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DEVELOPING A RESILIENT SUPPLY CHAIN IN COMPLEX PRODUCT SYSTEMS THROUGH INVESTMENT IN RELIABILITY AND COOPERATIVE CONTRACTS

Jafar Gheidar-kheljani[1,*] and Kourosh Halat[2]

Abstract. In recent years, finding mitigation strategies for supply chain disruptions has become one of the most critical challenges for businesses. This issue is crucial for complex product industries because of their role in the modern economy, few suppliers, and their need for high investment in research and development (R&D). This paper studies a resilient supply chain in complex product systems to overcome its specific challenges through supplier reliability enhancement and cooperative contracts. Utilising a game theoretic approach and analytical models, this paper aims to improve the supply chain performance from the resilience perspective while considering R&D investment, supplier learning effect, buyer fairness concern, and market sensitivity to the product's technology. Investment in supplier reliability enhancement with different contracts is proposed to mitigate disruption risks for a two-echelon supply chain. Analytical mathematical models have been developed, and a simulation approach has been used in optimisation. The results show how proposed contracts effectively increase supply chain performance from financial and resilience perspectives. Moreover, the market sensitivity to the product's technological level and the sensitivity to the price could adversely affect performance. The buyer's fairness concern also improves the profit loss while decreasing the service level slightly.

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1. Introduction

The vulnerability of supply chains has grown in recent years due to globalisation and low inventory strategies. As a result, numerous events have disrupted supply chains [69]. Political changes, cyberattacks, business bankruptcies, and natural disasters are a few of the many events that can disrupt a supply chain. For instance, the workers at Apple's supplier factory in Zhengzhou, China, went on strike against the existing practices in 2022, which reduced the production of nearly six million iPhones [48]. Additionally, operations of many supply chains were halted in 2020 due to the COVID-19 pandemic. On the supply side, firms experienced issues receiving parts and raw materials because of the shutdown of production facilities, transportation constraints, and a lack of human resources [27]. On the demand side, some industries – like those that produce medical and

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[1] Associate Professor, Management and Industrial Engineering Department, Malek-Ashtar University of Technology

[2] KTP associate, University of Plymouth

*Corresponding author: kheljani@mut.ac.ir

pharmaceutical equipment – saw a drastic rise in demand, while others – like those that make automobiles – faced a fall in demand [53].

To combat disruption risk, managers should consider the concept of resilience, which is generally defined as the ability of a supply chain to respond to disturbances and keep operations running under control in the presence of unexpected events [15, 60]. Two types of mechanisms, overall, can be taken against a disruptive event: insurance mechanisms that aim to reduce the amount of loss and self-protection mechanisms that aim to decrease the likelihood of risk [24]. This paper focuses on the latter group, which is about lowering risks. Firms can minimise the risk by investing in their production infrastructure. For example, Benteler, one of the largest suppliers of the BMW automotive group, invested in information technology to make more flexible processes and increased production capacity; as a result, its operations continued during the COVID-19 pandemic and helped BMW to deliver products to its customers [23].

The resilient supply chain subject is more critical for complex products and infrastructure industries than others. Supply chains with complex products are technology-oriented and add value to the modern economy, such as the aviation, auto, and defence industries [55,73]. These industries are vital for the economy and national security, and during a disruption, their ability to supply the products to the market is even more important than profitability. There are often few suppliers in industries with complex products, and sometimes building an extensive network of suppliers is impossible. Thus, it is essential to make reliable systems and reduce the risk of disruption in those industries [54].

On the other hand, the complex products sector needs significant investment in product design and development due to the rapid advancement of technology and changes in consumer expectations. In technological and complex product systems, the primary source of competitive advantage generally is the research and development (R&D) phase rather than manufacturing. Markets of complex products are growing rapidly, and companies need to devote more of their resources to R&D. The investment in R&D impacts the level of product technology, which could attract more customers. This investment also could boost performance, which benefits resilience [39]. Both upstream and downstream supply chain entities can invest in R&D, and each has the potential to add value to the final product. For instance, BMW signed a $117 million contract with a Chinese battery manufacturer, CATL, for its electric vehicles. In addition to BMW that design technologies it requires, CATL develops battery technology and has its own intellectual property rights and patents. The producer and the supplier thus collaborate to increase the product's technological value [67]. Suppliers in complex products industries usually deploy cooperation strategies in technology development to maximise their market share due to the presence of a learning effect over time [73].

Besides the investment in R&D and reliability, supply chains with complex products should make operational decisions in a way to improve resilience and profit. Because in the event of a disruption (on either the supply or demand side), supply and demand get imbalanced immediately, and operational decisions regarding order and price are crucial in maintaining this equilibrium [24]. Moreover, in this regard, the cooperation mechanism between the supply chain's members must be well planned so that all firms reach their objectives and have enough commitment and dedication to continue working together [44].

Although there has been a great deal of research on supply chain resilience, exploring supply chains in complex product systems under the disruption risk is scant in the literature. This paper introduces a model for a resilient two-echelon supply chain which includes a buyer and a supplier. Additionally, the R&D investment, the market's sensitivity to the level of product technology, the buyer's degree of fairness, and the supplier's learning effect in reducing manufacturing costs have all been considered. We propose a Stackelberg game approach with a multi-period planning horizon to answer these research questions: (1) How to model a supply chain under the demand and supply disruptions, considering the investment in R&D and supplier reliability enhancement? (2) How does disruption and reliability investment affect R&D costs, profitability, and resiliency? (3) How will different types of contracts, supplier learning, buyer fairness, and customer sensitivity to product technology level affect the solutions?

In the following, literature is reviewed in Section 2. The problem description and scenarios of the problem are developed in Sections 3 and 4, respectively. Solving approach and results are presented in Section 5. Finally, Section 6 presents the conclusions.

2. Literature review

The literature is categorised into four subsections. The first subsection reviews research that has been done in the area of the resilient supply chain. The risks of a disruption in supply and demand are covered in the second subsection. The literature on contracts is studied in the third subsection. The research gap and the paper's contribution to the literature are presented last.

2.1. Assessment of supply chain resilience

Researchers developed the concept of the resilient supply chain in the first decade of the new century, and in the most recent decade, practical research in this area has been growing. This paper focuses on the modelling and quantitative assessment of resiliency for a supply chain with demand and supply disruption. Some studies, including [5,14,43], have proposed different metrics for resiliency in a supply chain from design and performance perspectives. From the supply chain performance point of view, several authors, such as Zavala *et al.* [68] and Jain *et al.* [16], measured resiliency based on the system's return time to its initial performance. However, most literature quantifies resiliency based on the customer service level and profit lost. Qiang and Nagurney [40] used two different metrics based on the level of demand satisfaction and the system's cost to examine the resilience performance of a multi-echelon supply chain. Behzadi *et al.* [3] introduced another measure where the net present value of the lost profit is modelled. Arquer *et al.* [9] examined recovery time and lost profit to increase resiliency. Massari and Gionnoccaro [32] explored how profit is affected by the degree of cooperation and competition between supply chain members in complex systems. Moosavi and Hosseini [34] investigated resilient supply chains based on the severity of the shortage and financial performance. Their study revealed that a trade-off between cost and resilience must be obtained to improve overall performance. Tirkolaee *et al.* [59] proposed a framework for resilient supplier selection based on a multi-attribute decision-making approach.

The mentioned papers in this part are used to define measures for supply chain resilience assessment. But none of these studies explored how investments in product technology and risk reduction affect resiliency, unlike ours.

2.2. Demand and supply disruption in the supply chain management

A demand disruption or demand shock is a result of sudden changes in customer expectations, typically because of changes in the external environment. One of the earliest studies that developed a mathematical model for demand disruption can be found in [26]. Then, research on pricing during a demand shock was carried out by Gagnon and López-Salido [12]. Although numerous studies have investigated demand uncertainty in the supply chain management literature, only a few have addressed the problem of demand disruption. In this regard, Nilakantan [36] developed a demand disruption model and examined its impact on inventory ordering policies. Lu *et al.* [29] provided a model for demand disruption in the food supply chain. Some researchers have studied the supply chain coordination problem under the risk of demand disruption like [4, 70]. Additionally, Zheng *et al.* [72] constructed a model for cooperation under demand shock while considering the learning effect from social factors. Zhao *et al.* [71] examined the impact of supply chain investment in information technology under the risk of demand disruption. Shaw *et al.* [50] developed a multi-objective optimisation model to resource management of a humanitarian supply chain under uncertainty. In this context, Meyer-Nieberg *et al.* [33] developed an optimisation model with an agent-based simulation approach to investigate tactical and operational decisions. Hashemi Doulabi and Khalilpourazari [13] examined a planning problem with stochastic parameters and introduced a state-variable model.

On the other hand, supply disruption has been studied by many papers. Supply disruption could occur because of several incidents, including extreme weather like storms, disease outbreaks, equipment failures, corporate failures, terrorists, and cyberattacks. Most of the literature studied the impact of supply disruption on supply chain profitability [56,66]. Silbermayr and Minner [52] examined the effects of supplier learning for cost reduction on the performance of the supply chain in the event of supply disruption. Based on the development of a backup supplier and additional production capacity, Rahman *et al.* [41] suggested various solutions to lower the risk of supply disruption and evaluated them using the simulation approach. In a two-echelon supply chain with a risk of supply disruption, Liu *et al.* [24] developed a model for investing in supplier reliability and studied pricing strategies. Li *et al.* [22] also examined the impact of reliability investments on a supply chain with asymmetric information among parties. A study on investment allocation problems under differential game can be seen in [47]. Besides, a model for trade-off between profit and risk in financial markets can be found in [18].

