# Coordination Mechanism of Wooden Furniture Supply Chains with Consideration of Carbon Footprint

Hui Wang, Jinzhuo Wu,* Bing Han, and Yilin Fang

This study emphasizes a three-level wooden furniture supply chain, which involves one supplier, one manufacturer, and one retailer. Focusing on maximizing the profit of the supply chain while adhering to low-carbon principles, the Three-level Leader-follower Game (TLG) model, Stackelberg Game Model I (SGI model), Stackelberg Game Model II (SGII model), and Cooperative Decision-making (CD) model were established by using game theory. The carbon emission reduction cost and benefit sharing contract was introduced into the model with the maximum profit, and the ranges of sharing coefficients for a solid wood bed supply chain and the optimal decision-making process for each supply chain member were discussed. Results showed that the profit for the solid wood bed supply chain reached maximum under the CD model, followed by the SGII model, and then the SGI model, and the TLG model showed the lowest profit. A higher preference for low-carbon products can lead to lower demand for products and higher retail prices. Through introducing the cost and benefit-sharing contract into the CD model, the profit of the supply chain can be guaranteed with different sharing coefficients, and the profit of each member was improved compared to the TLG model.

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## INTRODUCTION

Mitigating climate change by decreasing global greenhouse gas emissions is currently one of the major challenges faced by human beings (Vicente-Vicente and Piorr 2021). To control carbon emissions and achieve carbon reduction targets, a series of carbon reduction policies have been introduced by governments, and green supply chain management in all sectors have gained increased attention (Zhu and Côté 2004; Dragomir 2012; Zhou *et al.* 2014). According to a report by the Intergovernmental Panel on Climate Change (IPCC), the forestry industry is the third-largest source of greenhouse gas emissions after the energy industry and manufacturing industry (Bai 2013). Currently, China has become the world's largest emitter of carbon dioxide. Both the total carbon footprints and carbon footprint intensity of the wooden furniture industry in China are rather large; therefore, it is critically important to reduce the carbon footprints of the wooden furniture supply chain (Gu *et al.* 2014). To promote the low-carbon development of the forestry industry, the core enterprises of the supply chains must expand their internal greening activities through vertical and horizontal integration with their upstream and downstream stakeholders (Noh and Kim 2019). The biggest challenge to the supply chain is to manage disparate but dependent members of the supply chain. For an efficient supply chain, it is required that all supply chain members behave coherently to achieve supply chain coordination (Whang 1995). This can be realized by making joint decisions on all processes of the supply chain, including procurement, production, distribution, as well as the allocations of resources and economic benefits (Kim *et al*. 2005). Therefore, it is necessary to introduce the coordination mechanism into the wooden furniture supply chain, which is of great significance to low-carbon development and green supply chain management for the wooden furniture industry.

Currently, most studies on the carbon footprint of the wooden furniture supply chain have aimed to identify the links with higher carbon footprint in business operations and supply chain management. For example, González-García *et al*. (2011) completed a life cycle assessment on several indoor and outdoor wood products from a cradle-to-gate perspective. The results showed that metals, boards, and energy usage were the most important factors contributing to the environmental impact of the different products under assessment, with total contributions ranging from 40% to 90%. Bai (2013) compared the carbon footprint of the production and processing process for tea cabinets made of wood-based panels and coffee tables and cabinets made of solid wood. The results showed that the carbon footprints of wood panel-based tea cabinets, solid wood-based coffee tables, and solid wood-based cabinets were 160 kg $CO_2$-eq, 89.9 kg $CO_2$-eq, and 139 kg $CO_2$-eq, respectively, and the carbon footprints of different products were mainly sourced from the processing of raw materials and the finishing process of the products. Wang *et al*. (2021) applied the ILCD 2011 midpoint assessment method to calculate the life-cycle carbon footprint of a solid wood bed (1800 mm × 2000 mm) based on imported logs. The results show that the carbon footprint of the upstream process accounted for 74.56% to 80.69% of the total carbon footprint, which was the major contributor to the total carbon footprint, followed by the downstream and manufacturing process. In summary, most of the carbon footprint of wooden furniture supply chains is borne by the upstream members in the supply chain, which has become an important link in reducing the carbon footprint of the entire supply chain.

Similar to other supply chains, a wooden furniture supply chain is also composed of different decision-makers pursuing different goals, and there may be conflicts among these goals, which may lead to the problem of “Double Marginalization” for the contract supply chain (Pang *et al.* 2014). The number of business members in the supply chain and the efforts of members to reduce carbon emissions can greatly affect the market demand for the wood furniture supply chain (Yong *et al*. 2007). In fact, supply chain members need to bear a certain amount of cost for their efforts, and the conflict between green effort level and cost will affect the coordination of the supply chain (Zui *et al.* 2008). Revenue sharing coordination mechanism is a coordination and profit distribution mechanism on the profits generated in a supply chain, negotiating commercial rules among the parties in the supply chain (Cachon and Lariviere 2005). In recent years, some studies have been conducted on the coordination mechanism of furniture supply chains to improve the operational performance of the supply chain. For example, Kang (2013) proposed revenue sharing and franchise fee coordination between suppliers and retailers in a furniture supply chain system based on the Stackelberg game model and found that the channel profit and member profit after coordination were greater than those under decentralized independent decision-making. Wen (2020) developed a model for furniture sellers to share the environmental costs with furniture manufacturers and analyzed the game between manufacturers and sellers in the case of revenue sharing. The calculations demonstrated that increasing the share of the manufacturer's environmental costs by a furniture seller under a revenue-sharing scheme had a positive effect on the manufacturer's improvement of environmental protection. Zheng (2020) analyzed the benefit distribution of a four-level furniture manufacturing green supply chain composed of raw material suppliers, furniture manufacturers, furniture sellers, and third-party logistics. A comprehensive benefit distribution model was established to determine the sharing value of each member in the green supply chain under comprehensive evaluation of multiple factors.

Since the carbon footprint of wood furniture products contributes to the combined emissions of upstream and downstream enterprises in the supply chain, the carbon reduction behavior of a single enterprise cannot effectively reduce the carbon footprint of the entire supply chain. Previous studies seldom considered the carbon reduction efforts of corporations from the perspective of supply chain. In fact, the carbon reduction behavior of supply chain members through technical carbon emission reduction or trading in the carbon emission market will increase the marginal cost of product, and the cost increment will be passed on to the downstream, thus causing the variations of market demand (Zui *et al.* 2008). Currently, China has set up carbon emission caps for some key enterprises and is moving the regional carbon emissions trading market to the national carbon emissions trading market (Liu *et al.* 2015). The part that exceeds the carbon emission cap can be traded in the carbon emission market. It is believed that the existence of emission regulation can promote collaboration of supply chain members (Benjaafar *et al.* 2013). With regard to wood furniture supply chain, the implementation of carbon reduction measures also requires the members to jointly bear a certain amount of costs, which will affect the profitability of the supply chain. Because the coordinated strategy between carbon footprint and profit in the three-level wooden furniture supply chain is rarely reported, it is necessary to coordinate the wood furniture supply chain to maximize the profits of the supply chain and the members with consideration of the carbon footprint of the supply chain.

The objectives of the study are to: (1) Establish four game models for the three-level (supplier-manufacturer-retailer) wooden furniture supply chain; (2) Compare the optimal decision-making under different models and conduct sensitivity analyses by considering different consumers' preferences on products with low carbon footprint; (3) Introduce the sharing contract of carbon emission reduction cost and benefit into the model with maximum profit to obtain the ranges of the optimal sharing coefficient for the members of the wooden furniture supply chain.

