, to improve the green technology level of PCMs, PCMs and platforms should strengthen cooperation, adopt an integration strategy, and make decisions to maximize the profit of the supply chain system.

Figure 6 shows that when the cost parameter of PCM 2 is small ( $t_2 < 5$ ), it is more favorable for PCM 1 to choose to form a manufacturing alliance with PCM 2, but when the cost parameter of PCM 2 is large ( $t_2 > 6$ ), PCM 1 does not have an incentive to cooperate with PCM 2. As can be seen in Figure 7, the vertical cooperation strategy of cooperation between PCM 1 and SCMP is the most unfavorable for PCM 2. Moreover, the optimal cooperation strategy of PCM 2 is the opposite of that of PCM 1. When PCM 2's cost parameter is large, the horizontal cooperation strategy is more profitable for PCM 2, whereas when PCM 2's cost parameter is small, the Nash game with PCM 1 leads to greater profitability. This is because when the cost parameter of PCM 2 is larger, the cost of upgrading green technology increases, and PCM 2 contributes less to the coalition but splits a larger profit, leading to a lower profit for PCM 1. This indicates that the way of dividing profits equally in manufacturing alliances is not reasonable and will most likely lead to alliance rupture, and it is important to develop a reasonable profit distribution method to maintain alliance stability [35]. In addition, Figures 6 and 7 indicate that when the cost parameter of PCM 2 roughly satisfies  $t_2 \in [4.5, 5]$ , PCM 1 and PCM 2 have the largest profits under the horizontal cooperation strategy. This means that when the cost parameters of the competing PCMs do not differ much, the formation of a cooperative alliance can realize Pareto improvement of both parties, and the horizontal cooperation strategy can realize a win-win situation for the PCMs.

From the point of view of the SCMP, as shown in Figure 8, the profit is the largest under the vertical cooperation strategy with PCM 1 but is the smallest under the horizontal cooperation strategy. This is because, under the vertical cooperation strategy, the SCMP integrates PCM 1 to maximize profit. However, under the horizontal strategy, the SCMP sets the highest service commission and has the lowest profit due to the lowest level of green technology and the negative impact on transactions. Figure 9 shows that the supply chain system has the lowest profit under the horizontal cooperation strategy, where the level of green technology is the lowest, so the prefabricated-component alliance formed by the horizontal cooperation of PCMs is the most unfavorable to the supply chain system. This is similar to the conclusion of the study on competitive supply chain cooperation strategies under the carbon trading mechanism, that horizontal cooperation among manufacturers is not beneficial to the development of firms [29]. Therefore, the SCMP should design coordination contracts to encourage PCMs to give up horizontal cooperation to realize greater environmental benefits. When the market competition coefficient is small ( $\beta < 0.4$ ), the supply chain system profit under the vertical cooperation strategy is larger than that under the non-cooperation strategy, but the lowest level of green technology in the vertical cooperation strategy is detrimental to environmental protection. When the competition is fierce ( $\beta > 0.6$ ), the supply chain system profit under the non-cooperative strategy is larger than that under the vertical cooperative strategy, and the non-cooperative strategy is more favorable to the supply chain system. Therefore, when the market competition is fierce, it is necessary to make full use of the competition to improve the level of green technology, rely upon science and technology to improve effectiveness, and make rapid developments through innovation. From a comprehensive point of view, the system under the integration strategy is the most profitable, and the green technology level is higher, which is the most favorable for the supply chain system and environmental protection. However, the integration strategy requires PCMs and the SCMP to form an integrated operation mode, which is difficult to realize, requires the integrated PCMs to strengthen data integration, improves the informatization level of the SCMP, and realizes multi-party collaborative supply chain management [42].

## 5.2. Case Analysis

To further illustrate the practical significance of green cooperation in the PBSC, this subsection chooses the Hunan Assembly Building Industry Chain Intelligent Construction Platform led by the Hunan Provincial Government as a case to demonstrate that PBSC firms have to strengthen green cooperation with the SCMP.