Tsao *et al.* [61] proposed a model for supply disruption and explored the customers' panic buying behaviour. They stated that supply disruptions could cause buyers' fear of shortage in many circumstances, creating a shock in demand. In addition, a paper in the defence industry has shown a need to simultaneously consider supply and demand disruptions in studies [45]. Even though supply and demand disruptions frequently happen simultaneously, few studies have incorporated these risks in mathematical models. Lei *et al.* [21] developed a model for ordering problems in a supply chain consisting of buyer and supplier under supply and demand disruptions. Their main focus was examining the impact of incomplete information among supply chain members. Another aspect of the researches in this area, is the optimisation algorithm as models deal with uncertainties and stochastic variables. Savku and Weber [46] developed a maximisation algorithm for a Markov regime- switching model under partial information system. In addition, frameworks for optimisation of stochastic models with fuzzy approaches can be found in works of [19, 31].

This paper differs from the literature by considering supply and demand disruption risks to overcome specific challenges of complex products' supply chains. None of the cited papers in this section considered R&D investment and its impact on resiliency. Through experimental research, only Parast [39] demonstrated that organisations that have invested more in innovation and R&D have higher resilience to disruptions.

2.3. Supply chain contracts for risk reduction

As alluded to earlier, the relationship between the buyer and the supplier is crucial in the risk mitigation strategy. Researchers have proposed and examined many contracts in the literature on supply chain risk management. Yu *et al.* [67] demonstrated how an R&D cost-sharing contract contributes to higher supply chain performance levels. Zhou *et al.* [73] studied supplier–producer collaboration in technological development. They examined the cost-sharing and license-sale contract models and demonstrated how cooperation in technology development could raise profitability and technological product levels. Liu *et al.* [25] explored the investment problem for supplier's technology improvement and found conditions in which an investment in a new supplier is preferable for the supply chain's profit.

Tuncel *et al.* [62] examined the impact of various contracts on the performance of a supply chain with a newsvendor problem. They showed that a minimum order quantity (MOQ) contract performs better because of its simplicity and lower cognitive load, making it easier to implement. Some researchers [1, 11] presented a flexible MOQ contract with a backup supplier and demonstrated that this type of contract could effectively reduce supply disruption risk. To limit the risk of a supply disruption, Choi and Shi [6] also proposed a MOQ contract with trade credit. Davis and Leider [8] investigated how different contracts impact a supply chain's motivation for capacity investment. Those contracts include a service-level agreement, MOQ, and a two-part tariff contract. They showed how each contract affects the supply chain's performance differently under various conditions. Lotfi *et al.* [28] proposed vendor-managed inventory for a healthcare supply chain and used a robust optimisation approach.

All the above studies examined the impact of contracts on profitability, and only a few research studies have investigated the effect of contracts on resiliency. Namdar *et al.* [35] and Bakshi and Kleindorfer [2] designed cooperative contracts to enhance the performance of a resilient supply chain. Shokouhifar and Goli [51] developed a mechanism to improve resilient network lies in vertical and horizontal inventory transshipments. However,

Table 1. List of related studies in the resilient supply chain literature.

Reference	Resiliency	Demand disruption	Supply disruption	R&D investment	Learning effect	Planning horizon	Risk mitigation strategy	Contract mechanism	Methodology approach
[9]	✓	✓				Multi-period	Inventory management	–	Simulation
[1]		✓				Single period	Backup supplier	MOQ	Multi-level programming
[2]	✓		✓			Single period	Reliability investment	Cost-sharing	Multi-level programming
[6]			✓			Single period	Inventory management	MOQ	Multi-level programming
[8]		✓				Single period	Capacity investment	MOQ; service-level agreement; two-part tariff	Multi-level programming
[22]			✓			Singleperiod	Reliability investment	Menu of contracts	Multi-level programming
[25]				✓		Single period	Reliability investment	–	Multi-level programming
[24]			✓			Single period	Reliability investment	–	Multi-level programming
[28]	✓	✓				Single period	Inventory management	VMI	Robust optimisation
[29]	✓	✓				Multi-period	Product substitution	–	Simulation
[32]	✓		✓			Multi-period	Suppliers' cooperation	Centralisation	Simulation
[35]	✓		✓			Single period	Reliability investment	Two-part tariff; capacity reservation	Non-linear programming
[40]	✓	✓	✓			Single period	Operational adjustment	–	MODM
[41]	✓		✓			Multi-period	Capacity investment; backup supplier	–	Simulation
[52]			✓		✓	Multi-period	Dual channel supply	–	Multi-level programming
[68]	✓	✓	✓			Multi-period	Inventory management	–	Heuristic
[71]		✓		✓		Single period	Technology investment	Cost-sharing	Multi-level programming
[72]		✓			✓	Two-period	Inventory management	–	Multi-level programming
[73]			✓	✓		Single period	Technology investment	Cost-sharing	Multi-level programming
This paper	✓	✓	✓	✓	✓	Multi-period	Reliability investment	Cost-sharing; MOQ; two-part tariff; service-level agreement	Multi-level programming and simulation

according to Duong and Chong [10], which reviewed the literature on supply chain contracts under disruption, the impact of contracts on supply chain resilience has not been explored adequately in the previous literature.

2.4. Research gap and contribution

Based on our review, Table 1 summarises the distinction of this paper from the literature. The contribution of this paper is as follows: (1) Developing a multi-period model for a supply chain in complex product systems while considering R&D and reliability investments under the disruption risks. (2) Examining the impact of R&D costs, product technology level, reliability enhancement costs, supplier's learning effect, and the buyer's fairness concern on supply chain resilience. (3) Analysing how different contracts could change the equilibrium, including R&D cost-sharing, reliability investment cost-sharing, two-part tariff, MOQ, and service-level agreement.

3. Problem description

This paper considers a supply chain containing a buyer and a supplier. Before the selling season, both firms invest in R&D to design the product. During the selling season, the firms decide on ordering size and price. The buyer's demand and the supplier's production are prone to disruption risk. Thus, the buyer considers customer service level alongside its profit maximisation objective. The supplier's objective is to maximise profit. Table 2 contains a list of notations used in modelling the problem. The assumptions of the model and the game between members are described in the following.

TABLE 2. List of notations and variables.

Parameters	
t	Index for period $t \in \{1, 2, \ldots, T\}$;
A_t	The market size of the product in period t (\$/t);
β	The market price sensitivity to the quantity, $\beta \in [0, 1]$;
α	The market sensitivity to the product's technological level, $\alpha \in [0, 1]$;
ε_t	The random variation of price in period t (\$/t);
x_t	The demand disruption in period t (\$/t);
y_t	The random disruption of the supplier production in period t (units/t);
K	The supplier production capacity in each period (units/t);
k	The familiarity factor of the supplier with the technology;
g_b/g_s	The R&D investment cost of the buyer/supplier (\$);
γ	The coefficient of the increase in production cost due to the technology level (\$/t);
L	The supplier's learning rate for cost reduction, $L \in [0, 1]$;
δ	The fairness concern of the buyer, $\delta \in [0, 1]$;
φ	The probability of successful R&D outcome for the supplier, $\varphi \in [0, 1]$;
Ω	The weight of the service level in the utility function of the buyer, $\Omega \in [0, 1]$;
I_r	The interest rate (%/T);
Independent variables	
q_t	The order quantity in period t (units/t);
e_b/e_s	The effort of the buyer/supplier in the R&D process, $e_{b(s)} \in [0, 1]$;
w	The wholesale price of the supplier (\$);
z	The reliability enhancement cost (\$);
Dependent variables	
p_t	The retail price (\$);
c_t	The supplier production cost in period t (\$/t);
v	The value of the product's technological level (\$);
π_b/π_s	The profit of the buyer/supplier (\$);
Π_{sc}	The total profit of the supply chain (\$);
U_b	The utility function of the buyer;
SL	The service level (%);
QL_t	The quantity loss in period t (units/t);
PL_t	The profit loss in period t (\$/t);
NPVPL	The net present value of the profit loss (\$);

Assumptions

- The planning period T is divided into several finite discrete periods. Each period is represented by t; we have $t \in \{1, 2, \ldots, T\}$.
- In the first period, the supply chain's members decide on the R&D investment; in other periods, they decide on operational decisions regarding order quantity and price.
- There is sequential decision-making in the supply chain under which the buyer is the Stackelberg leader, and the supplier is the follower.
- The product's technological level is a stochastic outcome of the R&D efforts.
- The market price is a function of supply quantity and the product's technological level.
- The market size and supplier's production are prone to a disruption risk.
- The supplier's production cost is a function of the product's technological level.
- The supplier has a constrained production capacity at each period.

Game description and modelling: before the selling season, the buyer first chooses the type of contract and offers the contract to the supplier. If the contract is accepted, the buyer invests in product design and R&D.

For simplification by following Liu *et al.* [25], the level of effort that the buyer puts into the R&D process is normalised to one, $e_b \in [0,1]$, and its cost is $\frac{g_b}{2}e_b^2$.

In addition to the buyer, the supplier could make an R&D investment to enhance the product's technological level. The supplier effort is $e_s \in [0,1]$, and the related cost becomes $\left(\frac{g_s}{2}+\frac{1}{k}\right)e_s^2$. The parameter k is the familiarity factor of the supplier with product technology. The higher it is, the more familiar the supplier is with the technology, and the less money it must invest in R&D to reach a certain level of e_s [67]. As stated by Yenipazarli [65], the output of the supplier's R&D effort is not always successful. Thus, by following the Bernoulli distribution function, we consider the supplier's R&D outcome is technically successful with probability φ, and there is no result or added value to the product with probability $1-\varphi$.

