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## Article

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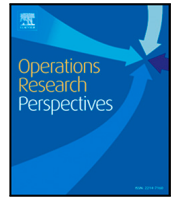
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# Cooperation and competition in an oligopolistic and mature industry: A case study on the cationic reagent industry based on an optimization model

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## ABSTRACT

A cationic reagent is an essential raw material in printing paper production. The market environment of the cationic reagent industry is influenced by the printing paper industry. Owing to the COVID-19 pandemic, the global expansion of remote work and home education has decreased the demand for printing papers. Consequently, competition among market players (*i.e.*, suppliers and buyers) in the cationic reagent industry is intensifying. This study focuses on cooperation between market players in the cationic reagent industry, representing a typical oligopolistic and mature industry. It proposes a supply chain optimization model that minimizes the costs of the entire supply chain, incorporating buyers' risk hedge tendency to address market uncertainty. The model is empirically tested using accessible and reliable data to assess its business applicability. Numerical experiments are conducted to explore scenarios that can occur in real market environment, such as levels of risk hedging, trade disputes, decreases in demand, and changes in production capacity. The experimental results provide managerial implications. As buyers maximize the degree to which they diversify their purchase quantities across multiple suppliers to reduce risks, differential costs of the entire supply chain increase by 19%, which are costs that cannot be reduced by suppliers' capabilities and inevitably arise due to differences between suppliers (*e.g.*, geography, politics, and government policies). However, in unfavorable market conditions, such as trade disputes and decreases in demand, less competitive suppliers can survive. This study shows that when market demand in the cationic reagent industry decreases, two suppliers may potentially experience operational outages. In reality, these two suppliers deteriorated under the challenging market conditions during the COVID-19 pandemic.

## 1. Introduction

The cationic reagent industry operates in the business-to-business sector, where suppliers manufacture cationic reagents for buyers. The industry is characterized as oligopolistic and mature. *Oligopolistic markets* are typically dominated by a small number of companies, often between two and ten. Several companies control a substantial market share, and thus have significant pricing power and influence [1]. The cationic reagent industry has an oligopolistic nature due to the limited number of suppliers and buyers. Additionally, the industry corresponds to the *maturity stage* of the product life cycle, which consists of introduction, growth, maturity, and decline stages [2]. The mature nature of the cationic reagent industry is evidenced by the long history of the industry. The cationic reagent industry traces its origins back to the early 20th century with the development of quaternary ammonium compounds [3]. In the 1970s, chemical companies such as Dow and Degussa developed the most common cationic reagent 3-chloro-2-hydroxypropyl trimethylammonium chloride. Most of the demand

for this cationic reagent is consumed for the production of cationic starch. Cationic starch enhances the bonding strength between micro-layers of paper by ionizing pulp fiber, which enhances the bonding strength between the micro-layers of paper by ionizing pulp fibers. Additionally, it improves overall strength and printability of papers by evenly distributing fillers. As an essential raw material in the production of printing papers, the market environment of the cationic reagent industry are closely tied to those of the printing paper industry.

The printing paper industry is currently experiencing an unprecedented crisis due to the COVID-19 pandemic. While the demand for printed materials such as office paper, magazines, and books had been declining even before the pandemic. The expansion of remote work and home education, driven by the pandemic, has further accelerated the contraction of the printing paper market. RISI, Inc., a consulting firm specializing in the paper industry, has focused the potential collapse of the printing paper market owing to the COVID-19 pandemic [4].

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Moody's, a global credit rating agency, has forecasted decreased operating profits for paper companies primarily selling printing papers [5]. In 2020, 16 printing paper factories in North America either permanently closed or switched their main product to other product focus due to the lack of demand. The situation in the European paper industry is similar to that of North America [6]. Oligopolistic markets can contribute to economic stability by maintaining price levels and reducing volatility. However, excessive market dominance or collusion may lead to market distortions and hinder overall economic efficiency [7,8]. According to Porter [9] companies in mature industries tend to lower their product prices to secure a larger market share, intensifying competition with other companies. In fact, market players (*i.e.*, suppliers and buyers) in the cationic reagent industry, an oligopolistic and mature industry, experience reduced profits due to excessive competition. Additionally, the COVID-19 pandemic has created an unfavorable market environment for the printing paper industry.

Oligopolistic companies wield significant market power, enabling them to influence prices and market outcomes to their advantage. However, this can lead to inefficiencies and inequality within the market, as smaller competitors struggle to compete [10]. This study aims to explore the strategic decisions that market players can make for the public good in an oligopolistic industry (*i.e.*, the cationic reagent industry), which is characterized by strategic interactions [11]. One potential strategy to establish a competitive and robust supply chain in the oligopolistic and mature industry is cooperation between suppliers and buyers. In this regard, there is the concept of competitive cooperation (*i.e.*, co-opetition). Co-opetition is a business strategy that uses insights gained from the game theory to understand when it is better for competitors to work together [12]. The value net model, which consists of customers, complementors, suppliers, and competitors, centered on the co-opetition, emphasized cooperation among competitors [13]. Inspired by this concept, cooperation among competitors (*i.e.*, between suppliers or between buyers) is also highlighted in this study.

In this study, we propose a supply chain optimization model that minimizes costs to improve the competitiveness of the entire industry; The term *entire industry* refers to all business and organizations engaged in a particular product or service. The buyers' risk hedge tendency is incorporated into the proposed model to examine market uncertainty. The model subsequently analyzes the effects on supply chains based on fluctuations in the buyers' risk hedge tendency. The proposed model is empirically tested using accessible and reliable data. Managerial implications are derived through numerical experiments under various market environments. The results align with practical events observed during the study. Moreover, based on the experimental results, we present the reasons why reaching an agreement among market players for an ideal equilibrium, where cooperation among market players is achieved, is difficult. Notably, the experimental results, which show that two suppliers are unable to continue their businesses, align with what actually occurred during this study.

The contributions of this study are structured into theoretical, managerial, and methodological aspects and presented as follows. (i) From the theoretical perspective, this study proposes a simple yet versatile supply chain optimization model for an oligopolistic and mature industry. This methodology is effective and solid because the model considers only differential costs that inevitably arise due to differences between suppliers. Given the minimal technological and quality differences between suppliers in a mature industry, the optimization model is designed to be effectively tractable by excluding non-differential costs (*i.e.*, convergent costs) affected by technological and quality differences. (ii) From the managerial perspective, by analyzing supply chains of the controlled environment of an oligopolistic and mature industry under various scenarios, the importance of cooperation strategy is highlighted. (iii) From the methodological perspective, the optimization model is designed as an MILP (mixed integer linear program). The proposed model is applicable as a practical methodology for making

decisions of market players in various industrial sectors (*e.g.*, raw materials, petrochemical, and rare earths industry) that operate in similar business environment (*e.g.*, an oligopolistic and mature industry). By manipulating parameters that reflect changes in market environment (*e.g.*, trade disputes, changes in demand, changes in supply), players' status can be analyzed by observing the changes in decision variables (*e.g.*, see Jeon et al. [14] and Cha et al. [15]). In this context, the business environment and market environment refer to the characteristics of an industry and the situations or conditions in which market players operate, respectively.

To obtain clear managerial insights from the experimental results, several research questions are raised here and answered in Section 4.7:

1. How does cooperation among market players affect the competitiveness of the entire industry?
2. How do costs of the entire supply chain increase or decrease in response to different levels of risk hedging?
3. How do trade disputes affect sales quantities of suppliers and costs of the entire supply chain?
4. How do decreases in demand cause changes in costs of the entire supply chain?
5. How does increase or decrease in production capacity of suppliers affects costs of the entire supply chain?

The remainder of this paper is organized as follows: Section 2 describes the related literature. Section 3 introduces a supply chain optimization model that reflects characteristics of an oligopolistic and mature industry. In Section 4, we empirically test the proposed model, analyzing the experiment results to derive managerial implications. Section 5 concludes this study.

## 2. Related literature

Companies maintain a competitive advantage by connecting or integrating components of their supply chains [16]. Selecting the most suitable suppliers is crucial because it significantly influences the supply chains components [17]. Accordingly, various industrial sectors, including manufacturing, processing, and logistics, have explored supply chain optimization based on mathematical programming. This section examines previous studies from two perspectives: first, whether the studies focused on maximizing individual companies' profits or the entire industry's profitability, as well as on the type of competitive strategy (*i.e.*, either competition or cooperation); second, whether market uncertainty is incorporated into a model. *Market uncertainty* refers to fluctuations in market environment, including freight costs, raw material prices, labor costs, electricity rates, and import tariffs, driven by sudden events such as the COVID-19 pandemic or trade disputes. Table 1 illustrates the characteristics of previous studies and the proposed model in this study.

### 2.1. Supply chain perspective and competitive strategy

Jayaraman et al. [17] proposed a supplier selection model that enables buyers to minimize fixed and variable costs when choosing suppliers. The model pursued the profit of a single buyer and assumed a competitive situation among multiple suppliers and buyers. Sakawa et al. [18] proposed a supply chain model that minimizes production and transportation costs, given suppliers' production capacities and market demand. They presented a scheme for profits and cost allocation among game participants from the perspective of cooperative game theory, employing fuzzy logic to ensure stable production and transportation in an uncertain environment. Papageorgiou et al. [19] suggested a model for the pharmaceutical industry, which is an oligopolistic and mature industry, incorporating the characteristics of an oligopolistic and mature industry and the global trade structure. The model allowed a company to decide business strategies in the market environment. Vidal and Goetschalckx [20] presented a model that maximizes the after-tax profit of a multinational company.