## METHODOLOGY

### Model Description and Hypotheses

A supply chain is usually comprised of suppliers, manufacturers, distributors, and consumers, involving supply, production, sales, transportation, consumption, recycling, and so on (Pang *et al*. 2014). In this study, the wooden furniture supply chain is composed of one supplier, one manufacturer, and one retailer, as shown in Fig. 1. It is assumed that the information among suppliers, manufacturers, and retailers is completely symmetrical. The supplier, the manufacturer, and the retailer are the main sources of carbon emissions in the wooden furniture supply chain, which can meet the demand for carbon emission rights for normal operations by reducing technological emissions and purchasing carbon credits from the trading market. In this study, profit maximization is assumed to be the highest priority of all actors with considerations of policy and/or other motivators such as consumer preferences, short-term priorities of compliance, and consumer satisfaction. The cost of carbon emissions reduction, as an environmental performance cost, may be considered as a corporate/capital investment. When suppliers and manufacturers invest in carbon emission reduction technologies or trade in the carbon market, part of the marginal cost of emission reduction is passed along to consumers at the per-unit price level. The explanations of the parameters in the study are shown in Table 1.

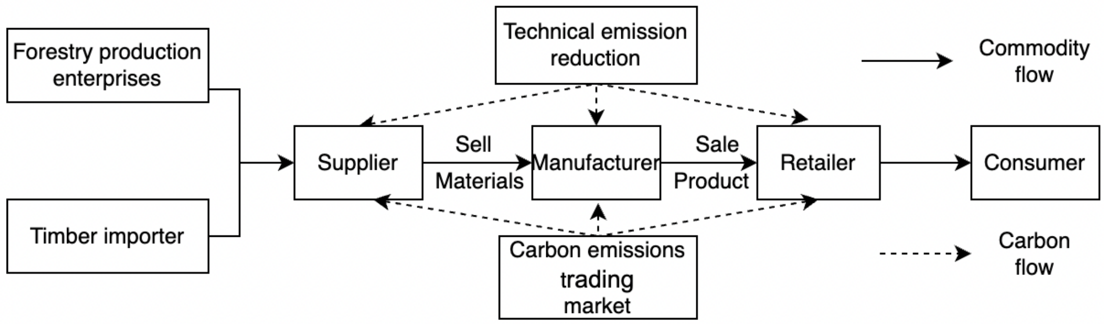


**Fig. 1.** Structure of the wooden furniture supply chain with consideration of carbon emissions

**Table 1.** Model Parameters for the Three-level Supply Chain

| Parameter | Explanation | Parameter | Explanation |
|---|---|---|---|
| $c_s$ | Raw material production cost per unit of product (US$/one piece) | $q$ | Demand on products (pieces) |
| $c_m$ | Manufacturing cost per unit of product (US$/one piece) | $w_s$ | Supply price of raw materials per unit of product (US$/one piece) |
| $e_s$ | Carbon emissions from supplying raw materials per unit of product (t $CO_2$-eq /one piece) | $w_m$ | Wholesale price per unit of product for the manufacturer (US$/one piece) |
| $e_m$ | Carbon emissions from manufacturing per unit of product (t $CO_2$-eq /one piece) | $P$ | Retail price per unit of product (US$/one piece) |
| $e_r$ | Carbon emissions from retailing per unit of product (t $CO_2$-eq /one piece) | $p_c$ | Carbon transaction price (US$/ t $CO_2$-eq) |
| $r$ | Cost coefficient of carbon reduction | $C$ | Enterprise's carbon reduction cost (US$) |
| $k$ | Consumers' preference on low carbon footprint | $E$ | Carbon footprint of the supply chain (t $CO_2$-eq) |
| $\Delta e$ | Supply chain emission reduction level (t $CO_2$-eq) | $G$ | Carbon emission cap of the entire supply chain (t $CO_2$-eq) |
| $\Pi_s$ | Profit of the supplier (US$) | $\Pi_r$ | Profits of the retailer (US$) |
| $\Pi_m$ | Profit of the manufacturer (US$) | $\Pi_{sc}$ | Profit of the supply chain (US$) |

The hypotheses for the three-level supply chain are as follows:

(1) The supplier sells the raw materials to the manufacturer at price $w_s$, the manufacturer sells the wooden furniture products to the retailer at price $w_m$, and the retailer sells the products at market price $P$. Assuming that the supply chain emission reduction level $\Delta e$ is a continuous variable, the carbon reduction cost

of supply chain is expressed as: $C = r\Delta e^2$ ($r > 0$), where $r$ is the carbon emission reduction cost coefficient (Subramanian *et al*. 2007).

(2) The carbon emissions cap for the entire supply chain and the carbon transaction price set by the carbon trading regulations are $G$ and $p_c$, respectively. The carbon transaction price is a linear function of the upper limit of carbon emissions set by the government, that is, the carbon transaction price $p_c = a - bG$, where $a$ and $b$ are constants (Luo *et al*. 2014).

(3) The retail price $P$ of a product depends on the carbon emissions $E$ of the supply chain, that is $P = v - kE$ ($0 < k < 1$), where $v$ is a constant and $k$ reflects the consumers' preference for carbon footprint. A higher $k$ value meant a greater appeal of low-carbon products to consumers; a smaller $k$ meant consumers were less sensitive to the carbon emissions of the supply chain. The carbon footprint of the supply chain is: $E=(e_s+e_m+e_r)q-\Delta e$, where $e_s$ is the carbon emissions from raw materials per unit of product, $e_m$ is the carbon emissions from manufacturing per unit of product, $e_r$ is carbon emissions from transporting per unit of product per kilometer, $\Delta e$ is the carbon emission reduction level of the supply chain, and $q$ is the demand on products (Yang and Ji 2013).

## Game Modeling Approach

*Three-level leader–follower game model (TLG model)*

The Three-level leader-follower game model is a non-cooperative three-level Stackelberg game between the members of the supply chain in an attempt to maximize their own interests (Pakseresht *et al*. 2020). Under the TLG model, the supplier, manufacturer and retailer, as different decision-making subjects, have not reached a binding agreement, and they make decisions with the goal of maximizing their own profits. The game sequence is as follows: firstly, according to the cost of raw materials $c_s$, the supplier determines the optimal supply price of raw materials $w_s^{TLG}$; then, according to the supply price $w_s^{TLG}$provided by the supplier and the carbon emission cap $G$ stipulated by the government, the manufacturer invests in technology emission reduction and determines the optimal wholesale price $w_m^{TLG}$of the retailed product and the optimal carbon reduction level $\Delta e^{TLG}$; finally, according to the wholesale price $w_m^{TLG}$of the manufacturer, the retailer determines the optimal demand on products $q^{TLG}$to maximize its profit. Therefore, the TLG model composed of one supplier, one manufacturer, and one retailer can be expressed as follows:

$$\begin{cases} max\Pi_s^{TLG} = (w_s^{TLG} - c_s)q^{TLG} \\ max\Pi_m^{TLG} = (w_m^{TLG} - c_m - w_s^{TLG})q^{TLG} - r\Delta e^{TLG^2} \\ -[(e_s + e_m + e_r)q^{TLG} - \Delta e^{TLG} - G](a - bG) \\ max\Pi_r^{TLG} = q^{TLG}\{v - k[(e_s + e_m + e_r)q^{TLG} - \Delta e^{TLG}] - w_m^{TLG}\} \end{cases} \tag{1}$$

Under the TLG model, the above optimization problem can be solved by reverse induction. Take the partial derivative of the retailer's profit with respect to the product demand under the TLG model, and set the result equal to 0 to obtain the retailer's optimal product demand $q^{TLG}$ (Eq. 2).