From the product technological standpoint, the buyer and supplier can raise the product's value for the customer through the R&D process. The v represents the product's added value, and we have $v = e_b + \varphi e_s$. In the case $v = 0$, there is no added value in the basic product. For example, manufacturers of air conditioning systems should develop product technology to reduce energy usage to achieve environmental regulations and customer satisfaction [25, 64].

After the R&D phase, the supply chain produces the products and delivers them to the market in each period t during the selling season. The supplier determines its wholesale price w, and the buyer chooses the order quantity in each period q_t. Based on the Cournot model and considering product technological value and the risk of demand disruption, the price function can be expressed as follows:

$$p_t = x_t A_t + \alpha v - \beta q_t + \varepsilon_t. \tag{1}$$

In the above formula, A_t represents the market size, and it is the price baseline that a customer is willing to pay for the product in a period t. The term αv is the growth in the market because of the product's technical capabilities; that is, α is the additional price the customer is willing to pay due to the product's technological level. q_t is the amount of product supply in that period, β is the price's sensitivity to the amount of supply, and ε_t is the random variations in demand during the period. In this equation, we have $\alpha \geq 0$, $0 \leq \beta \leq 1$, and $\varepsilon_t \sim N\left(0,\sigma^2\right)$. Besides, the parameter x_t shows the magnitude of the demand disruption in period t. If $x_t = 1$, there is no demand disruption. $x_t > 1$ denotes an incremental demand shock in which customers are willing to more of the product during period t, and if $0 < x_t < 1$, the market has decreased. This kind of price modelling can be found in some studies [42, 67, 73].

After receiving the order, the supplier begins production. The supplier has a limited capacity K for production in each period, and its cost of production c_t is a function of the technology level. In the first period, the production cost per unit is $c_1 = c_0 + \gamma v$, where c_0 is the production cost for the basic product, v is the level of added value in the product due to R&D efforts, and γ is the amount of increase in production cost because of the rise in technology level [63]. The production cost is not constant over time, and in the presence of the supplier learning effect, it could decrease dynamically over the planning horizon. If the cumulative production quantity in period T is $Q = \sum_{t=1}^{T} q_t$, then the production cost is obtained from the following formula:

$$c_T = c_{T-1} - LQ, \tag{2}$$

where L is the learning rate [20, 52].

The supplier is also prone to disruption risk. The random yield function determines its output rate. If the supplier receives an order of q_t within the period t, then in the event of a disruption, it will deliver the amount $Y_t = y_t q_t$, where $y_t \in [0,1]$. This type of supply disruption modelling has been used by many researchers [17]. Figure 1 summarises the sequence of decision-making in the game.

In the following, first, we propose a model under the deterministic condition as the benchmark model. Then, the model under the supply and demand disruptions is developed.

3.1. Benchmark model

Here, we present a deterministic model for the supply chain. The results of this model are used as a baseline for comparison with other scenarios. The related variables and functions of this model are denoted by superscript

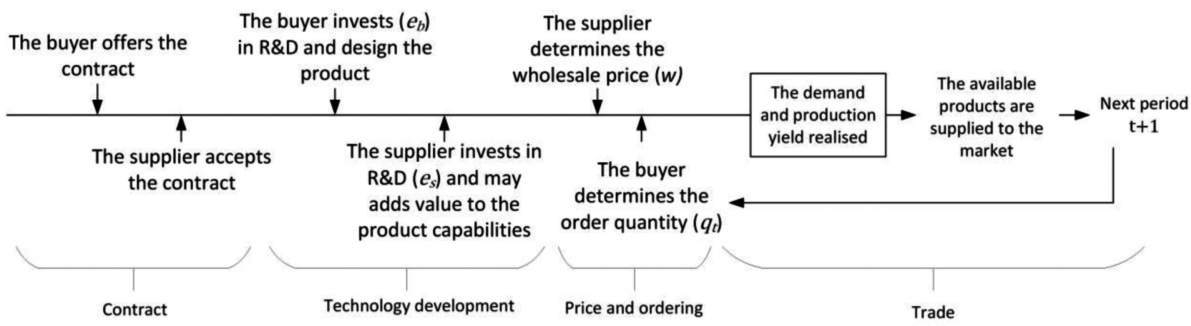


Figure 1. Sequence of events.

B. Assume we have $x_t = 1$, $y_t = 1$ and $\varepsilon_t = 0$ for each period. Thus, we have $p_t = A_t + \alpha v - \beta q_t$ as well as $Y_t = q_t$. According to the proposed game, the profit functions of the buyer and supplier are defined, respectively, as follows:

$$\pi_b^B = \sum_t (p_t - w)q_t - \frac{g_b}{2}e_b^2, \tag{3}$$

$$\pi_s^B = \sum_t wq_t - c_t q_t - \left(\frac{g_s}{2} + \frac{1}{k}\right)e_s^2. \tag{4}$$

The optimal values of the variables in this setting are stated in the following.

Proposition 1. *Under the benchmark model, the profit functions are concave if* $g_S > \frac{Tk\phi^2(\alpha-\gamma)^2-8\beta}{4\beta k}$ *and* $g_b > \frac{2\beta T(2+g_s k)^2(\alpha-\gamma)^2}{\left(\phi^2 kT(\alpha-\gamma)^2-4\beta(2+g_s k)\right)^2}$. *The optimal solutions can be expressed as follows.*

$$q_t^{B^*} = \frac{A_t - w + \alpha\left(e_b + \phi e_s\right)}{2\,\beta}, \tag{5}$$

$$w^{B^*} = \frac{\sum_{t=1}^{T}(A_t - Lq_{t-1}) + ((\alpha+\gamma)(e_s\phi + e_b) + c_0)T}{2T}, \tag{6}$$

$$e_s^{B^*} = \frac{k\Big(\Big(\sum_{t=1}^{T} T\phi(\alpha-\gamma)(A_t + Lq_{t-1})\Big) + T^2\phi(\alpha-\gamma)(\alpha e_b - e_b\gamma - c_0)\Big)}{T\Big(4\beta(2+g_s k) - k\phi^2 T(\alpha-\gamma)^2\Big)}, \tag{7}$$

$$e_b^{B^*} = \frac{(Z_2T - 4Z_3\beta)\Big(\sum_{t=1}^{T} 4A_tT\beta Z_3(\gamma-\alpha)\Big) + 2((Z_2T - 4\beta Z_3)Z_1 - T(Z_1Z_2 - 4c_0\beta Z_3))\beta TZ_3(\gamma-\alpha)}{4\beta T\Big(k^2\phi^4 g_b(\alpha-\gamma)^4T^2 - 2(2+k(4g_b\phi^2+g_s))(\alpha-\gamma)^2\beta TZ_3 + 16\beta^2 g_b Z_3^2\Big)}\cdot \tag{8}$$

The proof of this proposition is presented in Appendix A. The concavity conditions of the problem define a lower bound for R&D cost.

3.2. Decentralised supply chain under disruption risk (Scenario DN)

In this section, we take demand and supply disruptions into account. Yet no specific initiative is considered for risk reduction; this scenario is also called the risk acceptance scenario.

Assume that at the end of period t, the market size changes to x_tA_t, and the number of products supplied by the supplier reduces to y_tq_t. As a result of the discrepancy between the order quantity and received quantity, the supply chain's profit differs from its optimal level, and the market may also face shortages and increased prices for customers.

Under this condition, at the upper-level problem, the buyer defines its objective function based on reducing profit loss and increasing customer service level. This function reflects the resilience of the supply chain. In this regard, we propose the following two metrics:

Service Level: if the optimal order quantity for the product in period t is q_t^*, additionally Y_t is the actual supply quantity of the product, then the quantity loss in the period can be computed as $\mathrm{QL}_t = q_t^* - Y_t$ [14]. The customer service level index for the planning horizon can be defined as follows [5, 43].

$$\mathrm{SL} = \sum_t \frac{1 - \frac{\mathrm{QL}_t}{q_t}}{T}. \tag{9}$$

This metric represents the average service ranging from 0 to 1 over all periods.

Net Present Value of Profit Loss (NPVPL): when the supply chain is disrupted, the amount of profit under risk conditions may be less than the deterministic case (benchmark model). The amount of profit loss in period t is calculated as follows [34]:

$$\mathrm{PL}_t = \frac{\Pi_t^B - \Pi_t^S}{\Pi_t^B}. \tag{10}$$

In the above, Π_t^B represents the profit in the benchmark model and Π_t^S is the profit in Scenario S. The buyer, as the game's leader, could calculate the amount of PL_t considering either its own profit or including the supplier's profit. Therefore, the parameter δ is defined as the degree of fairness concern $0 \le \delta \le 1$, and we have:

$$\Pi_{sc} = \pi_b + \delta \pi_s. \tag{11}$$

The net present value of profit loss is determined using the following formula considering the time value of money during the planning horizon [3, 5].

$$\mathrm{NPVPL} = \sum_t \frac{\mathrm{PL}_t}{(1 + I_r)^t}, \tag{12}$$

where I_r is the interest rate.

Now, based on the above two metrics, the utility function of the buyer is defined as follows:

$$\text{maximize } U_b = \Omega\,\mathrm{SL} - (1 - \Omega)\,\mathrm{NPVPL}. \tag{13}$$

In equation (13), Ω represents the weight of the service level from the buyer's perspective, $0 \le \Omega \le 1$. When Ω is zero, the buyer is solely concerned with minimising financial losses; if this parameter equals one, the buyer is only involved with increasing customer service level.

