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Impact of power structures in a subcontracting assembly system

Guo Li[1,2,3] · Lin Li[1,2,3] · Mengqi Liu[4] · Suresh P. Sethi[5]

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Abstract
We investigate the impact of power structures on the production and pricing strategies in a decentralized subcontracting assembly system consisting of two suppliers (key supplier and subcontractor) and one manufacturer (assembler). The key supplier, who is also the general contractor, negotiates with the manufacturer and assigns partial component production to the subcontractor. We first identify a single power regime (SPR), in which either the key supplier or the manufacturer determines the wholesale price or the order/production quantity. Under SPR, we consider three power structures, namely, KSA, KAS, and SKA. We find that the assembly system will substantially benefit under KAS. Results show that the subcontracting mechanism between the two suppliers can increase each firm's profit and disperse the bargaining power. Such a decentralization of powers can weaken the horizontal decentralization between the suppliers and improve the system's performance, thereby achieving a win–win situation. Furthermore, we extend our analysis to a dual power regime (DPR), in which the key supplier or the manufacturer decides on price and quantity. We show that the proposed assembly system performs optimally under DPR. Moreover, the system will benefit if the firm that is substantially near the end market makes the centralization decision. Compared with the classical pull and push contract model, the proposed assembly system provides the best performance under DPR.

Keywords Assembly system · Power structure · Production and pricing strategy · Subcontracting mechanism · Case study

✉ Mengqi Liu
liumengqi76@163.com

1 School of Management and Economics, Beijing Institute of Technology, Beijing 100081, China

2 Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing 100081, China

3 Sustainable Development Research Institute for Economy and Society of Beijing, Beijing 100081, China

4 Business School, Hunan University, Changsha 410082, China

5 Naveen Jindal School of Management, The University of Texas at Dallas, Dallas, TX 75080, USA

1 Introduction

An assembly system is a common manufacturing system, in which individual components provided by suppliers are assembled by the manufacturer to satisfy the end demand (Butala and Mpofu 2015). To meet the specified requirement of the manufacturer, a key supplier may outsource a subcomponent to his matched supplier under the authorization of the manufacturer, who eventually assembles these components. In particular, a manufacturer may entrust a powerful supplier to procure the required components and this supplier may subcontract components of his workload to other matched suppliers (Pun and Heese 2015). In such a subcontracting assembly system, the wholesale price can either be determined by the key supplier or manufacturer; this situation is similar to a push or pull contract first proposed by Cachon (2004). Cachon (2004) and Granot and Yin (2008) explained that under the push contract, suppliers initially set the wholesale price and the manufacturer places the order from the suppliers thereafter before the realization of demand. By contrast, the manufacturer under the pull contract initially sets the wholesale price and the suppliers decide the production quantity thereafter prior to the selling season.

We consider two real cases. Xiamen King Long United Automotive Industry[1] (King Long), one of the leading enterprises in China, has an annual production of 25,000 buses and coaches and 30,000 minivans. Before the assembly and production of the coaches, Cummins (China) Investment Co., Ltd.[2] (Cummins, Inc.) contracts with King Long on the engine and post-processing assembly productions. Cummins, Inc provides the engine assembly parts for and negotiates with King Long under a push contract. To optimize resource allocation and decrease production cost, Cummins, Inc subcontracts the post-processing assembly to Cummins Emission Solutions (China) Co., Ltd.[3] (Cummins Emission Solutions). In particular, Cummins Emission Solutions directly delivers the components to King Long. In this assembly system, Cummins, Inc. is regarded as the general contractor, while Cummins Emission Solutions is the subcontractor. The second case is that of Beijing Hongzhi Huitong Industrial Co., Ltd,[4] which contracts with Beijing Support Power Technology Co., Ltd.[5] for it to manage the network construction and equipment procurement for Hongzhi's information engineering room. Hongzhi implements a pull contract with Beijing Support which determines the production quantity after receiving the wholesale price. Subsequently, Beijing Support subcontracts anti-static flooring and computer cabinet subprojects to Beijing Anchuang Zhongke Room Equipment[6] (Anchuang), and determines the subcontracting price. Both Beijing Support and Anchuang deliver their compatible components to Hongzhi for the final assembly.

The aforementioned stylized facts illustrate that in practice, a subcontracting assembly system may operate under either a pull or push contract, in which the manufacturer (assembler) and the two suppliers are provided with a variety of powers. We consider such powers and explore three typical power structures under a single power regime (SPR), in which either the key supplier or manufacturer determines the wholesale price or the order/production quantity.

[1] For the Xiamen King Long United Automotive Industry, see http://www.king-long.com.

[2] For the Cummins (China) Investment Co., Ltd., see http://www.cummins.com.cn.

[3] Cummins Emission Solutions, a wholly owned subsidiary of Cummins, Inc., is the largest world integration provider in after-treatment technology and emission solutions for the commercial on and off highway engine market.

[4] For the Beijing Hongzhi Huitong Industrial Co., Ltd, see http://www.9540880.1024sj.com.

[5] For the Beijing Support Power Technology Co., Ltd, see http://www.Support.cn.

[6] For the Beijing Anchuang Zhongke Room Equipment, see http://www.anchuang.com.cn.

First, the key supplier decides the wholesale price and subcontracting price ratio. Thereafter, the manufacturer determines the production quantities for two suppliers (KSA). Second, the key supplier decides the subcontracting price ratio and the manufacturer eventually sets the wholesale price. Thereafter, the two suppliers simultaneously make the production decisions (KAS). Third, the subcontracted supplier sets the subcontracting price ratio and the key supplier determines the wholesale price thereafter. Lastly, the assembler decides the production quantities prior to the demand realization (SKA). To our knowledge, the aforementioned power structures in an assembly system involving a subcontracting mechanism have never been sufficiently investigated. This research gap motivated us to analyze the impact of subcontracting cooperation mechanism and power structures on the production and pricing strategy in a decentralized assembly system. In particular, we ask the following questions: (1) What are the firms' strategic behaviors and performances when a subcontracting mechanism exists in the assembly system? (2) Is the introduction of a subcontracting mechanism beneficial to an assembly system? (3) Which factor affects the optimal strategy of firms? (4) Given that either the manufacturer or the key supplier holds the wholesale price decision power without the quantity power, which power structure benefits the assembly system and firms? (5) Given the results under a dual power regime (DPR), in which the key supplier or manufacturer holds the pricing and quantity decision power, what is the best power structure under DPR compared with the classical results by Granot and Yin (2008)?

To answer these questions, we investigate a subcontracting assembly system comprising one manufacturer and two suppliers and construct several multi-stage Stackelberg models under varying power structures. We refer to Chen et al. (2014) and define SPR as either the key supplier or manufacturer holding the wholesale price decision power, as well as posit that a push or pull contract is implemented between the manufacturer and key supplier. In addition, the subcontracting price ratio is determined by either the key supplier or subcontractor. In particular, this regime contains three power structures, namely, KSA, KAS, and SKA. We derive several interesting results from our models. First, the assembly system achieves the maximum profit under KAS. Second, the increase of the key supplier's cost proportion results in the profit difference between KSA and KAS to decrease, whereas that between KSA and SKA to increase. Compared with the results in Granot and Yin (2008), we show that KAS performs better than under the pure pull contract, thereby verifying the effectiveness of the subcontracting mechanism. Third, KAS benefits the manufacturer as the key supplier's cost proportion increases, whereas KSA benefits the manufacturer when the key supplier's cost proportion is sufficiently low. The key supplier consistently prefers KSA. In addition, we determine that either KAS or SKA can become the subcontractor's dominant option, depending on the key supplier's cost proportion.

We further extend the models to DPR, in which the key supplier or manufacturer can determine both the component's wholesale price and production quantity. We compare the pricing and production strategies under SPR, DPR, and the classical model and determine that the assembly system performs best under DPR. Note that this regime exists when a firm is considered powerful in making pricing and quantity decisions simultaneously.

The remainder of this paper is organized as follows. Section 2 presents a review of the related literature. Section 3 presents the proposed model. Section 4 analyzes the equilibrium pricing and production strategies under SPR. Section 5 compares the different power structures under SPR. Section 6 extends the model to DPR, in which either the key supplier or manufacturer makes both the pricing and production decisions. Lastly, Sect. 7 concludes the paper. The "Appendix" provides the proofs.