$$q^{TLG} = (\Delta e^{TLG}k + v - w_m^{TLG}) / [2k(e_s + e_m + e_r)] \tag{2}$$

The manufacturer maximizes its own profit through decision ($w_m^{TLG}$, $\Delta e^{TLG}$). Substitute Eq. 2 into Eq. 1 to calculate the partial derivative of the manufacturer's profit with respect to the wholesale price and carbon emission reduction level under the TLG model, and then make the result equal to 0, and solve the simultaneous equations to obtain the manufacturer's optimal wholesale price $w_m^{TLG}$ (Eq. 3) and the optimal carbon reduction level $\Delta e^{TLG}$ (Eq. 4):

$$w_m^{TLG} = [4(a - bG)(e_s + e_m + e_r)^2 r + k(e_s + e_m + e_r)(a - bG) - k(w_s^{TLG} + c_m) + 4(e_s + e_m + e_r)r(w_s^{TLG} + c_m + v)] / [8(e_s + e_m + e_r)r - k] \quad (3)$$

$$\Delta e^{TLG} = [3(a - bG)(e_s + e_m + e_r) - c_m - w_s^{TLG} + v] / [8(e_s + e_m + e_r)r - k] \quad (4)$$

The supplier maximizes its own profit through decision $w_s^{TLG}$. Substitute Eqs. 2 through 4 into Eq. 1 to calculate the partial derivative of the supplier's profit with respect to the supply price under the TLG model, and make the result equal to 0, then the optimal supply price of raw materials per unit of product $w_s^{TLG*}$ (Eq. 5) can be obtained according to the first-order optimal condition:

$$w_s^{TLG*} = \{(a - bG)[k - 2(e_s + e_m + e_r)r] + 2r(c_s - c_m + v)\} / 4r \quad (5)$$

According to hypothesis 3, equilibrium solutions can be obtained from Eqs. 2 through 5, When the condition $0 < k < 8(e_s + e_m + e_r)r$ is met, the manufacturer's optimal wholesale price $w_m^{TLG*}$ (Eq. 6), the optimal carbon reduction level $\Delta e^{TLG*}$ (Eq. 7), and the retailer's optimal demand on products $q^{TLG*}$ (Eq. 8) can be obtained, respectively:

$$w_m^{TLG*} = \{(a - bG)[-k^2 + 10k(e_s + e_m + e_r)r + 8(e_s + e_m + e_r)^2 r^2] + 4(e_s + e_m + e_r)r(c_s + 3v) - k(c_s + v) - 2rc_m[k - 4(e_s + e_m + e_r)r]\} / \{4r[8(e_s + e_m + e_r)r - k]\} \quad (6)$$

$$\Delta e^{TLG*} = \{(a - bG)[k - 14(e_s + e_m + e_r)r] + 2r(c_s + c_m - v)\} / \{4r[8(e_s + e_m + e_r)r - k]\} \quad (7)$$

$$q^{TLG*} = \{(a - bG)[-k + 2(e_s + e_m + e_r)r] + 2r(c_s + c_m - v)\} / \{2k[k - 8(e_s + e_m + e_r)r]\} \quad (8)$$

Based on the above analysis, the optimal carbon emissions of the supply chain $E^{TLG*}$ (Eq. 9), the optimal retail price of the product $P^{TLG*}$ (Eq. 10), the optimal profit of the supplier $\Pi_s^{TLG*}$ (Eq. 11), the optimal profit of the manufacturer $\Pi_m^{TLG*}$ (Eq. 12), the optimal profit of the retailer $\Pi_r^{TLG*}$ (Eq. 13), and the profit of the whole supply chain $\Pi_{sc}^{TLG*}$ (Eq. 14) can be obtained, respectively:

$$E^{TLG*} = (e_s + e_m + e_r)q^{TLG*} - \Delta e^{TLG*} \quad (9)$$

$$P^{TLG*} = v - k[(e_s + e_m + e_r)q^{TLG*} - \Delta e^{TLG*}] \quad (10)$$

$$\Pi_s^{TLG*} = (w_s^{TLG*} - c_s)\, q^{TLG*} \quad (11)$$

$$\Pi_m^{TLG*} = (w_m^{TLG*} - w_s^{TLG*} - c_m)\, q^{TLG*} - r(\Delta e^{TLG*})^2 - [(e_s + e_m + e_r)q^{TLG*} - \Delta e^{TLG*} - G](a - bG) \quad (12)$$

$$\Pi_r^{TLG*} = q^{TLG*}\{v - k[(e_s + e_m + e_r)q^{TLG*} - \Delta e^{TLG*}] - w_m^{TLG*}\} \quad (13)$$

$$\Pi_{sc}^{TLG*} = \Pi_s^{TLG*} + \Pi_m^{TLG*} + \Pi_r^{TLG*} \quad (14)$$

*Stackelberg game model I*

The Stackelberg game model I (SG model I) takes the cooperation between the supplier and the manufacturer into consideration, which is a non-cooperative two-level Stackelberg game between the small alliance I that is formed by the supplier and the manufacturer and the retailer and dominated by the alliance I (Zhang and Liu 2013). Under the SG model I, the alliance I is the major sources of carbon emissions in the wooden furniture supply chain. The game sequence is as follows: firstly, according to the cost of raw materials $c_s$, manufacturing cost $c_m$, and the carbon emission cap $G$ stipulated by the government, the alliance I invests in technology emission reduction and determines the optimal wholesale price $w_m^{SGI}$ of the retailed product and the optimal carbon reduction level $\Delta e^{SGI}$ of the supply chain; then, according to the wholesale prices $w_m^{SGI}$provided by the alliance I, the retailer determines the optimal demand on products $q^{SGI}$ to maximize its profit. Therefore, the SG model I can be expressed as follows:

$$\begin{cases} max\Pi_{sm}^{SGI} = (w_m^{SGI} - c_m - c_s)q^{SGI} - [(e_s + e_m + e_r)q^{SGI} - \Delta e^{SGI} - G] \\ (a - bG) - r{\Delta e^{SGI}}^2 \\ max\Pi_r^{SGI} = q^{SGI}\{v - k\,[(e_s + e_m + e_r)q^{SGI} - \Delta e^{SGI}) - w_m^{SGI}]\} \end{cases} \tag{15}$$

Under the SG mode I, the above optimization problem can be solved by reverse induction. According to the first-order optimal condition, the optimal product demand $q^{SGI}$ is obtained *via* Eq. 16;

$$q^{SGI} = (\Delta e^{SGI}k + v - w_m^{SGI}) / [2k(e_s + e_m + e_r)] \tag{16}$$

The alliance I maximizes its own profit through decision ($w_m^{SGI}$, $\Delta e^{SGI}$). Substitute Eq. 16 into Eq. 15 to calculate the partial derivative of the alliance I 's profit with respect to the wholesale price and carbon emission reduction level under the SG model I, make the result equal to 0, and solve the simultaneous equations to obtain the optimal carbon reduction level $\Delta e^{SGI*}$ (Eq. 17) and the manufacturer's optimal wholesale price $w_m^{SGI*}$ (Eq. 18):

$$\Delta e^{SGI*} = [-c_m - 3(e_s + e_m + e_r)(a - bG) - c_s + v] / [8(e_s + e_m + e_r)r - k] \tag{17}$$

$$w_m^{SGI*} = [k(c_s + c_m) - (e_s + e_m + e_r)(a - bG) - 4(a - bG)(e_s + e_m + e_r)^2 r - 4(e_s + e_m + e_r)r(c_s + c_m + v)] / [k - 8(e_s + e_m + e_r)r] \tag{18}$$

