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OPTIMIZATION OF SUPPLY AND DEMAND MATCHING IN SUPPLY CHAIN COUPLING MECHANISM

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Abstract. The mismatch between supply and demand caused by asymmetry of market information has long been an issue. This paper studies a two-tier supply chain model consisting of automaker and chip suppliers with unstable supply and fluctuating prices. First, an analysis is conducted on how the manufacturer's order strategy is affected by the supplier's wholesale price and reliability when the supplier dominates the market. Then a set of supply chain coupling mechanisms is designed to analyze its feasibility in solving the supply shortage issue. Finally, the coupling coefficient is solved to maximize the revenue of the supply chain. Theoretical analysis results show that there is a threshold point for the supplier's effort cost coefficient, and when the effort cost coefficient exceeds the threshold point, the supply is no longer stable, and it triggers a sharp increase in supply price. This threshold point is affected by the supplier's production cost, manufacturer's order quantity, and asymmetry of demand information. According to simulation studies, there is always a supply chain coupling coefficient that optimizes the total benefit of the supply chain. In this coupling coefficient, the supplier's reliability and the manufacturer's order quantity reach the maximum. Finally, compared with vertical integration, a coupling mechanism is more advantageous in coordinating the supply chain in the field of high-end chips.

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1. Introduction

The outbreak of the COVID-19 epidemic and the increasing complexity of international relations triggered supply and demand contradictions between chip suppliers and automakers. On the one hand, automakers' misjudgment of downstream market demand leads to fewer chip purchases from upstream and causes serious economic loss. For example, Ford expects a 10% to 20% drop in production in the first quarter of 2021, and Ford's total revenue in 2020 fell by 18% compared to 2019 [2]. On the other hand, chip suppliers prioritize orders for consumer electronics as automakers cut orders, resulting in a shortage of chip supply for automobiles [9]. Meanwhile, chip shortage also adversely affects chip suppliers, as Taiwan Semiconductor Manufacturing Company (TSMC) grows at an average year-on-year rate of 25% in the four quarters of 2020, while year-on-year

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Keywords. Supply chain coupling, supply, demand matching, price optimization, Stackelberg game.

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revenue growth in September 2021 is expected to be only 19%. As a result, Infineon, the largest semiconductor company in Europe, also warns automakers to consider purchasing more chips in stock.

Since automakers are more proximate to the downstream market, their demand forecasts are typically trusted. However, it is challenging to increase production without adequate planning because of the lengthy production cycle of automotive chips. The demand forecast of chip manufacturers is very important and market demand forecast made by both supply and demand parties in the automotive supply chain leads to asymmetry of demand information. At the beginning of 2020, automakers cut down chip orders in anticipation of sluggish downstream demand, but they underestimated the rapidity of demand recovery. When demand rebounded at the end of 2020, chip suppliers were busy producing chip orders for consumer electronics [34]. Faced with the pressure of soaring automotive chip orders, TSMC had to raise the price of automotive chips by about 20% in 2021 [25]. Obviously, chip suppliers are worried that manufacturers suddenly cutting down orders will cause more inventory backlog and ultimately results in the mistrust of market demand forecast by both supply and demand parties. In addition, automakers realize that chip supply can no longer solely rely on market regulation, since few automakers are willing to develop their own chips, and automakers such as Volkswagen only want to establish closer ties with chip suppliers [33]. Under the influence of price response, supply, and demand matching, and revenue distribution, the supply and demand party forms a close cooperation and interdependent benign relationship, which can be defined as a coupling relationship.

This paper suggests a coupling mechanism-based solution in light of the problem and backdrop mentioned above, which is the mismatch between supply and demand brought on by the asymmetry of market demand information. A two-tier supply chain system consisting of supplier and manufacturer with unstable productivity is studied. First, based on information asymmetry, a supply chain model with partial information sharing dominant by supplier is constructed, and optimal pricing, production, and order strategy for both supply and demand party are found. Then, by means of vertical integration, a traditional supply chain coordination method, the impact of complete information sharing between upstream and downstream of the supply chain on the previous model is analyzed. Finally, a new supply chain coordination mechanism of supply chain coupling is proposed, by comparing it with the vertical integration mechanism, and marginal conditions for achieving supply chain coupling are found.

The innovations of this paper mainly are: (1) The traditional chip supply chain pricing method adopts a linear pricing method, and this paper sets price dynamically based on market demand so as to optimize the supplier's chip pricing issue. (2) In previous research, the supplier's reliability is designed as a fixed parameter or random variable, and this paper considers and models the reliability of the supplier as an endogenous decision variable. (3) A new supply chain coordination mechanism of supply chain coupling is proposed, and marginal contract conditions for achieving the supply chain coupling state are obtained through simulation experiments.

Based on the research on supply chain systems in the coupling mechanism, the contributions of this paper are:

- The manufacturer's optimal order decision and the supplier's optimal pricing and production decision are obtained to maximize the revenue.
- There is a threshold point for the supplier's effort cost coefficient. When the effort cost coefficient exceeds the threshold point, the supply is no longer stable, and the price surges.
- The optimal coupling state when the supply chain revenue reaches the maximum is obtained, and the marginal condition of the corresponding coupling state is obtained through simulation analysis.
- By comparing and analyzing two supply chain coordination mechanisms of vertical integration and supply chain coupling, it is found that the revenue of low-end chips is significantly higher than that of the vertical integration mechanism, while the revenue of high-end chips is higher in the supply chain coupling mechanism.

The remaining chapters of this paper include: Section 2 is a literature review of relevant research; Section 3 is model construction of the research issue and presents hypotheses accordingly; Section 4 is simulation analysis; Section 5 is sensitivity analysis; Section 6 summarizes conclusions. All relevant proofs are provided in the appendix.

2. Literature review

The research topics of this paper include supply shortage, asymmetry of supply and demand information, and supply chain coordination mechanisms. So, let's sort out the relevant literature from these three aspects.

Many scholars have conducted studies on the issue of supply shortage. Carvalho *et al.* [8] analyze the impact of two common reasons for supply shortage (capacity shortage and material shortage) on the resilience of supply chain, and analyze how to make supply chain more resilient in an empirical manner. Li and Dong [26] analyze how government ensures the supply of life-saving materials during the epidemic, and sets up three forms of government regulations to assess the impact of different regulatory methods on the supply of life-saving materials. Huang and Wu [18] propose a self-reservation policy strategy based on Markov decision processes from the perspective of manufacturer to ensure that the total cost of fixed and variable inventory expenditure is minimized. Jia and Zhao [22], based on Pareto, improve contract and find that rising medicine price cannot alleviate medicine shortage, and analyze the impact of IPS method (Price increases being paired with strengthened failure-to-supply clauses) on all parties in the supply chain. Giri and Bardhan [17] and Cai *et al.* [6] set production uncertainty as a random variable of $[0, 1]$ and discuss the changes in decision-maker's decision in the supply chain with different probabilities of disruption in the form of distribution function. Li *et al.* [30] analyze how to meet random demand from the perspective of manufacturer building its production capacity, and also analyze whether manufacturer has the incentive to expand its capacity when retailer and manufacturer share risks. Li and Ou [28] analyze how an assembler can use an appropriate order strategy for its commodity parts to maximize revenue when there are multiple complementary parts of commodity parts and allow for temporary stock-out. Shan *et al.* [36] analyze the supplier's pricing issue when manufacturer can choose dual-channel purchase, and also analyzes manufacturer's corresponding pricing strategy in the case of supplier's incomplete reliability and linear demand [29]. Giri and Bardhan [17] also discuss the coordination of dual-channel supply chain disruption with a backup supplier. In addition, Barman *et al.* [3], taking into account the challenges posed by deteriorating products and imperfect quality production within a neutrosophic environment, endeavor to construct a multi-objective framework for supply chain inventory management. As for more complex supply chain networks, Lotfi *et al.* [31,32] consider frameworks of renewable energy or closed-loop supply, optimizing the network within the supply chain to enhance supply resilience and alleviate the pressure of supply shortages.

In supply chain management, the study of demand information asymmetry has long been a popular topic. Fu *et al.* [16] represent random demand with distribution function and demand information asymmetry with variance of distribution function, and also introduce the concept of two-way trust to coordinate the decision-making of supply and demand with demand information asymmetry. Avinadav and Shamir [1] distinguish demand information between retailer and manufacturer in the form of prior probability, and analyze whether retailer would conceal private information from manufacturer if the retailer has more accurate demand information. Kim *et al.* [24] examine how e-tailer address inventory availability commitment (IAC) of direct carrier in the decision-making of operation with demand information asymmetry. Ebrahim-Khanjari *et al.* [12] examine retailer's incomplete trust in salesperson recommendations. It is generally believed that the accuracy of market demand forecast tends to be different due to different positions of different enterprises in the supply chain [23]. Cahill *et al.* [5] propose that if manufacturers fully trust information provided by the downstream, manufacturers will not feel the risk of using information provided. However, Ismail *et al.* [21] further finds that if manufacturer believes that the information provided downstream is not completely reliable, manufacturer perceives significant risks when using such information. When risks arise due to information asymmetry between upstream and downstream enterprises, Fu *et al.* [15] study the method of coordinating decision-making of supply and demand of supply chain with trust.

In response to the aforementioned problem, numerous studies on supply chain coordination mechanisms have been conducted. Zhang *et al.* [38] study the coordination of dual-channel supply chain in the form of contract mechanism in centralized decision-making, obtain the optimal revenue of whole supply chain, coordinate contradictions of all parties, and further considers the contract formulation in the case of supply chain disruption.

TABLE 1. Summary of the literature on the match between supply and demand.