2 Literature review

Pricing and production strategies in an assembly system have attracted much attention from both academics and practitioners in operations management. Extensive studies (e.g., Cachon 2004; Gerchak and Wang 2004; Gurnani and Gerchak 2007; Nagarajan and Bassok 2008; Jiang and Wang 2010; Leng and Parlar 2010; Pan and So 2010) have focused on the pricing and ordering decisions of suppliers and manufacturers in a decentralized setting. These studies have shown that decentralization exists in the horizontal and vertical levels and proposed subsequent cooperation mechanisms to coordinate the supply chain (Chu et al. 2006; Li et al. 2013). Furthermore, a few scholars have extended the assembly system consisting of a manufacturer and two independent suppliers by considering the vendor inventory liability period (Guan et al. 2016a; Fang et al. 2008), time-based payment contracts (Guan et al. 2016b; Li et al. 2017a), and capacity reservation contracts (Lv et al. 2015). The aforementioned studies have focused on an assembly system, in which the suppliers have the same bargaining powers. In addition, a few studies consider that two suppliers have different bargaining powers in an assembly system but consistently make simultaneous production quantity decisions (e.g., Nagarajan and Sošić 2009; Li et al. 2017b; Feng et al. 2018). Guan et al. (2015) followed Granot and Yin (2008) and investigated a decentralized assembly system consisting of two suppliers and a manufacturer under a hybrid push–pull contract. Guan et al. (2015) analyzed the production and pricing decision of an assembly system, in which one supplier determines the wholesale price and the other decides on the production quantity once the manufacturer sets the wholesale price. Accordingly, Kyparisis and Koulamas (2016) analyzed a push assembly with sequential suppliers.

The research most closely related to the present study refers to Chen et al. (2014). The aforementioned research proposed two power structure regimes in an assembly system with one assembler and two suppliers, namely, SPR and DPR, and discussed how the firms' power levels affect the system. They also indicated that the system's highest profit is obtained when the assembler is the most powerful among the two suppliers. By contrast, our study investigates an assembly system's power structure by integrating the classical pull–push contract and subcontracting mechanism. Given a pull or push contract between the key supplier and manufacturer, we consider that either the key supplier or subcontractor can set the subcontracting price ratio depending on the decision-making power in the system. That is, two suppliers are linked by the subcontracting mechanism. Furthermore, we investigate which power structure benefits the assembly supply chain.

Our study also contributes to the expanding literature on outsourcing and subcontracting contracts. Lee and Kim (1999) identified the impact of partnership quality on outsourcing success. Kouvelis and Milner (2002) showed that the increase of supply uncertainty leads to vertical integration, whereas the increase of demand uncertainty increases outsourcing activities. Kim (2003) studied how to make dynamic outsourcing decisions based on the suppliers' improvement potential in reducing costs. Cachon and Lariviere (2005) discussed various supply chain contracts and provided direction for the outsourcing research. Jiang (2015) analyzed the sequential sourcing of the manufacturer and showed that sequentially sourcing the components can create additional benefits for the supply chain members than simultaneously sourcing in Saouma (2008).

Bernstein and Decroix (2004) explained that the assembler outsources a few assembly tasks to the sub-assemblers (key suppliers), who outsource partial component production tasks thereafter to the other suppliers. The sub-assemblers and suppliers produce the same quantity for the assembler with a minimum capacity limitation, thereby showing which suppliers should be selected for the sub-assemblers. Pun and Heese (2015) investigated a supply chain, in which the manufacturer outsources two tasks to a first-tier supplier. Thereafter, the first-tier supplier selectively subcontracts a task to a second-tier supplier based on the specific situation. They determined that designing a contract to incentivize the first-tier's subcontracting behavior benefits the manufacturer if the cost difference between the two suppliers and the correlation of the two tasks are small. Sinha and Krishnamurthy (2016) used queuing models and analyzed the subcontracting policies with dual index-based policies. Our research differs from previous studies based on the following aspects. First, we consider an assembly system with one assembler and two suppliers who provide complementary components. The key supplier generally contracts the assembler's production task and subcontracts one component to the other supplier. Moreover, they directly deliver their products to the assembler. Given the relationship among the assembler and the two suppliers, we discuss three power structures under SPR and further extend to the DPR setting.

Lastly, a substantial stream of literature has analyzed power structures. Given a firms' market power, the system operates in a certain decision sequence based on the powers in supply chains (Dahl 2002; Li et al. 2016a, b). The firms with power often act first in a non-cooperative game (Lieberman and Montgomery 1988; Shi et al. 2013). For instance, Zhao et al. (2008) investigated the impact of power on supply chain integration. Wang et al. (2014) determined that the equilibrium production quantity is higher under control structure than under delegation in the push contract, whereas the result is the opposite in the pull contract. Dennis et al. (2017) considered a dual-channel supply chain, in which the manufacturer sells through online and traditional retailers. The aforementioned study also revealed that a manufacturer prefers a batch ordering traditional retailer as the first mover in a sequential pricing game than a drop shipping retailer. Wang and Gerchak (2003) assumed that firms have an incentive contract to induce suppliers to increase the capacity in an assembly system with a manufacturer and multi-suppliers. The preceding study considered two power structures. One structure is that the assembler sets the price for the suppliers, while the other is that the suppliers choose the prices for their components. Luo et al. (2017) determined that various power structures have an influence on the system members' profitability, in which two manufacturers supply substitutable products for a retailer (see Edirisinghe et al. 2011). The aforementioned research showed that power imbalance harms the supply chain's performance. Cachon (2004) believed that a powerful firm can transfer the inventory risk to the less powerful firm in a supply chain, thereby resulting in the push and pull contracts. Thereafter, the research on power structure focused on the pull or push contract (see Granot and Yin 2008; Gou et al. 2016; Li et al. 2017c). Li et al. (2017c) analyzed the assembly system's production strategies under two power structures, and posited that the two suppliers decide simultaneously or sequentially. Ray and Jenamani (2016) considered consumer risk aversion to analyze two power structures and assumed that the decision-maker is risk neutral or averse. The current study differs from previous research in two ways. First, this study introduces the subcontracting mechanism between the two suppliers, in which the subcontracting price ratio is determined by either the key supplier or subcontractor. Second, we investigate the assembly system under SPR and DPR. We compare these regimes to derive important managerial insights.

3 Model

We consider a decentralized assembly system consisting of a manufacturer (assembler), key supplier (Supplier 1), and subcontractor (Supplier 2). The two suppliers produce complementary components for the manufacturer and their production costs are c_i $(i = 1, 2)$. Thereafter, the manufacturer assembles the components and sells the final products to the market. We assume that the market demand D is random. F and f are the cumulative distribution function and probability distribution function of demand, respectively, where $F(x)$ is strictly increasing in x and $F(0) = 0$. Let $\overline{F}(x) = 1 - F(x)$ and $S(q)$ be the expected sales, that is $S(q) = q - \int_0^q F(x)dx$. In line with Cachon (2004), Li et al. (2013), and Chen et al. (2014), we assume that demand distribution has a strictly increasing generalized failure rate (IGFR) property. That is, $g(x) = xh(x)$ denotes the generalized failure rate, and $h(x)$ denotes the failure rate, where $h(x) = f(x)/(1 - F(x))$. Thereafter, $h^{'}(x) > 0$ and $g^{'}(x) > 0$. Note that the majority of common distributions have the IGFR property, including uniform, normal, exponential, and Weibull, and others. The retail price is p, while $p > c_1 + c_2$ guarantees that the profitability is positive. The wholesale price w is determined by the manufacturer or key supplier depending on whether the key supplier adopts a pull or push contract (Guan et al. 2015).

Subcontracting mechanism The key supplier generally contracts partial production and outsources complementary components to the subcontractor with a subcontracting price ratio. The subcontractor directly delivers the component to the manufacturer for assembly; this process is different from the traditional subcontracting mechanism in project construction, where the contractor usually signs a strict contract with the subcontractor who delivers the corresponding task to the contractor. The subcontracting mechanism, extensively applied to the manufacturing field (Williamson 1985), has been recognized as an important instrument for maintaining assembly compatibility and aggregate production efficiency (Kamien and Li 1990).

Power structure and sequence The key supplier and subcontractor undergo an ex-ante negotiation regarding the subcontracting price ratio. By positing that the push or pull contract[7] is implemented between the key supplier and the manufacturer, the leader and follower may differ under varying power structures. We first consider SPR where either the key supplier or manufacturer decides the wholesale price or production quantity first. Under such regime, the assembly system is exposed to different power structures, namely, KSA, KAS, and SKA (see Fig. 1). Without loss of generality, we denote the key supplier and the subcontractor as Supplier 1 and Supplier 2, respectively.

For the KSA mode, the key supplier has a powerful bargaining power in the subcontracting mechanism. The key supplier first makes a simultaneous ex-ante decision on the subcontracting price ratio and his component's wholesale price. Thereafter, the manufacturer decides the number of components to order from the two suppliers. Furthermore, the subcontractor is a price-taker and produces the order quantity. Consequently, the manufacturer has to manage the excessive inventory risk. In connection with the KAS mode, the key supplier makes an ex-ante decision on the subcontracting price ratio and the manufacturer implements thereafter a pull contract on the key supplier. Thus, the manufacturer is the wholesale price decision-maker and the key supplier and the subcontractor simultaneously decide the number of components to produce for the manufacturer. Therefore, the two suppliers in this

[7] Note that under the push contract, the key supplier determines the wholesale price first and requires the manufacturer thereafter to decide the order quantity and bear the inventory risk before the demand realization. Under the pull contract, the manufacturer first decides the wholesale price, after which the key supplier decides the production quantity in advance of the selling season.