According to hypothesis 3, equilibrium solutions can be obtained from Eqs. 16 through 18. When the condition $0 < k < 8(e_s + e_m + e_r)r$ is met, the optimal demand on products $q^{SGI*}$ (Eq. 19), the optimal carbon emissions of the supply chain $E^{SGI*}$ (Eq. 20), the optimal retail price of the product $P^{SGI*}$ (Eq. 21), the optimal profit of the alliance I $\Pi_{sm}^{SGI^*}$ (Eq. 22), the optimal profit of the retailer $\Pi_r^{SGI^*}$ (Eq. 23), and the profit of the whole supply chain $\Pi_{sc}^{SGI^*}$ (Eq. 24) can be obtained, respectively:

$$q^{SGI*} = \{(-a + bG)[k - 2(e_s + e_m + e_r)r] + 2r(c_s + c_m - v)\} / \{k[k - 8(e_s + e_m + e_r)r]\} \tag{19}$$

$$E^{SGI*} = (e_s + e_m + e_r)q^{SGI*} - \Delta e^{SGI*} \tag{20}$$

$$P^{SGI*} = v - k[(e_s + e_m + e_r)q^{SGI*} - \Delta e^{SGI*}] \tag{21}$$

$$\Pi_{sm}^{SGI^*} = (w_m^{SGI*} - c_s - c_m)\, q^{SGI*} - r(\Delta e^{SGI*})^2 - [(e_s + e_m + e_r)q^{SGI*} - \Delta e^{SGI*} - G](a - bG) \tag{22}$$

$$\Pi_{\mathrm{r}}^{\mathrm{SGI}*} = q^{\mathrm{SGI}*}\{v - k[(e_{\mathrm{s}} + e_{\mathrm{m}} + e_{\mathrm{r}})q^{\mathrm{SGI}*} - \Delta e^{\mathrm{SGI}*}] - w_{\mathrm{m}}^{\mathrm{SGI}*}\} \quad (23)$$

$$\Pi_{\mathrm{sc}}^{\mathrm{SGI}^*} = \Pi_{\mathrm{sm}}^{\mathrm{SGI}^*} + \Pi_{\mathrm{r}}^{\mathrm{SGI}^*} \quad (24)$$

*Stackelberg game model II*

The Stackelberg game model II (SG model II) takes the cooperation between the manufacturer and the retailer into consideration, which is a two-level Stackelberg game between the small alliance II that is formed by the manufacturer and the retailer and the supplier. Different from the SG model I, the SG model II is dominated by the supplier (Chen *et al*. 2020). Under the SG model II, the alliance II has a preference for low-carbon products in the wooden furniture supply chain. The game sequence is as follows: firstly, according to the cost of raw materials $c_{\mathrm{s}}$, the supplier determines the optimal supply price $w_s^{\mathrm{SGII}}$ of the raw materials; then, according to supply price $w_s^{\mathrm{SGII}}$ of the raw materials provided by the supplier, the alliance II invests in technology emission reduction and determines the optimal demand on products $q^{\mathrm{SGII}}$ and the optimal carbon reduction level $\Delta \mathrm{e}^{\mathrm{SGII}}$ to maximize its profit. Therefore, the SG model II can be expressed as follows:

$$\begin{cases} max\Pi_{\mathrm{s}}^{\mathrm{SGII}} = (w_{\mathrm{s}}^{\mathrm{SGII}} - c_{\mathrm{s}})q^{\mathrm{SGII}} \\ max\Pi_{mr}^{\mathrm{SGII}} = \{v - k[(e_{\mathrm{s}} + e_{\mathrm{m}} + e_{\mathrm{r}})q^{\mathrm{SGII}} - \Delta e^{\mathrm{SGII}}] - c_{\mathrm{m}} - w_s^{\mathrm{SGII}}\}q^{\mathrm{SGII}} \\ -[(e_{\mathrm{s}} + e_{\mathrm{m}} + e_{\mathrm{r}})q^{\mathrm{SGII}} - \Delta e^{\mathrm{SGII}} - G](a - bG) - r\Delta e^{\mathrm{SGII}^2} \end{cases} \quad (25)$$

Under the SG model II, the above optimization problem can be solved by reverse induction. The alliance II maximizes its own profit through decision ($q^{\mathrm{SGII}}$, $\Delta \mathrm{e}^{\mathrm{SGII}}$), the optimal carbon reduction level $\Delta e^{\mathrm{SGII}}$ (Eq. 26), and the optimal demand on products $q^{\mathrm{SGII}}$ (Eq. 27) can be obtained:

$$\Delta e^{\mathrm{SGII}} = [-(a - bG)(e_{\mathrm{s}} + e_{\mathrm{m}} + e_{\mathrm{r}}) - c_{\mathrm{m}} - w_s^{\mathrm{SGII}} + v] / [4(e_{\mathrm{s}} + e_{\mathrm{m}} + e_{\mathrm{r}})r - k] \quad (26)$$

$$q^{\mathrm{SGI\,I}} = [(a - bG)k - 2r(c_{\mathrm{m}} + w_s^{\mathrm{SGII}} - v) - 2(a - bG)(e_{\mathrm{s}} + e_{\mathrm{m}} + e_{\mathrm{r}})r] / \{ - k[k + 4(e_{\mathrm{s}} + e_{\mathrm{m}} + e_{\mathrm{r}})r]\} \quad (27)$$

Substituting Eqs. 26 and 27 into Eq. 25, the optimal supply price of raw materials per unit of product $w_s^{\mathrm{SGII}*}$ (Eq. 26) can be obtained according to the first-order optimal condition. Take the partial derivative of the supplier's profit with respect to the supply price under the SG model II, and make the result equal to 0, the optimal supply price of raw materials per unit of product $w_s^{\mathrm{SGII}*}$ (Eq. 28) can be obtained according to the first-order optimal condition:

$$w_s^{\mathrm{SGII}*} = \{(a - bG)[k - 2(e_{\mathrm{s}} + e_{\mathrm{m}} + e_{\mathrm{r}})r] + 2r(c_{\mathrm{s}} - c_{\mathrm{m}} + v)\} / 4r \quad (28)$$

According to hypothesis 3, equilibrium solutions can be obtained from Eqs. 26 through 28. When the condition $0 < k < 4(e_{\mathrm{s}} + e_{\mathrm{m}} + e_{\mathrm{r}})r$ is met, the optimal demand on products $q^{\mathrm{SGII}*}$ (Eq. 29), the optimal carbon reduction level $\Delta \mathrm{e}^{\mathrm{SGII}*}$(Eq. 30), the optimal carbon emissions of the supply chain $E^{\mathrm{SGII}*}$ (Eq. 31), the optimal retail price of the product $P^{\mathrm{SGII}*}$ (Eq. 32), the optimal profit of the alliance II $\Pi_{\mathrm{sm}}^{\mathrm{SGII}^*}$ (Eq. 33), the optimal profit of the supplier $\Pi_s^{\mathrm{SGII}^*}$ (Eq. 34), and the profit of the whole supply chain $\Pi_{sc}^{\mathrm{SGII}^*}$ (Eq. 35) can be obtained, respectively:

$$q^{\mathrm{SGII}*} = \{(-a + bG)\,[k - 2(e_{\mathrm{s}} + e_{\mathrm{m}} + e_{\mathrm{r}})r] + 2r(c_{\mathrm{s}} + c_{\mathrm{m}} - v)\} / \{2k[k - 4(e_{\mathrm{s}} + e_{\mathrm{m}} + e_{\mathrm{r}})r]\} \quad (29)$$