Literature	Supply shortage	Demand information	Coordination mechanism
Carvalho *et al.* [8]	$\surd$	Asymmetry	Non-coordination
Li and Dong [26]	$\surd$	Symmetry	Non-coordination
Huang and Wu [18]	$\surd$	/	Non-coordination
Cai *et al.* [6]	$\surd$	Symmetry	Option Contract
Jia and Zhao [22]	$\surd$	Asymmetry	Purchase Contract
Giri and Bardhan [17]	$\surd$	Asymmetry	Penalty Contract
Li *et al.* [30]	$\times$	Symmetry	Reservation Contract
Li *et al.* [29]	$\surd$	Asymmetry	Non-coordination
Fu *et al.* [16]	$\times$	Asymmetry	Discount Contract
Avinadav and Shamir [1]	$\times$	Asymmetry	Quantity Contract
Zhang *et al.* [38]	$\times$	Symmetry	WPF Contract
Cai *et al.* [7]	$\surd$	Symmetry	Order Contract
Shafiq and Savino [35]	$\times$	Asymmetry	Revenue Contract
Fan *et al.* [13]	$\times$	/	Economic Coupling
Shen *et al.* [37]	$\times$	/	Economic Coupling
This paper	$\surd$	Asymmetry	Revenue Coupling

Cai *et al.* [7] design a commitment order contract and analyze Vendor-Managed Inventory operation of a single supplier-manufacturer supply chain model in three different scenarios. Chen and Ulya [10] and Chick *et al.* [11] examine the positive role that government can play in supply chain coordination, the former designs a reward and punishment mechanism for government department to force manufacturer to recycle their scrapped product so as to reduce environmental damage, and the latter argues that the government needs to monitor the production of enterprises during the pandemic to eliminate the information cost caused by information asymmetry to the maximum extent. Shafiq and Savino [35] propose a commitment-based revenue sharing and punishment mechanism to coordinate supply chain with one manufacturer and one retailer. Barman *et al.* [4] put forward dual selling channels, carbon diminution rate and online delivery lead-time as marketing efforts to deal with a dual-channel green supply chain centralized system, and to attract customers to buy more products. At the same time, many scholars study the interaction degree between system or element based on coupling coordination mechanism. Fan *et al.* [13] analyze the coupling degree and coupling coordination degree between regional economy and environment, tourism and new urbanization indicators, socioeconomic subsystem, and ecological environment subsystem by establishing a basic coupling evaluation and coupling coordination degree model. Shen *et al.* [37] revise coupling model by improving the calculation method of comprehensive coordination index weight, so that the coupling coordination model is more adaptable, and the feasibility of such improvement is proved by evaluating the coordination relationship between socioeconomic and carbon emission. To compare with the related literature and better highlight our contributions, we list them in Table 1.

Unlike the above literature, this paper differs in that (1) supplier's reliability is set as an endogenous variable between $(0, 1]$. (2) Supply chain coupling mechanism, a new supply chain coordination method is introduced. (3) Effects of vertical integration and supply chain coupling mechanism on supply chain coordination are compared and analyzed.

3. MODELING AND ANALYSIS

This paper establishes a supply chain model consisting of a single manufacturer (her) and a single supplier (he) with three-stage transaction. Then a supplier-dominant Stackelberg game model is constructed. Finally, two supply chain coordination methods, vertical integration mechanism, and supply chain coupling mechanism,

TABLE 2. Symbols and descriptions.

	Manufacturer	Supplier
Parameter	p: Manufacturer's unit selling price; d: Unit recycle price for product exceeding market demand; s: Unit penalty cost for product not meeting market demand	β: Supplier's effort cost coefficient; c: Supplier's unit production cost; λ: Revenue distribution coefficient, value range $(0, 1)$
Decision Variable	Q: Manufacturer's order quantity	θ: Supplier's reliability, the stability of supplier's production, value range $(0, 1]$; w: Supplier's unit wholesale price
Environment Variable	x: Market demand is a random variable	

are used respectively to optimize the supply chain. The symbolic variables used in this paper are shown in Table 2.

In the whole decision-making process, parameters are assumed as $p > w > c > d > 0, p > s > d > 0$. This assumption guarantees that the revenue of the decision-making party in transaction process is positive, and both parties are motivated to trade. While ensuring there will be no aimless order, it also ensures that manufacturer meet market demand as much as possible.

As information sharing deepens, the model can be divided into three cases: partial information sharing, supply chain coupling, and complete information sharing. First, for supply chain with partial information sharing, automaker and parts supplier decide their optimal order quantity Q, optimal reliability θ and wholesale price w. Second, for supply chain with coupling mechanism under revenue-sharing contract proposed in this study, manufacturer is willing to share her revenue with supplier. Obviously, when the manufacturer is dominant, it is illogical if she is still willing to share her own revenue with supplier. Therefore, in the contract, the specific profit distribution coefficient λ is determined by supplier, and manufacturer can only choose to accept or reject the contract, and the supply chain model at this time is led by supplier. Finally, for the supply chain with complete information sharing, the supply and demand party in supply chain choose to coordinate supply chain with centralized decision-making, and choose optimal reliability θ and order quantity Q to maximize the overall expected revenue of supply chain.

3.1. Analysis supply chain in partial information sharing

There is undoubtedly a greater need for chips in electric vehicles than in fuel-powered ones. On the one hand, semiconductor components already account for about 35% of automobile manufacturing costs, and this figure may rise to 50% by 2030 [14]. On the other hand, while the demand for automotive chip may total 100 million, this may not even come close to one-tenth of smartphone chip orders. Automotive chip orders rank lower in the pecking order of chip suppliers, which means that automakers have to spend more time waiting for chip production [34]. Therefore, it can be said chip suppliers grasp the "lifeblood" of automobile production.

In light of the monopoly of chip suppliers, the long delivery time of chips and the feature of booking chip orders, chip suppliers often first decide the wholesale price of chip in the game process [20,27]. Besides, due to low production capacity and long production cycle, the supplier is motivated to convey their reliability information to the automaker, but the manufacturer may not fully trust the information provided by the supplier, and the automaker is not prepared for sufficient inventory when market demand rebounds [34]. The specific decision-making process is shown in Figure 1.

The decision-making process is shown in Figure 1: At stage 1, supplier and manufacturer first forecast market demand. At stage 2, supplier set his wholesale price w. At stage 3, supplier forecast manufacturer's order quantity based on his forecast market demand and formulates his optimal reliability θ. At stage 4, manufacturer decides

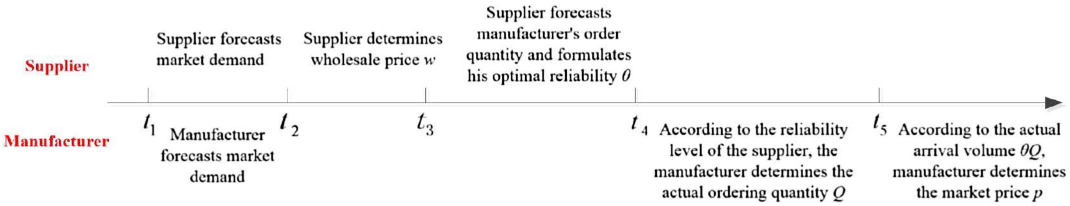

Figure 1. Decision-making chart.

order quantity Q based on supplier's reliability and wholesale price w. When the real market demand is available, supplier delivers goods to manufacturer on the basis of manufacturer's order quantity Q and his reliability θ. At stage 5, after the manufacturer receives goods, the product is sold to the market at unit market price p.

According to above decision-making process, we analyze optimal decision for both supplier and manufacturer in the event of supply disruption when manufacturer is dominant. The expected revenue model for both parties is.

The supplier's expected revenue model is expressed as [36],

$$\pi_s(w,\theta) = \theta w Q - cQ - \frac{1}{2}\beta\theta^2. \tag{1}$$

The first term of equation (1) represents revenue from selling product, the second represents cost of manufacturing product, and the third represents effort cost to reach current reliability.

The manufacturer's expected revenue model is expressed as [17],

$$\pi_m(Q) = p\min\{x, \theta Q\} + d(\theta Q - x)^+ - s(x-\theta Q)^+ - w\theta Q, \tag{2}$$

where the expression $(x)^+ = \max\{0, x\}$. In equation (2), the first item represents revenue received from selling products to the market based on the actual product quantity, the second item accounts for recycled revenue when the manufacturer's actual product quantity exceeds market demand, the third item denotes the penalty cost incurred when the manufacturer's actual product quantity falls short of market demand, and the fourth item represents the cost of actually purchasing parts.

3.1.1. Analysis of manufacturer's optimal order quantity

For manufacturer, the probability distribution function of downstream market demand is $F(\bullet)$, and the probability density function is $f(\bullet)$. Then manufacturer formulates her optimal order strategy based on the forecast of supplier's reliability, and the following shows equation (2) is rewritten as expected revenue model equation (3),

$$\pi_m(Q) = p\left(\int_0^{\theta Q} x f(x)\,\mathrm{d}x + \int_{\theta Q}^{+\infty} \theta Q f(x)\,\mathrm{d}x\right) + d\int_0^{\theta Q}(\theta Q - x) f(x)\,\mathrm{d}x - s\int_{\theta Q}^{+\infty}(x-\theta Q) f(x)\,\mathrm{d}x - w\theta Q. \tag{3}$$

Lemma 1. *In the case of partial information sharing, manufacturer's optimal order quantity*

$$Q^* = \frac{1}{\theta}F^{-1}\left(\frac{p+s-w}{p+s-d}\right).$$

It should be noted that this $F^{-1}(\bullet)$ is the inverse function of the demand distribution function $F(\bullet)$. According to Lemma 1, the manufacturer's optimal order quantity is inversely proportional to the supplier's wholesale price and reliability coefficient, and proportional to manufacturer's recycle price, unit market penalty cost and unit market sales price. Therefore, when manufacturer is more reliable to the supplier, manufacturer reduces order quantity.

3.1.2. Analysis of supplier's optimal reliability

For the supplier, the probability distribution function of downstream market demand is $G(\cdot)$, and the probability density function is $g(\cdot)$. Since manufacturer is closer to the market, it is assumed that manufacturer's variance is smaller than supplier's, and supplier's forecast of optimal order quantity is always greater than manufacturers. At this stage, supplier's reliability is mainly analyzed, and supplier forecast manufacturer's optimal order quantity $Q' = \frac{1}{\theta}G^{-1}(\frac{p+s-w}{p+s-d})$ based on his own forecast demand, where $G^{-1}(\bullet)$ is the inverse function of the demand distribution function $G(\bullet)$. Supplier's expected revenue at this time is:

$$\pi_s(w,\theta) = wG^{-1}\left(\frac{p+s-w}{p+s-d}\right) - \frac{c}{\theta}G^{-1}\left(\frac{p+s-w}{p+s-d}\right) - \frac{1}{2}\beta\theta^2. \tag{4}$$

In this stage, supplier maximizes expected revenue $\pi_s(\theta)$ by determining his own optimal reliability θ^*.