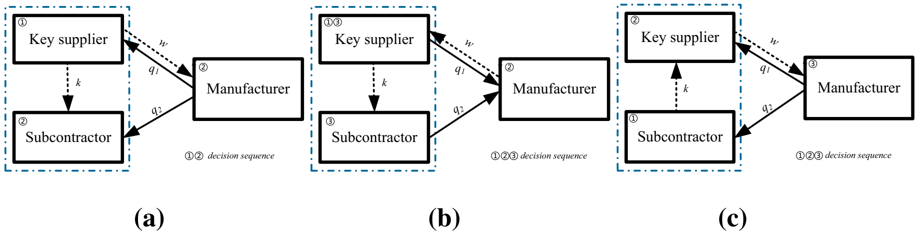

Fig. 1 Sequence of events. **a** KSA, **b** KAS and **c** SKA

Table 1 Model notation

Notation	Explanation
c_i $(i=1, 2)$	Supplier i's unit production cost
p	Unit retail price that the manufacturer sells to the end consumers
w	General contracting wholesale price
k	Subcontracting price ratio
q_i $(i=1, 2)$	Supplier i's production quantity
q_m	Manufacturer's procurement quantity

mode have to bear the leftover inventory. Under SKA, the subcontractor makes an ex-ante decision on the subcontracting price ratio. Subsequently, the key supplier decides his component's wholesale price. Lastly, the manufacturer decides on the number of components to order from the two suppliers.

In the extension section, we formulate a DPR, in which the key supplier or manufacturer simultaneously determines the component's wholesale price and production quantity. Similarly, we construct three modes, namely, KSA$^{\#}$, KAS$^{\#}$, SKA$^{\#}$, which are interpreted in Sect. 6. Note that SPR and DPR were first proposed and evaluated by Chen et al. (2014).

The aforementioned three modes are multi-stage Stackelberg game models. These models mainly analyze the benefits because of the change in the power structure. We use a backward induction to derive the optimal solution. An analysis of the different decision solutions provides managerial insights into the optimal strategy choice. For ease of exposition, we normalize firms' salvage and penalty costs to zero and all the information among the firms is common knowledge. All firms are risk neutral and pursue profit maximization. Table 1 presents the model notation.

4 Analysis

4.1 Centralized assembly system

This section conducts an analysis on the centralized assembly system, which maximizes the total profit of the supply chain. The supply chain's expected payoff in the centralized system is as follows:

$$\prod_C = pE\min(D, q_1, q_2) - (c_1 q_1 + c_2 q_2). \quad (1)$$

The optimal solution (q_1, q_2) maximizes the supply chain's payoff. In equilibrium, the two suppliers' production quantities are identical. That is, $q_m = q_1 = q_2$ (see Li et al. 2017c). Given that $S(q) = q - \int_0^q F(x)dx$, $\prod_C$ is a concave in q_m. Hence, the optimal production quantity q^* satisfies the following equation:

$$\overline{F}(q^*) = \frac{c_1 + c_2}{p}. \tag{2}$$

Accordingly, we use q^* to denote the optimal production quantity in the centralized assembly system, which will be compared with the decentralized assembly system. Under SPR, we derive the equilibrium pricing and production strategies of firms under KSA, KAS, and SKA.

4.2 KSA mode

In this subsection, we consider the scenario where a push contract is implemented between the key supplier and manufacturer. In addition, the key supplier has the power in the subcontracting mechanism. In a selling season, the key supplier initially sets a wholesale price w and a subcontracting price ratio k. Given w, the manufacturer decides on the number to order before the selling season. Lastly, the two suppliers produce the order quantity. We use backward induction method to derive the optimal decisions.

In the second stage, the manufacturer maximizes his expected profit when given a wholesale price. Given that the two suppliers determine the production separately, we can show that the manufacturer constantly places the equilibrium production quantity, which is $q_{ksa} = q_1 = q_2$. Thus, the manufacturer's expected profit is presented as follows:

$$\prod_M(q_{ksa}) = pE\min(D, q_{ksa}) - wq_{ksa}. \tag{3}$$

After taking the first and second derivatives of Eq. (3) on q_{ksa}, $\frac{\partial \prod_M}{\partial q_{ksa}} = p\,\overline{F}(q_{ksa}) - w$ and $\frac{\partial^2 \prod_M}{\partial q_{ksa}^2} = -pf(q_{ksa}) < 0$. Thereafter, $w = p\,\overline{F}(q_{ksa})$,

In the first stage, the key supplier decides the wholesale price and subcontracting price ratio. The expected profit of the key supplier is as follows:

$$\prod_{S1}(w, k) = (w - kw - c_1)q_{ksa}. \tag{4}$$

Thereafter, we substitute $w = p\,\overline{F}(q_{ksa})$ into Eq. (4). Hence,

$$\prod_{S1} = [p(1-k)\,\overline{F}(q_{ksa}) - c_1]q_{ksa}. \tag{5}$$

The key supplier's expected profit evidently decreases in q_{ksa}. Moreover, the subcontractor is a price-taker in this mode. The subcontractor's expected profit can be expressed as follows:

$$\prod_{S2} = (kw - c_2)q_{ksa}. \tag{6}$$

Lemma 1 *Under KSA, the optimal production quantity satisfies* $p[1 - g(q_{ksa})] = \frac{c_1+c_2}{\overline{F}(q_{ksa})}$ *and the optimal wholesale price and subcontracting price ratio are characterized by* $w^* = \frac{c_1+c_2}{1-g(q_{ksa})}$ *and* $k^* = \frac{c_2}{c_1+c_2}[1 - g(q_{ksa})]$, *where* $g(x) = \frac{xf(x)}{\overline{F}(x)}$.

Under KSA, Lemma 1 shows that the two suppliers' optimal equilibrium production quantity q_{ksa} is evidently independent of the subcontracting price ratio. The intuition is that the key supplier generally contracts the production task of the manufacturer. Thereafter, the manufacturer determines the suppliers' production quantity before the selling season without considering the subcontracting price ratio. In addition, when the suppliers' total cost is fixed, the optimal production quantities, wholesale price, and subcontracting price ratio mode remain constant under KSA. The reason is that the subcontractor lacks a bargaining power in the subcontracting mechanism. Thus, the key supplier reserves zero profit for the subcontractor to optimize his profit in equilibrium. Therefore, the subcontractor's production cost does not affect the key supplier's decision and the manufacturer's order quantity.

4.3 KAS mode

In the KAS mode, a pull contract is implemented between the key supplier and manufacturer. The sequence of this mode is as follows. First, the key supplier determines the subcontracting price ratio. Second, the manufacturer decides the wholesale price w. Third, given k and w, the two suppliers decide on the number of components to produce separately. Lastly, the manufacturer orders the actual demand quantity from the two suppliers. We use backward induction method to derive the three-stage Stackelberg game theory.

In the third stage, given k and w, the key supplier and the subcontractor decide on the production quantity to maximize their profit. The two suppliers' expected profit functions are defined as follows:

$$\prod\nolimits_{S1}(k, q_1) = w(1-k)E\min(D, q_1, q_2) - c_1q_1 \tag{7}$$

$$\prod\nolimits_{S2}(q_2) = kwE\min(D, q_1, q_2) - c_2q_2. \tag{8}$$

Lemma 2 *In equilibrium, the key supplier's and the subcontractor's production quantities are the same, thereby satisfying* $q_{kas} = q_1^* = q_2^* = q_1 \wedge q_2$*, where* $q_1 = \bar{F}^{-1}\left(\frac{c_1}{w(1-k)}\right)$ *and* $q_2 = \bar{F}^{-1}\left(\frac{c_2}{kw}\right)$.

Under KAS, Lemma 2 indicates that the manufacturer can set an appropriate wholesale price to induce the two suppliers to adjust the inventory risk, thereby resulting in the same production quantity between the two suppliers in equilibrium. Accordingly, equalizing the production quantity of the two suppliers will maximize their payoffs. Either q_1 is higher or lower than q_2 is detrimental to suppliers. Thus, we define $q_{kas} = q_1^* = q_2^* = q_1 \wedge q_2$, where q_{kas} represents the equilibrium production quantity under KAS. Furthermore, the preceding Lemma shares the same principle with that of Guan et al. (2015).

In the second stage, the manufacturer decides the wholesale price w given the subcontracting price ratio k. Therefore, the manufacturer's expected profit is as follows:

$$\prod\nolimits_{M}(w) = (p-w)E\min(D, q_1, q_2). \tag{9}$$

From Lemma 2, $q_1 = \bar{F}^{-1}\left(\frac{c_1}{w(1-k)}\right)$ and $q_2 = \bar{F}^{-1}\left(\frac{c_2}{kw}\right)$. Thereafter, we can obtain $w = \frac{c_1}{\overline{F}(q_1)} + \frac{c_2}{\overline{F}(q_2)}$. Substituting $w = \frac{c_1}{\overline{F}(q_1)} + \frac{c_2}{\overline{F}(q_2)}$ into Eq. (9), the manufacturer's profit function can be written as follows:

$$\prod\nolimits_M(q_1, q_2) = \left[p - \frac{c_1}{\overline{F}(q_1)} - \frac{c_2}{\overline{F}(q_2)}\right] E\min(D, q_1, q_2). \tag{10}$$

In the first stage, the key supplier makes an ex-ante decision on the subcontracting price ratio k. The preceding analysis indicates that the key supplier decides the subcontracting price ratio to maximize his profit from Eq. (7).