For Scenario DN, we shall formulate the model as follows:

$$\begin{cases} \text{maximize} & U_b^{\mathrm{DN}} = \Omega \mathrm{SL} - (1-\Omega)\mathrm{NPVPL} & (14) \\ \text{subject to} & \pi_b^{\mathrm{DN}} = \sum_t ((p_t - w)Y_t) - \frac{g_b}{2} e_b^2, & (15) \\ & 0 \le e_b \le 1, & (16) \\ & 0 \le q_t \le K, & (17) \\ & w \le p_t, & (18) \\ \begin{cases} \text{maximize} & \pi_s^{\mathrm{DN}} = \sum_t ((w - c_t)Y_t) - \left(\frac{g_s}{2} + \frac{1}{k}\right) e_s^2 & (19) \\ \text{subject to} & Y_t = y_t q_t, & (20) \\ & 0 \le e_s \le 1, & (21) \\ & c_t \le w. & (22) \end{cases} \end{cases}$$

In the first level of the problem, the buyer decides on (e_b, q_t), and in the lower level, the supplier chooses (e_s, w). In equation (14) the functions of SL and NPVPL can be calculated from equations (9) and (12), respectively. The disruptions in demand and supply and the supplier's limited capacity could impact the chain's profit and product quantity brought to the market. In the next section, we extend the model by considering an investment in reliability enhancement and different cooperative contracts. The approach for solving models is then presented.

4. Reliability enhancement

Increasing reliability to improve responsiveness can be accomplished through multiple actions, including production capacity expansion, increasing equipment, improving communication and transportation infrastructures, establishing an emergency production capacity, and growing work shifts [22]. Because implementing these projects would require investment and additional expenditures, the supplier is willing to invest if the buyer provides an incentive. In this context, a cooperative contract can be beneficial.

Assume that the investment in supply reliability is made before the selling season, which diminishes the supply disruption probability. As a result, the game's equilibrium has been changed [24]. In the following, we first develop the model with reliability enhancement for the decentralised supply chain, and then, the models under the contracts are extended.

Decentralised supply chain with reliability enhancement (Scenario DI): the supplier with the disruption probability y_t would enhance its reliability and increase the production yield to $\hat{y}_t$. Using the inverse Cobb–Douglas function, the disruption probability becomes to $\hat{y} = 1 - \frac{1}{(1+z)^{\mu}} y$, where z is the amount of investment and μ is the efficiency of the investment [24, 49]. Under this scenario, the problem is converted to the following:

$$\begin{cases} \text{maximize} & U_b^{\text{DI}} = \Omega\text{SL} - (1-\Omega)\text{NPVPL} & (23)\\ \text{subject to} & \pi_b^{\text{DI}} = \sum_t ((p_t - w)Y_t) - \frac{g_b}{2} e_b^2, & (24)\\ & 0 \le e_b \le 1, & (25)\\ & 0 \le q_t \le K, & (26)\\ & w \le p_t, & (27)\\ \begin{cases} \text{maximize} \\ \text{subject to} \\ \\ \\ \\ \\ \end{cases} & \begin{matrix} \pi_s^{\text{DI}} = \sum_t ((w - c_t)Y_t) - z - \left(\frac{g_s}{2} + \frac{1}{k}\right) e_s^2 \\ \hat{y} = 1 - \frac{1}{(1+z)^{\mu}} y, \\ Y_t = \hat{y}_t q_t, \\ 0 \le e_s \le 1, \\ c_t \le w, \\ z \ge 0. \end{matrix} & \begin{matrix} (28)\\ (29)\\ (30)\\ (31)\\ (32)\\ (33) \end{matrix} \end{cases}$$

To reduce the inefficiency of the decentralised structure, we propose the following cooperative contracts.

R&D cost-sharing contract (Scenario RC): the buyer and the supplier jointly invest in R&D, and the total R&D cost is shared. This contract is also known as technology development collaboration. The parameter ψ represents the buyer's share of the total R&D cost. Under this setting, the buyer's and supplier's profit functions are rewritten as follows:

$$\pi_b^{\text{RI}} = \sum_t ((p_t - w)Y_t) - \psi\left(\frac{g_b}{2} e_b^2 + \left(\frac{g_s}{2} + \frac{1}{k}\right) e_s^2\right), \tag{34}$$

$$\pi_s^{\text{RI}} = \sum_t ((w - c_t)Y_t) - z - (1-\psi)\left(\frac{g_s}{2} e_s^2 + \left(\frac{g_s}{2} + \frac{1}{k}\right) e_s^2\right). \tag{35}$$

Two-part tariff contract (Scenario TT): the wholesale price is divided into two parts: fixed and variable. The variable cost per unit is w, and the fixed payment is f that paid by the buyer at the commencement of the contract.

Minimum order quantity contract (Scenario MOQ): the buyer commits to purchase a quantity m at a price w^m in each period, regardless of the amount of its order. For orders greater than m, the supplier offers the wholesale price w. It is also considered that $w \leq w^m$ is held. Thus, the supplier provides lower price for larger orders.

Service-level agreement (Scenario SL): the wholesale price of each product unit is w, but for each lost quantity, the buyer imposes a penalty ρ per unit on the supplier.

Reliability enhancement cost-sharing contract (Scenario CS): the reliability enhancement cost z is shared between parties. The buyer pays a percentage ξ of the overall cost.

The profit functions under the above contracts can be expressed as follows.

$$\pi_b = \sum_t \left((p_t - w)Y_t + (p_t - w^m)m + \rho(q_t - Y_t)\right) - \xi z - \frac{g_b}{2}e_b^2 - f, \tag{36}$$

$$\pi_s = \sum_t \left((w - c_t)Y_t + (w^m - c_t)m - \rho(q_t - Y_t)\right) - (1-\xi)z - \left(\frac{g_s}{2} + \frac{1}{k}\right)e_s^2 + f. \tag{37}$$

In the above equations, if we put $m = 0$, $\rho = 0$, $\xi = 0$, and $f > 0$, we obtain the two-part tariff model. The MOQ is made by setting $m > 0$, $\rho = 0$, $\xi = 0$, and $f = 0$. The service-level agreement is found in the case of $m = 0$, $\rho > 0$, $\xi = 0$, and $f = 0$; and finally, we can write the model of reliability enhancement cost-sharing contract if we set $m = 0$, $\rho = 0$, $0 < \xi \leq 1$, and $f = 0$.

5. Solution approach and results

This section describes the method for solving the models and obtains the results through a numerical study.

5.1. Solution approach

We confront a hierarchical bi-level mathematical programming problem. The bi-level problem can be reformulated to a single-level model by substituting the Karush–Kuhn–Tucker (KKT) conditions of the lower-level model (follower's problem) into the upper-level model (leader's problem) only when the lower-level model is convex and regular [7, 57]. From Proposition 1, we know that the problem is convex under the benchmark model. Due to the collectability property of convexity, the lower-level models of the extended problems under uncertainty are also convex. Generally, for a maximisation problem with i decision variables and j constraints such as follows:

$$\begin{aligned} &\text{maximize } \pi(x_i), \\ &\qquad f_j(x_i) \leq b_j \qquad \forall j, \end{aligned} \tag{38}$$

the optimal solution satisfies the following system of equations using the KKT conditions.

$$\begin{aligned} &\frac{\partial \pi(x_i)}{\partial x_i} - \sum_j \lambda_j \frac{\partial f_j(x_i)}{\partial x_i} = 0 && \forall i, \\ &\lambda_j [b_j - f_j(x_i)] && \forall j, \\ &\lambda_j \geq 0 && \forall j. \end{aligned} \tag{39}$$

Under Scenario DN, the supplier model, equations (19)–(22), has two decision variables (e_s, w) and two constraints: $0 \leq e_s \leq 1$ and $c_t \leq w$. The KKT conditions of this problem can be computed by the following equations:

$$\frac{\partial \pi_s^{\mathrm{DN}}}{\partial w} - \lambda_1 \left(\frac{\partial(-w)}{\partial w}\right) = 0, \tag{40}$$

TABLE 3. Solution algorithm of the problem.

Step 1	Start
Step 2	Select the scenario $S = \{\text{DN, DI, RC, TT, MOQ, SL, CS}\}$
Step 3	Input values of the model parameters
Step 4	Set periods T and iteration number N
Step 5	Set $n = 1$
Step 6	Generate random numbers for random parameters $\varepsilon_t \in N(0, \sigma^2)$ $y_t \in U(0, 1)$ $x_t \in \Delta(t)$ $\varphi \in U(0, 1)$
Step 7	Write q_t as a function of w, e_s and e_b from the first order condition $\frac{\partial U_b}{\partial q_t} = 0$
Step 8	Calculate c_t and p_t
Step 9	Calculate the KKT conditions of the lower-level problem and put it into the upper-level problem using equations (38) and (39)
Step 10	Use the solver package (such as fmincon solver in Matlab) to find the optimal decision variables
Step 11	Calculate the average of profits, service level, profit loss, NPVPL, and U_b
Step 12	If $n < N$: set $n = n + 1$ and go to *Step 6*, otherwise: go to *Step 2*.

$$\frac{\partial \pi_s^{\mathrm{DN}}}{\partial e_s} - \lambda_2 \left(\frac{\partial (e_S)}{\partial e_S} \right) = 0, \tag{41}$$

$$\lambda_1(-c_t + w) = 0, \tag{42}$$

$$\lambda_2(e_s - 1) = 0, \tag{43}$$

$$\lambda_1, \lambda_2 \geq 0, \tag{44}$$

where (λ_1, λ_2) is the coefficient related to each constraint in KKT conditions and can be regarded as the shadow price. The single-level model of Scenario DN is obtained by substituting equations (40)–(44) into the buyer's problem. Similarly, one can convert each scenario to a single-level non-linear programming problem.