The model included transfer prices and the allocation of transportation costs as explicit decision variables. They developed an algorithm that employed successive linear programming based on relaxation, yielding acceptable-quality solutions. Thanh et al. [21] proposed an optimization model for a production-distribution system that supports decision-making processes such as supplier selection and flows along the supply chain, considering multi-echelon and multi-commodity factors. In other words, the model helps companies make strategic and tactical decisions. Companies pursue a cooperation strategy in that suppliers offer purchase cost discounts when buyers purchase multiple items in supplier selection. Chang et al. [22] proposed a model that considered multiple buyers and a single supplier while enhancing cooperative relationships across the industry. They found that a policy of shipping small volumes of various items rather than large volumes of a few items could reduce integrated costs, enhancing profits for both buyers and suppliers. Jakhar et al. [23] developed a partner selection and flow allocation model, proposing sustainable supply chain performance measures. They considered the profit of the entire industry and approached competitive strategy through cooperation. Alikhani et al. [24] proposed a model that considers factors such as sustainability and risk at the same time. The proposed model uses interval type-2 fuzzy sets to quantify the decision maker's input and combines with DEA to efficiently select a supplier. Guo et al. [25] presented a mixed integer linear program and a distributed approximation approach for a sustainable supply chain network design. This model structured the supply chain to consist of suppliers, transformers, distributors, and customers to target the entire industry. Their experimental results indicated the importance of connectivity and collaboration among market players. Gao and You [26] developed a two-stage game-theory-based stochastic mixed linear program. They examined how multiple stakeholders' independent profit-seeking behaviors affect supply chain performance in non-cooperative environments. Vafaeenezhad et al. [27] proposed a multi-objective linear program for a multi-echelon and multi-product supply chain management. The model was characterized by simultaneously considering environmental, economic, and social impacts. This research was applied to a wood and paper industry case. Experimental results demonstrated that decision-makers could plan a supply chain that best aligned with the characteristics they considered important (*i.e.*, economy, environment, and society). Gholizadeh et al. [28] developed an optimization model and heuristic algorithm to maximize the total profit and minimize environmental effects for a closed-loop supply chain. This study evaluated the model's performance using data from Saleh Industrial Dairy Group, a well-known dairy product producer in Iran. The optimality gaps obtained by the heuristic algorithm for all experiments demonstrated an acceptable range (less than 5%). Fathollahi-Fard et al. [29] proposed a fuzzy mixed integer linear program to handle uncertain parameters in supply chain networks. This model incorporates a dual-channel (online and offline) and multi-product approach to account for recent consumer purchasing behavior (*i.e.*, Online to Offline). Through experiments, they demonstrated that for the successful implementation of an O2O policy, appropriate pricing for both online and offline channels must be established. Otherwise, it could lead to negative effects on the entire supply chain. Chowdhury et al. [30] presented a mixed-integer program for a vaccine supply chain that ensures the entire network's economic performance. They applied the model to the COVID-19 vaccine distribution systems of a densely populated city in Bangladesh and verified that the supply chain network is efficient and well-designed. Mosallanezhad et al. [31] proposed an optimization model in the medical supply chain to ensure the reliable distribution of personal protective equipment for medical personnel in situations like a global epidemic. The objective function of the model is to simultaneously minimize the total costs and the amount of unsatisfied demand for participants such as manufacturers, distributors, and hospitals.

## 2.2. Market uncertainty

Sakawa et al. [18] addressed a real problem regarding the production and transportation of a housing material manufacturer. In the real world, market demand and production capacity were determined based on expert judgment, so they were not always precise values. To tackle this issue, this study incorporated fuzzy goals and fuzzy constraints into a mixed zero-one program. Liu and Nagurney [32] studied the impact of foreign exchange uncertainty and competition intensity on a supplier engaged in overseas outsourcing. They highlighted that companies' decisions regarding pricing, procurement, outsourcing, transportation, and production can be influenced by foreign exchange uncertainty and competition. Gao and You [26] incorporated various uncertainties into their two-stage game-theory-based stochastic mixed linear program for supply chain networks involving multiple stakeholders. In a case study on shale gas supply chain, they considered the productivity uncertainty of shale gas producers and the operational uncertainty of shale gas processors. Stakeholders showed a tendency to choose more conservative options when market uncertainty, including the uncertainties of other stakeholders, was present. Yılmaz et al. [33] proposed a scenarios-based two-stage stochastic optimization model for reverse supply chain design. They considered the ripple effect that results from sudden disruptions at one or more points in the supply chain and affects the entire network as a form of uncertainty. Experimental results showed that the ripple effect can increase the emission level and total cost by up to 40%. Focusing on uncertainties from the ripple effect, Yılmaz et al. [34] developed a two-stage stochastic optimization model for medical supply chain resilience by employing lean tools and considering the ripple effect, emphasizing preparedness strategies to mitigate pandemic-related risks. Similarly, Özçelik et al. [35] also considered the ripple effect. They developed a robust optimization model for reverse supply chain networks aligned with green principles. Gholizadeh et al. [28] proposed a mixed integer linear program for a sustainable closed-loop supply chain in the dairy industry. The demand, shipping and operating costs, facility capacity, and product return rates are considered as uncertain parameters. For the uncertain parameters, they generated pessimistic, optimistic, and worst-case scenarios and evaluated the model performance. Fathollahi-Fard et al. [29] tackled the uncertainty parameters using a fuzzy model. They considered all parameters related to prices and the rate of waste production as uncertain. Chowdhury et al. [30] considered inventory holding costs, unit assembly costs of packaged vaccines, unit prices of raw materials, supplier capacity, and transportation costs as uncertain parameters in the vaccine supply chain. These parameters were defined as probabilistic with a uniform probability distribution. Naturally, through experiments, it was confirmed that these uncertain parameters impact profitability.

## 3. Problem definition

This section describes a supply chain optimization model that incorporates the characteristics of the target industry (*i.e.*, oligopolistic and mature industry). The objective function of the proposed model is to minimize the total differential costs (TDCs) of the supply chains in the industry through cooperation among market players. Sections 3.1 and 3.2 define the terminologies and assumptions for the model, respectively. The proposed model is formulated as a mixed integer linear program (MILP) and presented in Section 3.3.

### 3.1. Terminologies

- *Differential costs* refer to the costs that inevitably arise due to differences between suppliers. These costs are influenced by factors such as geography, politics, and government policies, which cannot be reduced by suppliers' capabilities. In the proposed model, logistics, electricity, labor, raw material costs, and import tariffs are considered differential costs.



**Table 1**  
Related papers and their considerations †.

| Authors                     | Methodology ‡ | Perspective        |                 | Competitive strategy |             | Consideration of market uncertainty |
|-----------------------------|---------------|--------------------|-----------------|----------------------|-------------|-------------------------------------|
|                             |               | Individual company | Entire industry | Competition          | Cooperation |                                     |
| Jayaraman et al. [17]       | MILP          | ✓                  |                 | ✓                    |             |                                     |
| Sakawa et al. [18]          | MBIP          | ✓                  |                 |                      | ✓           | ✓                                   |
| Papageorgiou et al. [19]    | MILP          | ✓                  |                 | ✓                    |             |                                     |
| Vidal and Goetschalckx [20] | MILP          | ✓                  |                 |                      |             |                                     |
| Thanh et al. [21]           | MILP          | ✓                  |                 |                      | ✓           |                                     |
| Chang et al. [22]           | MILP          |                    | ✓               |                      | ✓           |                                     |
| Liu and Nagurney [32]       | LP            | ✓                  |                 | ✓                    |             | ✓                                   |
| Jakhar et al. [23]          | MILP          |                    | ✓               |                      | ✓           | ✓                                   |
| Guo et al. [25]             | MILP          |                    | ✓               |                      | ✓           |                                     |
| Alikhani et al. [24]        | LP            | ✓                  |                 |                      | ✓           | ✓                                   |
| Gao and You [26]            | SMIP          |                    | ✓               | ✓                    |             | ✓                                   |
| Vafaenezhad et al. [27]     | LP            |                    | ✓               |                      |             |                                     |
| Yilmaz et al. [33]          | SMIP          |                    | ✓               |                      |             | ✓                                   |
| Özcelik et al. [35]         | ROM           | ✓                  |                 |                      |             | ✓                                   |
| Gholizadeh et al. [28]      | MILP          | ✓                  |                 |                      |             | ✓                                   |
| Fathollahi-Fard et al. [29] | FMIP          | ✓                  |                 | ✓                    |             | ✓                                   |
| Mosallanezhad et al. [31]   | DOM           |                    | ✓               |                      | ✓           |                                     |
| Chowdhury et al. [30]       | MIP           |                    | ✓               |                      |             | ✓                                   |
| Sawik [36]                  | SMIP          |                    | ✓               |                      |             | ✓                                   |
| Yilmaz et al. [34]          | SOM           | ✓                  |                 |                      |             | ✓                                   |
| <b>This study</b>           | <b>MILP</b>   |                    | ✓               |                      | ✓           | ✓                                   |

† Note that any characteristics (i.e., perspective, competitive strategy, market uncertainty) that are not explicitly described or cannot be reasonably inferred in a paper have been left blank.

‡ LP: linear program, MIP: mixed integer program, MILP: mixed integer linear program, FMIP: fuzzy mixed integer linear program, SMIP: stochastic mixed integer program, MBIP: mixed binary integer program, ROM: robust optimization model, SOM: stochastic optimization model, DOM: deterministic optimization model.

- *Convergent costs* are the varied costs that can be reduced by suppliers' capabilities and efforts.
- *Direct material costs* are the costs of direct and raw materials identified in the production of products.
- *Direct labor costs* are those for explicitly identifiable labor used to produce products.
- *Manufacturing overhead costs* are the costs that are challenging to identify, encompassing all costs required to produce products except direct material costs and direct labor costs.
- *Cost and freight (CFR)* is a delivery condition that includes freight costs and import tariffs. Under this condition, a supplier covers all costs from their loading location to the buyers' designated port.
- *Free on board (FOB)* is a delivery condition that excludes freight costs and import tariffs. Under this condition, a supplier is responsible for covering the related costs and procedures until the products are loaded onto a ship at the port of export. However, once the ship departs, the buyer is responsible for the transportation costs and risks.
- *Buyers' risk hedge tendency* is the degree to which a buyer's purchase quantities are distributed across multiple suppliers. From a buyers' point of view, instability caused by monopolistic supply from a few suppliers, price fluctuations, unresponsiveness to a buyer's order, and uncertainty in lead times are risks associated with suppliers. Diversifying suppliers is a way to mitigate these risks. To quantitatively consider the risk in a supply chain [37], the proposed model suggests a parameter called buyers' risk hedge tendency, which controls the maximum amount of demand that is able to be assigned to a supplier.

### 3.2. Assumptions

- The target industry is oligopolistic and mature with multiple suppliers and buyers; The growth of supply and demand in a mature industry is slow, with few technological and quality differences among suppliers. Although technology continues to evolve, reducing costs in the industry is challenging. Due to the characteristics of the mature industry, all buyers have an equal level of buyer risk hedge tendency. Due to the high price elasticity

of demand and characteristics of oligopolistic industries (i.e., interdependence between companies, high similarity of products, buyer's budget constraint, supplier's price-driven strategy, buyer's expectation) [38,39], all buyers execute price-oriented purchasing decisions. Price-oriented competition is overheating, and the possibility of supply chain restructuring (e.g., withdrawal from the business due to low profitability) exists [2].