Lemma 3 *Under KAS, the optimal equilibrium production quantity satisfies* $\frac{\overline{F}(q_{kas})}{1+j(q_{kas})h(q_{kas})} = \frac{c_1}{p-\frac{c_2}{\overline{F}(q_{kas})}}$ *and the optimal wholesale price and subcontracting price ratio are characterized by* $w^* = \frac{c_1+c_2}{\overline{F}(q_{kas})}$ *and* $k^* = \frac{c_2}{c_1+c_2}$*, respectively, where* $j(x) = \frac{S(x)}{\overline{F}(x)}$, $h(x) = \frac{f(x)}{\overline{F}(x)}$.

From Lemma 3, we know that the wholesale price determined by the manufacturer is a constant when the two suppliers' total production cost is fixed. Evidently, the wholesale price determined by the manufacturer increases in the two suppliers' production cost under KAS. In particular, as the key supplier's production cost increases, the subcontracting cost ratio decreases. Thus, the key supplier sets a low component's sale price for the subcontractor to decrease his production quantity, thereby offsetting the negative effect of the increased production cost.

4.4 SKA mode

Under SKA, the subcontractor makes an ex-ante decision on the subcontracting pricing ratio. The key supplier exerts a push contract on the manufacturer. Thereafter, the sequence follows a definite pattern. First, the subcontractor decides on the subcontracting price ratio k. Second, given k, the key supplier decides the wholesale price w. Third, given k and w, the manufacturer decides the order quantity q_1 and q_2 from the two suppliers. Under KSA, the manufacturer orders the same components from the two suppliers to maximize profit. Therefore, $q_{ska} = q_1 = q_2$, where q_{ska} denotes the order quantity under SKA. Lastly, the two suppliers produce the components based on the order quantity.

The key supplier's profit function in terms of w is as follows:

$$\prod\nolimits_{S1}(w) = (w - kw - c_1)E\min(D, q_1, q_2). \tag{11}$$

The subcontractor's profit function is as follows:

$$\prod\nolimits_{S2}(k) = (kw - c_2)E\min(D, q_1, q_2). \tag{12}$$

The manufacturer's profit function in terms of q_1 and q_2 is as follows:

$$\prod\nolimits_M(q_1, q_2) = pE\min(D, q_1, q_2) - wE\min(D, q_1, q_2). \tag{13}$$

Table 2 Firms' pricing and quantity equilibriums under SPR

Mode	Order quantity q	Wholesale price w	Subcontracting price ratio k
KSA	$p[1-g(q_{ksa})]=\frac{c_1+c_2}{\overline{F}(q_{ksa})}$	$w^*=\frac{c_1+c_2}{1-g(q_{ksa})}$	$k^*=\frac{c_2}{c_1+c_2}[1-g(q_{ksa})]$
KAS	$\frac{\overline{F}(q_{kas})}{1+j(q_{kas})h(q_{kas})}=\frac{c_1}{p-\frac{c_2}{\overline{F}(q_{kas})}}$	$w^*=\frac{c_1+c_2}{\overline{F}(q_{kas})}$	$k^*=\frac{c_2}{c_1+c_2}$
SKA	$p\,\overline{F}(q_{ska})[1-g(q_{ska})]-q_{ska}\frac{c_1 g^{'}(q_{ska})}{[1-g(q_{ska})]^2}=\frac{c_1}{1-g(q_{ska})}+c_2$	$w^*=p\,\overline{F}(q_{ska})$	$k^*=1-\frac{c_1}{p\,\overline{F}(q_{ska})[1-g(q_{ska})]}$

Table 3 Firms' optimal profits under SPR

Mode	Key supplier	Subcontractor	Manufacturer
KSA	$\frac{q_{ksa}g(q_{ksa})}{1-g(q_{ksa})}(c_1+c_2)$	0	$pS(q_{ksa})-\frac{q_{ksa}}{1-g(q_{ksa})}(c_1+c_2)$
KAS	$\frac{c_1}{\bar{F}(q_{kas})}S(q_{kas})-c_1q_{kas}$	$\frac{c_2}{\bar{F}(q_{kas})}S(q_{kas})-c_2q_{kas}$	$\left[p-\frac{c_1+c_2}{\bar{F}(q_{kas})}\right]S(q_{kas})$
SKA	$\frac{q_{ska}g(q_{ska})}{1-g(q_{ska})}c_1$	$\left[p\bar{F}(q_{ska})-\frac{c_1}{1-g(q_{ska})}-c_2\right]q_{ska}$	$p[S(q_{ska})-q_{ska}\bar{F}(q_{ska})]$

Similarly, we obtain the optimal pricing and quantity decisions by backward induction.

Lemma 4 *Under SKA, the optimal equilibrium production quantity satisfies* $p\,\overline{F}(q_{ska})[1-g(q_{ska})]-q_{ska}\frac{c_1 g^{'}(q_{ska})}{[1-g(q_{ska})]^2}=\frac{c_1}{1-g(q_{ska})}+c_2$, *while the optimal wholesale price and subcontracting price ratio are characterized by* $w^*=p\,\overline{F}(q_{ska})$ *and* $k^*=1-\frac{c_1}{p\,\overline{F}(q_{ska})[1-g(q_{ska})]}$, *respectively, where* $g(x)=\frac{xf(x)}{\overline{F}(x)}$ *and* $h(x)=\frac{f(x)}{\overline{F}(x)}$.

The preceding lemma indicates that the subcontracting price ratio decreases with the key supplier's production cost. The reason is that under SKA, the subcontractor determines his subcontracting price ratio. As the key supplier's production cost increases, the subcontractor will lower his sale price to induce the manufacturer to increase the order quantities.

Lastly, we conclude firms' optimal pricing and quantity decisions as well as optimal profits under SPR (see Tables 2, 3). In subsequent sections, we compare these results to identify which power structure benefits firms and the total supply chain.

5 Comparison and implication

This section compares firms' optimal decisions to show which power structure benefits the assembly system the most. We analyze how the suppliers' production cost affects firms' optimal decision by considering the real case data. In our real case analysis, through data normalization, the market demand follows a uniform distribution $U[0, 1]$, $p = 40$, and $c_1 + c_2 = 20$.[8]

[8] We use the aforementioned case (King Long, Cummins, Inc, and Cummins Emission Solutions) to derive and verify our main findings. The details of real case data will be elaborated in Sect. 6.3.

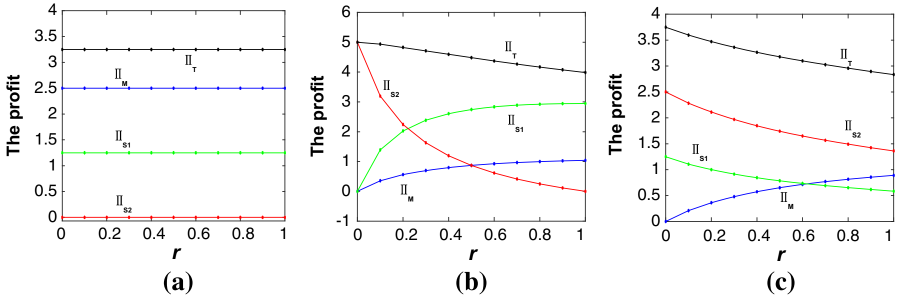

Fig. 2 Effects of r on firms' profits under SPR. **a** KSA, **b** KAS and **c** SKA. *Note* $\prod_T$ represents the total profit of decentralized assembly system

5.1 Cost implication

We first consider how the suppliers' production cost affects the firms' profits. We determine which power structure under SPR benefits firms the most by analyzing the cost proportion changes. For simplicity, we present the following equations:

$$r = c_1/(c_1 + c_2), \tag{14}$$

which denotes production cost proportion for the key supplier. We obtain the following proposition:

Proposition 1 *Under SPR, we can obtain the following results when the total production cost is fixed:*

(1) *Under KSA, firms' profits are independent of the cost proportion r.*
(2) *The manufacturers' profit is increasing in the cost proportion r under KAS and SKA, whereas the subcontractor's profit is decreasing in the cost proportion r. In addition, the key supplier's profit is increasing in the cost proportion r under KAS, and decreasing under SKA.*

Proposition 1 derives a few results that are contrary to traditional wisdom. First, firms' profits under KSA are unaffected by the cost proportion. Second, as the cost proportion increases under KAS, the key supplier and manufacturer are likely to attain a high profit, although the total channel profit decreases. Surprisingly, switching to the SKA mode entails that a high cost proportion does not benefit the key supplier even if the key supplier is the wholesale price decision-maker. Lastly, a substantial difference is observed in the system's performance under KAS and SKA. Figure 2 also illustrates the above characteristics.