As the problem contains uncertain random parameters, a simulation method is used in the solution approach. In many real-world problems, complexities such as non-linearity and non-deterministic variables make it impossible to calculate the closed-form optimal variables analytically. To solve complex non-deterministic systems, different approaches have been proposed by scholars; for example, Özmen *et al.* [38] developed an algorithm based on robust optimisation and Maiti and Roy [30] introduced a solution approach with a ranking function procedure. One of the useful approaches is a computer simulation. However, there are restrictions on its application because it cannot guarantee the optimal result [58]. Thus, combining simulation and optimisation is an effective way to find a feasible optimal or nearly optimal solution. Such a strategy deploys the optimisation technique to identify the optimal variables and uses simulation to see the impact of random parameters on the model [37]. We solve each scenario several times by generating random parameters and computing the moving average of the variables. For this purpose, we designed the algorithm described in Table 3.

5.2. Numerical example

This section investigates the results of the presented models through a numerical example. The aim is to calculate the model's variables and analyse the supply chain's performance. The proposed models and the problem-solving algorithm in Section 5.1 were written in Matlab software, and the fmincon tool was used for

Table 4. Input parameters for the numerical study.

Parameter	Value
T	12 weeks
A_t	Uniform$(800, 1000)$ \$/t
β	0.2
α	200 \$/t
ε_t	Normal$(0, 20)$ \$/t
x_t	$\Delta(0.3)$ \$/t
y_t	Uniform$(0, 1)$ units/t
φ	Uniform$(0, 1)$
K	2000 units/t
k	2
g_b	5.1e+6 \$
g_s	6.2e+6 \$
c_0	100 \$/t
γ	80 \$/t
L	0.01
δ	0.7
Ω	0.5
I_r	20% in the year

optimisation. The planning horizon is 12 weeks (about three months), and the iteration number in the simulation is set to 100, plus 25 iterations for the simulation warmup period. The input parameters are shown in Table 4.

Through random number generation, demand disruption has occurred in 30% of the periods by using unit impulse function, where the market size is reduced meaningfully. As shown in Figure 2, we have $U_b^{\mathrm{RC}} > U_b^{\mathrm{TT}} > U_b^{\mathrm{CS}} > U_b^{\mathrm{SL}} > U_b^{\mathrm{MOQ}} > U_b^{\mathrm{DI}} > U_b^{\mathrm{DN}}$. The average utility function of the buyer in the decentralised structures (Scenarios DN and DI) are significantly lower than that in the other scenarios. It is evident that supplier reliability enhancement cannot solely improve U_b meaningfully. The resilience in the RC, TT, and CS scenarios has the highest value on average. Thus, in addition to investments in reliability, cooperation contracts have effectively increased resilience.

Figure 3a depicts the buyer's profit per period for each scenario. The decentralised scenarios yielded the lowest values, and the RC and MOQ scenarios yielded the highest. From the service level perspective, Figure 3b shows that Scenarios CS and RC have better performance.

Two other performance measures in the models are R&D investment and the reliability enhancement cost, which are shown separately in Figure 4. From Figure 4a, it can be seen that under the decentralised structures (Scenarios DN and DI), both the buyer and the supplier make less investment in the R&D rather than other structures. Besides, cooperation in R&D (Scenario RC) induces higher R&D investment. The level of product technology is directly related to the amount of R&D investment in our model. As a result, the technological level of the product v is higher in Scenario RC. In Figure 4b, we see that Scenario CS reduces the reliability enhancement cost z.

For further analysis, the sensitivity of the supply chain's variables with regard to the model's parameters has been investigated. First, we analyse the impact of market sensitivity to the product's technological level on the variables. Figures 5a and 5b shows that both SL and NPVPL decrease as α increases. Also, in this situation, z is reducing. As presented in Figure 5d, the supply chain needs to invest more in R&D when the market is more sensitive to the product's technological level; thus, v is getting higher. The supply chain experiences more loss in the service level and the profit when the market is more sensitive to the technology level of the product. However, Scenario CS is more robust to changes of α.

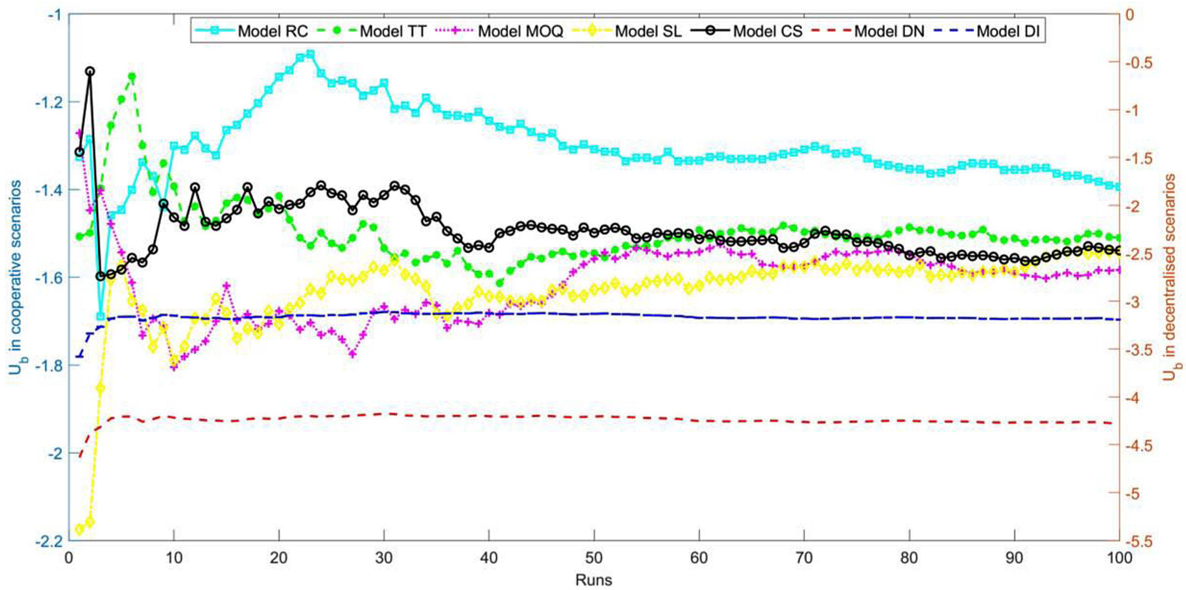


Figure 2. Resilience performance in each scenario.

As illustrated in Figure 6, the value of SL decreases slightly by increasing the market price sensitivity β. The variations of NPVPL are less sensitive to β. But in Scenario MOQ, both SL and NPVPL significantly worsen for a high value of β. When the market is highly sensitive to the price, Scenario TT makes higher utility. Besides, the reliability enhancement drops when the market sensitivity to the price increases. The supply chain could be more vulnerable to disruptions when the market is more competitive.

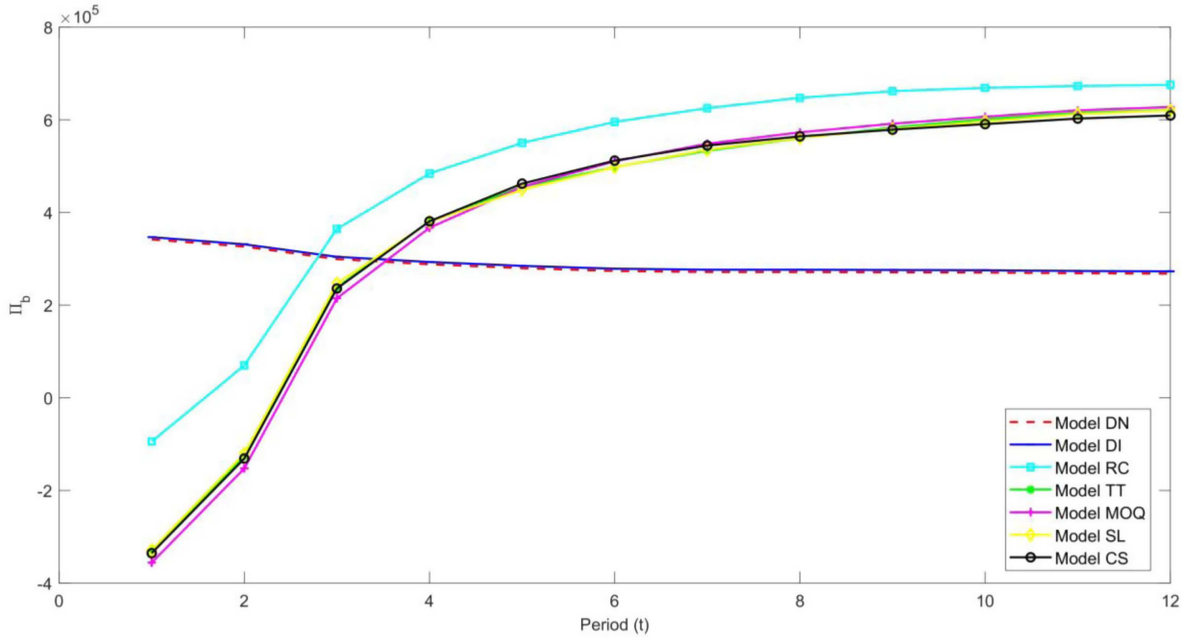
Figure 7a indicates that the service level is not very sensitive to changes of γ. However, as Figure 7b shows, the profit loss increases as γ increases. We can see the overall resilience is worse off by increasing the γ. In this case, the supply chain spends less on reliability improvement and exerts less effort on R&D. As a result, the product's technological level is decreasing.

Furthermore, we study the impact of the buyer's fairness level on the problem. As presented in Figure 8, increasing δ reduces the utility slightly from the SL standpoint. However, the NPVPL decreases significantly, which results in higher utility. It is also evident that resiliency in Scenario MOQ is less sensitive to the parameter δ. For high values of δ, investment in reliability is increased under Scenario TT. Therefore, a higher service level is obtained. Moreover, from Figure 8d, we can infer that although we showed earlier that v is higher under Scenario RC, there is a threshold for δ where for the values above that the R&D cooperation could result in higher technology level than other scenarios.