- Product costs are divided into differential and convergent costs; In manufacturing companies, three general types of product costs are direct material, direct labor, and manufacturing overhead costs [40]. In the proposed model, these product costs are redefined as uncontrollable differential and controllable convergent costs. Due to the minimal technological and quality differences between suppliers in a mature industry, convergent costs are ignored in the mathematical formulation of Section 3.3.
- CFR and FOB are adopted based on International Commercial Terms (INCOTERMS); INCOTERMS are standards for product delivery, cost allocation, risk transfer, transportation, and liability between parties in a trade transaction. If a supplier and a buyer agree to accept INCOTERMS, they are bound by the conditions of the trade contract.
- Freight costs are considered inter-country freight rates; In an oligopolistic market where buyers must follow price-oriented purchasing from a few suppliers, transportation is usually conducted by container ships at sea. Small-volume products can be transported by less-than-container load (LCL) shipments. The inter-country freight rate per unit weight for products transported by LCL is assumed to be the same as that charged for container ships. When a supplier within a country transports products to the same country, freight costs are not charged. In Europe, land transportation between countries is conducted by truck or railroad, incurring significantly low freight costs.
- The number of workers for each supplier is calculated using the full-time equivalent (FTE) concept; FTE is the total hours worked divided by the maximum number of compensable hours in a full-time schedule. Based on FTE [41], the number of workers required to complete a task within a given period is calculated as a real number, not an integer.

**Table 2**  
Notations used in the proposed model.

| Sets       |  |
|------------|--|
| $S$        | Set of suppliers   |
| $B$        | Set of buyers  |
| Parameters |  |
| $y_i$      | Capacity of supplier $i$ (MT)  |
| $d_j$      | Demand of buyer $j$ (MT)   |
| $f_{i,j}$  | Freight costs of route per unit of product from supplier $i$ to buyer $j$ (USD/MT) |
| $r_i$      | Raw material costs per unit of product for supplier $i$ (USD/MT)                   |
| $e_i$      | Electricity costs per unit of product for supplier $i$ (USD/MT)                    |
| $b_j$      | FOB price per unit of product for buyer $j$ (USD/MT)                               |
| $u_i$      | USD sales per employee of supplier $i$   |
| $w_i$      | Annual average wage for supplier $i$   |
| $x_{i,j}$  | Import tariff rate per unit of product from supplier $i$ to buyer $j$              |
| $m$        | Number of supplier   |
| $\gamma$   | Buyers' risk hedge tendency ( $0 \leq \gamma < 1 - \frac{1}{m}$ )                  |
| Variables  |  |
| $t_{i,j}$  | Quantity transported from supplier $i$ to buyer $j$ (MT)                           |

- Metric ton (MT) is used as the material unit. Moreover, 1 MT is equivalent to 1 ton (2204.6 lb).

### 3.3. Mathematical formulation

Table 2 illustrates a summary of parameters and variables.  $S$  and  $B$  are the sets of suppliers and buyers, respectively.  $y_i$  represents the manufacturing capacity of supplier  $i$ , and  $d_j$  denotes the demand of buyer  $j$ .  $f_{i,j}$  refers to freight costs per unit of product from supplier  $i$  to buyer  $j$ .  $r_i$  and  $e_i$  indicate raw material costs per unit of product and electricity costs per unit of product for supplier  $i$ , respectively.  $b_j$  indicates a product price (i.e., FOB price) per unit of product for buyer  $j$ .  $u_i$  is USD sales per employee of supplier  $i$  and  $w_i$  is annual average wage for supplier  $i$ .  $x_{i,j}$  refers to import tariff rate per unit of product from supplier  $i$  to buyer  $j$ .  $\gamma$  indicates buyers' risk hedge tendency and acts as a constraint on the quantity of product purchased from a supplier.

The proposed model aims to find the transported quantities that minimize the TDCs of the target industry to improve its overall competitiveness (i.e., the equilibrium). The objective function is formulated as follows:

$$\begin{aligned} \text{Minimize } & \sum_{i \in S} \left[ \sum_{j \in B} f_{i,j} t_{i,j} + r_i \sum_{j \in B} t_{i,j} + e_i \sum_{j \in B} t_{i,j} \right. \\ & \left. + \frac{\sum_{j \in B} (b_j + f_{i,j}) t_{i,j} w_i}{u_i} + \sum_{j \in B} (b_j + f_{i,j}) t_{i,j} x_{i,j} \right] \end{aligned} \quad (1)$$

TDCs are the summation of differential costs from all suppliers. The differential costs for supplier  $i$  are categorized into five components: total freight, total raw material, total electricity, total labor costs, and total import tariffs. Total freight costs of supplier  $i$  is expressed as  $\sum_{j \in B} f_{i,j} t_{i,j}$ , total raw material costs of supplier  $i$  as  $r_i \sum_{j \in B} t_{i,j}$ , total electricity costs of supplier  $i$  as  $e_i \sum_{j \in B} t_{i,j}$ , total labor costs of supplier  $i$  as  $\sum_{j \in B} \frac{(b_j + f_{i,j}) t_{i,j} w_i}{u_i}$ , and total import tariffs of supplier  $i$  as  $\sum_{j \in B} (b_j + f_{i,j}) t_{i,j} x_{i,j}$ , respectively.

$$\sum_{j \in B} t_{i,j} \leq y_i, \forall i \in S \quad (2)$$

$$\sum_{i \in S} t_{i,j} \geq d_j, \forall j \in B \quad (3)$$

$$t_{i,j} \leq (1 - \gamma) d_j, \forall i \in S, \forall j \in B \quad (4)$$

Eq. (2) ensures that the total sales quantity of a supplier cannot exceed the supplier's production capacity  $y_i$ . Eq. (3) guarantees that the total purchase quantity of a buyer satisfies the buyer's demand  $d_j$ .

Eq. (4) forces the quantity transported from supplier  $i$  to buyer  $j$  is less than or equal to the buyer's demand considering  $\gamma$ .

Fig. 1 illustrates how the supply chain works in the proposed model. In this example, we assume that there are only two suppliers and two buyers in the supply chain. The USD sales per employee of suppliers A and C are \$1,000,000 each. Products from suppliers A and C arrive at each export port via land routes, with delivery conditions specified as FOB. Large quantities of products are transported by container ships and small quantities are transported by LCLs from export ports to the buyers' designated ports. At this stage, the delivery conditions are specified as CFR. To explain the TDCs calculation in detail, using the freight volume in Fig. 1 and the data from Section 4.2, an example to calculate TDCs is presented as follows.

#### Differential costs of Supplier A

$$\begin{aligned} &= \frac{4146}{20} \times 20 + \frac{1166}{20} \times 8 + 456 \times 28 + 69 \times 28 \\ &+ \frac{\left( \left( 1140 + \frac{4146}{20} \right) \times 20 \times 63093 \right) + \left( \left( 1056 + \frac{1166}{20} \right) \times 8 \times 63093 \right)}{1000000} \\ &+ \left( \left( 1140 + \frac{4146}{20} \right) \times 20 \times 0 + \left( 1056 + \frac{1166}{20} \right) \times 8 \times 0.039 \right) \\ &= 21922.6 \end{aligned}$$

#### Differential costs of Supplier C

$$\begin{aligned} &= \frac{3053}{20} \times 2 + \frac{315}{20} \times 40 + 867 \times 42 + 98 \times 42 \\ &+ \frac{\left( \left( 1140 + \frac{3053}{20} \right) \times 2 \times 39472 \right) + \left( \left( 1056 + \frac{315}{20} \right) \times 40 \times 39472 \right)}{1000000} \\ &+ \left( \left( 1140 + \frac{3053}{20} \right) \times 2 \times 0 + \left( 1056 + \frac{315}{20} \right) \times 40 \times 0.039 \right) \\ &= 44931.44 \end{aligned}$$

$$\begin{aligned} TDCs &= \text{Differential costs of Supplier A} \\ &+ \text{Differential costs of Supplier C} \\ &= 66854.04 \text{ (USD)} \end{aligned}$$

## 4. Case study: Cationic reagent industry

### 4.1. Background

A cationic reagent is considered as a mature product. The cationic reagent industry is oligopolistic with only seven suppliers spread across

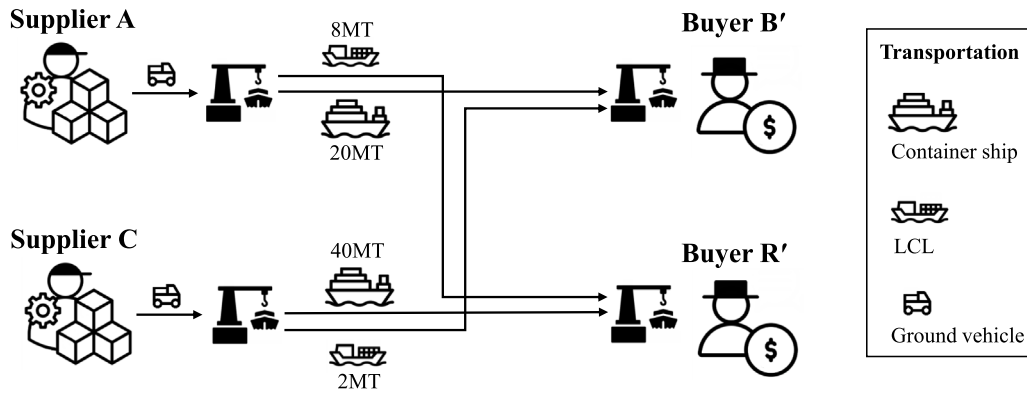


Fig. 1. A schematic example of the supply chain in this study.