Intuitively, Lemma 1 shows that the cost proportion under KSA does not affect the firms' profit because the subcontractor has no power in the subcontracting mechanism. Thus, the key supplier leaves no profit for the subcontractor to optimize his profit in equilibrium. Under KAS, the key supplier's profit increases in the cost proportion. In our model, the two suppliers' profit is exposed to the inventory risk. Compared with the subcontractor, the key supplier has strong risk controlling ability. If the cost of key supplier 1 increases, then the key supplier will reduce the production and decrease the subcontracting price ratio to adjust the risk. For the subcontractor, the reduction in the subcontracting price ratio leads to a reduction in the wholesale price. Thus, the subcontractor decreases his production accordingly. Therefore, both suppliers' production quantities decrease, thereby reducing the final quantity q_{kas}. This outcome ultimately results in the decline of the overall system performance. At this time, the key supplier transfers the inventory risk to the subcontractor because of the subcontracting mechanism. With the increase in cost proportion, q_{kas} decreases and the key supplier can still achieve an increasing profit.

The results under SKA are more interesting than that under KAS. When the key supplier's cost proportion increases, the key supplier has to increase the wholesale price, thereby decreasing the manufacturer's order quantity. Under SKA, the manufacturer bears the inventory risk and increasing the wholesale price reduces the procurement quantity and inventory leftover. Thus, the key supplier raises the wholesale price. Lastly, the order quantity's decline in equilibrium also decreases the two suppliers' overall profit.

5.2 Payoff comparison

We likewise discuss which power structure benefits the firms or the channel under SPR. The result can suggest the method to select the optimal power structure from either the perspective of firms or channels.

5.2.1 Channel efficiency

Table 3 shows firms' optimal profits under three power structures and thus the total profit of decentralized supply chain under each structure can be represented by $\prod_T = pS(q) - (c_1 + c_2)q$, where q denotes the optimal production quantity of each mode (see Table 2). We compare our model with that of Granot and Yin (2008) and focus on whether our study optimizes the supply chain. Therefore, we suggest the following propositions based on Tables 2 and 3.

Proposition 2 (1) *Under SPR, $\prod_T^{KAS} > \prod_T^{KSA} > \prod_T^{SKA}$. As the key supplier's cost proportion increases, the difference between the total profits of KSA and KAS decreases. By contrast, the difference between KSA and SKA increases.*
(2) *KAS outperforms the pure pull contract.*

Proposition 2 demonstrates a positive relationship between the system's total profit and manufacturer's power. That is, the greater the power of a manufacturer, the higher the efficiency of the assembly system has. This result is intuitive because considerable double marginalization exists at the business-level under KSA and SKA. First, Fig. 3a shows that KAS constantly outperforms the other two modes. The manufacturer decides the wholesale price, thereby weakening the horizontal decentralization. However, the double marginalization for the SKA mode achieves the maximum level. We refer to Chen et al. (2014) to consider the KAS mode as a partial centralized assembly system compared with SKA. Thus, KSA outperforms SKA from the perspective of the assembly system's efficiency.

In addition, Fig. 3a shows that with the increase in the key supplier's cost proportion, the difference between the total profits of KSA and KAS decreases and that between KSA and SKA increases. The reason is that the increase in the key supplier's cost proportion increases the negative effect of decentralization, thereby decreasing the system efficiency. In addition, the decrease in the difference for the KAS mode also attributes to the decrease in order quantity.

Proposition 2 also suggests that the system performance is better than that of the classical models, in which the push and pull contracts in terms of pricing decision power were proposed by Granot and Yin (2008). Thus, the system performance is enhanced in the pull contract.

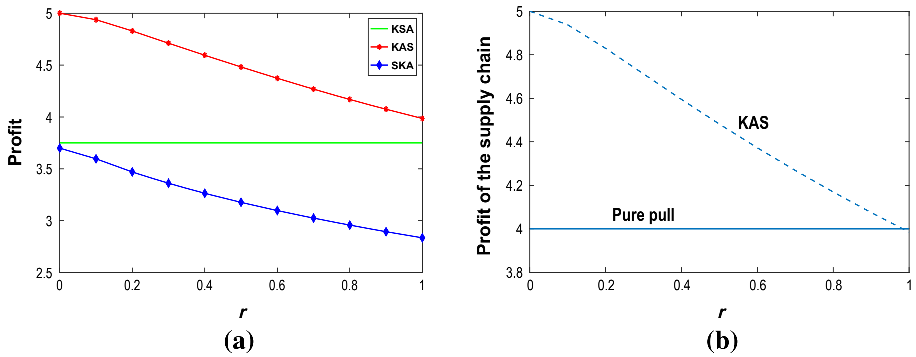

Fig. 3 Profit comparison. **a** Three modes and **b** typical modes

The current study introduces the subcontracting mechanism, which increases the cooperation and contact between the two suppliers. Accordingly, KAS outperforms the previous optimal pull model (see Fig. 3b). However, KAS does not achieve the coordination of a centralized supply chain.

5.2.2 Firms' profitability

Tables 2 and 3 show that we further investigate the firms' optimal decisions. Accordingly, we obtain the following proposition.

Proposition 3 *In equilibrium under SPR:*

(1) *The key supplier obtains the highest and lowest profits under KSA and SKA, respectively.*
(2) *For the manufacturer, the KAS mode dominates, whereas the KSA mode dominates because the key supplier's cost proportion is sufficiently low.*
(3) *For the subcontractor, either the KAS or SKA mode can become the dominant option, depending on the key supplier's cost proportion.*

Figure 4 illustrates how the firms' payoffs react to the key supplier's cost proportion r, in which case the firms benefit the most from the increased cost proportion. Figure 4a shows that the key supplier prefers KSA mode because the key supplier decides the wholesale price and subcontracting ratio under KSA. By contrast, the supplier decides either the wholesale price or subcontracting ratio under SKA or KAS. That is, the first-mover advantage provides the key supplier additional opportunities to maximize his profit. By contrast, under SKA, the subcontractor decides the subcontracting ratio first, thereby going against the key supplier's profit.

Under KAS, the manufacturer determines the wholesale price and bears no inventory risk. Subsequently, as the cost proportion increases, the power structure increases the manufacturer's payoff by decreasing the channel's double marginalization. Interestingly, Fig. 4b shows that when the key supplier's cost proportion r is sufficiently low, the other two power structures outperform KAS mode. The reason is that the subcontractor reduces his production for the increase of his cost proportion $1 - r$. Therefore, the manufacturer has to offer a high wholesale price to the suppliers to retain the production incentive between the two suppliers. That is, the subcontractor extracts additional profit from the manufacturer, thereby ultimately decreasing the manufacturer's payoff.

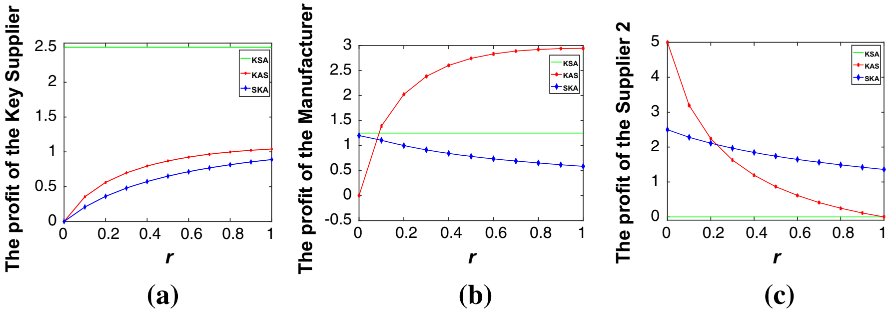

Fig. 4 Firms' profits. **a** Key supplier, **b** manufacturer and **c** subcontractor

Table 4 Dominant mode for firms

Mode	Key supplier	Subcontractor	Manufacturer	Channel
Classical models in Granot and Yin (2008)	Push/pull	Push/pull	Pull	Pull
SPR	KSA	KAS/SKA	KAS/KSA	KAS
Dominant mode	KSA	KAS/SKA	Pull	KAS

Similar to the preceding discussion, the perspective of the subcontractor indicates that as the cost proportion $1 - r$ increases, the manufacturer and key supplier offer a high price to incentivize the production of the subcontractor under KAS. Nonetheless, under SKA, only the key supplier has the incentive that stimulates the subcontractor to increase production as his cost proportion increases. Thus, the subcontractor's payoff is more sensitive to the cost proportion r under KAS than that under SKA. Consequently, either the KAS or SKA mode can become the dominant option, depending on the balance of the subcontractor's first-mover advantage and the other firm's incentive.

Table 4 shows that we compare the three different modes to the classical models of Granot and Yin (2008). Consistent with Proposition 2, we show that the subcontracting mechanism weakens the possible decentralization among supply chain members and improves the system's performance. From the manufacturer's perspective, the power structure under SPR is inferior to the classical pull model. When the cost proportion falls into an intermediate range, the performance of the manufacturer is the same under KAS and the classical pull contract.