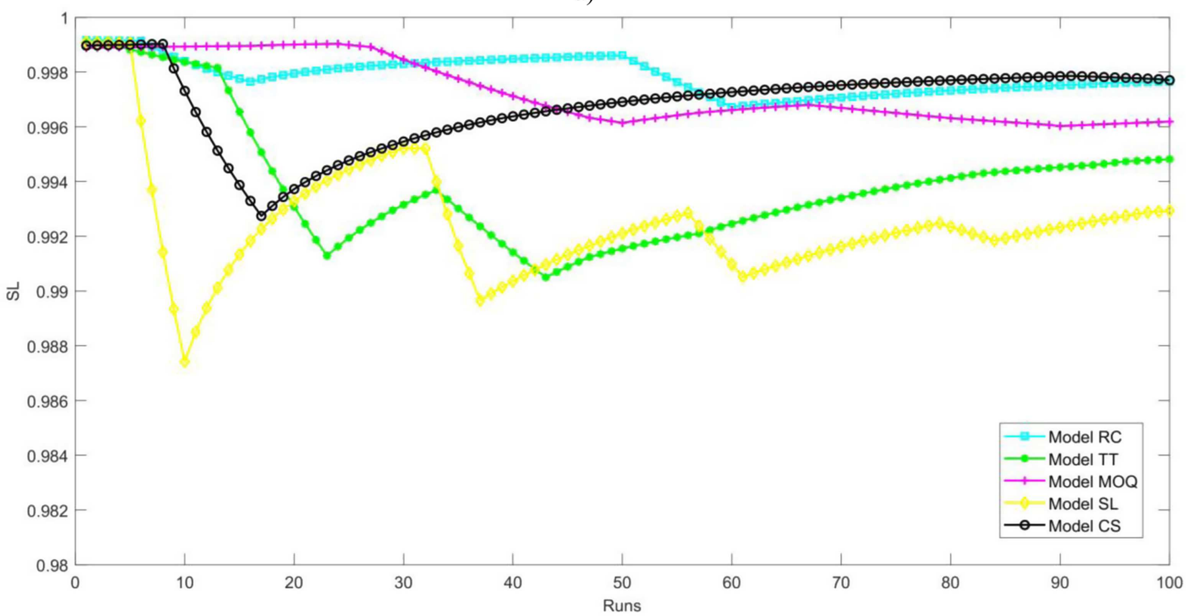
5.3. Managerial insights

Facing the proactive disruption risk management with reliability investment and including contract, this study presents managerial insights for supply chain and operations managers as follows:

- Among the investigated structures, the decentralised scenario has the lowest performance than others. In the decentralised structure, the supplier delivers the products at a fixed price per unit as a wholesale price contract. This mechanism has no long-term relationship and coordination among chain members. Therefore, the results show that the level of investment in both the R&D stage and the reliability enhancement stage is significantly low. On the other hand, the double profit marginalisation effect occurs in the operational decision-making phase, which reduces the financial performance of the entire supply chain. Therefore, in this



a)



b)

FIGURE 3. Total profit and service level of the supply chain in each scenario. (a) Total profit of the supply chain. (b) Service level of the supply chain.

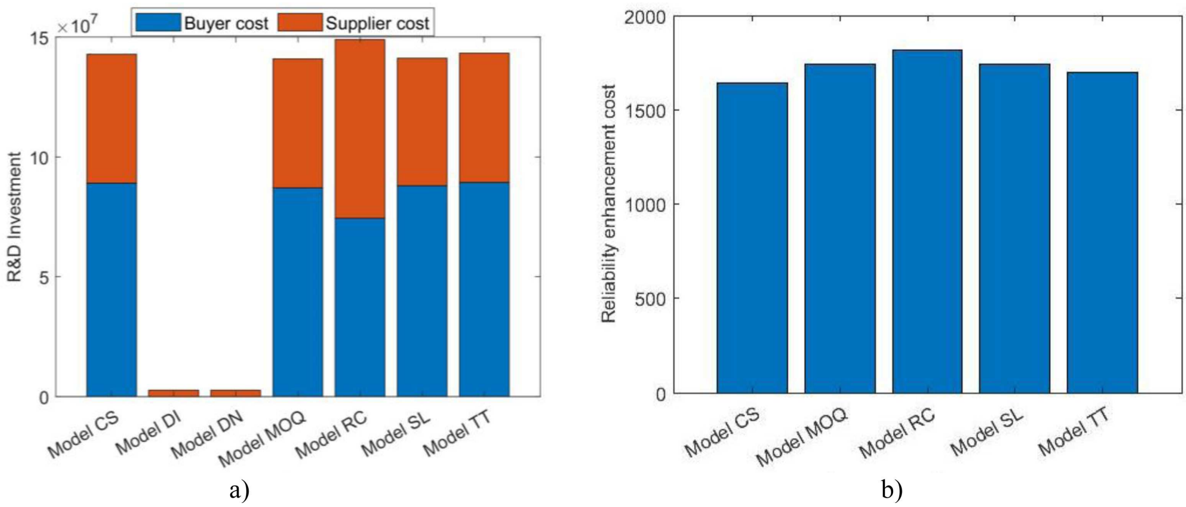


FIGURE 4. R&D cost and reliability enhancement cost for each scenario. (a) R&D investment. (b) The reliability enhancement cost.

structure, at the time of a disruption, the performance is reduced from the perspectives of the service level and profit loss.

– This study shows that an investment in the system's reliability leads to an increase in the service level. But in the decentralised scenario, the profit loss metric did not improve significantly because of the cost element of reliability enhancement. In this regard, the proposed cooperative contracts have been found as an effective way to improve the whole metrics and resilience level. Therefore, managers should consider concluding cooperative contracts with proper incentives with their suppliers along with investment in the infrastructures to improve reliability. In addition, the proposed contracts could increase the R&D investment.
– Under the supply and demand disruption risks, the performance of the supply chain from the resilience perspective is better under the R&D cost-sharing contract and the MOQ contract. Also, in terms of service level, the reliability enhancement cost-sharing contract and the R&D cost-sharing contract have performed better. Besides, R&D cooperation has resulted in a product with a higher level of technology and cooperation in reliability cost has led to a reduction in investment expenditure.
– By increasing the sensitivity of the market to the product's technological level (when customers are willing to pay more for higher technology), clearly, the level of investment in R&D increases, but on the other hand, it causes a reduction in the reliability enhancement investment, and as a result, the resiliency is decreased. In this situation, the R&D cost-sharing contract is more robust to variations. On the other hand, when the sensitivity of the market to the product's technological level is relatively low, the two-part tariff contract and service level agreement are found to be more suitable.
– In this paper, the behaviour of the buyer's fairness concern was investigated in the model. Inconsistent with the literature, this paper indicates that by increasing the degree of fairness, the performance of the entire supply chain improves from the financial aspect. However, this paper sheds new light on the effect of the fairness concern. When the buyer's fairness concern increases, the level of investment in reliability enhancement decreases due to the willingness to maintain profitability. As a result, the service level of the supply chain faces a reduction. Therefore, to improve the supply chain's resilience, the degree of fairness concern should be adequately established and balance financial performance and service level.