The Hunan Assembly Building Industry Chain Intelligent Construction Platform consists of a government-side industrial public service platform and an enterprise-side industrial application platform. The PBSC formed by the enterprise-side industrial application platform, integrating designers, component manufacturers, contractors, etc., is the real-life operation case of the integration strategy. The platform has a digital production system for prefabricated components, and the platform applies modern information technology to integrate PBSC firms such as BIM centers, PCMs, and contractors; effectively integrates component dealer information; and facilitates green cooperation through the establishment of a standardized building product library. It is reported that in Dongfanghong Group's pilot project for the construction of teaching and living facilities at Jishou University Teachers College, 70% of the prefabricated laminated floor slabs and 60% of the prefabricated internal partition walls are made of components in the standardized building component library. (The report is available at <https://www.hunantoday.cn/news/xhn/202109/15275551.html> (accessed on 6 November 2023)). All prefabricated components are digitally modeled and transferred to the production chain through the BIM design software, the BOM list is automatically generated and transferred to the production management system, and the data are transferred to the production management system for the processing of reinforcement and concrete pouring. The data-driven automatic production of equipment was realized in steel processing and concrete pouring, which reduced material waste. Due to the optimized scheduling management, the production lines were reasonably deployed, the overall efficiency was increased by 30%, and the cost was reduced by 20%.

## 6. Discussion

### 6.1. Results

The carbon peaking and carbon neutrality goals proposed by China have put forward higher requirements for the green technology level of the construction supply chain, and green cooperation between upstream and downstream firms in the supply chain is an important way to realize the high-quality development of the construction industry. However, the green input cost reduces the willingness of firms to improve the green technology level, and the competitive environment makes the green cooperation strategy of the PBSC more complicated. This paper constructs a PBSC consisting of an SCMP, a contractor, and competitive PCMs. Four green cooperation strategies of PCMs and the SCMP, i.e., the integration strategy, non-cooperation strategy, horizontal cooperation strategy, and vertical cooperation strategy, are explored and the green technology level and supply chain profit under different cooperation strategies are examined.

The study shows that the optimal service commission of the SCMP increases with the cost parameter of the green technology, and the more intense the competition among PCMs is, the higher the optimal service commission. However, the green technology level decreases with the competition, which is different from the conclusion that the green level increases with the increase in the intensity of competition among manufacturers [34,35]. This is because, although an increase in the level of green technology by PCMs is beneficial to green construction, the cost of technology testing that the SCMP requires PCMs to conduct also increases. Whereas in the existing literature, there is a lack of research on the constraint that the manufacturer's green level incurs testing costs, this practical issue is considered in this paper, and thus the result shows that the green technology level decreases with the increase in competitive intensity. This result suggests that competition among PCMs is not conducive to the improvement of green technology and PCMs should strengthen cooperation.



The integration strategy does not necessarily achieve the highest level of green technology, which is highest under the non-cooperative strategy when the competition is fierce, the cost of green technology is high, and the transaction price is high. This is different from the conclusion that horizontal cooperation among retailers is more favorable when the competition is strong [38]. The horizontal cooperation of retailers in the existing literature is to optimize the pricing strategy and the greenness of products, and the increasing of greenness helps expand the market share and gain more sales profits; in this paper, if the transaction price is high and the cost parameter of a competing PCM is large under the non-cooperative strategy, it can be sufficiently driven by the PCM to capture the market by increasing the level of green technology, so when the intensity of the competition is large, it may be possible to conclude that the level of green technology is highest under the non-cooperative strategy.

Although horizontal cooperation among competing PCMs is not conducive to improving the green technology level, PCMs always have incentives to form horizontal cooperative alliances to achieve Pareto improvement when the cost parameters of green technology do not differ significantly. For the SCMP, the vertical cooperation strategy with PCMs is the most favorable, but the horizontal cooperation strategy of PCMs is the least favorable. For the PBSC, the system profit under the integration strategy is the most profitable, which is consistent with existing research [36,37]. It is further shown that the economic and environmental benefits of the supply chain system are the greatest under the integration strategy with a high level of green technology.

### 6.2. Managerial Implications

Based on the aforementioned conclusions, the following management insights can be obtained.

PCMs should strengthen the competitiveness of prefabricated components and enhance the differentiation of components to prevent the emergence of malicious competition. They should continuously improve the level of green technology to help environmental protection production and form benign competition through green technology innovation. Moreover, PCMs should control carbon emissions in the production process and realize sustainable development through the innovation of green technology and the improvement of lean production [43].