6 Extensions

The previous section analyzed the impact of the three different modes on the firms' equilibrium payoffs under SPR. This section extends to a more powerful setting and assumes that the key supplier or manufacturer determines both the component's wholesale price and production quantity. Compared with SPR, we denote this regime as DPR. Similarly, we build three sub-models, namely, KSA$^{\#}$, KAS$^{\#}$, SKA$^{\#}$. To avoid confusion, we use $\prod_T^{KSA}$, $\prod_T^{KAS}$, $\prod_T^{SKA}$, $\prod_T^{KSA^{\#}}$, $\prod_T^{KAS^{\#}}$, $\prod_T^{SKA^{\#}}$, $\prod_T^{pull}$, $\prod_T^{push}$ to denote the channel's expected profit under different modes.

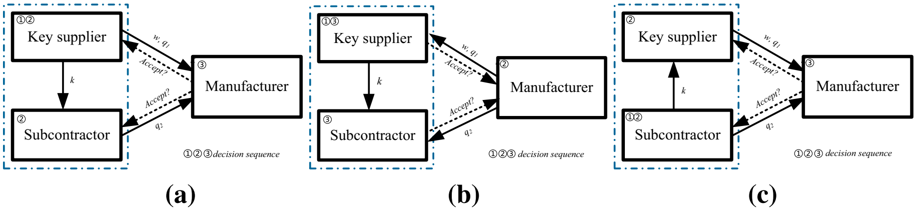

Fig. 5 Sequence of events under DPR. **a** KSA#, **b** KAS# and **c** SKA#

6.1 Pricing and production strategies under DPR

Under KSA#, the key supplier determines his component's wholesale price w and production quantity q_1 together with the subcontracting price ratio k. Thereafter, the subcontractor decides his component's production quantity q_2. Given the wholesale price and two components' production quantity, the manufacturer decides whether to accept the contract. The two suppliers have to manage the risk of the leftover inventory under KSA#. For KAS#, the key supplier first decides the subcontracting price ratio k for the subcontractor. Thereafter, the manufacturer determines the wholesale price w and two suppliers' production quantity q_m. Lastly, the two suppliers determine whether to accept the manufacturer's decisions. Intuitively, the key supplier's and the subcontractor's production quantities q_1 and q_2 are either 0 or q_m. Moreover, the manufacturer bears the inventory risk under KAS#. For the SKA# mode, the subcontractor decides the subcontracting price ratio k first. Thereafter, the key supplier determines the wholesale price. The two suppliers determine their production quantities q_1 and q_2. Under this mode, the two suppliers have to afford the leftover inventory risk, while the manufacturer decides whether to accept the wholesale price and subsequent order quantity. Thereafter, we discuss how DPR affects firms' pricing and production decisions in equilibrium. We further compare the results with those of SPR. A graphic illustration is given in Fig. 5.

Under DPR, the model analysis procedure is similar to that under SPR. Thus, we simplify the analysis process. The preceding discussion indicates that under KSA#, KAS#, and SKA#, the expected payoffs of firms are separately defined as follows.

KSA#:

$$\prod_{S1}(q_1, w, k) = (1-k)wE\min(D, q_1, q_2) - c_1q_1 \tag{15a}$$

$$\prod_{S2}(q_2) = kwE\min(D, q_1, q_2) - c_2q_2 \tag{15b}$$

$$\prod_{M}(q_m) = (p-w)E\min(D, q_1, q_2) \tag{15c}$$

KAS#:

$$\prod_{S1}(q_1, k) = [(1-k)w - c_1]q_1 \tag{16a}$$

$$\prod_{S2}(q_2) = (kw - c_2)q_2 \tag{16b}$$

$$\prod_{M}(q_m, w) = pE\min(D, q_1, q_2) - wE\min(D, q_1, q_2) \tag{16c}$$

SKA#:

$$\prod S1(q_1, w) = w(1-k)E\min(D, q_1, q_2) - c_1q_1 \tag{17a}$$

Table 5 Firms' optimal pricing and quantity decisions under DPR

Mode	Order quantity q	Wholesale price w	Subcontracting price ratio k
KSA$^{\#}$	$p\bar{F}(q_{ksa^{\#}}) = c_1 + [1 + j(q_{ksa^{\#}})h(q_{ksa^{\#}})]c_2$	$w^* = p$	$k^* = c_2/[p\bar{F}(q_{ksa^{\#}})]$
KAS$^{\#}$	$p\bar{F}(q_{kas^{\#}}) = c_1 + c_2$	$w^* = c_1 + c_2$	$k^* = c_2/(c_1 + c_2)$
SKA$^{\#}$	$p\bar{F}(q_{ska^{\#}}) = [1 + j(q_{ska^{\#}})h(q_{ska^{\#}})]c_1 + c_2$	$w^* = p$	$k^* = 1-c_1/[p\bar{F}(q_{ska^{\#}})]$

Table 6 Firms' optimal profits under DPR

Mode	Key supplier	Subcontractor	Manufacturer
KSA$^{\#}$	$pS(q_{ksa^{\#}}) - c_2 j(q_{ksa^{\#}}) - c_1 q_{ksa^{\#}}$	$c_2 j(q_{ksa^{\#}}) - c_2 q_{ksa^{\#}}$	0
KAS$^{\#}$	0	0	$pS(q_{kas^{\#}}) - (c_1 + c_2)q_{kas^{\#}}$
SKA$^{\#}$	$c_1 j(q_{ska^{\#}}) - c_1 q_{ska^{\#}}$	$pS(q_{ska^{\#}}) - c_1 j(q_{ska^{\#}}) - c_2 q_{ska^{\#}}$	0

$$\prod\nolimits_{S2}(q_2, k) = kwE\min(D, q_1, q_2) - c_2 q_2 \tag{17b}$$

$$\prod\nolimits_{M}(q_m) = (p - w)E\min(D, q_1, q_2) \tag{17c}$$

We derive each mode's optimal decisions through backward induction (see Tables 5, 6).

Proposition 4 *Under DPR, we have the following equilibrium results:*

(1) $\prod_C = \prod_T^{KAS^{\#}} > \prod_T^{KSA^{\#}}$, $\prod_C = \prod_T^{KAS^{\#}} > \prod_T^{SKA^{\#}}$;
(2) $\prod_M^{KAS^{\#}} > \prod_M^{KSA^{\#}} = \prod_M^{SKA^{\#}} = 0$;
(3) $\prod_{S1}^{KSA^{\#}} > \prod_{S1}^{SKA^{\#}} > \prod_{S1}^{KAS^{\#}} = 0$;
(4) $\prod_{S2}^{SKA^{\#}} > \prod_{S2}^{KSA^{\#}} > \prod_{S2}^{KAS^{\#}} = 0$.

The preceding proposition indicates that the KAS$^{\#}$ mode achieves the centralized system performance (see Fig. 6). First, the manufacturer determines the wholesale price and production quantity, thereby inducing him to abstract most profit from the suppliers. Thus, this power structure decreases the double marginalization effect and maximizes the channel's profit. Second, the subcontracting price ratios are separately determined by various suppliers under KSA$^{\#}$ and SKA$^{\#}$. We use the optimal decisions in Table 5 as bases to use $1 + j(q)h(q)$ to represent the double marginalization effect between the two suppliers, in which q denotes the equilibrium production quantity under KSA$^{\#}$ and SKA$^{\#}$. The horizontal decentralization between the two suppliers will decrease the system's performance.

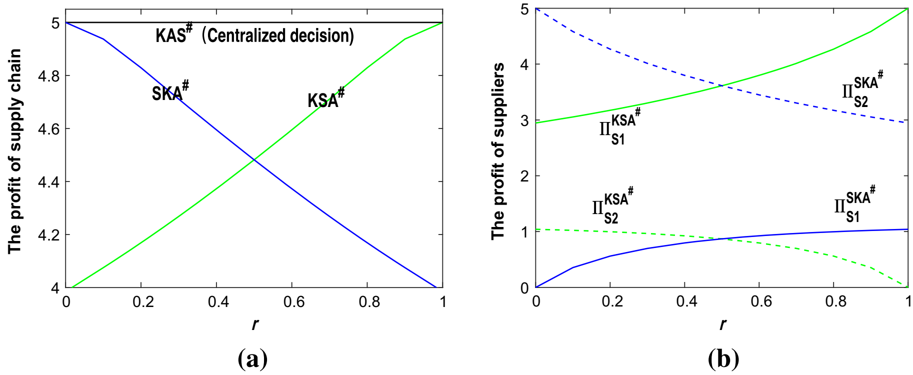

Fig. 6 Profit comparison of different modes under DPR. **a** Assembly system and **b** suppliers

Table 7 Dominant modes for different firms

Mode	Key supplier	Subcontractor	Manufacturer	Channel
Classical models in Granot and Yin (2008)	Push/pull	Push/pull	Pull	Pull
SPR	KSA	KAS/SKA	KAS/KSA	KAS
DPR	KSA#	SKA#	KAS#	KAS#
Dominant mode	KSA#	SKA#	KAS#	KAS#

6.2 Comparison between SPR and DPR

We next compare the optimal pricing and production strategies under SPR with that under DPR. We build upon the preceding analysis to derive the following proposition (Table 7).