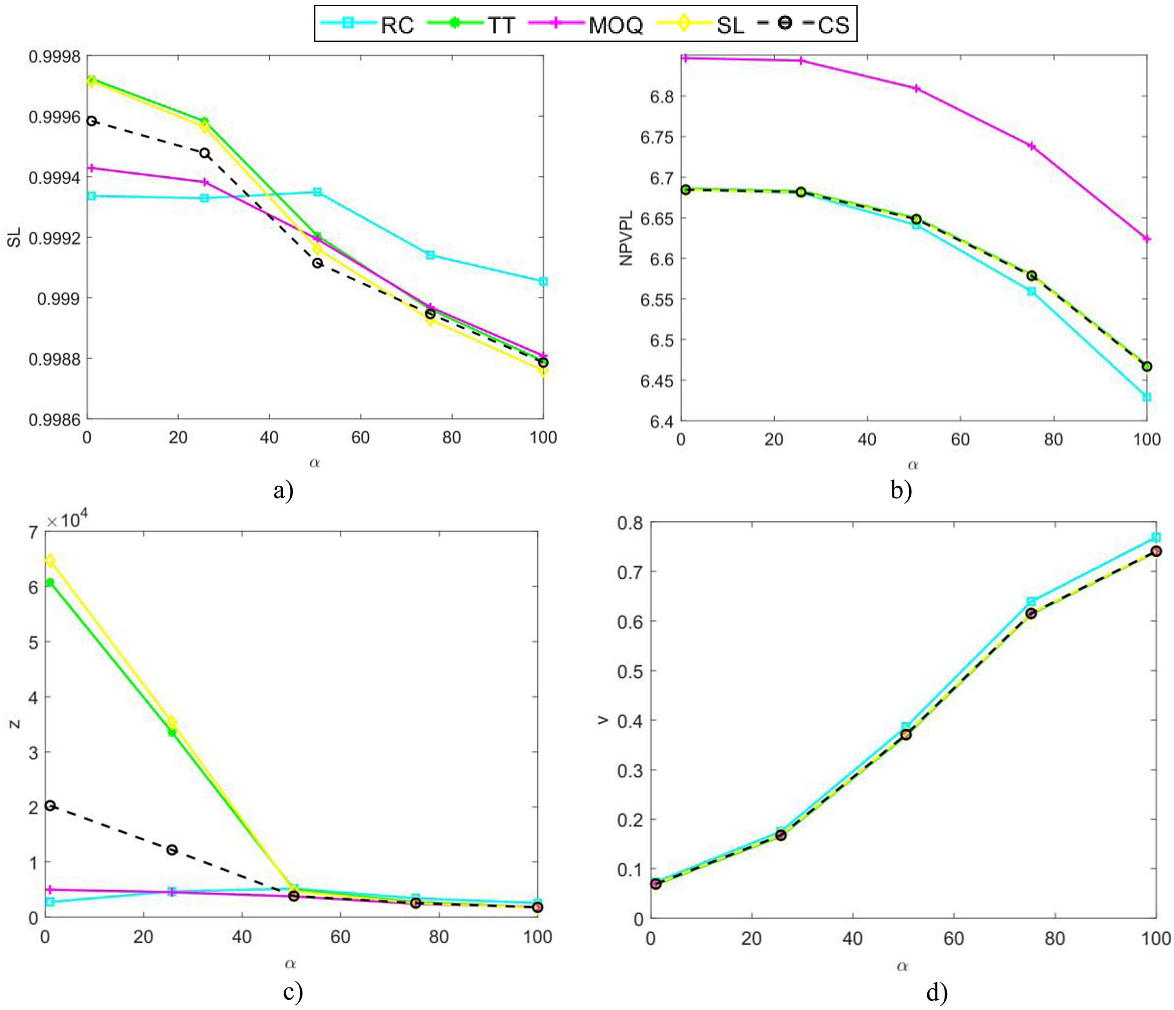


FIGURE 5. The impact of market sensitivity to the product's technological level on variables. (a) Impact of α on SL. (b) Impact of α on NPVPL. (c) Impact of α on z. (d) Impact of α on v.

6. Conclusions

This research aims to improve the resilient supply chain with a complex product under demand and supply disruptions. This study established a model of R&D investment, supplier reliability enhancement, and cooperative contracts and investigated their impact on supply chain profitability and resiliency. Using the Stackelberg game approach, a decentralised supply chain model is developed under disruption risks, and the resilience function was built based on the customers' service level and the net present value of the profit loss. The supplier reliability enhancement was then added to the model. Besides, the impact of various contracts was examined, including R&D cost-sharing, two-part tariff, MOQ, service-level agreement, and reliability enhancement cost-sharing. The scenarios of the problem were all bi-level non-linear programming models. The KKT conditions of the lower-level problem are incorporated to obtain single-level models. Then, an algorithm based on simulation and optimisation is presented to find optimal solutions.

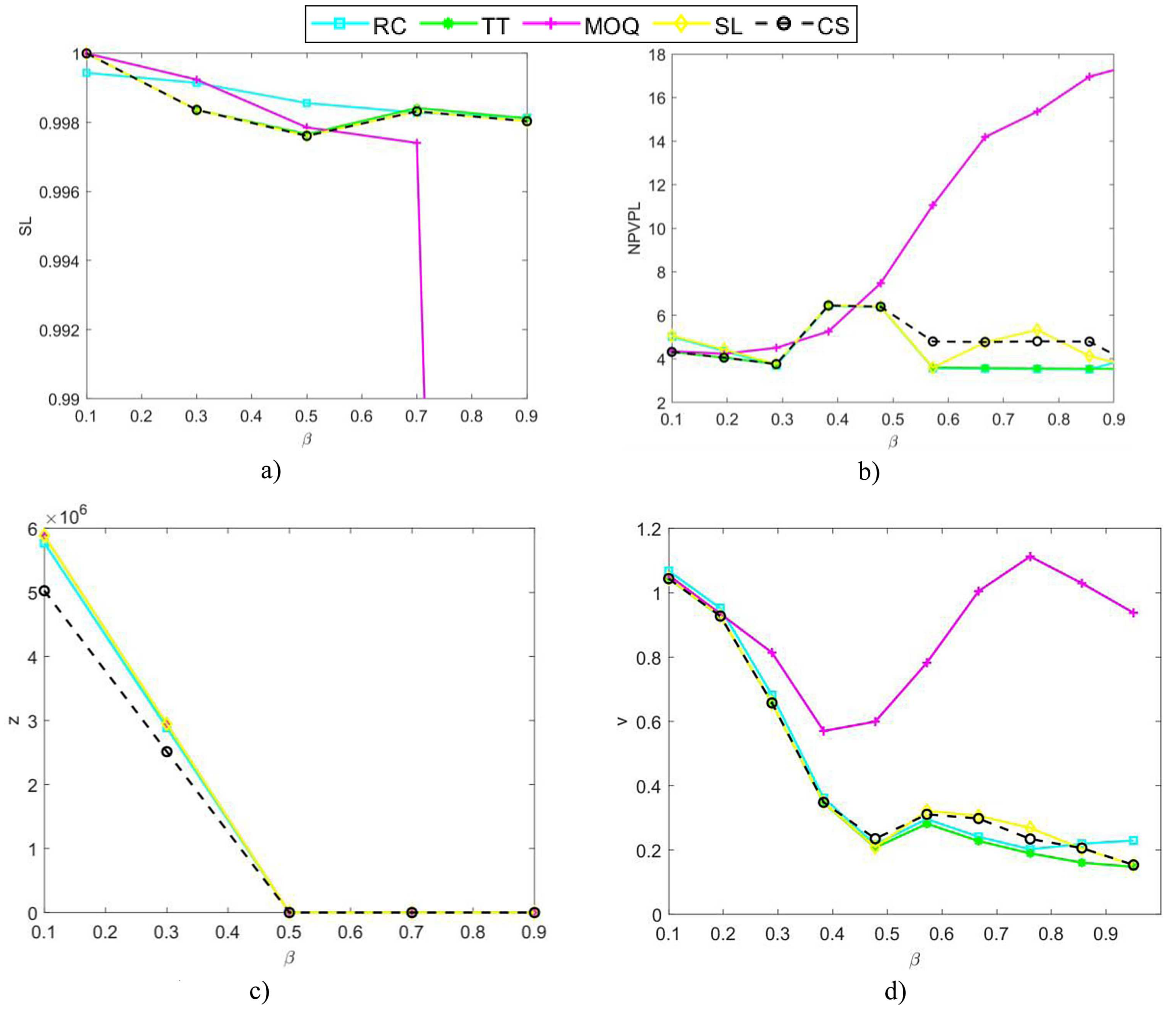


FIGURE 6. The impact of market price sensitivity on variables. (a) Impact of β on SL. (b) Impact of β on NPVPL. (c) Impact of β on z. (d) Impact of β on v.

The findings of this study indicate that investing in supplier reliability enhancement might reduce supply chain losses when demand and supply are disrupted. Alongside this, a cooperative contract between the supply chain's members is needed to improve resilience. The R&D cost-sharing contract causes a high product technology level and a significant improvement in resiliency. Besides, the reliability enhancement cost-sharing contract improves the service level better than other scenarios. The higher the market sensitivity to the product's technology and price, the less resilient the supply chain. In the markets with higher sensitivity to the product's technological level, more investment occurs in R&D, which could increase the profit. But the disruptions have a more severe impact on the service level. Moreover, when the market is extremely sensitive to the price, less investment makes in the reliability and R&D by the supply chain; consequently, the utility decreases. Thus, supply chains must adopt mitigation strategies in more competitive markets. The buyer's fairness concern also substantially affects the supply chain's performance during disruptions. This behaviour bias could reduce service level but significantly improve profit loss.