Firms should take into account the economic and environmental benefits and choose appropriate cooperation strategies based on the cost parameters of green technology and market competition. When levels of green technology research and development are comparable, PCMs should form a cooperative alliance which can realize Pareto improvement, and the horizontal cooperation strategy can realize a win-win situation for PCMs. But when the market competition is fierce, it is necessary to make full use of the competition to improve the level of green technology.

The PBSC should make full use of the SCMP, strengthen information exchange, realize horizontal and vertical cooperation between upstream and downstream firms, and realize win-win economic and environmental benefits.

### 6.3. Limitations and Future Research

This paper explores the cooperation strategy between PCMs and the SCMP in the PBSC but does not consider the cooperation strategy between the SCMP and contractors. The contractors need to be integrated into the decision-making system of the PBSC to research the green cooperation strategy between contractors and the SCMP. Moreover, the pricing decisions of contractors are considered as the exogenous variable in this paper, but the pricing can influence the decision-making process, and future research considering the pricing decision is necessary.

## 7. Conclusions

SCMPs integrate multiple participating entities of the PBSC through Internet technology to realize green collaborative management. This paper constructs an operation PBSC model and four green cooperation strategies are examined, that is, the integration strategy, non-cooperation strategy, horizontal cooperation strategy, and vertical cooperation strategy. Stackelberg game models are used to study the green technology level and supply chain profit. It is found that competition among PCMs is not conducive to the improvement of the green technology level, and the integration strategy does not necessarily achieve the highest green technology level. The horizontal cooperation among competing PCMs is not conducive to the improvement of the green technology level, but when the cost parameters of green technology improvement are close, PCMs always have incentives to form a horizontal cooperation alliance to realize Pareto improvement. The SCMP profits most from the vertical cooperation strategy but profits least from the horizontal cooperation strategy. The integration strategy has the highest system profit and the highest level of green technology, which can realize a win-win situation in terms of economic and environmental benefits. This study enriches the operational research on green cooperation and provides theoretical guidance for PBSC firms for green cooperation.

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## Appendix A

### Appendix A.1. Proof of Conclusion 1

$$\begin{aligned}\rho^h - \rho^d &= \frac{t\beta}{2(1-\beta)^2} > 0, \quad \frac{\partial \rho^d}{\partial t} = \frac{1}{2-2\beta} > 0, \quad \frac{\partial \rho^h}{\partial t} = \frac{1}{2(1-\beta)^2} > 0, \\ \rho^d - \rho^v &= \frac{\beta \left\{ 2t(2c+t)^3 + \beta(c+p+t)(2c^3 - 3c^2t - 4ct^2 - t^3) - \beta^2(c+t)[2c^3 - cpt - pt^2 + 2c^2(2p+t)] \right.}{2(1-\beta)[2(2c+t)^3 - (2c+t)(7c^2 + 4ct + t^2)\beta^2 - 2c^3\beta^4]} \\ &\quad \left. - 2c\beta^3(c^3 + c(c-3p)t - pt^2) + 2c^3(c+2p)\beta^4 - 2c^3p\beta^5 \right\}, \\ \frac{\partial \rho^v}{\partial t} &= \frac{\left\{ (2c+t)^2(5c+3p+4t) + 3c(2c+t)^2\beta - 2c[c(c+3p) + (c+p)t]\beta^2 + cp(3c+2t)\beta^3 \right\}}{\left\{ 2(2c+t)^3 - (2c+t)(7c^2 + 4ct + t^2)\beta^2 - 2c^3\beta^4 \right\} + 3[2(2c+t)^2 - (5c^2 + 4ct + t^2)\beta^2]} \\ &\quad \times \frac{\left\{ (2c+t)^3(c+p+t) + c(2c+t)^3\beta - c(2c+t)[4cp + (c+p)t]\beta^2 + c(c^2(c+p) + 3cpt + pt^2)\beta^3 + c^4\beta^4 - c^3p\beta^5 \right\}}{\left\{ 2(2c+t)^3 - (2c+t)(7c^2 + 4ct + t^2)\beta^2 - 2c^3\beta^4 \right\}^2}.\end{aligned}$$

Since  $0 < \beta < 1$  and  $p(1-\beta) > c$ , then  $\rho^d > \rho^v$  and  $\frac{\partial \rho^v}{\partial t} > 0$ . Similarly, the first derivatives of the optimal service commission for  $c$  and  $\beta$  under different cooperation strategies are positive.