Lemma 2. *In the case of partial information sharing, supplier's optimal reliability is*

$$\theta^* = \min\left\{\sqrt[3]{\frac{c}{\beta}G^{-1}\left(\frac{p+s-w}{p+s-d}\right)}, 1\right\}.$$

According to Lemma 2, supplier's optimal reliability is inversely proportional to wholesale price, effort coefficient, and proportional to his production cost, manufacturer's recycle price, unit market penalty cost and unit market sales price. Therefore, when supplier's production cost rises, his reliability also rises, *i.e.*, supplier minimizes capacity waste. However, the rise of supplier's wholesale price causes the drop in reliability, triggering more expensive downstream components in the case of short supply.

When supplier determines his optimal reliability, the message is conveyed to manufacturer, who combines her own forecast of downstream market demand. Supplier's reliability is

$$\theta = \min\left\{\sqrt[3]{\frac{c}{\beta}F^{-1}\left(\frac{p+s-w}{p+s-d}\right)}, 1\right\}.$$

3.1.3. Analysis of supplier's optimal wholesale price

Supplier develop his own optimal wholesale price strategy mainly based on the forecast of his reliability and manufacturer's optimal order quantity. Since suppliers can be divided into completely reliable and incompletely reliable, the supplier's optimal wholesale price can be discussed in two cases

Case 1. When the constraint $\sqrt[3]{\frac{c}{\beta}G^{-1}(\frac{p+s-w}{p+s-d})} \geq 1$, the supplier is completely reliable, *i.e.*, $\theta^* = 1$.

Case 2. When the constraint $\sqrt[3]{\frac{c}{\beta}G^{-1}(\frac{p+s-w}{p+s-d})} < 1$, the supplier is not completely reliable at this time, *i.e.*, $\theta^* = \sqrt[3]{\frac{c}{\beta}G^{-1}(\frac{p+s-w}{p+s-d})}$.

Lemma 3. *In the case of partial information sharing, supplier's optimal wholesale price is* $w_1^* = \min\{w_1, p + s - (p + s - d)G(\frac{\beta}{c})\}$ *when the supplier is completely reliable; the supplier's optimal wholesale price is* $w_2^* = \max\{w_2, p + s - (p + s - d)G(\frac{\beta}{c})\}$ *when the supplier is not completely reliable.*

Where $h_1(w) = G^{-1}(\frac{p+s-w}{p+s-d})$, w_1 can satisfy equation $h_1(w_1) = (c - w_1)h_1'(w_1)$, w_2 can be expressed as $h_1(w_2) = (\frac{c^{2/3}\beta^{1/3}}{h_1(w_2)^{1/3}} - w_2)h_1'(w_2)$. It is theoretically proved that supplier's optimal expected price exists, and it is found that when supplier is completely reliable, supplier's wholesale price w_1 is not affected by effort cost coefficient, and when supplier is not completely reliable, effort cost coefficient affects supplier's wholesale price w_2, that is, when $\beta > ch_1(w_2)$, effort cost coefficient affects supplier's wholesale price decision.

3.2. Decision analysis of supply chain coupling

This section examines the feasibility of a supply chain coupling method to adjust the supply and demand imbalance for automotive chips. The term "coupling" refers to the coordinated condition of the supply chain. In this coupling state, manufacturer shares part of her revenue with supplier to get a lower wholesale price. Since supplier is in an advantageous position in supply chain model, manufacturer can only choose to accept or reject the specific situation of the contract drafted by supplier.

Manufacturers share $(1-\lambda)$ part of her revenue with supplier, and it is assumed that manufacturer's revenue is π_m^λ [19]:

$$\pi_m^\lambda = p\left(\int_0^{\theta_\lambda Q_\lambda} xf(x)\,\mathrm{d}x + \int_{\theta_\lambda Q_\lambda}^{+\infty} \theta_\lambda Q_\lambda f(x)\,\mathrm{d}x\right) + d\int_0^{\theta_\lambda Q_\lambda} (\theta_\lambda Q_\lambda - x)f(x)\,\mathrm{d}x. \tag{5}$$

In this case, the supplier's expected revenue can be expressed as:

$$\Pi_s(\theta_\lambda, w_\lambda) = \theta_\lambda w_\lambda Q_\lambda - cQ_\lambda - \frac{1}{2}\beta\theta_\lambda^2 + (1-\lambda)\pi_m^\lambda. \tag{6}$$

The expected revenue of manufacturer can be expressed as:

$$\Pi_m(w_\lambda, Q_\lambda) = \lambda\pi_m^\lambda - s\int_{\theta^{RS'}Q^{RS}}^{+\infty} (x-\theta_\lambda Q_\lambda)f(x)\,\mathrm{d}x - w_\lambda\theta_\lambda Q_\lambda. \tag{7}$$

The condition for manufacturer to accept contract is $\Pi_m(Q_\lambda) \geq \pi_m(Q)$.

3.2.1. Analysis of manufacturer's order strategy

Manufacturer's order strategy is first analyzed, and manufacturer can maximize her expected revenue $\Pi_m(Q_\lambda^*)$ by deciding optimal order strategy Q_λ^*.

Lemma 4. *In the case of coupling supply chain, optimal order quantity*

$$Q_\lambda^* = \frac{1}{\theta_\lambda}F^{-1}\left(\frac{\lambda p + s - w_\lambda}{\lambda p + s - \lambda d}\right).$$

The manufacturer's optimal order quantity is inversely proportional to supplier's wholesale price and reliability coefficient, and is proportional to supply chain coupling coefficient, manufacturer's recycle price, unit market penalty cost and unit market sales price. Combined with Lemma 1, it can be seen that in addition to coupling coefficient, other parameters have the same effect on manufacturer's optimal order quantity in the case of the partial information sharing and coupling state. Moreover, when coupling coefficient increases, the revenue shared by manufacturer to supplier decreases, and manufacturer increases her own optimal order quantity.

3.2.2. Analysis of supplier's reliability

Supplier develops optimal reliability strategy based on the forecast of manufacturer's order strategy and his own wholesale price strategy to maximize his expected revenue. At this point, the supplier's forecast of manufacturer's order strategy is $Q_\lambda' = \frac{1}{\theta_\lambda}G^{-1}(\frac{\lambda p+s-w_\lambda}{\lambda p+s-\lambda d})$.

Lemma 5. *In the case of supply chain coupling, supplier's optimal reliability is*

$$\theta_\lambda^* = \min\left\{\sqrt[3]{\frac{c}{\beta}G^{-1}\left(\frac{\lambda p + s - w_\lambda}{\lambda p + s - \lambda d}\right)}, 1\right\}.$$

According to Lemma 5, supplier's optimal reliability is inversely proportional to wholesale price and effort coefficient, and proportional to the coupling coefficient of his production cost and supply chain, manufacturer's recycling price, unit market penalty cost, and unit market sales price. Based on Lemma 2, it can be seen that as order quantity, except for coupling coefficient, other parameters have the same effect on supplier's optimal reliability in the case of partial information sharing and the coupling state. When coupling coefficient increases, the revenue shared by manufacturer to supplier decreases, and supplier increases his own optimal reliability.

3.2.3. Analysis of supplier's wholesale price

Supplier develops his own optimal wholesale price strategy based on his own forecast of reliability and manufacturer's order strategy to maximize expected revenue $\Pi_s(w_\lambda)$.

Lemma 6. *In the case of coupling, when supplier is completely reliable, supplier's optimal wholesale price strategy is* $w_3^* = \min\{w_3, \lambda p + s - (\lambda p + s - \lambda d)G(\frac{\beta}{c})\}$*; when supplier is not completely reliable, supplier's optimal wholesale price strategy is* $w_4^* = \max\{w_4, \lambda p + s - (\lambda p + s - \lambda d)G(\frac{\beta}{c})\}$.

Let $h_2(w) = G^{-1}(\frac{\lambda p+s-w_\lambda}{\lambda p+s-\lambda d})$, $m(w) = \frac{\lambda p+s-w_\lambda}{\lambda p+s-\lambda d}$, where optimal wholesale price w_3 when supplier is completely reliable can be expressed as

$$h_2(w_3) = [c - w_3 - (1-\lambda)(p(1-m(w_3)) + dm(w_3))]h_2'(w_3),$$

and optimal wholesale price w_4 when supplier is not completely reliable can be expressed as

$$h_2(w_4) = \left[\frac{c^{2/3}\beta^{1/3}}{h_2(w_4)^{1/3}} - w_4 - (1-\lambda)(p(1-m(w_4)) + dm(w_4))\right]h_2'(w_4).$$

Compared to Lemma 3, supplier's decision on wholesale price in coupling state is more complicated. A similar conclusion to partial information sharing is that when supplier is completely reliable, supplier's wholesale price w_3 is not affected by effort cost coefficient, and when supplier is not completely reliable, the effort cost coefficient begins to affect supplier's wholesale price w_4, that is, when $\beta > ch_2(w_4)$ is true, effort cost coefficient affects the supplier's wholesale price decision.

Corollary 1. (1) *In the case of partial information sharing, wholesale price when supplier is not completely reliable is always higher than when supplier is completely reliable, that is,* $w_2 > w_1$ *is always true.*

(2) *In the case of supply chain coupling, wholesale price when supplier is not completely reliable is always higher than when supplier is completely reliable, that is,* $w_4 > w_3$ *is always true.*
(3) *When supplier is completely reliable, supplier's wholesale price in coupling state is always lower than that in partial information, that is,* $w_3 < w_1$.