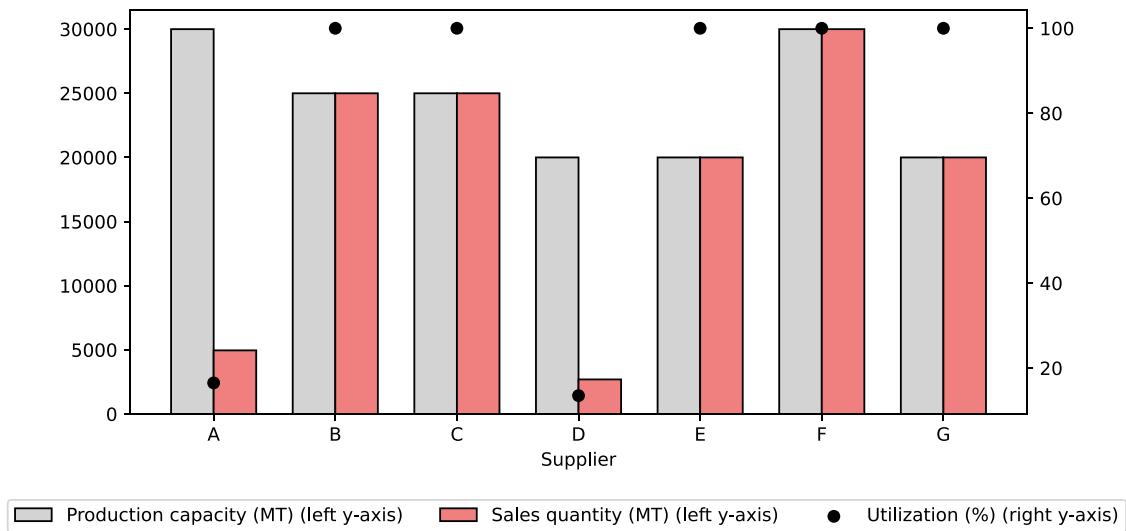


Fig. 2. Capacity utilization and sales quantity in the ideal equilibrium.

five countries. In 2019, the total production capacity of these suppliers was 170,000 tons, while the total demand from all buyers was 127,654 tons. In other words, the market is experiencing an oversupply of cationic reagents, leading to intense competition among suppliers. Cationic reagents are typically traded in 230-kg drums, 1,100-kg intermediate bulk containers, and 20,500-kg flex bags, and are usually transported in 20-foot dry containers with a capacity of 20 tons.

#### 4.2. Data

This case study uses publicly available and accessible data from the cationic reagent industry [42]. The global supply chain for cationic reagents includes seven suppliers and twenty-six buyers. Table 3 and Table 4 illustrate the data for the suppliers and buyers, respectively.

The primary raw material for cationic reagents is propylene [43]. The raw material price (*i.e.*, the price of propylene) illustrated in Table 3 is based on the second week of October 2020 [44]. It requires 0.2 MT of propylene to synthesize 1 MT of cationic reagents. The annual labor costs for each supplier are referenced from the data of their respective countries, published by the OECD in 2020 [45]. To standardize the unit of annual labor costs into U.S. dollars (USD), we use the exchange rate from 2019. While reliable data on the labor productivity of suppliers A, B, D, E, F, and G are lacking, we do have reliable data for supplier C. Given the mature nature of the industry, with minimal technological and quality differences among suppliers, supplier C's labor productivity is assumed to be representative of the other suppliers ( $u_C = u_i$ , where  $i \in S$ ). Industrial electricity prices are

obtained from the data of each supplier's country [46]. For reference, this case study sets the electricity requirement for producing one unit of cationic reagents at 250 kWh. Freight costs from suppliers to buyers are collected from relevant online sources [47,48]. The import tariff rate for each country is based on the HS-CODE 2923.90 for cationic reagents. The HS-CODE is an internationally standardized system for classifying traded products and facilitating global customs processes and trade regulations [49].

#### 4.3. Ideal equilibrium and purpose of market players

The ideal equilibrium, achieved through cooperation among market players, is obtained by solving the MILP described in Section 3.3 with  $\gamma$  set to zero. The results, which minimize TDCs in the cationic reagent industry, are presented in Table 5 and Fig. 2. Suppliers B, C, E, F, and G achieve full utilization, while suppliers A and D show low utilization. If market players make multilateral concessions and cooperate, TDCs in the cationic reagent industry can be reduced, thereby increasing the competitiveness of the entire industry.

However, achieving the ideal equilibrium is challenging due to market players pursuing their individual interests. To test this hypothesis, experiments are conducted to maximize the profits of market players. Given that the target industry is oligopolistic and competitors are well-informed about each other, the objective functions are set to maximize the overall sales of suppliers and minimize the overall costs of buyers.

First, an experiment is conducted to maximize suppliers' sales (*i.e.*, FOB sales) reflecting suppliers' interests. In this experiment, Eq. (5)

**Table 3**  
Data on suppliers.

| Supplier <i>i</i> | Location        | Capacity<br>(MT/Year) | Raw material price<br>(USD/MT) | Labor costs<br>(USD/Year) | Industrial electricity price<br>(USD/MWH) |
|-------------------|-----------------|-----------------------|--------------------------------|---------------------------|---|
| A                 | North America   | 30,000                | 456                            | 63,093                    | 69  |
| B                 | North America   | 25,000                | 456                            | 63,093                    | 96  |
| C                 | North East Asia | 25,000                | 867                            | 39,472                    | 98  |
| D                 | Western Europe  | 20,000                | 920                            | 54,262                    | 86  |
| E                 | Western Europe  | 20,000                | 920                            | 44,111                    | 74  |
| F                 | North east Asia | 30,000                | 899                            | 10,941                    | 40  |
| G                 | North East Asia | 20,000                | 899                            | 10,941                    | 40  |

**Table 4**  
Data on buyers.

| Buyer <i>j</i> | Location              | Demand<br>(MT/Year) | Sale price<br>(USD) | Freight costs (USD/20 ft container)<br>when purchasing from supplier <i>i</i> |       |       |       |       |       |       | Import tariffs (%)<br>when purchasing from supplier <i>i</i> |     |     |     |     |     |     |
|----------------|-----------------------|---------------------|---------------------|---|-------|-------|-------|-------|-------|-------|--|-----|-----|-----|-----|-----|-----|
|                |                       |                     |                     | A   | B     | C     | D     | E     | F     | G     | A  | B   | C   | D   | E   | F   | G   |
| A'             | USA                   | 29,960              | 1,140               | 0   | 0     | 3,539 | 2,058 | 2,503 | 3,406 | 3,406 | 0  | 0   | 0   | 6.2 | 6.2 | 6.2 | 6.2 |
| B'             | Canada                | 4,674               | 1,140               | 4,146   | 4,613 | 3,053 | 2,495 | 2,695 | 2,949 | 2,949 | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| C'             | Brazil                | 2,133               | 1,208               | 796   | 2,190 | 3,650 | 420   | 834   | 3,650 | 3,650 | 2  | 2   | 2   | 2   | 2   | 2   | 2   |
| D'             | Mexico                | 1,823               | 1,208               | 1,095   | 2,929 | 3,815 | 1,780 | 1,835 | 3,815 | 3,815 | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| E'             | Rest of Latin America | 3,182               | 1,208               | 685   | 1,882 | 3,650 | 420   | 834   | 3,650 | 3,650 | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| F'             | Germany               | 5,674               | 1,163               | 491   | 993   | 892   | 7     | 8     | 839   | 839   | 6.5  | 6.5 | 0   | 0   | 0   | 6.5 | 6.5 |
| G'             | Italy                 | 4,355               | 1,163               | 622   | 1,755 | 950   | 14    | 34    | 950   | 950   | 6.5  | 6.5 | 0   | 0   | 0   | 6.5 | 6.5 |
| H'             | France                | 2,879               | 1,163               | 472   | 811   | 867   | 4     | 12    | 839   | 839   | 6.5  | 6.5 | 0   | 0   | 0   | 6.5 | 6.5 |
| I'             | UK                    | 4,625               | 1,163               | 491   | 940   | 1,307 | 4     | 11    | 1,339 | 1,339 | 6.5  | 6.5 | 0   | 0   | 0   | 6.5 | 6.5 |
| J'             | Spain                 | 2,305               | 1,163               | 682   | 1,046 | 1,265 | 9     | 28    | 1,097 | 1,097 | 6.5  | 6.5 | 0   | 0   | 0   | 6.5 | 6.5 |
| K'             | Benelux               | 2,622               | 1,163               | 497   | 993   | 867   | 0     | 10    | 839   | 839   | 6.5  | 6.5 | 0   | 0   | 0   | 6.5 | 6.5 |
| L'             | Russia                | 5,136               | 1,163               | 1,319   | 1,852 | 1,485 | 516   | N/A   | 1,427 | 1,427 | 3  | 3   | 3   | 3   | 3   | 3   | 3   |
| M'             | Rest of Europe        | 3,225               | 1,163               | 472   | 993   | 867   | 3     | 17    | 839   | 839   | 6.5  | 6.5 | 0   | 0   | 0   | 6.5 | 6.5 |
| N'             | India                 | 7,452               | 1,091               | 1,309   | 1,652 | 1,075 | 923   | 1,939 | 1,075 | 1,075 | 10   | 10  | 0   | 10  | 10  | 10  | 10  |
| O'             | ASEAN                 | 9,655               | 1,091               | 1,077   | 1,177 | 65    | 950   | 1,123 | 125   | 125   | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| P'             | Rest of South Asia    | 5,272               | 1,091               | 1,010   | 1,170 | 410   | 1,027 | 1,198 | 260   | 260   | 5  | 5   | 0   | 5   | 5   | 0   | 0   |
| Q'             | China                 | 14,046              | 1,056               | 877   | 890   | 120   | 800   | 1,048 | 0     | 0     | 10   | 10  | 0   | 6.5 | 6.5 | 0   | 0   |
| R'             | Japan                 | 5,623               | 1,056               | 1,166   | 1,166 | 315   | 1,060 | 1,298 | 300   | 300   | 3.9  | 3.9 | 3.9 | 0   | 0   | 3.9 | 3.9 |
| S'             | South Korea           | 5,210               | 1,056               | 777   | 1,002 | 0     | 800   | 1,048 | 300   | 300   | 0  | 0   | 0   | 0   | 0   | 2.6 | 2.6 |
| T'             | Australia             | 2,065               | 1,116               | 1,661   | 1,661 | 1,145 | 958   | 958   | 1,345 | 1,345 | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| U'             | New Zealand           | 556                 | 1,116               | 1,661   | 1,661 | 1,145 | 958   | 958   | 1,345 | 1,345 | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| V'             | GCC                   | 2,340               | 1,228               | 1,048   | 1,336 | 586   | 689   | 1,089 | 855   | 855   | 5  | 5   | 5   | 5   | 5   | 5   | 5   |
| W'             | Turkey                | 396                 | 1,228               | 972   | 1,209 | 1,325 | 595   | 1,161 | 1,325 | 1,325 | 6.5  | 6.5 | 0   | 0   | 0   | 6.5 | 6.5 |
| X'             | North Africa          | 865                 | 1,228               | 1,272   | 1,256 | 1,682 | 686   | 1,320 | 1,714 | 1,714 | 2  | 2   | 2   | 0   | 0   | 2   | 2   |
| Y'             | South Africa          | 940                 | 1,228               | 1,880   | 2,363 | 1,069 | N/A   | N/A   | 1,620 | 1,620 | 0  | 0   | 0   | 0   | 0   | 0   | 0   |
| Z'             | Rest of Middle East   | 641                 | 1,228               | 1,201   | 1,299 | 882   | 739   | 1,064 | 1,024 | 1,024 | 5  | 5   | 5   | 5   | 5   | 5   | 5   |