## Appendix A.2. Proof of Conclusion 2

$$\begin{aligned}
g_i^d - g_i^h &= \frac{\beta[c^2 + pt + c(p - p\beta)]}{2[t + c(2 - \beta)][t + 2c(1 - \beta)]} > 0, \quad g_i^c - g_i^h = \frac{c + t + p(1 - \beta)^2 - c\beta}{2[t + 2c(1 - \beta)](1 - \beta)} > 0. \\
g_i^c - g_i^d &= \frac{1}{2} \left\{ \frac{p}{c} + \frac{p - c}{t + c(2 - \beta)} - \frac{2c^2 + pt}{c[t + 2c(1 - \beta)]} - \frac{1}{1 - \beta} \right\}. \quad \text{Solving } g_i^c - g_i^d = 0 \text{ obtains} \\
p^* &= \frac{t^2 + ct(3 - 2\beta) + 2c^2(1 - \beta)^2}{(1 - \beta)[2t\beta - 2c(1 - \beta)^2 - t]}. \\
\frac{\partial g_i^c}{\partial t} &= -\frac{p(1 - \beta) - c}{(t - 2c(-1 + \beta))^2} < 0, \quad \frac{\partial g_i^d}{\partial t} = -\frac{p - c}{2(t - c(-2 + \beta))^2} < 0, \quad \frac{\partial g_i^h}{\partial t} = -\frac{p(1 - \beta) - c}{2(t - 2c(-1 + \beta))^2} < 0. \\
\frac{\partial g_1^v}{\partial t} &= \frac{F(p)}{[2(2c + t)^3 - (2c + t)(7c^2 + 4ct + t^2)\beta^2 - 2c^3\beta^4]^2}, \quad \frac{\partial F(p)}{\partial p} = -(1 - \beta)f(c), \text{ and it is obvious that} \\
f(c) &> 0; \quad \text{therefore } \frac{\partial F(p)}{\partial p} < 0, \quad F(p)|_{\max} = F(p)|_{p=\frac{c}{1-\beta}} = \\
c\beta &\left( -2(2c + t)^4 - (c - t)(2c + t)^2(3c + t)\beta^2 + 2c(2c + t)(4c + t)(3c + 2t)\beta^4 - 4c^4\beta^6 \right) < 0 \text{ and } \frac{\partial g_1^v}{\partial t} < 0. \\
\text{Note that}
\end{aligned}$$

$$\begin{aligned}
F(p) &= 3 \left[ 2(2c + t)^2 - (5c^2 + 4ct + t^2)\beta^2 \right] \left\{ 2(c - p)(2c + t)^2 + (2c + t)[5c^2 + t(p + t) + \right. \\
&\quad \left. c(p + 4t)]\beta + [c^3 + 4cpt + pt^2 + c^2(5p + t)]\beta^2 - c^2(c + 2p + t)\beta^3 + cp(3c + t)\beta^4 \right\} + [-2 \\
&\quad (2c + t)^3 + (2c + t)(7c^2 + 4ct + t^2)\beta^2 + 2c^3\beta^4]c^2(8 + \beta(13 + \beta - \beta^2)) + t[3t\beta + 2p(-2 \\
&\quad + \beta + \beta^2)] + c\{4(t + 3t\beta) + p[-8 + \beta(3 + 4\beta + \beta^3)]\},
\end{aligned}$$

$$\begin{aligned}
f(c) &= t^4(2 + \beta)(2 - \beta^2) + 4c^3t(1 + \beta)(32 - 4\beta + 7\beta^3 - 8\beta^4) + 2ct^3(2 - \beta^2) \\
&\quad [8 + \beta(5 + \beta + \beta^2)] + c^4(1 + \beta)[64 + \beta^3(36 - 21\beta + 2\beta^3)] + 3c^2t^232 + \beta[24 - \beta \\
&\quad (8 + \beta + 3\beta^2 + 5\beta^3)].
\end{aligned}$$

Similarly, it can be proved that  $\frac{\partial g_2^v}{\partial t} < 0$ ,  $\frac{\partial g_i^j}{\partial c} < 0$ , and  $\frac{\partial g_i^j}{\partial \beta} < 0$ .

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