Combining Lemmas 3 and 6, it is found that when supplier's effort cost coefficient $\beta > ch(w)$, supplier's effort cost coefficient begins to affect supplier's wholesale price decision, and supplier's reliability at this time decreases, and wholesale price rises. According to Corollary 1, when supplier's supply is stable, supplier in supply chain coupling lowers his wholesale price.

Corollary 2. *When supplier is dominant in coupling, it is difficult to decide supplier's optimal wholesale price.*

Combining Lemmas 3 and 6, in partial information sharing state and coupling state, supplier's expectation function $\Pi_s(w_\lambda)$ is often not a convex function of wholesale price w, so it is difficult for us to directly obtain his optimal wholesale price strategy. It can be seen that the wholesale price of chip supplier will not be completely decided by supply and demand, rather, it is more complex decision-making process. To further standardize and regulate the supplier's pricing and stabilize the chip market, it is necessary to introduce a stronger social constraining force to monitor and guide.

3.2.4. Optimal supply chain coupling with revenue maximization

For supply chain coupling realized through revenue sharing contract, it is first necessary to find marginal conditions for revenue sharing coefficient λ with different effort cost coefficient and production cost of different suppliers. Furthermore, with marginal constraint, the value at which supplier, manufacturer and overall supply chain revenue reach Pareto optimal time λ can be obtained, and this supply chain state is called optimal coupling state of supply chain.

$$\max\ \gamma\Pi_s + (1-\gamma)\Pi_m$$
$$\text{s.t.} \begin{cases} 0 < \lambda < 1 \\ \Pi_s > \pi_s \\ \Pi_m > \pi_m \end{cases}, \quad \gamma \in [0,1].$$

3.3. Analysis of supply chain strategy in complete information sharing

In this section, the supply chain model in vertical integration mechanism, where supplier and manufacturer jointly decide optimal reliability strategy and order strategy (θ_c, Q_c) so as to maximize expected revenue of whole supply chain π_c.

The expected revenue of whole supply chain π_c can be expressed as:

$$\begin{aligned} \pi_c(\theta_c, Q_c) = p\left(\int_0^{\theta_c Q_c} x f(x)\,\mathrm{d}x + \int_{\theta_c Q_c}^{+\infty} \theta_c Q_c f(x)\,\mathrm{d}x\right) + d\int_0^{\theta_c Q_c} (\theta_c Q_c - x) f(x)\,\mathrm{d}x \\ - s\int_{\theta_c Q_c}^{+\infty} (x - \theta_c Q_c) f(x)\,\mathrm{d}x - cQ_c - \frac{1}{2}\beta\theta_c^2. \end{aligned} \tag{8}$$

In equation (8), the first item represents revenue of selling product, the second item represents recycle revenue for product exceed market demand, the third item is penalty cost for product not meeting market demand, the fourth item is production cost of product raw material, and the fifth item represents effort cost of current reliability.

Lemma 7. *In the case of complete information sharing, manufacturer's optimal order quantity* $Q_c^* = \frac{1}{\theta_c^*}F^{-1}(\frac{(p+s)\theta_c^* - c}{(p+s-d)\theta_c^*})$ *and supplier's optimal reliability satisfy the equation* $(p+s-d)Q_c^* F(\theta_c^* Q_c^*) + \beta\theta_c^* = (p+s)Q_c^*$.

Combining Lemmas 1 and 4, when supplier is completely reliable, since $c < w$ is always true and $F^{-1}(x)$ monotonically increasing, manufacturer's optimal order quantity $Q_c^* = F^{-1}(\frac{p+s-c}{P+s-d})$ in the state of complete information sharing is always greater than $Q^* = F^{-1}(\frac{p+s-w}{p+s-d})$ in the state of partial information sharing, indicating that complete information sharing promotes transaction between two parties and improves overall revenue.

Theorem 1. (1) *As information sharing deepens, only manufacturer's order quantity strategy influences supplier's decision on optimal reliability.*

(2) *When supplier's reliability and wholesale price are the same, manufacturer's optimal order quantity in partial information sharing is always greater than that in coupling state.*

Supplier's optimal reliability in partial information sharing is $\theta^* = \sqrt{\frac{c}{\beta}Q'}$; supplier's optimal reliability in coupling is $\theta_\lambda^* = \sqrt{\frac{c}{\beta}Q'_\lambda}$; supplier's optimal reliability in complete information sharing is $\theta_c^* = \sqrt{\frac{c}{\beta}Q_c^*}$. It is evident that more information sharing does not affect a supplier's reliability, and it can be inferred that the change in the manufacturer's optimal order quantity determination is the primary reason for the supplier's decreased reliability.

In summary, the manufacturer's order quantity strategy and manufacturer's optimal reliability in partial information sharing, coupling mechanism, and complete information sharing can be solved and shown in Table 3.

Theorem 2. *In different states of supply chain, there is a threshold point* β_0 *for effort cost coefficient, when effort cost coefficient exceeds threshold, supplier is no longer completely reliable. In partial information sharing and coupling state, threshold point* β_0 *also positively change supplier's optimal wholesale price.*

Table 3. Optimal decision table.

Cases	Supplier	Manufacturer
Partial Information Sharing	$\theta^* = \min\left\{\sqrt[3]{\frac{c}{\beta}G^{-1}\left(\frac{p+s-w}{P+s-d}\right)}, 1\right\}$	$Q^* = \frac{1}{\theta^*}F^{-1}\left(\frac{p+s-w}{p+s-d}\right)$
Supply Chain Coupling	$\theta_\lambda^* = \min\left\{\sqrt[3]{\frac{c}{\beta}G^{-1}\left(\frac{\lambda p+s-w_\lambda}{\lambda p+s-\lambda d}\right)}, 1\right\}$	$Q_\lambda^* = \frac{1}{\theta_\lambda^*}F^{-1}\left(\frac{\lambda p+s-w_\lambda}{\lambda p+s-\lambda d}\right)$
Complete Information Sharing	$\theta_{\mathrm{c}}^* = \min\left\{\sqrt{\frac{c}{\beta}Q_{\mathrm{c}}^*}, 1\right\}$	$Q_c^* = \frac{1}{\theta_{\mathrm{c}}^*}F^{-1}\left(\frac{(p+s)\theta_{\mathrm{c}}^*-c}{(p+s-d)\theta_{\mathrm{c}}^*}\right)$

In the case of incomplete reliability, threshold point $\beta_0 = cG^{-1}(\frac{p+s-w}{p+s-d})$; in coupling, threshold point $\beta_0^\lambda = cG^{-1}(\frac{\lambda p+s-c}{\lambda p+s-\lambda d})$; in complete information sharing, threshold point $\beta_0^{\mathrm{c}} = cF^{-1}(\frac{(p+s)\theta_{\mathrm{c}}^*-c}{(p+s-d)\theta_{\mathrm{c}}^*})$. Threshold point β_0 in different states are related to supplier's production cost c, manufacturer's order quantity, and asymmetry of demand information. In other words, if the supplier's production costs are too high, he will do everything in his power to increase his own reliability and minimize waste in production capacity; conversely, if a manufacturer places a larger order, the supplier will give the manufacturer's order more weight. Combining Corollary 1(3) with information partial sharing and coupling, the supplier's wholesale price rises noticeably when the effort cost coefficient exceeds the threshold point. In essence, keeping the supplier's effort cost coefficient away from the threshold point is essential to guaranteeing that supply and demand are met.

In addition to focusing on the epidemic-related shortage of supplies, this paper also examines the analysis of new game relationships in which supplier dominates and where there are no obvious advantages between supply and demand. These relationships are framed by the rising supplier dominance in the high-tech industry and the declining traditional manufacturer dominance in the industry, as well as supplier optimal strategies regarding wholesale prices, reliability, and manufacturer's order quantity.

4. Simulation experiment analysis

To further analyze the above model, based on relevant literature, the impact of demand information uncertainty σ_s, σ_m, unit recycle price d and unit penalty cost s on sales price are discussed first and parameters are adjusted by optimizing model. Combining with actual situation and theoretical derivation, parameters are set as $\sigma_s = 30, \sigma_m = 20$, $d = 3$, $\mu = 100$, $p = 96$, $s = 2$, $c = 4$ (see Tab. 4). In post-epidemic era, chip price no longer follows previous chip pricing strategy and production cost rise to a certain extent, but the increase in production cost of chip is not significant. Therefore, to facilitate simulation analysis, it is assumed that production cost of chip is based on production cost in normal conditions.

Experiment 1. In coupling state, supplier's optimal wholesale price, reliability and manufacturer's optimal order quantity changes with the increase of revenue distribution coefficient.

It can be seen from Figure 2 that when effort cost coefficient is in low range $\beta \leq 600$, supplier's reliability and manufacturer's order quantity are positively related to revenue distribution coefficient. And when effort cost coefficient is in high range, supplier's reliability and manufacturer's order quantity first increase and then drop with the increase of revenue distribution coefficient.

It can be seen from Figure 3 that supplier's optimal wholesale price has a positive relationship with the revenue distribution coefficient on the whole. With the increase in effort cost coefficient, supplier's wholesale price rises faster, and supplier's optimal wholesale price is significantly higher. Therefore, it is concluded that

TABLE 4. Parameters of the numerical example.

Parameters	Value	Unit
Variance of the supplier demand function σ_s	30	/
Variance of the manufacturer demand function σ_m	20	/
The mean of the demand function μ	100	/
Supplier's unit production cost c	4	$
Manufacturer's unit selling price p	96	$
Unit recycle price for product exceeding market demand d	3	$
Unit penalty cost for product not meeting market demand s	2	$

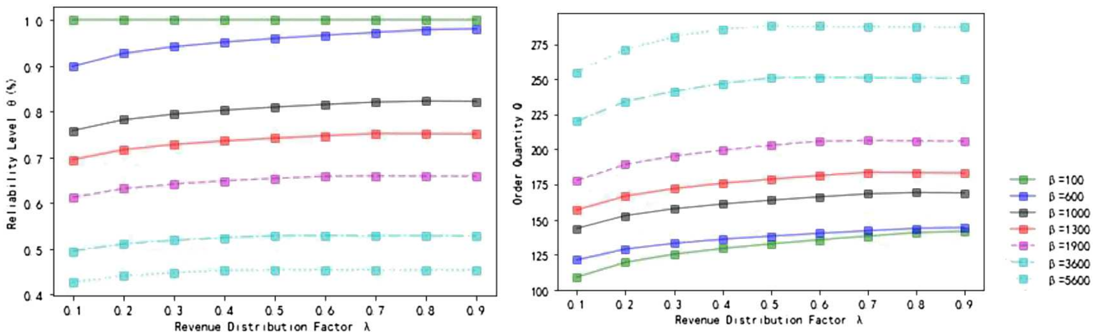

FIGURE 2. Analysis of supplier's wholesale price and reliability, and manufacture's order quantity in coupling.