**Table 5**  
Experimental results of the ideal equilibrium (units: million USD).

| Costs              | Supplier |       |       |      |       |       |      | Total  |
|--------------------|----------|-------|-------|------|-------|-------|------|--------|
|                    | A        | B     | C     | D    | E     | F     | G    |        |
| Differential costs | 7.13     | 35.94 | 26.35 | 3.98 | 23.04 | 14.58 | 9.66 | 120.69 |
| Freight costs      | 0        | 0     | 0.74  | 0.06 | 0.02  | 0.02  | 0.94 | 3.31   |
| Import tariff      | 0        | 0     | 0.24  | 0.05 | 0     | 0     | 0.19 | 0.72   |
| Raw material costs | 0.45     | 2.28  | 4.34  | 0.50 | 3.68  | 3.68  | 3.60 | 20.24  |
| Electricity costs  | 0.09     | 0.43  | 0.61  | 0.06 | 0.37  | 0.37  | 0.20 | 2.06   |
| Labor costs        | 6.59     | 33.22 | 20.43 | 3.32 | 18.97 | 18.97 | 4.74 | 94.36  |

replaces Eq. (1) as the objective function, as described in Section 3.3. 6 illustrates that maximizing supplier sales diminishes the competitiveness of the entire industry. Specifically, maximizing FOB sales increases TDCs by \$11.06 million compared to the ideal equilibrium. Additionally, Table 6 indicates a significant rise in import tariffs for suppliers B, E, F, and G, who have low levels of FTAs. Furthermore, supplier D's labor costs significantly increase, reducing its cost competitiveness.

$$\text{Minimize } \sum_{i \in S} \sum_{j \in B} b_{ij} t_{i,j} \tag{5}$$

Second, similar to previous studies [17,18,22], an experiment is conducted to minimize the costs for buyers (i.e., CFR sales) reflecting buyers' interests. In this experiment, Eq. (6) replaces Eq. (1) as the objective function, as described in Section 3.3. CFR sales encompass the sum of FOB sales, freight costs, and import tariffs paid by buyers representing the actual purchase costs. Table 7 illustrates that minimizing buyers' actual purchase costs results in a \$20.83 million increase

**Table 6**  
Experimental result of maximizing sales of suppliers (unit: million USD).

| Costs              | Supplier |       |       |       |       |       |       | Total  | Increase † |
|--------------------|----------|-------|-------|-------|-------|-------|-------|--------|------------|
|                    | A        | B     | C     | D     | E     | F     | G     |        |            |
| Differential costs | 0        | 21.72 | 25.00 | 27.83 | 28.28 | 17.33 | 11.58 | 131.75 | 11.06      |
| Freight costs      | 0        | 0.90  | 0.28  | 0.50  | 2.30  | 2.49  | 1.83  | 8.30   | 4.99       |
| Import tariff      | 0        | 0.59  | 0.24  | 0     | 1.44  | 1.90  | 0.88  | 5.05   | 4.33       |
| Raw material costs | 0        | 1.16  | 4.32  | 3.68  | 3.68  | 5.39  | 3.60  | 21.84  | 1.60       |
| Electricity costs  | 0        | 0.22  | 0.61  | 0.43  | 0.37  | 0.30  | 0.20  | 2.13   | 0.07       |
| Labor costs        | 6        | 18.85 | 19.55 | 23.22 | 20.49 | 7.25  | 5.07  | 94.43  | 0.07       |

† Increase refers to the rise in each type of costs compared to what is seen in the ideal equilibrium.

in TDCs compared to the ideal equilibrium. This increase is primarily due to a significant rise in labor costs for suppliers A and D, making them less cost-competitive. The competitiveness of the cationic reagent



**Table 7**  
Experimental result of minimizing buyers' actual purchase costs (units: million USD).

| Costs              | Supplier |      |       |       |       |       |   | Total  | Increase † |
|--------------------|----------|------|-------|-------|-------|-------|---|--------|------------|
|                    | A        | B    | C     | D     | E     | F     | G |        |            |
| Differential costs | 43.95    | 6.94 | 26.46 | 29.36 | 23.07 | 11.72 | 0 | 141.51 | 20.83      |
| Freight costs      | 0.20     | 0    | 0.66  | 0.81  | 0.006 | 0.17  | 0 | 1.90   | -1.41      |
| Import tariff      | 0        | 0    | 0.19  | 0.24  | 0     | 0.23  | 0 | 0.66   | -0.07      |
| Raw material costs | 2.74     | 0.44 | 4.34  | 3.68  | 3.68  | 5.00  | 0 | 19.88  | -0.36      |
| Electricity costs  | 0.52     | 0.08 | 0.61  | 0.43  | 0.37  | 0.28  | 0 | 2.29   | 0.23       |
| Labor costs        | 40.49    | 6.42 | 20.66 | 24.21 | 18.97 | 6.03  | 0 | 116.78 | 22.42      |

† Increase refers to the rise in each type of costs compared to what is seen in the ideal equilibrium.

industry is therefore adversely affected by market players' efforts to maximize their individual profits.

$$\text{Minimize } \sum_{i \in S} \sum_{j \in B} (b_j + f_{i,j})(1 + x_{i,j})t_{i,j} \quad (6)$$

#### 4.4. Risk management

This subsection investigates supply chain risk management through two experiments. The first examines how TDCs increase or decrease in response to different levels of risk hedging. The second assesses the impact of trade disputes on supply chains and TDCs. The equilibrium is obtained by solving the MILP described in Section 3.3 changing  $\gamma$ .

##### 4.4.1. Impact of risk hedging on TDCs

Buyers want to reduce the risk from suppliers failing to deliver products when designing their supply chains. Even if additional costs are needed, concessions and cooperation between market players can lower risks [50]. Apart from concession and market players cooperating, diversifying suppliers is an effective strategy for reducing the risk for buyers. In Section 3.2, it is assumed that buyers have an equivalent level of risk hedge tendency ( $\gamma$ ) in their purchasing strategies. In this experiment, adjusting  $\gamma$  in Constraint (4) yields changes in TDCs. As  $\gamma$  approaches zero, the quantity that a buyer receives becomes more concentrated on a single supplier. Conversely, as  $\gamma$  approaches  $1 - \frac{1}{m}$ , suppliers become more diversified. For example, if  $\gamma$  is 0.5, a buyer does not purchase more than 50% of the demanded quantity from any single supplier. With 7 suppliers, the minimum percentage required to satisfy more than 100% of the total demand is 15% when considering only integers. However, under this condition, a buyer has to purchase similar amounts close to 15% from each of the 7 suppliers, making it hard to observe changes in sales quantities depending on the market environment. Therefore, the maximum  $\gamma$  is limited to 0.84 in this study.

TDCs are lowest when a buyer can purchase the entire demanded quantity from a single supplier ( $\gamma = 0$ ), as shown in Fig. 3. TDCs and freight costs generally increase when suppliers are diversified. This is because when buyers diversify their suppliers, they eventually purchase the remaining quantities from suppliers located far away. However, despite the increases in TDCs and purchase costs, buyers can ensure supply chain stability by establishing business relationships with various suppliers, making it challenging for the cationic reagent industry to reach the ideal equilibrium. Note that freight costs slightly decrease when  $\gamma$  is 0.4 compared to 0.3. This is because, as the buyer's purchase limit from a supplier is reduced from 70% to 60%, supplier E, located in Western Europe, diversifies exports to buyers D' (Mexico), E' (the rest of Latin America), T' (Australia), and U' (New Zealand), where freight costs are higher. (see Fig. 4).

##### 4.4.2. Impact of trade dispute on supply chains

When trade disputes arise between countries, trade barriers such as tariffs are often imposed on products and services from the affected counterparts. For example, when a trade dispute between the United States and China erupted in October 2019, both countries imposed retaliatory tariffs on each other's products [51]. In this subsection, we examine the effects of increased retaliatory tariffs between the United States and China on supply chains. Prior to the dispute, a 10% import tariff was applied to products from US-based suppliers A and B when exported to China, while a 6.2% import tariff was applied to products from Chinese-based suppliers F and G when exported to the US. Following the trade dispute, both countries increased the retaliatory tariff to 30%. Fig. 5 illustrates that when  $\gamma$  is zero, the increase in TDCs is negligible because each country has its domestic suppliers, and no trade exists between the two countries. As  $\gamma$  increases, the impact of trade disputes on TDCs increases. This trend intensifies when a hypothetical 100% retaliatory tariff is imposed on both countries. With a 100% retaliatory tariff applied, when  $\gamma$  exceeds 0.6, changes in sales quantities of each supplier before and after the dispute start to occur, as shown in Fig. 6. This means that as  $\gamma$  increases, the trade network between buyers and suppliers becomes significantly complex, and retaliatory tariff rates between two countries owing to the trade dispute also affect other market players.

##### 4.5. Decrease in demand

The outbreak of COVID-19 has led a contraction in global economic activity and major downstream sectors of the cationic reagent industry, such as the printing paper industry, have significantly deteriorated. As non-face-to-face social activities were encouraged, remote work and home education spread, decreasing the production of printed promotional materials. Pandemics, such as COVID-19, accelerated the risk of disruptions in production lines, decreasing product demand for all market participants [50].

This subsection examines the effects of a decrease in demand in supply chains. The equilibrium is obtained by solving the MILP described in Section 3.3, changing  $\gamma$  in Eq. (4) and  $d_j$  in Eqs. (3) and (4). Sales quantities are observable when demand from all buyers decreases by 15% and 30%, respectively.

When  $\gamma$  is zero, a 15% decrease in demand results in sales quantities of suppliers A and D dropping to zero, leading to their operations being halted, as shown in Fig. 7. A 30% decrease in demand results in supplier's operation (i.e., supplier B) being halted in addition to suppliers A and D. When  $\gamma$  is 0.6, a 15% decrease in demand does not cause any supplier to cease operations. However, a 30% decrease in demand forces suppliers A, B, and D to cease their operations. When  $\gamma$  is 0.84, no supplier needs to halt operations even in the event of a 30% decrease in demand.