$$\Delta e^{SGII*} = \{(a - bG)[k - 6(e_s + e_m + e_r)r] + 2r(c_s + c_m - v)\} / \{4r[k - 4(e_s + e_m + e_r)r]\} \quad (30)$$

$$E^{SGII*} = (e_s + e_m + e_r)q^{SGII*} - \Delta e^{SGII*} \quad (31)$$

$$P^{SGII*} = v - k[(e_s + e_m + e_r)q^{SGII*} - \Delta e^{SGII*}] \quad (32)$$

$$\Pi_{sm}^{SGII^*} = \{v - k[(e_s + e_m + e_r)q^{SGII*} - \Delta e^{SGII*}] - c_m - w_s^{SGII*}\}q^{SGII*} - r(\Delta e^{SGII*})^2 - [(e_s + e_m + e_r)q^{SGII*} - \Delta e^{SGII*} - G](a - bG) \quad (33)$$

$$\Pi_{s}^{SGII^*} = (w_s^{SGII*} - c_s)\, q^{SGII*} \quad (34)$$

$$\Pi_{sc}^{SGII^*} = \Pi_{s}^{SGII^*} + \Pi_{sm}^{SGII^*} \quad (35)$$

*Cooperative decision-making model*

The cooperative decision-making model (CD model) is a cooperative three-level Stackelberg game under centralized decision-making among the members of the supply chain in an attempt to maximize the profits of the supply chain (Landgren *et al*. 2021). Under the CD model, the supplier, the manufacturer, and the retailer determine the optimal demand on products $q^{CD}$ and the optimal carbon reduction level $\Delta e^{CD}$ of the supply chain to maximize its profit. The expected profit function of the supply chain can be expressed as follows:

$$max\Pi_{sc}^{CD} = \{v - k[(e_s + e_m + e_r)q^{CD} - \Delta e^{CD}] - c_s - c_m\}q^{CD} - r(\Delta e^{CD})^2 - [(e_s + e_m + e_r)q^{CD} - \Delta e^{CD} - G](a - bG) \quad (36)$$

Under the CD model, the above optimization problem can be solved by reverse induction. According to the first-order optimal condition, the supplier, the manufacturer, and the retailer maximize the profit of the supply chain through decision ($q^{CD}$, $\Delta e^{CD}$), the optimal carbon reduction level $\Delta e^{CD*}$ (Eq. 37), and the optimal demand on products $q^{CD*}$Eq. 38) can be obtained. When the condition $0 < k < 4(e_s + e_m + e_r)r$ is met, the optimal carbon emissions of the supply chain $E^{CD*}$ (Eq. 39), the optimal retail price of the product $P^{CD*}$ (Eq. 40), and the profit of the whole supply chain $\Pi_{sc}^{CD^*}$ (Eq. 41) can be obtained, respectively:

$$\Delta e^{CD*} = [-c_m - (a - bG)(e_s + e_m + e_r) - c_s + v] / [-k + 4(e_s + e_m + e_r)r] \quad (37)$$

$$q^{CD*} = [(a - bG)k - 2(a - bG)(e_s + e_m + e_r)r + 2r(-c_s - c_m + v)] / \{-k[k + 4(e_s + e_m + e_r)r]\} \quad (38)$$

$$E^{CD*} = (e_s + e_m + e_r)q^{CD*} - \Delta e^{CD*} \quad (39)$$

$$P^{CD*} = v - k[(e_s + e_m + e_r)q^{CD*} - \Delta e^{CD*}] \quad (40)$$

$$\Pi_{sc}^{CD*} = \{v - k[(e_s + e_m + e_r)q^{CD*} - \Delta e^{CD*}] - c_s - c_m\}q^{CD*} - r(\Delta e^{CD*})^2 - [(e_s + e_m + e_r)q^{CD*} - \Delta e^{CD*} - G](a - bG) \quad (41)$$

## Coordination Mechanism with the Contract of Sharing Carbon Emission Reduction Cost and Benefit

Centralized decision-making is better than decentralized decision-making, but centralized decision-making will harm the interests of one participant. The carbon emission reduction cost-sharing and benefit-sharing coordination mechanism is a method to solve the problem of benefit distribution among supply chain enterprises and improve supply chain efficiency (Song and Gao 2018). In the present study, a carbon emission reduction cost-sharing and benefit-sharing coordination mechanism was introduced into the CD model under centralized decision-making introduces in order to improve the supply chain's efficiency. The explanations of the variables in the mechanism are shown in Table 2.

**Table 2.** Model Variables for the Coordination Mechanism

| Parameter | Explanation | Parameter | Explanation |
|---|---|---|---|
| $\varphi_s$ | shares of emission reduction cost for the supplier ($0 < \varphi_s < 1$) | $\phi_s$ | allocation of revenues on the supplier ($0 < \phi_s < 1$) |
| $\varphi_m$ | shares of emission reduction cost for the manufacturer ($0 < \varphi_m < 1$) | $\phi_m$ | allocation of revenues on the manufacturer ($0 < \phi_m < 1$) |
| $\varphi_r$ | shares of emission reduction cost for the retailer ($0 < \varphi_r < 1$) | $\phi_r$ | allocation of revenues on the retailer ($0 < \phi_r < 1$) |

Firstly, the supplier, the manufacturer, and the retailer share the cost of emission reduction in the supply chain according to $\varphi_s$, $\varphi_m$, and $\varphi_r$; the supplier supply raw materials to the manufacturer at lower supply prices, and the manufacturer sell products to the retailer at lower prices; then, once the product sale is completed, the supplier, the manufacturer, and the retailer allocate the revenue $q^{RS}\{v - k[(e_s + e_m + e_r)q^{RS} - \Delta e^{RS}]\}$according to $\phi_s$, $\phi_m$ ,and $\phi_r$. The conditions $\phi_s + \phi_m + \phi_r = 1$ and $\varphi_s + \varphi_m + \varphi_r = 1$ should be met. The decision models of the supplier (Eq. 42), the manufacturer (Eq. 43), and the retailer (Eq. 44) are established respectively:

$$max\ \Pi_s^{RS} = \phi_s\{v - k[(e_s + e_m + e_r)q^{RS} - \Delta e^{RS}]\}q^{RS} + w_s^{RS}q^{RS} - c_s q^{RS} - \varphi_s r(\Delta e^{RS})^2 \quad (42)$$

$$max\ \Pi_m^{RS} = \phi_m\{v - k[(e_s + e_m + e_r)q^{RS} - \Delta e^{RS}]\}q^{RS} + w_m^{RS}q^{RS} - c_m q^{RS} - w_s^{RS}q^{RS} - \varphi_m r(\Delta e^{RS})^2 - [(e_s + e_m + e_r)q^{RS} - \Delta e^{RS} - G](a - bG) \quad (43)$$

$$max\ \Pi_r^{RS} = \phi_r\{v - k[(e_s + e_m + e_r)q^{RS} - \Delta e^{RS}]\}q^{RS} - w_m^{RS}q^{RS} - \varphi_r r(\Delta e^{RS})^2 \quad (44)$$

Proposition: Under the coordination of the supply chain, the revenue sharing coefficient is the same as the carbon reduction cost coefficient for each supply chain member.

Prove: To make the profit function of the supply chain system under the carbon emission reduction cost-sharing and revenue sharing contract the same as the supply chain system profit in the CD model under centralized decision-making, it only needs to satisfy the following: $q^{RS*} = q^{CD*}$; $\Delta e^{RS*} = \Delta e^{CD*}$.