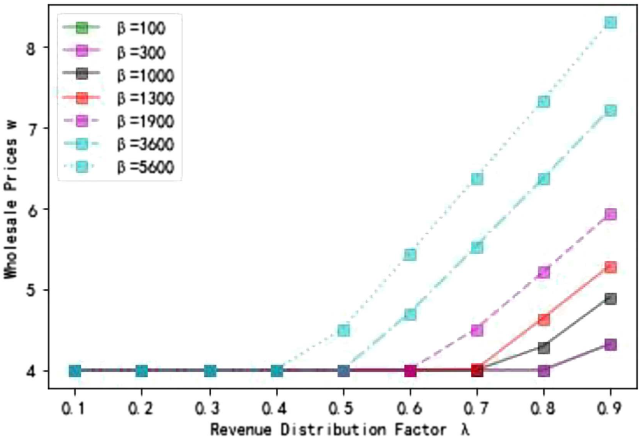

FIGURE 3. Analysis of supplier's wholesale price in coupling.

supply chain coupling can effectively coordinate the supplier's wholesale price, especially for high-tech type parts with high effort cost coefficient, and it also lowers suppliers' wholesale prices to a low level.

Experiment 2. Analysis of optimal coupling coefficient with different effort cost coefficients.

It can be seen from Figure 4 that, first, when effort cost coefficient is in lower range, supplier's expected revenue is positively related to revenue distribution coefficient. And when effort cost coefficient is in higher range,

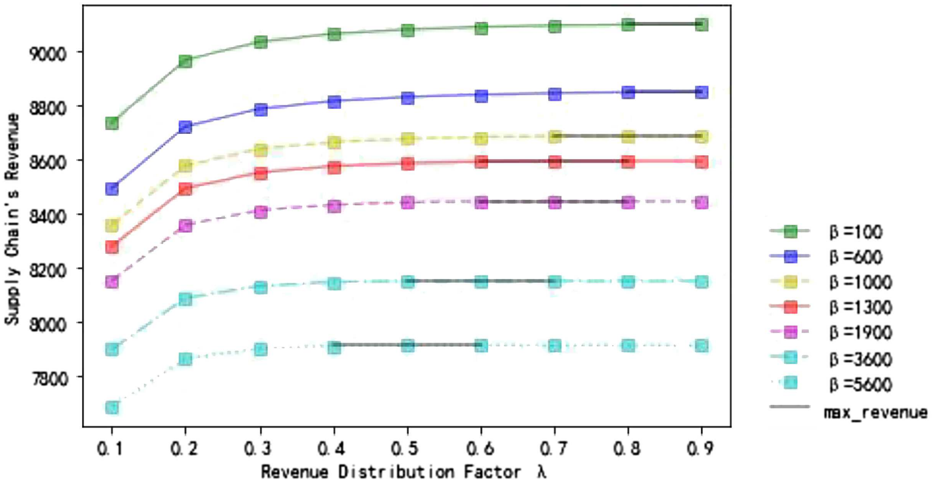

Figure 4. Analysis total expected revenue of supply chain.

supplier's expected revenue first increases and then decreases with the increase of revenue distribution coefficient. Then, as effort cost coefficient increases, optimal coupling coefficient gradually diminishes. For example, when $\beta = 1600$, optimal coupling coefficient $\lambda^* = 0.7$, and when $\beta = 4600$, optimal coupling coefficient drops to $\lambda^* = 0.5$, which means that when supplier faces greater production pressure, manufacturer is willing to share more revenues with supplier. Next, when revenue distribution coefficient $\lambda \in (0.1, 0.2)$, supplier's expected revenue rises rapid in a very short period. After that, supplier's expected revenue maintains a high stable level, which shows that manufacturer is more likely to choose a suitable revenue distribution coefficient to expand total expected revenue for both supply and demand parties as much as possible. It also verifies that supply chain coupling mechanism has strong stability and reliability. Finally, it is easy to determine that, at the optimal coupling coefficient, not only the total expected revenue of supply chain maximized, but also the manufacturer's order quantity and supplier reliability maximized. As a result, the optimal coupling coefficient can, to the greatest possible extent, guarantee a stable supply of components.

To facilitate the comparison of optimal decision and expected revenue of decision-maker in different information sharing cases, revenue distribution coefficient used in supply chain coupling is uniformly set as $\lambda = 0.7$ in the subsequent simulation analysis.

Experiment 3. Compare and analyze changes of supplier's optimal wholesale prices, reliability, and manufacturer's optimal order quantity with the increase of revenue distribution coefficient in partial information sharing, supply chain coupling and complete information sharing.

Figure 5 shows that supplier's wholesale price in supply chain coupling is always much lower than that in partial information sharing. Moreover, supplier's wholesale prices in supply chain coupling rise later and slower.

It can be seen from Figure 6, first, supplier's the reliability in supply chain coupling declines earliest, while in complete information sharing it declines latest and always higher than that in other cases. Second, in supply chain coupling, manufacturer's order quantity rises latest, while in complete information sharing it rises earliest and is always higher than that in other cases. Finally, in partial information sharing, manufacturer's order quantity changes earlier than supplier's reliability, but in supply chain coupling and complete information sharing, changes in supply and demand tend to be consistent, indicating that in partial information sharing, the manufacturer is closer to the market and more sensitive to market changes. In partial information sharing, however, the manufacturer's order quantity changes earlier than the supplier's reliability. The manufacturer's advantage steadily wanes as knowledge sharing deepens.

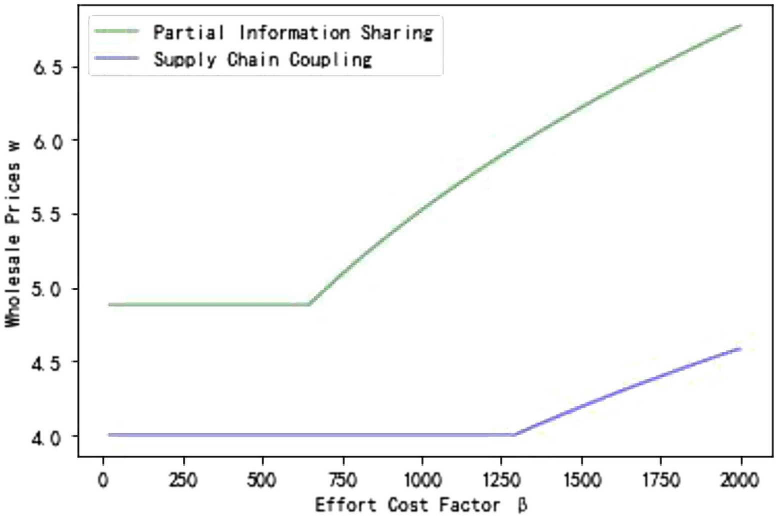

FIGURE 5. Supplier's wholesale price analysis in different information sharing states.

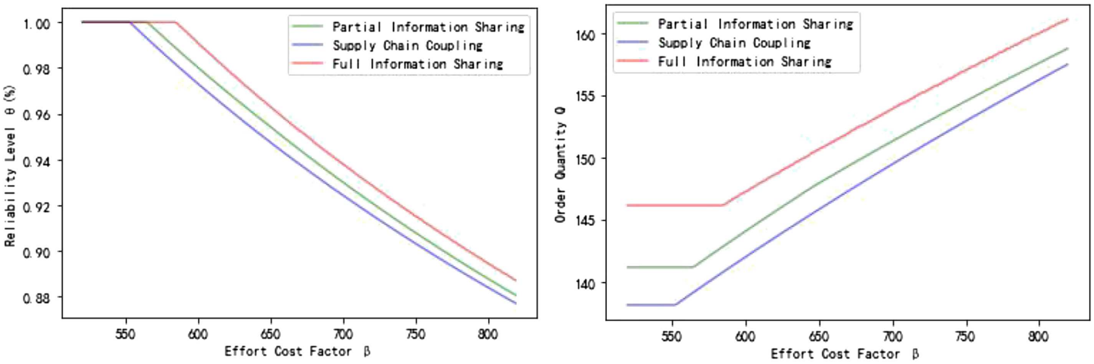

FIGURE 6. Analysis of supplier's reliability and manufacturer order quantity in different information sharing states.

In conclusion, thorough information exchange is more conducive to ensuring a steady supply, and supply chain coupling mechanisms are more conducive to maintaining low and stable wholesale pricing.

Experiment 4. Compare and analyze the changes of supplier's expected revenue with the increase of revenue distribution coefficient in partial information sharing, supply chain coupling and complete information sharing.

In Experiment 4, supplier's expected revenue in partial information sharing and supply chain coupling are first compared. Then by setting a range of different wholesale prices, supplier's expected revenue in complete sharing state is obtained. Next supplier's expected revenue in complete information sharing is compared with that in partial information sharing and supply chain coupling. Finally, marginal conditions of supply chain coordination mechanism of supply chain coupling and complete information sharing are obtained.