Since the total sales quantity decreases with a decrease in demand, the concept of TDCs per unit is used in this subsection to observe the effect of a decrease in demand on TDCs. TDCs per unit are obtained by dividing TDCs by the total sales quantity. As demand decreases, TDCs per unit also decrease, as shown in Fig. 8. This means that decreased demand increases the opportunity to reduce differential costs, including logistics costs, electricity costs, labor costs, raw material costs, and import tariffs. However, as  $\gamma$  increases, TDCs per unit decreases less significantly. This means that the opportunity to reduce differential costs diminishes because buyers are compelled to diversify suppliers.

Note that  $\gamma$  at which fluctuations in sales quantities occur increases as demand decreases by 15% or 30%. This is because buyers have to reduce their purchases as demand decreases, while suppliers' supply remains unchanged, allowing other buyers to purchase more products from cost-competitive suppliers. As shown in Table 8, the products of non-competitive suppliers A, B, and D are no longer purchased by buyers as demand decreases by 30%.

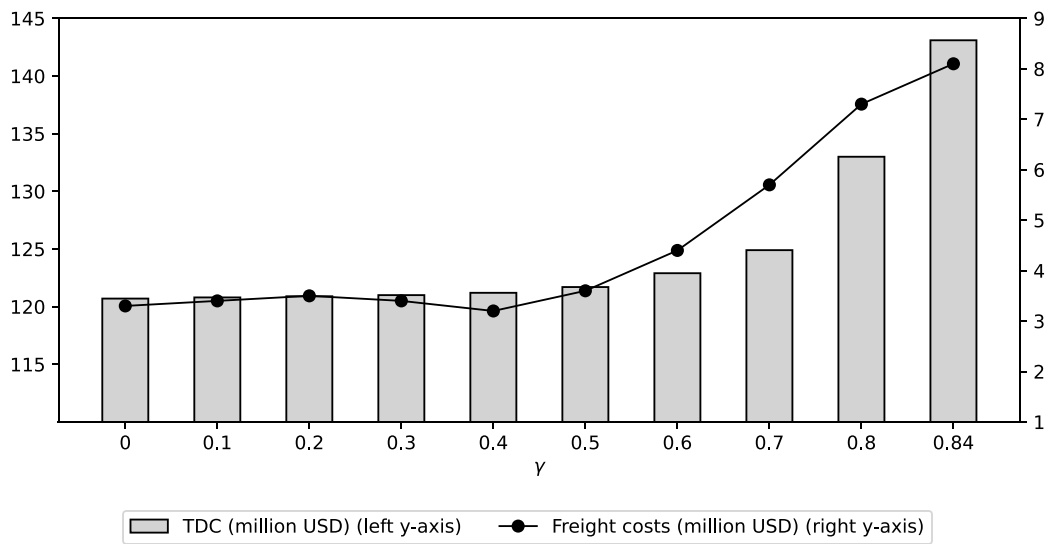


Fig. 3. Change of TDC and freight costs by  $\gamma$ .

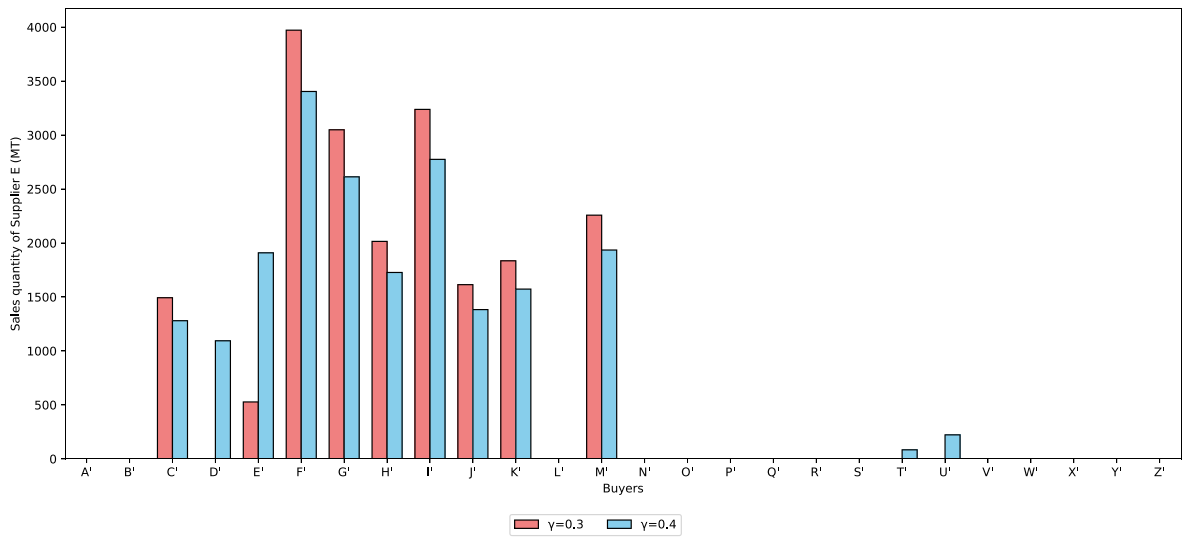


Fig. 4. Sales quantity of supplier E to all buyers.

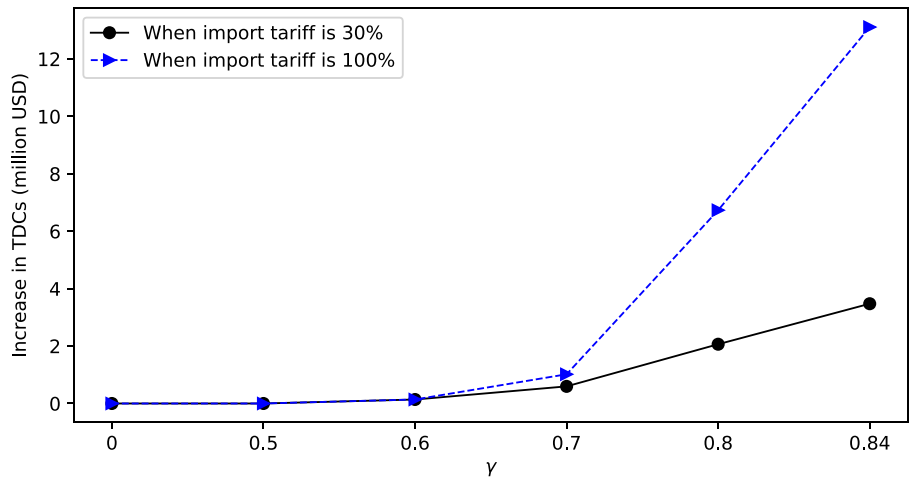


Fig. 5. Change of TDCs in trade dispute between the U.S. and China by  $\gamma$ .

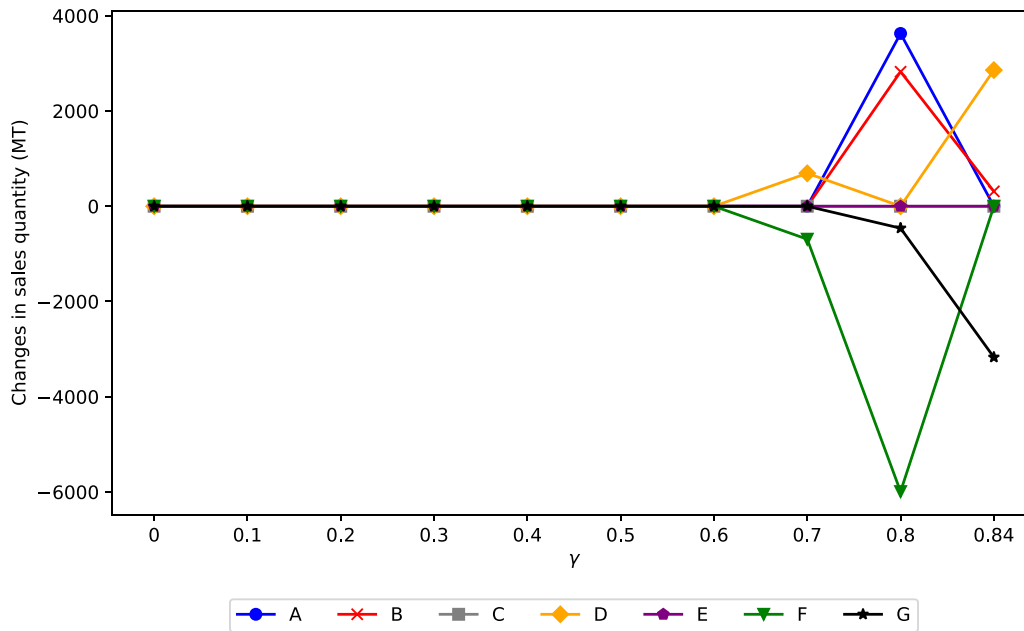


Fig. 6. Changes in sales quantity of each supplier by  $\gamma$  when import tariff is 100% (compared with  $\gamma = 0$  scenario).