Take the partial derivatives of Eq. 42 with respect to $q^{RS}$ and respectively and set them equal to 0, and solve the equations simultaneously. When the condition $0<k<4(e_s+e_m+e_r)r\varphi_s/\phi_s$is met, then the optimal carbon reduction level $\Delta e^{RS*}$ (Eq. 45), the optimal demand on products $q^{RS*}$ (Eq. 46), and the optimal supply price of the raw materials required for each product $w_s^{RS*}$ (Eq. 47) can be obtained:

$$q^{RS*} = -[2r(w_s^{RS*} - c_s + \phi_s v)\ \varphi_s]\ /\ \{k\phi_s\ [k\phi_s - 4(e_s + e_m + e_r)r\varphi_s]\} \quad (45)$$

$$\Delta e^{RS*} = (-w_s^{RS*} + c_s - \phi_s v)\ /\ [k\phi_s - 4(e_s + e_m + e_r)r\varphi_s] \quad (46)$$

$w_s^{RS*} = 1\ /\ (\{2r[-k + 4(e_s + e_m + e_r)r]\ \varphi_s\}\{-a\phi_s[k - 2(e_s + e_m + e_r)r]\}[k\phi_s - 4(e_s + e_m + e_r)r\ \varphi_s] + bG\phi_s\ [k - 2(e_s + e_m + e_r)r][k\phi_s - 4(e_s + e_m + e_r)r\ \varphi_s] + 2r\{-4(\phi_s - 1)(e_s +$

$e_m + e_r)rc_s\,\varphi_s + c_m\phi_s\,[k\phi_s - 4(e_s + e_m + e_r)r\,\varphi_s] + k[\phi_s{}^2(c_s - v) - c_s\varphi_s + \varphi_s\phi_s v]\})$ (47)

Then, $\phi_s = \varphi_s$. In the same way it can be proved that $\phi_m = \varphi_m$ and $\phi_r = \varphi_r$.

The mechanism must ensure that the income of each participating entity, regardless of the income model, is equal to or greater than the individual incomes under TLG, SGI, and SGII, so that each entity can maximize its profit without compromising the benefit of the others (Guo *et al.* 2020). Each supply chain member's revenue-sharing coefficient is the same as its carbon reduction cost coefficient. The sharing coefficient for the supplier, the manufacturer, and the retailer are $\phi_s(0 < \phi_s < 1)$, $\phi_m(0 < \phi_m < 1)$ and $\phi_r(0 < \phi_r < 1)$, respectively, which need to satisfy the following Eq. 48. (Pang *et al*. 2014):

$$\begin{cases} \phi_s \Pi_{\mathrm{sc}}^{\mathrm{CD}^*} \geq \Pi_{\mathrm{s}}^{\mathrm{TLG}^*},\ \phi_m \Pi_{\mathrm{sc}}^{\mathrm{CD}^*} \geq \Pi_{\mathrm{m}}^{\mathrm{TLG}^*}, \phi_r \Pi_{\mathrm{sc}}^{\mathrm{CD}^*} \geq \Pi_{\mathrm{r}}^{\mathrm{TLG}^*} \\ (\phi_s + \phi_m)\Pi_{\mathrm{sc}}^{\mathrm{CD}^*} \geq \Pi_{sm}^{\mathrm{SGI}^*}, (\phi_m + \phi_r)\Pi_{sc}^{\mathrm{CD}^*} \geq \Pi_{mr}^{\mathrm{SGII}^*} \end{cases} \quad (48)$$

## Data Sources and Model Realization

In this study, a large-scale wooden furniture manufacturer located in Yichun city, Northeast China, was investigated, which primarily produced solid wooden furniture and panel furniture and focused on mid and high-end customers. Because the solid wood box bed (2000 mm × 1800 mm) requires more work and consumes a lot of wood, a solid wood bed supply chain with imported wood as the raw material is taken as the research object. For the case of supply chain, the supplier is mainly responsible for supplying the beech timber from Germany and the *Pinus radiata* wood from New Zealand, the manufacturer processes in Yichun City, and the retailer is mainly responsible for regional distribution in China. The carbon emissions of the supplier mainly come from the raw materials and the transportation process from the supplier to the manufacturer; the carbon emissions of the manufacturer mainly come from the manufacturing process and the transportation process from the manufacturer to the retailer; the carbon emissions of the retailer mainly come from the carbon emissions of regional distribution in China. Based on the carbon emissions data at different links of the solid wood bed supply chain from the literature (Wang *et al.* 2021), combined with the purchase and sales lists of the surveyed core enterprise, the input parameters of the models are assumed as follows: $v = 1200$, $r = 3$, $a = 8$, $b = 0.015$, $c_s =$ US$ 400 per piece, $c_m =$ US$ 150 per piece, $e_s = 0.3$ t $CO_2$-eq per piece, $e_m = 0.12$ t $CO_2$-eq per piece, $e_r = 0.03$ t $CO_2$-eq per piece, and $G = 200$ t $CO_2$-eq per year.

The software Mathematica v.11.3 (Wolfram Research, Champaign, IL, USA) was used to obtain derivative models, conduct sensitivity analysis on the model parameters, and make plots. Mathematica is a mathematical analysis software that combines the world's most powerful math engine with an interface that makes it extremely easy to analyze, explore, visualize, and solve mathematical problems.

# RESULTS AND DISCUSSION

## Uncertainty Analysis on Carbon Footprint and Profit of Supply Chain

The probability of consumers' low-carbon consumption behavior is defined as their low-carbon preference. When consumers prefer low-carbon products, the supply chain members will be more inclined to produce them on the basis of profitability (Liu *et al.*

2021). Different optimization models (TLG, SGI, SGII, and CD models) were constructed. Under these models, the relationships between consumers' low-carbon preference coefficient (*k*) and the demand, price, carbon footprint of the supply chain, and profit were analyzed, which are illustrated in Fig. 2.