It can be seen from Figure 7 that, first, supplier's expect revenue in supply chain coupling is greater than that in partial information sharing, which verifies that supply chain coupling is a feasible mechanism to coordinate supply chain. Second, when $w = 5$, in area with low effort cost coefficient, supplier's expected revenue in

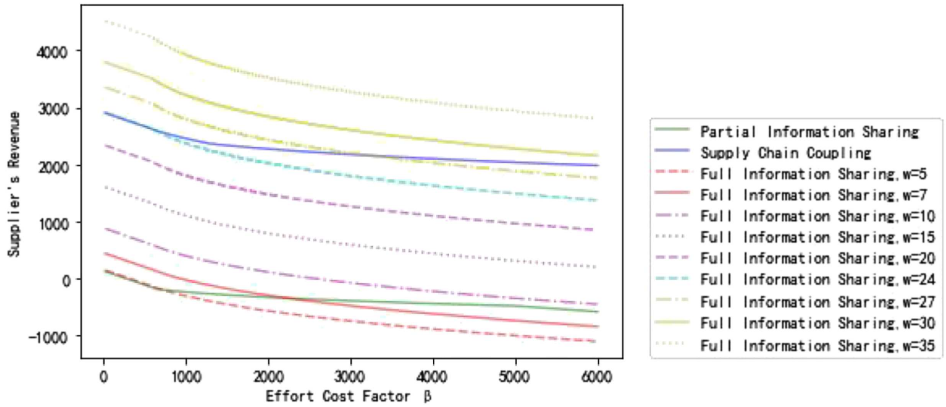

FIGURE 7. Supplier's expected revenue analysis in different information sharing cases.

complete information sharing begin to exceed that in partial information sharing, but in area with high effort cost coefficient, supplier's expected revenue in complete information sharing do not completely exceed until $w \geq 10$ indicating supply chain coordination mechanism of complete information sharing has limitations for high effort cost coefficient. Third, when $w = 24$, in area with low effort cost coefficient, supplier's expected revenue in complete information sharing begin to exceed that in supply chain coupling, but for area with high effort cost coefficient, supplier's expected revenue in complete information sharing do not completely exceed until $w \geq 30$. This demonstrates how effective supply chain coupling is as a tool for supply chain coordination when it comes to coordinating suppliers of high-effort cost coefficient items. When suppliers share fewer revenues, the supply chain coupling mechanism makes it possible for all kinds of component suppliers to coordinate.

To sum up, the supply chain coupling mechanism is a feasible and effective way to coordinate the supply of supply of automotive chips. In the case of a high-tech chip supply chain with a long manufacturing cycle and low productivity, a supply chain coupling mechanism offers definite advantages over a comprehensive information-sharing method.

5. SENSITIVITY ANALYSIS

In theoretical analysis, several important parameters are found, including unit market penalty cost s and unit market recycle revenue d. In Table 5, we discuss and analyze the impact of these parameters on supply chain revenue in partial information sharing, supply chain coupling, and complete information sharing respectively with effort cost coefficient and coupling state $\lambda = 0.7$.

Table 4 reveals that for the supply chain model in the coupling state, manufacturer's market penalty cost is positively correlated with supplier's optimal reliability, manufacturer's optimal order quantity, supplier's wholesale price, and expected revenue, but negatively correlated with the manufacturer's expected revenue and total expected revenue of supply chain. The manufacturer's market recycle revenue is positively correlated with supplier's optimal reliability, manufacturer's optimal order quantity, supplier's expected revenue, manufacturer's expected revenue, and supplier's total expected revenue, but negatively correlated with supplier's optimal wholesale price. Moreover, the manufacturer's market penalty cost is not as influential as market recycle revenue on the expected revenue of supplier and manufacturer.

6. CONCLUSION

Following the massive economic losses caused by the epidemic, there has been a severe chip shortage in the automotive industry due to downstream automakers' miscalculation of market demand based on their long

TABLE 5. Parameter numerical analysis results in supply chain coupling.

Variables	θ^*	Q^*	w^*	Π_m	%	Π_s	%	Π_T	%
s									
1	52.82%	251.05	5.51	6029.22	0.051	2121.53	−0.126	8150.74	0.005
1.5	52.82%	251.11	5.52	6027.67	0.026	2122.87	−0.063	8150.54	0.002
2	52.83%	251.16	5.53	6026.13	0	2124.21	0	8150.34	0
2.5	52.83%	251.22	5.54	6024.61	−0.025	2125.54	0.063	8150.14	−0.012
3	52.84%	251.27	5.55	6023.05	−0.051	2126.89	0.126	8149.94	−0.005
d									
2	52.59%	248.87	5.56	5999.62	−0.44	2117.98	−0.293	8117.59	−0.402
2.5	52.70%	249.95	5.55	6012.06	−0.233	2121.68	−0.119	8133.74	−0.204
3	52.83%	251.16	5.53	6026.13	0	2124.21	0	8150.34	0
3.5	52.97%	252.49	5.51	6040.56	0.239	2126.88	0.126	8167.44	0.21
4	53.12%	253.95	5.49	6055.37	0.485	2129.72	0.259	8185.09	0.426

production cycles and limited production capacity. Based on this background, first, a two-tier supply chain model with partial information sharing dominated by chip suppliers is constructed. Second, the impact of the supplier's reliability and wholesale price on the automaker's order strategy is analyzed. Then, by constructing a vertical integration mechanism and a coupling mechanism, the expected revenue is calculated, and finally, the application of these two supply chain coordination methods is compared.

Through mathematical analysis, the following results are obtained:

- This paper first proves the existence of supplier's optimal wholesale price and finds that when the supplier has higher reliability, his wholesale price also decreases.
- Second, there is always an effort cost coefficient threshold point, and when the effort cost coefficient exceeds the threshold, the supplier is no longer completely reliable and his optimal wholesale price begins to increase.
- In the simulation analysis, it is verified that there is always an optimal supply chain coupling coefficient to maximize the total expected revenue of the supply chain, and the value of this coupling coefficient decreases with the increase in effort cost coefficient, and it is found that with optimal coupling coefficient, both supplier's reliability and manufacturer's order quantity maximizes.
- Finally, the supply chain coupling mechanism is more successful in coordinating the supply chain for suppliers of high-end chips with advanced technical skills than the vertical integration mechanism is for suppliers of low-end chips, according to a comparative analysis of the supplier's expected revenue.

Some limitations of our approach include the supply chain structure's simplicity, which excludes complex supply systems. Furthermore, our analysis just looks at the best choices for supply elasticity and orders, treating pricing as an exogenous variable. The endogenous consequences of these choices on pricing are not taken into account. In the context of chip suppliers' wholesale prices, it might be advantageous to include a more legally binding contract mechanism in subsequent studies. Examining a static game in which supply and demand are played equally could yield insightful information. Research on the function of supply chain coupling in multi-cycle manufacturing orders is also possible.

APPENDIX A.

Proof of Lemma 1. According to equation (2), take $\pi_m(Q)$ as the first and second derivatives of Q,

$$\begin{aligned}\frac{\mathrm{d}\pi_m(Q)}{\mathrm{d}Q} &= p\theta\int_{\theta Q}^{+\infty} f(x)\,\mathrm{d}x + d\theta\int_{0}^{\theta Q} f(x)\,\mathrm{d}x - w\theta + s\theta\int_{\theta Q}^{+\infty} f(x)\,\mathrm{d}x\\ &= \theta(p+s-w) - \theta(p+s-d)F(\theta Q)\end{aligned}$$

$$\frac{\mathrm{d}^2\pi_m(Q)}{\mathrm{d}^2Q} = -\theta^2(p+s-d)f(\theta Q) < 0.$$

In the supplier-dominant supply chain model, $\pi_m(Q)$ is convex function of Q, so there is a unique extreme point Q^* so that $\pi_m(Q)' = 0$, at this time $\pi_m(Q)$ reaches the maximum value. The optimal order quantity $Q^* = \frac{1}{\theta}F^{-1}(\frac{p+s-w}{p+s-d})$. □

Proof of Lemma 2. According to equation (2), take $\pi_s(w,\theta)$ as the first and second derivatives of θ,

$$\frac{\mathrm{d}\pi_s(\theta)}{\mathrm{d}\theta} = \frac{c}{\theta^2}G^{-1}\left(\frac{p+s-w}{p+s-d}\right) - \beta\theta$$

$$\frac{\mathrm{d}^2\pi_s(\theta)}{\mathrm{d}^2\theta} = -\frac{c}{\theta^3}G^{-1}\left(\frac{p+s-w}{p+s-d}\right) - \beta < 0.$$

In the supplier-dominant supply chain model, $\pi_s(\theta)$ is convex function of θ, so there is a unique extreme point θ^* so that $\pi_s(\theta)' = 0$, at this time $\pi_s(\theta)$ reaches the maximum value. The optimal reliability $\theta^* = \sqrt[3]{\frac{c}{\beta}G^{-1}(\frac{p+s-w}{p+s-d})}$.

Since in this model, the supplier has no reason to produce more products than manufacturer's order quantity, but since the range of $\sqrt[3]{\frac{c}{\beta}G^{-1}(\frac{p+s-w}{p+s-d})}$ is $(0,+\infty]$, it is necessary to compare $\sqrt[3]{\frac{c}{\beta}G^{-1}(\frac{p+s-w}{p+s-d})}$ and 1. When $\sqrt[3]{\frac{c}{\beta}G^{-1}(\frac{p+s-w}{p+s-d})} >= 1$, supplier's optimal reliability $\theta^* = 1$, when $\sqrt[3]{\frac{c}{\beta}G^{-1}(\frac{p+s-w}{p+s-d})} < 1$, supplier's optimal reliability $\theta^* = \sqrt[3]{\frac{c}{\beta}G^{-1}(\frac{p+s-w}{p+s-d})}$. To sum up, supplier's optimal reliability is expressed as $\theta^* = \min\left\{\sqrt[3]{\frac{c}{\beta}G^{-1}(\frac{p+s-w}{p+s-d})}, 1\right\}$. □

Proof of Lemma 3. According to equation (2), take $\pi_s(w,\theta)$ as the first derivative w.

$$\frac{\partial\pi_s(w,\theta)}{\partial w} = h_1(w) - \left(\frac{c^{2/3}\beta^{1/3}}{h_1(w)^{1/3}} - w\right)h_1'(w)$$

where $h_1(w) = G^{-1}(p+s-wp+s-d)$.