Proposition 5 *Comparing DPR and SPR, we have the following equilibrium results:*

(1) $\prod_T^{KAS^{\#}} \geq \prod_T^{KAS} \geq \prod_T^{pull}$
(2) $\prod_M^{KAS^{\#}} \geq \prod_M^{pull} \geq \max(\prod_M^{KAS}, \prod_M^{KSA})$
(3) $\prod_{S1}^{KSA^{\#}} \geq \prod_{S1}^{KSA} \geq \max(\prod_{S1}^{push}, \prod_{S1}^{pull})$
(4) $\prod_{S2}^{SKA^{\#}} \geq \max(\prod_{S2}^{SKA}, \prod_{S2}^{KAS}) \geq \max(\prod_{S2}^{push}, \prod_{S2}^{pull})$

Proposition 5 reveals that each firm can benefit more from the corresponding power structure under DPR than under SPR (see Fig. 7). Moreover, integrating the pricing and production decisions into a firm generates first-mover advantage and reduces double marginalization among firms. This result suggests that the assembly system prefers the centralization of the decision-making power. In particular, our analysis indicates that to maximize the channel profit, the firm closest to the end market is most preferred to make the integrated decision.

6.3 Real case study

To verify our main findings, we use the first real case mentioned in the introduction to help understand the key insights. Recall that King Long is one of the leading automobile firms in

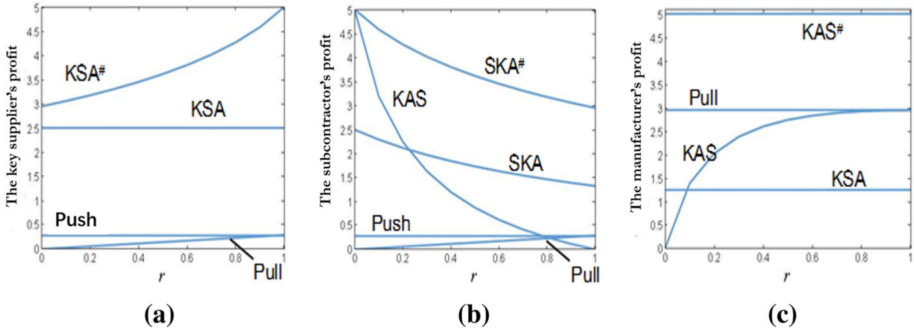

Fig. 7 Profit comparison under SPR, DPR, and pull–push contract. **a** Key supplier, **b** subcontractor and **c** manufacturer

China. Before the assembly and production of the coaches, King Long contracts Cummins, Inc. on the engine and post-processing assembly productions. To meet the standard of gas emissions and achieve compatible assembly, Cummins, Inc. subcontracts the post-processing assembly to Cummins Emission Solutions. In this particular subcontracting assembly system, we collect some real data and then normalize these data to facilitate our analysis. In this assembly system, the market demand can be regarded to be the uniform distribution $U[0, 1]$, $p = 40$, and $c_1 + c_2 = 20$.

We first compare the assembly system's profit and the suppliers' profit among the three modes under DPR. Figure 6 shows the impact of r on the total profit of the assembly systems as well as the profit of the suppliers. The entire assembly system achieves the same highest payoff under KAS$^{\#}$ as under the centralized decision (see Fig. 6a). From the perspective of the suppliers, both of them would like to move first since it brings more benefit for the first mover, as shown in Fig. 6b. This is consistent with the practical case that the dominant Cummins always would like to be the leader in KAS$^{\#}$ rather than a follower position in SKA$^{\#}$.

We then compare the optimal modes under each regime for the key supplier, the subcontractor, and the manufacturer, respectively, as shown in Fig. 7. The real case data shares the same principle with the analytical solution. Moreover, integrating the pricing and production decisions into a firm generates first-mover advantage and reduces double marginalization among the firms. This result suggests that the assembly system prefers the centralization of the decision-making power. In particular, our analysis indicates that to maximize the channel profit, the firm closest to the end market is most preferred to make the integrated decision. In our real case, King Long would prefer to make all the decisions for suppliers to extract the most channel profit, if King Long is powerful enough.

7 Conclusion

This study investigates the impact of power structures on the manufacturer, key supplier, and subcontractor in a decentralized assembly system. In this system, the two suppliers produce two complementary components for the manufacturer, who assembles them into a product and sells it to the end consumers. Different from the previous studies on the assembly system, our study develops a model of the subcontracting mechanism. In such mechanism, the key supplier generally assigns partial production to the subcontractor with a subcontracting price ratio. In particular, three different power structures under SPR are constructed, namely, KSA, KAS, and SKA. Through building multi-stage Stackelberg game models, we obtain the firms' equilibrium pricing and quantity decisions, thereby providing managerial insights into firm profitability, negotiation power allocation, and supplier cooperation.

We determine that the assembly system's profit achieves the maximum under KAS, in which the manufacturer and suppliers determine the wholesale price and the production quantities, respectively. Furthermore, the gap of the channel's performance between the KAS and KSA modes decreases in the key supplier's cost proportion. By contrast, the gap between the KSA and SKA modes increases. The intuition is that the manufacturer's pricing decision reduces the horizontal decentralization, thereby coordinating the suppliers' production quantities. In addition, we show that KAS performs better than the pure pull contract in Granot and Yin (2008). For the manufacturer, we demonstrate that KAS dominates, whereas KSA dominates when the key supplier's cost proportion is relatively low. The key supplier constantly prefers the KSA mode. We also determine that either the KAS or SKA mode can become the dominant option for the subcontractor, depending on the key supplier's cost proportion.

We also discuss the extension to DPR, in which the key supplier or manufacturer simultaneously determines the component's wholesale price and production quantity. Using the backward induction method, we derive the pricing and production strategies under DPR and further compare it with SPR. The results suggest that the assembly system prefers the centralization of decision-making power. We also demonstrate that the system will benefit if the firm closest to the end market makes the centralization decision. The real case study shares the same principle with the analytical solution in that a powerful King Long would prefers to make all the decisions for suppliers to extract the most channel profit.

The analysis in this study can be extended into several directions. First, we assume that the assembly system comprises a manufacturer and two suppliers. In fact, the manufacturer faces many suppliers, thereby resulting in many management problems. Moreover, analyzing the multi-supplier decisions would require a multi-product model. Second, this study does not consider the uncertainty of supply disruption, production lead time, or demand time. Hence, a multi-method approach should be adopted to model these uncertainties and investigate their impacts on the assembly systems (Choi et al. 2016). Third, our model can be extended to consider information asymmetry, which had been scarcely analyzed in the prior assembly system literature. Of particular interest would be to discuss whether the main results will remain robust when the asymmetric information is incorporated.

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Appendix

Proof for Lemma 1

Note that a critical condition $k = \frac{c_2}{w}$ guarantees the subcontractor's profit positive. That is, the optimal subcontracting price ratio is $\frac{c_2}{w}$. We calculate the first and second derivatives of Eq. (5) on q_{ksa} to obtain $\frac{\partial \prod_{S1}}{\partial q_{ksa}} = \left\{p[1 - g(q_{ksa})] - \frac{c_1+c_2}{\bar{F}(q_{ksa})}\right\}\bar{F}(q_{ksa})$ and $\frac{\partial^2 \prod_{S1}}{\partial q_{ksa}^2} =$

$-2\,\overline{F}(q_{ksa})g(q_{ksa}) < 0$, where $g(x) = \frac{xf(x)}{\overline{F}(x)}$. Thus, the supply chain's equilibrium production quantity satisfies $p[1 - g(q_{ksa})] = \frac{c_1+c_2}{\overline{F}(q_{ksa})}$. In addition, the optimal wholesale price and subcontracting price ratio are $w^* = \frac{c_1+c_2}{1-g(q_{ksa})}$ and $k^* = \frac{c_2}{c_1+c_2}[1 - g(q_{ksa})]$, respectively.

Proof of Lemma 2

Note that the two suppliers' optimal strategy has a unique Nash equilibrium as follows:

$$\prod_{S1}(k, q_1) = w(1 - k)E\min(D, q_1, q_2) - c_1 q_1 \quad \text{(A1)}$$

$$\prod_{S2}(q_2) = kwE\min(D, q_1, q_2) - c_2 q_2. \quad \text{(A2)}$$

We combine Eqs. (A1) and (A2). If $q_1 < q_2$, then we obtain the following equations:

$$\prod_{S1}(k, q_1) = w(1 - k)E\min(D, q_1) - c_1 q_1 \quad \text{(A3)}$$

and

$$\prod_{S2}(q_2) = kwE\min(D, q_1) - c_2 q_2. \quad \text{(A4)}$$

We consider the first and second derivatives of Eqs. (A3) and (A4) to obtain $\frac{\partial \prod_{S1}}{\partial q_1} = w(1-k)[1 - F(q_1)] - c_1,\ and\ \frac{\partial^2 \prod_{S1}}{\partial q_1^2} = -w(1 - k)f(q_1) < 0$. In addition, $\frac{\partial \prod_{S2}}{\partial q_2} = -c_2 < 0$. Thus, the two suppliers' optimal production quantity is $q_1 \wedge q_2$ and $q_1 = \bar{F}^{-1}\left(\frac{c_1}{w(1-k)}\right)$.