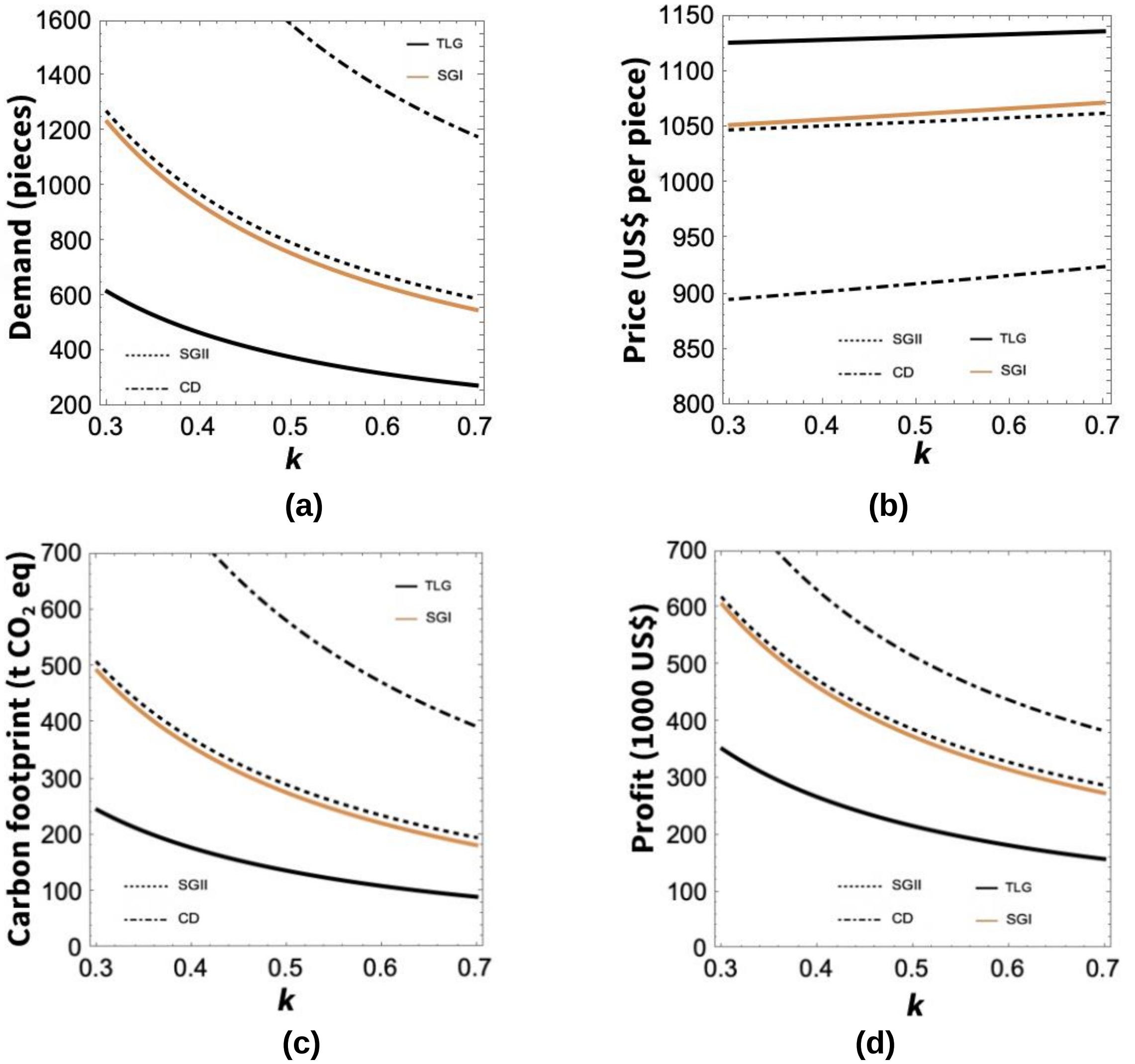


**Fig. 2.** The influence of consumers' low carbon preference coefficient (*k*) on product demand, retail price, carbon footprint and profit of the supply chain

It can be seen from Fig. 2 that the consumers' low carbon preference coefficient is negatively correlated with product demand (Fig. 2(a)). In fact, the demand is driven by multiple factors such as wholesale price, carbon reduction level of supply chain, and consumers' low carbon preference. Since the optimal wholesale price and carbon reduction level are associated with low carbon preference, the demand is ultimately determined by the low carbon preference coefficient. As the consumers' low carbon preference coefficient increased, the demand on solid wood furniture dramatically decreased. Similarly, the supply chain carbon footprint and profit decreased as the low carbon preference coefficient increased (Fig. 2(c) and 2(d)).

Under the four models, the retail price of solid wood bed products increased with the increase of consumers' low carbon preference coefficient (Fig. 2(b)). The TLG model had the highest retail price, followed by the SG I model and the SG II model, and the CD model. It is noted that the gradients of the retail price curves in Fig. 2(b) are not as steep as those of product demand curves in Fig. 2(a), which means that the retail price is less sensitive to changes in low-carbon preference coefficient. This can be explained by the relationship between the retail price and product demand as shown in hypotheses (3). The increase of low carbon preference can lead to the increase of carbon reduction level. That is to say, low-carbon preferences of consumers may motivate supply chain actors to increase the costs associated with carbon reduction efforts, thus increasing prices. Meanwhile, with the increase of consumers' low carbon preference coefficient ($k$), the eco-conscious consumers have to be subject to the "tax" of higher prices, then the growth potential of sales or product demand ($q$) may be limited, so the multiplication of $k$ and $q$ may further limit the increment of retail price.

Under different levels of low carbon preference, the product demand, supply chain carbon footprint and profit were the largest in the CD model; while these values were the smallest in the TLG model; there were no noticeable differences between the SGI model and the SG II model. Therefore, it is more profitable to form small alliances for some supply chain members compared to decentralized decision-makings. When all the members of the three-level solid wood bed supply chain made centralized decisions, the profit of the supply chain can reach the maximum value.

## Optimal Decision-making under Different Game Models

The public environmental awareness has increased over the years with the promulgation of national environment-related policies. In order to compare the optimal decision-making under different game models, three levels of low carbon preference ($k$ = 0.3, 0.5, and 0.7) were considered in this study. Under the condition that other parameters remained unchanged, the optimal expected profit of the supplier, manufacturer, retailer, the supply chain, the optimal retail price of the solid wood bed, and the optimal demand of the solid wood bed, as well as the carbon footprint of the supply chain under the four models of TLG, SGI, SGII, and CD can be obtained, which are shown in Table 3.

**Table 3.** Optimal Results Under Different Game Modes

<table>
<tr><th rowspan="2">k</th><th rowspan="2">Model</th><th colspan="4">Profit (US$)</th><th rowspan="2">Retail Price (US$ / Piece)</th><th rowspan="2">Product Demand (Pieces)</th><th rowspan="2">Carbon Footprint of the Supply Chain (t $CO_2$-eq)</th></tr>
<tr><th>Supplier</th><th>Manufacturer</th><th>Retailer</th><th>Supply Chain</th></tr>
<tr><td rowspan="4">0.3</td><td>TLG</td><td>199,954</td><td>100,979</td><td>51,417</td><td>352,350</td><td>1,126</td><td>617</td><td>246</td></tr>
<tr><td>SGI</td><td colspan="2">400,911</td><td>205,667</td><td>606,578</td><td>1,052</td><td>1,234</td><td>492</td></tr>
<tr><td>SGII</td><td>411,671</td><td colspan="2">206,837</td><td>618,508</td><td>1,048</td><td>1,271</td><td>507</td></tr>
<tr><td>CD</td><td colspan="3"></td><td>824,343</td><td>895</td><td>2,541</td><td>1,016</td></tr>
<tr><td rowspan="4">0.5</td><td>TLG</td><td>122,365</td><td>62,185</td><td>32,076</td><td>216,626</td><td>1,131</td><td>378</td><td>138</td></tr>
<tr><td>SGI</td><td colspan="2">245,732</td><td>128,305</td><td>374,037</td><td>1,062</td><td>755</td><td>276</td></tr>
<tr><td>SGII</td><td>257,216</td><td colspan="2">129,610</td><td>386,826</td><td>1,055</td><td>794</td><td>290</td></tr>
<tr><td>CD</td><td colspan="3"></td><td>515,435</td><td>909</td><td>1,587</td><td>581</td></tr>
<tr><td rowspan="4">0.7</td><td>TLG</td><td>89,180</td><td>45,592</td><td>23,840</td><td>158,612</td><td>1,136</td><td>275</td><td>91</td></tr>
<tr><td>SGI</td><td colspan="2">179,363</td><td>95,361</td><td>274,724</td><td>1,072</td><td>550</td><td>183</td></tr>
<tr><td>SGII</td><td>191,643</td><td colspan="2">96,823</td><td>288,466</td><td>1,062</td><td>591</td><td>196</td></tr>
<tr><td>CD</td><td colspan="3"></td><td>384,287</td><td>925</td><td>1,182</td><td>393</td></tr>
</table>

It is shown that as the consumers' preference was changed from a lower level of low carbon preference (*k*=0.3) to a higher level (*k*=0.7), the retail price increased 0.89%-3.35%, and the product demand decreased 53.48% to 55.43% under different models. Even though the profits of the supply chain decreased as the low carbon preference coefficient increased, the carbon footprint of the supply chain under different models also decreased due to carbon emission reduction, which is favorable to the sustainable development of the supply chain.