Table 8

Sales quantities of suppliers for each buyer when  $\gamma = 0.5$  (units: MT).

| Decrease<br>in demand | Suppliers | Buyers |       |     |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|-----------------------|-----------|--------|-------|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                       |           | A'     | B'    | C'  | D'    | E'    | F'    | G'    | H'    | I'    | J'    | K'    | L'    | M'    | N'    | O'    | P'    | Q'    | R'    | S'    | T'    |
| 0%                    | A         | 14,980 |       |     |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|                       | B         | 14,980 |       |     |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|                       | C         |        |       |     |       |       | 2,837 | 2,178 | 1,440 |       |       | 1,311 |       | 1,613 | 3,726 |       |       | 6,480 | 2,812 | 2,605 |       |
|                       | D         |        |       |     |       |       | 382   |       |       | 2,313 |       |       |       |       |       |       |       |       |       |       |       |
|                       | E         |        |       |     | 1,067 | 912   | 1,591 | 2,837 | 2,178 | 1,440 | 2,313 | 1,153 | 1,311 |       | 1,613 |       |       |       | 2,080 | 1,033 | 278   |
|                       | F         | 2,337  |       |     | 912   |       |       |       |       |       |       |       | 2,568 |       | 2,935 | 4,828 | 2,636 | 7,023 | 2,812 | 525   | 1,033 |
|                       | G         | 2,337  | 685   |     |       |       |       |       |       |       | 1,153 |       | 2,568 |       | 791   | 4,828 | 2,636 | 543   |       |       |       |
| 15%                   | A         | 775    |       |     |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|                       | B         | 12,733 |       |     |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|                       | C         |        |       |     |       |       | 2,412 | 1,851 | 1,224 | 1,996 |       | 1,115 |       | 1,371 | 3,167 | 1,323 |       | 5,970 | 2,390 | 2,215 |       |
|                       | D         |        |       |     |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|                       | E         | 163    |       | 907 | 775   | 1,353 | 2,412 | 1,851 | 1,224 | 1,966 | 980   | 1,115 |       | 1,371 |       |       |       | 2,390 | 2,215 | 878   | 237   |
|                       | F         | 6,400  | 1,987 | 907 |       | 1,353 |       |       |       |       | 980   |       | 2,183 |       | 3,167 | 2,781 | 2,241 | 5,970 |       |       | 995   |
|                       | G         | 5,395  | 1,987 |     | 775   |       |       |       |       |       |       |       | 2,183 |       |       | 4,104 | 2,241 |       |       |       | 169   |
| 30%                   | A         |        |       |     |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|                       | B         |        |       |     |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|                       | C         |        |       |     |       |       | 1,986 | 1,525 | 1,008 | 1,619 | 807   | 918   |       | 1,129 | 2,608 | 3,380 | 1,315 | 4,916 | 1,968 | 1,824 |       |
|                       | D         |        |       |     |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|                       | E         |        |       | 747 | 638   | 1,114 | 1,986 | 1,525 | 1,008 | 1,619 | 807   | 918   |       | 1,129 |       |       |       |       | 1,815 | 723   | 195   |
|                       | F         | 10,486 | 1,636 | 747 |       | 638   | 180   |       |       |       |       |       | 1,798 |       |       | 3,380 | 1,845 | 4,916 | 1,968 | 9     | 723   |
|                       | G         | 10,486 | 1,636 |     |       | 934   |       |       |       |       |       |       | 1,798 |       | 2,608 |       | 531   |       |       |       | 195   |

Suppliers, A and D operate when demand remains consistent and  $\gamma$  is zero, as shown in Fig. 9. However, when demand decreases by 15% and 30%, the utilization rates drop to 0%, making it impossible to run their business operations. When  $\gamma$  is 0.84, both suppliers are able to maintain their business operations. This suggests that supplier A and D need to compete with other suppliers to get as many buyers as possible to survive. In other words, market players try to establish business relationships in advance to prepare for decreased demand, making the ideal equilibrium challenging to reach.

#### 4.6. Change in supply

Finally, we examine the effect of increase or decrease in production capacity of suppliers. The equilibrium is obtained by solving the MILP described in Section 3.3, changing  $y_i$  of Constraint (2) and  $\gamma$  of Constraint (4).

##### 4.6.1. Increase in production capacity

Suppliers may face challenges in expanding facilities for manufacturing mature products. However, investing in process improvements can increase production capacity, eliminating bottlenecks [52]. Significantly increasing production capacity can positively affect fixed costs within manufacturing overhead costs. From the buyer's perspective, increased cost competitiveness among suppliers can lead to lower purchase prices, thereby sharing economic benefits. Fig. 10 illustrates the results of the experiment where  $\gamma$  is set to 0, 0.5, and 0.8, showing the impact of a 30% increase in production capacity for each supplier.

In oversupply situations, increasing production capacity does not necessarily reduce TDCs. Specifically, TDCs do not decrease as production capacities of suppliers A, B, and D increase. Conversely, TDCs generally decrease as the production capacities of suppliers C, E, F, and G increase. However, when  $\gamma$  is 0.8, supplier F does not have to increase production capacity because TDCs do not decrease as their

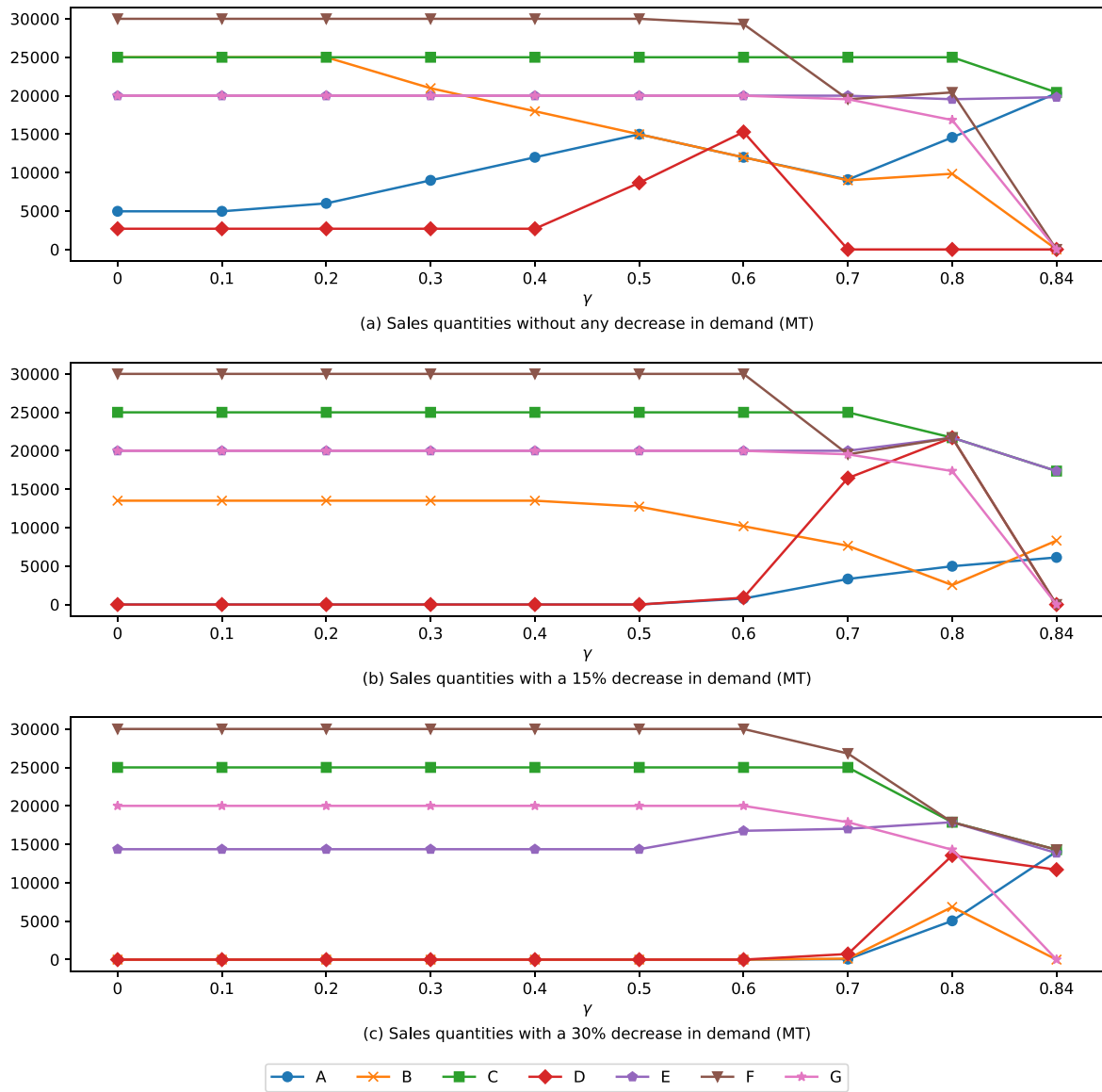


Fig. 7. Changes in sales quantities of each supplier by  $\gamma$  when decreases in demand occur.

production capacity increases. In conclusion, suppliers need to gather information and carefully assess market conditions, including the production capacity decisions of competitors. Otherwise, incorrect decisions may worsen industrial competitiveness, exacerbate oversupply, and intensify competition.

#### 4.6.2. Decrease in production capacity

If a supplier's profitability continues to deteriorate, the supplier may cease operations or go out of business. Figs. 11 and 12 show the experimental results for each case, where  $\gamma$  is 0, 0.5, and 0.8, respectively, when each supplier reduces production capacity by 30% or ceases operations. If there are no suppliers near a buyer, the buyer may have to purchase products from a distant location, increasing TDCs. Accordingly, buyers must cooperate with suppliers for their benefit, making it challenging to reach the ideal equilibrium. In addition, when production capacity decreases for the suppliers who decrease TDCs significantly in Section 4.6.1, TDCs also increase significantly. In other words, suppliers C, E, F, and G significantly influence the market owing to their close relationship with buyers.

#### 4.7. Discussion

To summarize the managerial insights obtained from the experimental results, the answers to the research questions raised in Section 1 are provided sequentially, in the order of the research questions:

1. If market players make multilateral concessions and cooperation, TDCs of the cationic reagent industry can be extremely reduced, and the competitiveness of the entire industry increases. However, market players pursue their own interests  $\dagger$ .
2. When buyers diversify their suppliers, they often end up purchasing the remaining quantities from suppliers located far away. In other words, high level of risk hedging behaviors makes TDCs increase. Despite the increases in TDCs and purchase costs, buyers ensure supply chain stability by establishing business relationships with a diverse range of suppliers  $\dagger$ .
3. As buyer's risk hedge tendency increases, the impact of trade dispute on TDCs becomes greater. Trade networks between buyers and suppliers become more complex and affect other market players.
4. If demand decreases and buyer's risk hedge tendency is small, interestingly, TDCs per unit decreases. This is because the opportunity to reduce costs increases. However, as buyer's risk hedge tendency

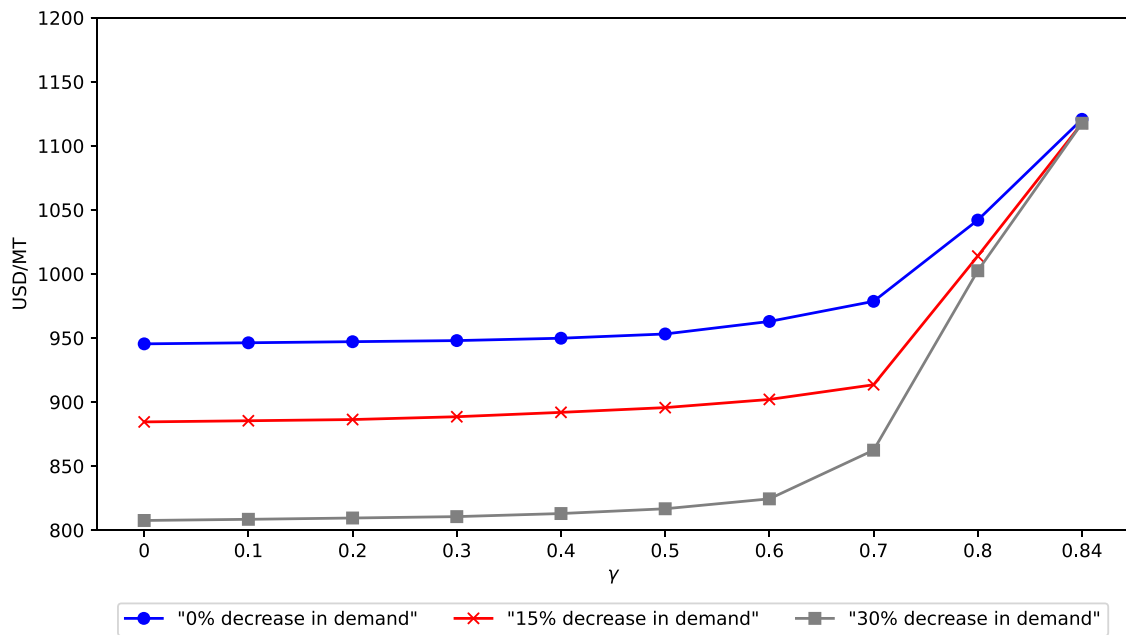


Fig. 8. Changes in unit TDCs by  $\gamma$  when decreases in demand occur.