If $q_1 > q_2$, then we obtain the following equations:

$$\prod_{S1}(k, q_1) = w(1 - k)E\min(D, q_2) - c_1 q_1 \quad \text{(A5)}$$

and

$$\prod_{S2}(q_2) = kwE\min(D, q_2) - c_2 q_2. \quad \text{(A6)}$$

When the first and second derivatives of Eqs. (A5) and (6) are calculated, we obtain $\frac{\partial \prod_{S2}}{\partial q_2} = kw[1 - F(q_2)] - c_2,\ and\ \frac{\partial^2 \prod_{S2}}{\partial q_2^2} = -kwf(q_2) < 0$.

In equilibrium, the two suppliers' optimal production quantity is $q_1 \wedge q_2$ and $q_2 = \bar{F}^{-1}\left(\frac{c_2}{kw}\right)$. Thus, we use Eqs. (A4) and (A5) to solve for q_1 and q_2 in terms of w and k. Accordingly, $q_1 = \bar{F}^{-1}\left(\frac{c_1}{w(1-k)}\right)$ and $q_2 = \bar{F}^{-1}\left(\frac{c_2}{kw}\right)$. Thereafter, we obtain $w = \frac{c_1}{\overline{F}(q_1)} + \frac{c_2}{\overline{F}(q_2)}$ and $k = \frac{c_2}{w\,\overline{F}(q_2)}$. Thus, the equilibrium production quantity of the KAS mode is defined by $q_{kas} = q_1 \wedge q_2$. Moreover, the integrated system shares the same principle with this Lemma.

Proof of Lemma 3

When the manufacturer's profit function in Eq. (10) is used, if $q_1 \geq q_2$, then we obtain the following equation:

$$\prod_{M}(q_1, q_2) = \left[p - \frac{c_1}{\overline{F}(q_1)} - \frac{c_2}{\overline{F}(q_2)}\right]E\min(D, q_2), \quad \text{(A7)}$$

which is evidently decreasing in q_1. In addition, the optimal q_1 equals the threshold q_2. If $q_1 \leq q_2$, then we obtain the following equation:

$$\prod_M (q_1, q_2) = \left[p - \frac{c_1}{\overline{F}(q_1)} - \frac{c_2}{\overline{F}(q_2)} \right] E \min(D, q_1). \tag{A8}$$

When the first and second derivatives of Eq. (A8) are calculated, we can obtain $\frac{\partial \prod_M}{\partial q_1} = \left[p - \frac{c_2}{\bar{F}(q_2)} \right] \bar{F}(q_1) - c_1[1 + j(q_1)h(q_1)]$, and $\frac{\partial^2 \prod_M}{\partial q_1^2} = -\left[p - \frac{c_2}{\bar{F}(q_2)} \right] f(q_1) - c_1[j(q_1)h(q_1)]' < 0$, where $j(x) = \frac{S(x)}{\overline{F}(x)}$ and $h(x) = \frac{f(x)}{\overline{F}(x)}$.

Hence, Eq. (A8) is concave in q_1 and $q_1^* = \min(q_1, q_2)$. From $\frac{\partial \prod_M}{\partial q_1} = 0$, we can obtain $\frac{\bar{F}(q_1)}{1+j(q_1)h(q_1)} = \frac{c_1}{p - \frac{c_2}{\bar{F}(q_2)}}$. Thus, the key supplier's profit function can be written in terms of q_1^* as $\prod_{S1}(q_1^*) = \frac{c_1}{\overline{F}(q_1^*)} E \min(D, q_1^*, q_2) - c_1 q_1^*$. If $q_1 \geq q_2$, there is $\prod_{S1}(q_2) = \frac{c_1}{\overline{F}(q_2)} E \min(D, q_2) - c_1 q_2$. Given that $\frac{\partial \prod_{S1}}{\partial q_2} = \frac{f(q_2)S(q_2)}{\overline{F}^2(q_2)} c_1 > 0$, $\prod_{S1}$ is decreasing in q_2. Thus, the optimal q_2 equals q_1. If $q_1 \leq q_2$, there is $\prod_{S1}(q_2) = \frac{c_1}{\overline{F}(q_1)} E \min(D, q_1) - c_1 q_1$. Given that $\frac{\partial \prod_{S1}}{\partial q_2} = \frac{f(q_1)S(q_1)}{\overline{F}^2(q_1)} \frac{\partial q_1}{\partial q_2} c_1 < 0$, $\prod_{S1}$ is decreasing in q_2. Thus, the optimal q_2 equals q_1.

In equilibrium, the optimal production quantity satisfies $q_{kas} = q_1 = q_2$ and $\frac{\bar{F}(q_{kas})}{1+j(q_{kas})h(q_{kas})} = \frac{c_1}{p - \frac{c_2}{\bar{F}(q_{kas})}}$. The optimal wholesale price and subcontracting price ratio are defined by $w^* = \frac{c_1+c_2}{\overline{F}(q_{kas})}$ and $k^* = \frac{c_2}{c_1+c_2}$, respectively, where $j(x) = \frac{S(x)}{\overline{F}(x)}$ and $h(x) = \frac{f(x)}{\overline{F}(x)}$.

Proof of Lemma 4

We use backward induction and start from the third stage, when the manufacturer decides the order quantity from the two suppliers. Given the manufacturer's profit function in Eq. (8), solving the first and second orders condition of $\prod_M$ will yield $\frac{\partial \prod_M}{\partial q_m} = p\,\overline{F}(q_m) - w$ and $\frac{\partial^2 \prod_M}{\partial q_m^2} = -pf(q_m) < 0$. Thereafter, the optimal order quantity satisfies $q_{ska} = \bar{F}^{-1}\left(\frac{w}{p}\right)$. That is,

$$w(q_{ska}) = p\,\overline{F}(q_{ska}). \tag{A9}$$

Thus, Eq. (9) is used to write the key supplier's profit in terms of q_{ska}. Hence,

$$\prod_{S1}(q_{ska}) = [(1-k)p\,\overline{F}(q_{ska}) - c_1] q_{ska}. \tag{A10}$$

When the first and second derivatives of Eq. (A10) are calculated, we can obtain that $\frac{\partial \prod_{S1}}{\partial q_{ska}} = p(1-k)[\bar{F}(q_{ska}) - q_{ska} f(q_{ska})] - c_1$ and $\frac{\partial^2 \prod_{S1}}{\partial q_{ska}^2} = -2p(1-k)f(q_{ska}) < 0$. Thereafter, Eq. (A10) is concave in q_{ska} and the optimal order quantity q_{ska} satisfies $p(1-k)\bar{F}(q_{ska})[1 - g(q_{ska})] = c_1$, where $g(x) = \frac{xf(x)}{\overline{F}(x)}$. Thereafter, substituting Eq. (A9) into the subcontractor's profit function will yield as follows:

$$\prod_{S2}(q_{ska}) = \left[p\,\overline{F}(q_{ska}) - \frac{c_1}{1 - g(q_{ska})} - c_2 \right] q_{ska}. \tag{A11}$$

Similarly, the derivative of Eq. (A11) yields $\frac{\partial \prod_{S2}}{\partial q_{ska}} = p\bar{F}(q_{ska})[1 - g(q_{ska})] - \frac{c_1}{1-g(q_{ska})} - c_2 - q_{ska} \frac{c_1 g'(q_{ska})}{[1-g(q_{ska})]^2}$. Given that $\frac{\partial \prod_{S2}}{\partial q_{ska}}\big|_{q_{ska}=0} = p - c_1 - c_2 > 0$, $\frac{\partial \prod_{S2}}{\partial q_{ska}}\big|_{q_{ska}=\infty} < 0$, and $\prod_{S2}$

is continuous, there exists a maximum q_{ska} at least to maximize $\prod_{S2}$. Moreover, the maximum q_{ska} satisfies $p\,\overline{F}(q_{ska})[1-g(q_{ska})] - q_{ska}\frac{c_1 g^{'}(q_{ska})}{[1-g(q_{ska})]^2} = \frac{c_1}{1-g(q_{ska})} + c_2$. Subsequently, the optimal wholesale price and subcontracting price ratio are defined by $w^* = p\,\overline{F}(q_{ska})$ and $k^* = 1 - \frac{c_1}{p\,\overline{F}(q_{ska})[1-g(q_{ska})]}$, where $g(x) = \frac{xf(x)}{\overline{F}(x)}$ and $h(x) = \frac{f(x)}{\overline{F}(x)}$.

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