Under the TLG model, there was an edge effect among the members of the three-level solid wood bed supply chain, which kept the price of solid wood beds high, thereby resulting in lower demand and profit for the entire supply chain. The carbon footprint of the supply chain was at a lower level; however the profit of the supply chain was not satisfied. Despite the moderate retail price and sales quantity in the supply chain when some supply chain members formed small alliances with their upstream (SGI) or downstream partners (SGII), the profit of the supply chain had not yet reached the optimum level due to the fact that non-alliance members pursued their own interests. Under the CD model, the retail price was the lowest among the four models (TLG, SGI, SGII, CD). The cost savings can be realized by cooperation in shortening the kilometers of distance shipped and reducing the number of times an item is handled. The lowest price can improve the competitiveness of solid wood beds in similar products, and make the profit of the supply chain reach the optimal level. When the caron footprint of the supply chain was greater than the carbon emission cap 200 t $CO_2$-eq, the excess would be traded in the carbon market, so the total carbon footprint of the supply chain would be equal to the emission cap. For example, the excess of 193 t $CO_2$-eq under the CD model at *k*=0.7would be traded.

In this study, profit maximization is the sole objective for the supply chain; however the carbon emission limit should also be considered in order to meet the national carbon regulations and policies. Therefore, the stakeholders of the supply chain should choose appropriate optimal decision-makings under different scenarios.

## Changes in the Expected Profit of Each Member under Cooperation Parameters

To reduce the carbon footprint of the entire supply chain, the supply chain members must actively participate in a joint cooperation model under centralized decision-making. This will allow the profit of the supply chain to reach the optimal level. The contract of sharing carbon emission reduction cost and benefit was introduced as a means of coordinating the reduction of greenhouse gases. Here, moderate low carbon preference (*k*=0.5) was assumed.

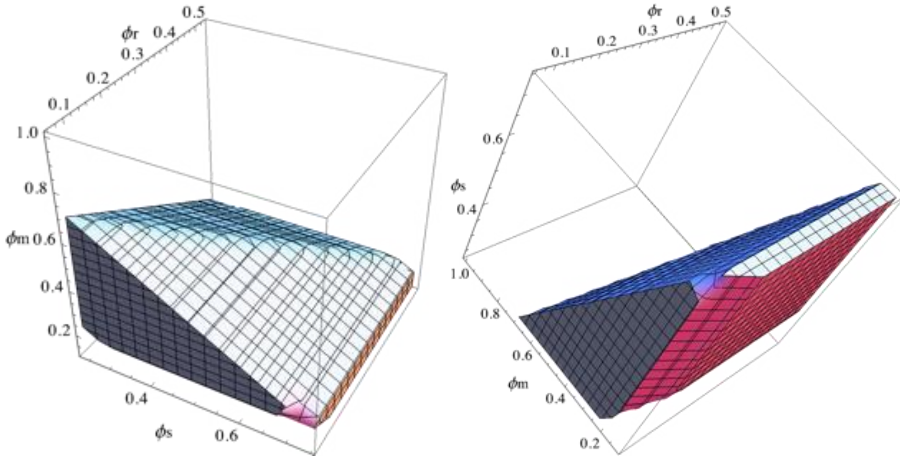


**Fig. 3.** Feasible intervals of the cooperation parameters

The value range of the carbon emission reduction cost and benefit-sharing coefficients $\boldsymbol{\phi_s}$, $\boldsymbol{\phi_m}$, and $\boldsymbol{\phi_r}$must conform to a certain feasible range, as shown in Fig. 3(a). For the convenience of observation, rotate Fig. 3(a) 45° to get Fig. 3(b). Once the parameters were out of this range, it would be difficult to continue cooperation, therefore the range of the cooperation parameters can provide references for the cooperation of the solid wood bed supply chain.

Based on the feasible range of cooperation parameters, three groups of carbon emission reduction cost and benefit-sharing coefficients were selected, and the optimal profit of each member was obtained under the contract of sharing carbon reduction cost and benefit, which are shown in Table 4.

**Table 4.** Optimal Decision Results Under Different Cooperation Parameters

| Cooperation parameters | | | Profit of Supplier (US$) | Profit of Manufacturer (US$) | Profit of Retailer (US$) |
|---|---|---|---|---|---|
| $\phi_s$ | $\phi_m$ | $\phi_r$ | | | |
| 0.4 | 0.3 | 0.3 | 208,365 | 155,333 | 151,737 |
| 0.4 | 0.4 | 0.2 | 208,365 | 206,776 | 100,293 |
| 0.35 | 0.35 | 0.3 | 182,319 | 181,055 | 152,061 |

It is shown that the final results for the benefit allocation among the participating members are greatly influenced by the cooperative parameters (Table 4). The sum of each member's profit under different cooperation parameters was US$ 515,435, which was greater than those of the other models (TLG, SGI, SGII). In addition, under the carbon emission reduction cost and benefit-sharing mechanism, the supplier, manufacturer, and retailer achieved greater profits than those under the decentralized TLG model. Therefore, within the acceptable range of cost and revenue-sharing coefficients, any combinations of $\phi_s$, $\phi_m$, and $\phi_r$ could help parties increase their profits and ensure that the supply chain achieved optimal profits in the collaborative model under centralized decision-making. The shares of increased revenue earned by the parties depended mainly on the sharing coefficients, which were influenced by the participating parties' positions in the supply chain and their bargaining power.

It is noted that this study only considers the three-level wooden furniture supply chain consisting of a single supplier, a single manufacturer, and a single retailer, and the system simulation was carried out under the condition of information symmetry. In fact, the wooden furniture supply chain may involve multiple independent participants, for instance, more than one supplier. The information asymmetry among the participants may exist due to the technical and human factors during information delivery. Each participant can choose whether to invest in emission reduction or choose different emission reduction methods to coordinate the profit of the supply chain and the carbon footprint of the product. There is also great uncertainty in the market demand caused by the uncertainty of low carbon preference of the consumers. In addition, the setting of a carbon emissions cap also has some impact on the profits of the supply as well as the participating members. Therefore, the efficiency of decision-making in a real situation may not be as high as in the computed case.

Future research can be conducted under the conditions of complex supply chain structure composed of multiple suppliers, multiple manufacturers, and multiple retailers, dynamics of competition, uncertain market demand, different carbon emission caps while coordinating the wooden furniture supply chains with consideration of carbon footprint.

## CONCLUSIONS

1. Implementation of the coordination mechanism can lead to a certain decrease in the retail price and an increase in profit for the solid wood bed supply chain compared to the non-cooperative game model. The TLG model showed the lowest supply chain profit, while the CD model showed the highest supply chain profit.
2. The decision-makings of the upstream and downstream parties in the solid wood bed supply chain are closely related to the consumers' low-carbon preferences. When the consumers' low carbon preference coefficient increased, the retail price increased, and demand, total carbon footprint, and profits of the supply chain declined. The consumers' low-carbon preference coefficient had the most noticeable impact on demand, supply chain profits, and carbon footprint in the CD model, but had the smallest impact in the TLG model.
3. With the coordination mechanism of sharing carbon reduction cost and benefit, the profits of the supply chain members can be improved under the premise of maximizing the profit of the supply chain compared to the TLG model. The increment of the profit for each member depends on the sharing coefficient of carbon reduction cost and benefit, which is determined by the position of the member in the supply chain and the bargaining power with each other.

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