When $w \to d$, $\pi_s'(w,\theta) > 0$, $\pi_s(w,\theta) > 0$.

When $w \to p+s$, $w - \frac{c^{2/3}\beta^{1/3}}{h(w)^{1/3}} < 0$, $\pi_s'(w,\theta) > 0$, $\pi_s(w,\theta) \to 0$.

Obviously, there is always a w^* so that $\pi_s(w,\theta)$ reaches the maximum. When $h_1(w^*) = (\frac{c^{2/3}\beta^{1/3}}{h_1(w^*)^{1/3}} - w)h_1'(w^*)$, and when supplier is completely reliable, constraints are satisfied as $w < p+s-(p+s-d)G(\frac{\beta}{c})$, otherwise $w_1 >= p+s-(p+s-d)G(\frac{\beta}{c})$. It is necessary to satisfy model constraints, $w^* = p+s-(p+s-d)G(\frac{\beta}{c})$.

In summary, supplier's optimal wholesale price strategy w^* is: when supplier is completely reliable, supplier's optimal wholesale price is $w_1^* = \min\{w_1, p+s-(p+s-d)G(\frac{\beta}{c})\}$; when supplier is not completely reliable, supplier's optimal wholesale price is $w_2^* = \max\{w_2, p+s-(p+s-d)G(\frac{\beta}{c})\}$, where w_1 satisfy the equation $h_1(w_1) = (c-w_1)h_1'(w_1)$, w_2 can be expressed as $h_1(w_2) = (\frac{c^{2/3}\beta^{1/3}}{h_1(w_2)^{1/3}} - w_2)h_1'(w_2)$. □

Proof of Lemma 4. According to equation (7), take $\Pi_m(w_\lambda, Q_\lambda)$ as the first and second derivatives of Q_λ

$$\frac{\partial\Pi_m(w_\lambda,Q_\lambda)}{\partial Q_\lambda} = -w_\lambda\theta_\lambda + \lambda[p\theta_\lambda(1-F(\theta_\lambda Q_\lambda)) + d\theta_\lambda F(\theta_\lambda Q_\lambda)] + s\theta_\lambda(1-F(\theta_\lambda Q_\lambda))$$

$$\frac{\partial^2\Pi_m(w_\lambda,Q_\lambda)}{\partial^2 Q_\lambda} = -\lambda(p-d){\theta_\lambda}^2 f(\theta_\lambda Q_\lambda) - s{\theta_\lambda}^2 f(\theta_\lambda Q_\lambda) < 0.$$

In supply chain coupling with revenue-sharing contract, $\Pi_m(w_\lambda, Q_\lambda)$ is convex function of Q_λ, so there is a unique extreme point Q^*_λ so that $\Pi'_m(w_\lambda, Q_\lambda) = 0$, at this time $\Pi_m(w_\lambda, Q_\lambda)$ reaches the maximum value. The optimal order quantity Q^*_λ is $Q^*_\lambda = \frac{1}{\theta_\lambda} F^{-1}(\frac{\lambda p+s-w_\lambda}{\lambda p+s-\lambda d})$. ☐

Proof of Lemma 5. According to equation (6), take $\Pi_s(\theta_\lambda, w_\lambda)$ as the first and second derivatives of θ_λ

$$\frac{\partial \Pi_s(\theta_\lambda, w_\lambda)}{\partial \theta_\lambda} = \frac{c}{\theta_\lambda^2} G^{-1}\left(\frac{\lambda p + s - w_\lambda}{\lambda p + s - \lambda d}\right) - \beta\theta_\lambda$$
$$\frac{\partial^2 \Pi_s(\theta_\lambda, w_\lambda)}{\partial^2 \theta_\lambda} = -2\frac{c}{{\theta_\lambda}^3} G^{-1}\left(\frac{\lambda p + s - w_\lambda}{\lambda p + s - \lambda d}\right) - \beta < 0.$$

In revenue-sharing contract, $\Pi_s(\theta_\lambda, w_\lambda)$ is convex function of θ_λ, so there is a unique extreme point θ^*_λ so that $\Pi'_s(\theta_\lambda, w_\lambda) = 0$, at this time $\Pi_s(\theta_\lambda, w_\lambda)$ reaches the maximum value. It is necessary to ensure $\theta^*_\lambda <= 1$. Supplier's optimal reliability strategy can be expressed as $Q^*_\lambda = \frac{1}{\theta_\lambda} F^{-1}(\frac{\lambda p+s-w_\lambda}{\lambda p+s-\lambda d})$. ☐

Proof of Lemma 6. According to equation (6), take $\Pi_s(w_\lambda, \theta_\lambda)$ as the first derivatives of w_λ

$$\frac{\partial \Pi_s(w_\lambda, \theta_\lambda)}{\partial w_\lambda} = h_2(w_\lambda) - \left[\frac{c^{2/3}\beta^{1/3}}{{h_2(w_\lambda)}^{1/3}} - w_\lambda - (1-\lambda)(p(1-m(w_\lambda)) + dm(w_\lambda))\right] h'_2(w_\lambda)$$

where $h_2(w) = G^{-1}(\frac{\lambda p+s-w_\lambda}{\lambda p+s-\lambda d})$, $m(w) = \frac{\lambda p+s-w_\lambda}{\lambda p+s-\lambda d}$.

When $w_\lambda \to \lambda d, \Pi'_s(w_\lambda, \theta_\lambda) > 0$, $\Pi_s(w_\lambda, \theta_\lambda) > 0$.

When $w_\lambda \to \lambda p + s, \pi'_s(w, \theta) > 0, \pi_s(w, \theta) \to 0$.

Obviously, there is always a w^*_λ so that $\Pi_s(w_\lambda, \theta_\lambda)$ reaches the maximum. When w^*_λ can satisfy $h_2(w^*_\lambda) = \left[\frac{c^{2/3}\beta^{1/3}}{{h_2(w^*_\lambda)}^{1/3}} - w^*_\lambda - (1-\lambda)(p(1-m(w^*_\lambda)) + dm(w^*_\lambda))\right] h'_2(w^*_\lambda)$ and when supplier is completely reliable, constraints are satisfied as $w_\lambda <= \lambda p + s - (\lambda p + s - \lambda d)G(\frac{\beta}{c})$, otherwise $w_3 >= \lambda p + s - (\lambda p + s - \lambda d)G(\frac{\beta}{c})$. It is necessary to satisfy model constraints, $w^*_\lambda = \lambda p + s - (\lambda p + s - \lambda d)G(\frac{\beta}{c})$.

In summary, supplier's optimal wholesale price strategy w^*_λ is: when supplier is completely reliable, supplier's optimal wholesale price is $w^*_3 = \min\{w_3, \lambda p + s - (\lambda p + s - \lambda d)G(\frac{\beta}{c})\}$; when supplier is not completely reliable, supplier's optimal wholesale price is $w^*_4 = \max\{w_4, \lambda p + s - (\lambda p + s - \lambda d)G(\frac{\beta}{c})\}$. ☐

Proof of Corollary 1. In the case of incomplete information symmetry, since $d < c < w < p$ and $\beta \gg c$. For chip industry, effort cost coefficient is $\beta \to +\infty$:

$$h_1(w_2) - \left(\frac{c^{2/3}\beta^{1/3}}{{h_1(w_2)}^{1/3}} - w_2\right) h'_1(w_2) > h_1(w_2) - (c - w_2)h'_1(w_2).$$

According to Lemma 3

$$h_1(w_2) - (c - w_2)h'_1(w_2) < 0$$
$$h_1(w_1) - (c - w_1)h'_1(w_1) = 0.$$

Let $z_1(w) = h_1(w) - (c - w)h'_1(w)$, take $z_1(w)$ as the first derivatives of w

$$z'_1(w) = 2h'_1(w) + (w - c)h''_1(w) < 0.$$

Obviously, in this case, supplier's wholesale price when he is not completely reliable is always higher than when he is completely reliable, that is $w_2 > w_1$ is always true.

The supply chain coupling is similar to above analysis.

Let $z_2(w) = h_2(w) - [c - w - (1-\lambda)(p(1-m(w)) + dm(w))]h_2'(w)$, take $z_2(w)$ as the first derivatives of w

$$z_2'(w) = [1 + (1-\lambda)(p(1-m'(w)) + dm'(w))]h_2'(w) - [c - w - (1-\lambda)(p(1-m(w)) + dm(w))]h_2''(w) < 0.$$

Since $p(1-m(w)) + dm(w) > 0$ is always true,

$$h_2(w_3) - [c - w_3 - (1-\lambda)(p(1-m(w_3)) + dm(w_3))]h_2'(w_3) < h_2(w_3) - (c - w_3)h_2'(w_3).$$

Therefore, when supplier is completely reliable, the supplier's wholesale price in coupling state is always lower than that in partial information relationship, that is, $w_3 < w_1$. □

Proof of Lemma 7.

$$\begin{aligned}
\frac{\partial \pi_c(\theta_c, Q_c)}{\partial \theta_c} &= (p+s)Q_c(1 - F(\theta_c Q_c)) + dQ_c F(\theta_c Q_c) - \beta\theta_c \\
\frac{\partial \pi_c(\theta_c, Q_c)}{\partial Q_c} &= (p+s)\theta_c(1 - F(\theta_c Q_c)) + d\theta_c F(\theta_c Q_c) - c \\
\frac{\partial^2 \pi_c(\theta_c, Q_c)}{\partial^2 \theta_c} &= -(p+s-d)Q_c^2 f(\theta_c Q_c) - \beta < 0 \\
\frac{\partial^2 \pi_c(\theta_c, Q_c)}{\partial^2 Q_c} &= -(p+s-d){\theta_c}^2 f(\theta_c Q_c) < 0 \\
\frac{\partial^2 \pi_c(\theta_c, Q_c)}{\partial Q \partial \theta_c} &= (p+s)(1 - F(\theta_c Q_c)) + dF(\theta_c Q_c) - (p+s-d)\theta_c Q_c f(\theta_c Q_c).
\end{aligned}$$