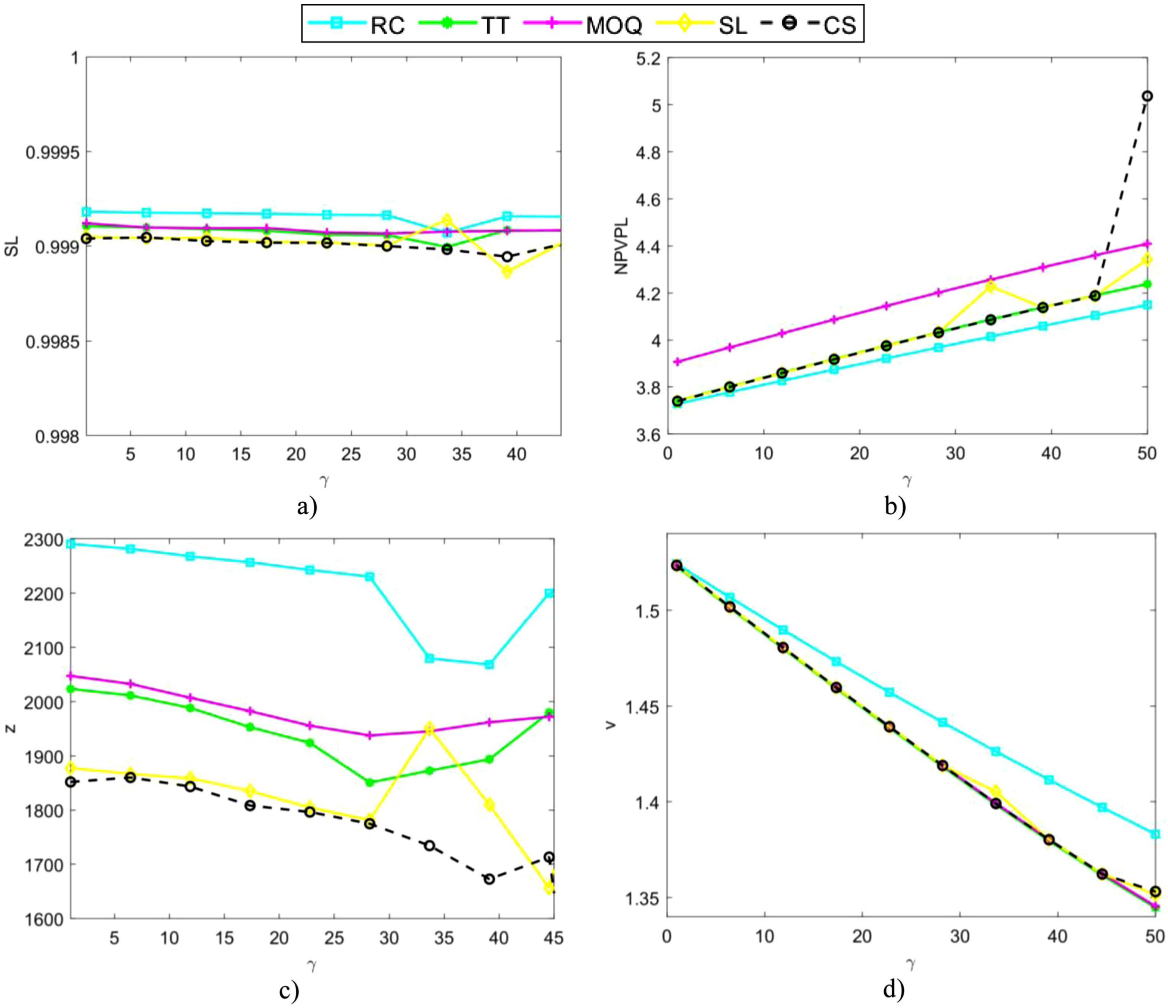


FIGURE 7. The impact of production cost sensitivity to technology level on variables. (a) Impact of γ on SL. (b) Impact of γ on NPVPL. (c) Impact of γ on z. (d) Impact of γ on v.

The authors realise that this paper has a few limitations. First, to study the impact of reliability investment and cooperative contracts on the model, a simple supply chain structure comprises one buyer and one supplier. Thus, researchers should analyse more complicated supply chain structures and multi-echelon networks for further studies. Second, the reliability enhancement is generally modelled to reduce the risk probability. This model can be expanded to include other mitigation strategies, such as using a backup supplier and increasing the number of suppliers. Third, the role of contracts relevant to technology trade, such as technology licensing, has not been examined in this study. Finally, the last limitation is that all parameters have been considered as known to both parties. Thus, it is advised to consider the impact of information asymmetry between the buyer and the supplier as well in future studies.

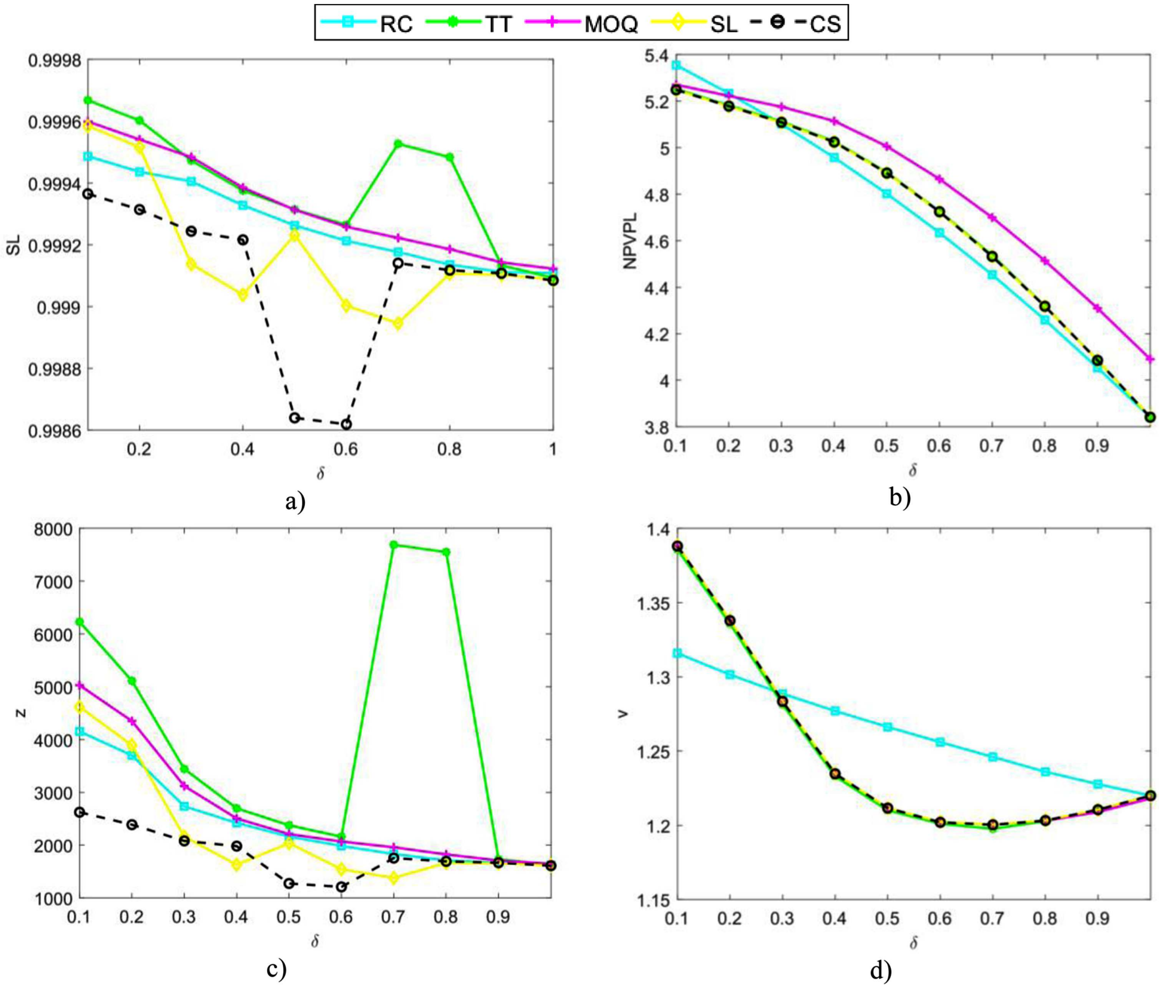


FIGURE 8. The impact of buyer's fairness concern on variables. (a) Impact of δ on SL. (b) Impact of δ on NPVPL. (c) Impact of δ on z. (d) Impact of δ on v.

APPENDIX A.

Proof of Proposition 1. Using the backward induction technique, we put equation (1) into equations (3) and (4), and calculate $\frac{\partial^2 \pi_b}{\partial q_t^2} = -2\,\beta$; thus, the π_B is concave with respect to q_t. From the first order condition, we have:

$$q_t^{B^*} = \frac{A_t - w + \alpha\,(e_b + \phi e_s)}{2\,\beta}. \tag{A.1}$$

The supplier's problem has two decision variables (w, e_s). By placing equation (A.1) into equation (4) and computing the Hessian matrix, we have:

$$H_{\pi_s} = \begin{pmatrix} -\frac{T}{\beta} & \frac{T\phi\,(\alpha+\gamma)}{2\,\beta} \\ \frac{T\phi\,(\alpha+\gamma)}{2\,\beta} & \frac{\left(-2\phi^2\gamma\alpha T - 2g_s\beta\right)k - 4\beta}{2\beta k} \end{pmatrix}, \tag{A.2}$$

$$\det(H_{\pi_s}) = -\frac{T\Big(T\phi^2 k(\alpha-\gamma)^2 - 4\beta g_s k - 8\beta\Big)}{4\beta^2 k}. \tag{A.3}$$

The π_s is concave if $g_s > \frac{Tk\phi^2(\alpha-\gamma)^2-8\beta}{4\beta k}$ holds. Now by solving $\frac{\partial \pi_s}{\partial w} = 0$ and $\frac{\partial \pi_s}{\partial e_s} = 0$, the following results can be obtained:

$$w^{B^*} = \frac{\sum_{t=1}^{T}(A_t - Lq_{t-1}) + ((\alpha+\gamma)(e_s\phi + e_b) + c0)T}{2T}, \tag{A.4}$$

$$e_s^{B^*} = \frac{k\Big(\Big(\sum_{t=1}^{T} T\phi(\alpha-\gamma)(A_t + Lq_{t-1})\Big) + T^2\phi(\alpha-\gamma)(\alpha e_b - e_b\gamma - c_0)\Big)}{T\Big(4\beta(2+g_s k) - k\phi^2 T(\alpha-\gamma)^2\Big)}. \tag{A.5}$$

We substitute above equations into π_b^B. From the calculation of second order derivative of π_b^B with respect to e_b, we conclude that π_b^B is concave if:

$$g_b > \frac{2\beta T(2+g_s k)^2(\alpha-\gamma)^2}{\Big(\phi^2 kT(\alpha-\gamma)^2 - 4\beta(2+g_s k)\Big)^2}. \tag{A.6}$$

As a result, by solving $\frac{\partial \pi_b}{\partial e_b} = 0$, we have:

$$e_b^{B^*} = \frac{(Z_2T - 4Z_3\beta)\Big(\sum_{t=1}^{T} 4A_tT\beta Z_3(\gamma-\alpha)\Big) + 2((Z_2T - 4\beta Z_3)Z_1 - T(Z_1Z_2 - 4c_0\beta Z_3))\beta TZ_3(\gamma-\alpha)}{4\beta T\Big(k^2\phi^4 g_b(\alpha-\gamma)^4T^2 - 2(2+k(4g_b\phi^2+g_s))(\alpha-\gamma)^2\beta TZ_3 + 16\beta^2 g_b Z_3^2\Big)}, \tag{A.7}$$

where $Z_1 = \sum_{t=1}^{T}(A_t + Lq_{t-1})$, $Z_2 = k\phi^2(\gamma-\alpha)^2$, and $Z_3 = 2 + g_s k$. □

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