Construct Hessian Matrix

$$H(\pi_c) = \begin{pmatrix} \dfrac{\partial^2 \pi_c(\theta_c, Q_c)}{\partial^2 \theta_c} & \dfrac{\partial^2 \pi_c(\theta_c, Q_c)}{\partial Q \partial \theta_c} \\ \dfrac{\partial^2 \pi_c(\theta_c, Q_c)}{\partial \theta_c \partial Q} & \dfrac{\partial^2 \pi_c(\theta_c, Q_c)}{\partial^2 Q_c} \end{pmatrix}.$$

The value of corresponding determinant is obtained as:

$$\begin{aligned}
H(\pi_c) = \beta(p+s-d){\theta_c}^2 f(\theta_c Q_c) &- [(p+s) - (p+s-d)F(\theta_c Q_c)] \\
&+ 2[(p+s) - (p+s-d)F(\theta_c Q_c)](p+s-d)\theta_c Q_c F(\theta_c Q_c).
\end{aligned}$$

So when the inequation $\frac{(p+s-d)\theta_c f(\theta_c Q_c)[\beta\theta_c + 2(p+s)Q_c - 2(p+s-d)F(\theta_c Q_c)Q_c]}{[(p+s)-(p+s-d)F(\theta_c Q_c)]^2} > 1$ is true, $\frac{\partial^2 \pi_c(\theta_c, Q_c)}{\partial^2 \theta_c} < 0$, $\frac{\partial^2 \pi_c(\theta_c, Q_c)}{\partial^2 Q_c} < 0$ and $H(\pi_c) > 0$ is always true, $H(\pi_c)$ is negative definite matrix, at this time the overall revenue of supply chain $\pi_c(\theta_c, Q_c)$ reaches the maximum value at $\frac{\partial \pi_c(\theta_c, Q_c)}{\partial \theta_c} = \frac{\partial \pi_c(\theta_c, Q_c)}{\partial Q_c} = 0$. □

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Conflict of Interest

The authors declared that they have no conflicts of interest to this work.

Data availability statement

All data included in this study are available upon request by contact with the corresponding author.

References

[1] T. Avinadav and N. Shamir, The effect of information asymmetry on ordering and capacity decisions in supply chains. *Eur. J. Oper. Res.* **292** (2021) 562–578.

[2] A. Belhadi, S. Kamble, C.J.C. Jabbour, A. Gunasekaran, N.O. Ndubisi and M. Venkatesh, Manufacturing and service supply chain resilience to the COVID-19 outbreak: lessons learned from the automobile and airline industries. *Technol. Forecasting Soc. Change* **163** (2021) 120447.

[3] H. Barman, S.K. Roy, L. Sakalauskas and G.W. Weber, Inventory model involving reworking of faulty products with three carbon policies under neutrosophic environment. *Adv. Eng. Inf.* **57** (2023) 102081.

[4] H. Barman, M. Pervin, S.K. Roy and G.W. Weber, Analysis of a dual-channel green supply chain game-theoretical model under carbon policy. *Int. J. Syst. Sci. Oper. Logistics* **10** (2023) 2242770.

[5] V. Cahill, E. Gray, J.M. Seigneur, C.D. Jensen, Y. Chen, B. Shand, N. Dimmock, A. Twigg, J. Bacon, C. English and W. Wagealla, Using trust for secure collaboration in uncertain environments. *IEEE Pervasive Comput.* **2** (2003) 52–61.

[6] J. Cai, M. Zhong, J. Shang and W. Huang, Coordinating VMI supply chain under yield uncertainty: option contract, subsidy contract, and replenishment tactic. *Int. J. Prod. Econ.* **185** (2017) 196–210.

[7] J. Cai, X. Hu, F. Jiang, Q. Zhou, X. Zhang and L. Xuan, Optimal input quantity decisions considering commitment order contracts under yield uncertainty. *Int. J. Prod. Econ.* **216** (2019) 398–412.

[8] H. Carvalho, B. Naghshineh, K. Govindan and V. Cruz-Machado, The resilience of on-time delivery to capacity and material shortages: an empirical investigation in the automotive supply chain. *Comput. Ind. Eng.* **171** (2022) 108375.

[9] H. Casper, A. Rexford, D. Riegel, A. Robinson, E. Martin and M. Awwad, The impact of the computer chip supply shortage, in Paper presented at the International Conference on Industrial Engineering and Operations Management Bangalore, India (2021).

[10] C.-K. Chen and M.A. Ulya, Analyses of the reward-penalty mechanism in green closed-loop supply chains with product remanufacturing. *Int. J. Prod. Econ.* **210** (2019) 211–223.

[11] S.E. Chick, S. Hasija and J. Nasiry, Information elicitation and influenza vaccine production. *Oper. Res.* **65** (2017) 75–96.

[12] N. Ebrahim-Khanjari, W. Hopp and S.M.R. Iravani, Trust and information sharing in supply chains. *Prod. Oper. Manage.* **21** (2012) 444–464.

[13] Y. Fan, C. Fang and Q. Zhang, Coupling coordinated development between social economy and ecological environment in Chinese provincial capital cities-assessment and policy implications. *J. Cleaner Prod.* **229** (2019) 289–298.

[14] B. Frieske and S. Stieler, The "Semiconductor Crisis" as a result of the COVID-19 pandemic and impacts on the automotive industry and its supply chains. *World Electr. Veh. J.* **13** (2022) 189.

[15] X. Fu, G. Han and J. Wang, Trust-based decisions in commission–agency relationships. *Manage. Decis. Econ.* **40** (2019) 569–579.

[16] X. Fu, H. Tan, E. Tsenina, S. Liu and G. Han, Information sharing based on two-way perceptions of trust and supply chain decisions: a simulation based approach. *Chaos Solitons Fractals* **157** (2022) 1119–1138.

[17] B.C. Giri and S. Bardhan, Coordinating a supply chain under uncertain demand and random yield in presence of supply disruption. *Int. J. Prod. Res.* **53** (2015) 5070–5084.

[18] B. Huang and A. Wu, Reduce shortage with self-reservation policy for a manufacturer paying both fixed and variable stockout expenditure. *Eur. J. Oper. Res.* **262** (2017) 944–953.

[19] H. Huang, Y. He and D. Li, Coordination of pricing, inventory, and production reliability decisions in deteriorating product supply chains. *Int. J. Prod. Res.* **56** (2018) 6201–6224.

[20] W. Hwang, N. Bakshi and V. DeMiguel, Wholesale price contracts for reliable supply. *Prod. Oper. Manage.* **27** (2018) 1021–1037.

[21] R. Ismail, C. Boyd, A. Jøsang and S. Russell, Private reputation schemes for P2P systems. *WOSIS* **2004** (2004) 196–206.

[22] J. Jia and H. Zhao, Mitigating the U.S. drug shortages through pareto-improving contracts. *Prod. Oper. Manage.* **26** (2017) 1463–1480.

[23] A. Jøsang and R. Ismail, The beta reputation system, in Proceedings of the 15th Bled Conference on Electronic Commerce (2002).

[24] N. Kim, B. Montreuil and W. Klibi, Inventory availability commitment under uncertainty in a dropshipping supply chain. *Eur. J. Oper. Res.* **302** (2022) 1155–1174.

[25] M. Leslie, Pandemic scrambles the semiconductor supply chain. *Engineering* **9** (2022) 10–12.

[26] D. Li and C. Dong, Government regulations to mitigate the shortage of life-saving goods in the face of a pandemic. *Eur. J. Oper. Res.* **301** (2022) 942–955.

[27] M. Li and S. Mizuno, Dynamic pricing and inventory management of a dual-channel supply chain under different power structures. *Eur. J. Oper. Res.* **303** (2022) 273–285.

[28] Y. Li and J. Ou, Optimal ordering policy for complementary components with partial backordering and emergency replenishment under spectral risk measure. *Eur. J. Oper. Res.* **284** (2020) 538–549.

[29] T. Li, S.P. Sethi and J. Zhang, Supply diversification with responsive pricing. *Prod. Oper. Manage.* **22** (2013) 447–458.

[30] J. Li, X. Luo, Q. Wang and W. Zhou, Supply chain coordination through capacity reservation contract and quantity flexibility contract. *Omega* **99** (2021) 1021–1095.

[31] R. Lotfi, B. Kargar, S.H. Hoseini, S. Nazari, S. Safavi and G.W. Weber, Resilience and sustainable supply chain network design by considering renewable energy. *Int. J. Energy Res.* **45** (2021) 17749–17766.

[32] R. Lotfi, Y.Z. Mehrjerdi, M.S. Pishvaee, A. Sadeghieh and G.W. Weber, A robust optimization model for sustainable and resilient closed-loop supply chain network design considering conditional value at risk. *Numer. Algebra Control Optim.* **11** (2021) 221.

[33] K.N. Ochonogor, G.S. Osho, C.O. Anoka and O. Ojumu, The COVID-19 pandemic and supply chain disruption: an analysis of the semiconductor industry's resilience. *Int. J. Tech. Sci. Res. Eng.* **6** (2023) 7–18.

[34] V. Ramani, D. Ghosh and M.S. Sodhi, Understanding systemic disruption from the COVID-19-induced semiconductor shortage for the auto industry. *Omega* **113** (2022) 102720.

[35] M. Shafiq and M.M. Savino, Supply chain coordination to optimize manufacturer's capacity procurement decisions through a new commitment-based model with penalty and revenue-sharing. *Int. J. Prod. Econ.* **208** (2019) 512–528.

[36] X. Shan, T. Li and S.P. Sethi, A responsive-pricing retailer sourcing from competing suppliers facing disruptions. *Manuf. Serv. Oper. Manage.* **24** (2021) 196–213.

[37] L. Shen, Y. Huang, Z. Huang, Y. Lou, G. Ye and S. Wong, Improved coupling analysis on the coordination between socio-economy and carbon emission. *Ecol. Indic.* **94** (2018) 357–366.

[38] P. Zhang, Y. Xiong and Z. Xiong, Coordination of a dual-channel supply chain after demand or production cost disruptions. *Int. J. Prod. Res.* **53** (2014) 3141–3160.