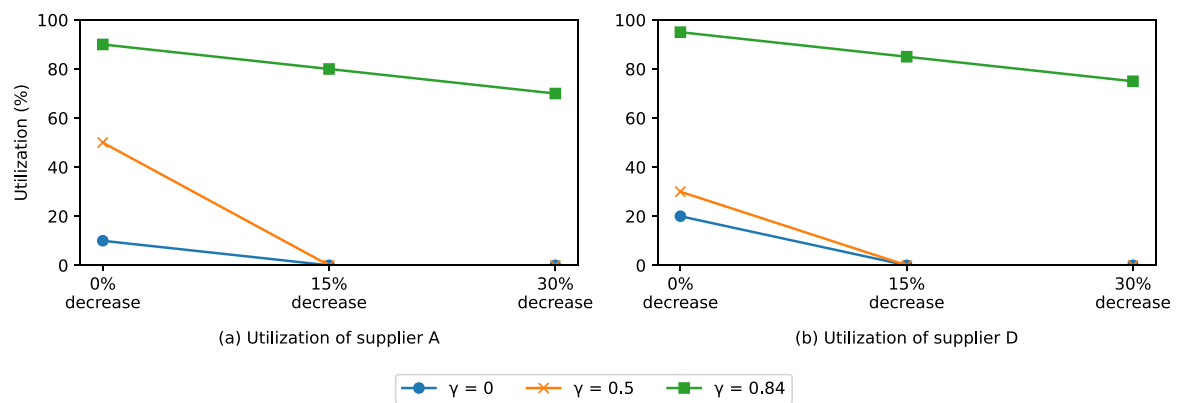


Fig. 9. Utilization of suppliers A and D by  $\gamma$  when demand decreases.

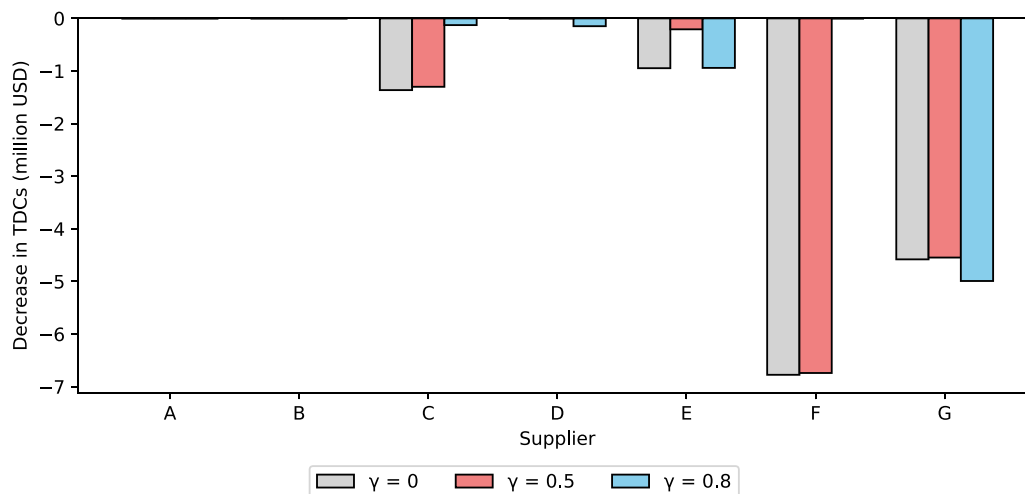


Fig. 10. Changes in TDCs as production capacity of each supplier increases by 30%.

increases, TDCs per unit decreases less significantly. The opportunity to reduce costs diminishes because buyers are compelled to diversify

suppliers. However, ironically, market players try to establish business relationships in advance to prepare for a decrease in demand  $\dagger$ .



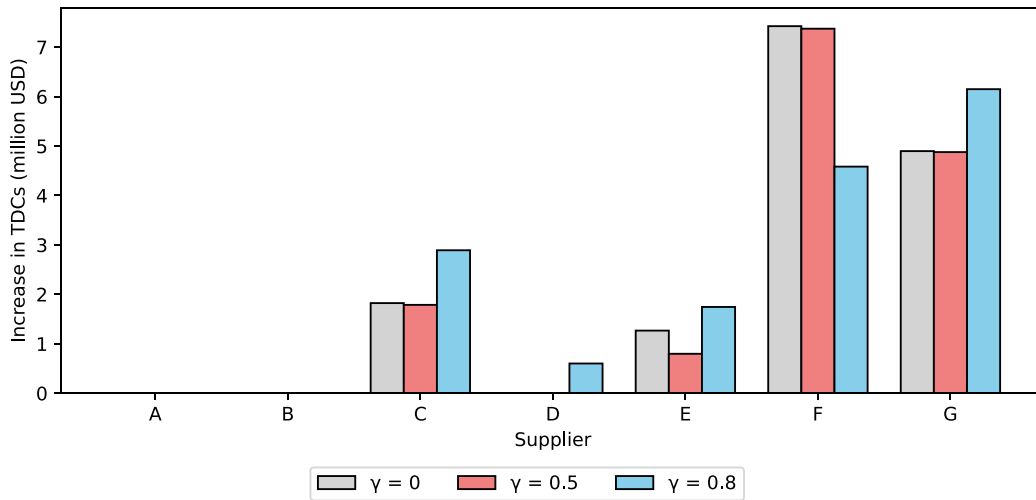


Fig. 11. Changes in TDCs as production capacity of each supplier decreases by 30%.

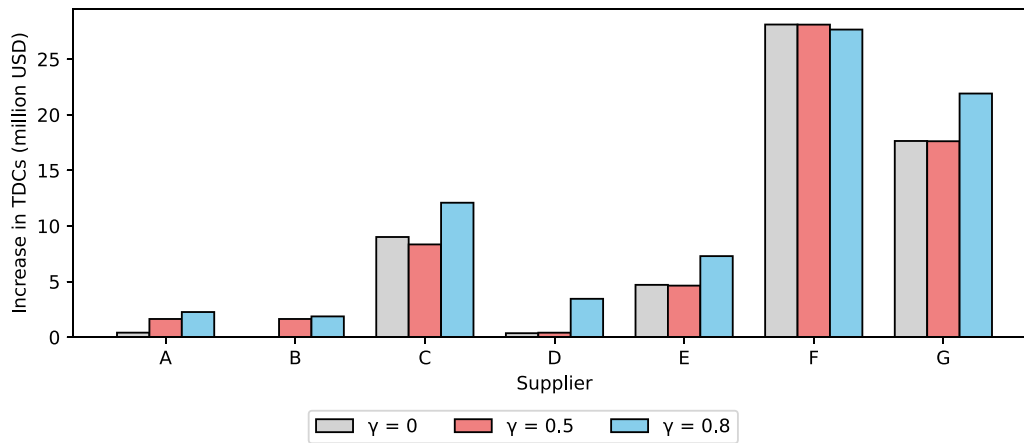


Fig. 12. Changes in TDCs when each supplier ceases operation.

5. TDCs hardly change when the production capacities of suppliers with less market influence change. On the other hand, TDCs significantly change when the production capacities of suppliers with greater market influence change. Note that the sentences marked with † explain why achieving the ideal equilibrium is not easy to reach in the cationic reagent industry.

Since a market tends to evolve toward achieving an ideal equilibrium [53,54], it is meaningful to obtain Table 5 and Fig. 2, as they represent the ideal equilibrium. At the ideal equilibrium, the total number of workers required by all suppliers is 105, averaging 15 employees per supplier. However, for suppliers A and D, the required number of employees based on sales quantity is 4 and 2.4, respectively. Given the need for employees in business planning, procurement, maintenance, production, quality control, and product delivery, suppliers A and D must consider restructuring to consolidate departmental functions. Historically, from 1972 to 2023, the average utilization rate in the United States exceeded 70% [55]. In contrast, supplier A has a utilization rate of 16.5%, and supplier D has 13.5%, as shown in Fig. 2. The experimental results indicate that if the two suppliers maintain their current levels of utilization rates, their business conditions could deteriorate, potentially leading to their exit from the market. In fact, according to recent market information, it is known that supplier A has exited the business, while supplier D is facing operational difficulties.

Achieving multilateral concessions and cooperation in oligopolistic competition is challenging due to several factors: First, cooperation among competitors can be viewed as unfair and is subject to legal scrutiny. In economic game theory, such interactions are typically managed through cartel regulations, requiring active control to prevent collusion [56]. Second, even if implicit agreements are reached to bypass regulations, sustaining non-binding cooperation is difficult. This is a dilemma that involves prioritizing the overall benefits of an industry versus the private profits of individual economic entities.

The classification of efforts to obtain sensitive information from competitors as collusion remains controversial. Thus, the question of whether information sharing, cooperation, and joint decision-making should be restricted in mature or declining industries must be considered. If the negative effects of monopoly are minimal, it might be advantageous to permit a leading market player to guide supply and purchase strategies for the mutual benefit of all players. In fact, empirical studies in economics have examined the positive effects of monopolies [56].

## 5. Concluding remarks

This study derives the ideal equilibrium that minimizes total differential costs to enhance the competitiveness of an oligopolistic and

mature industry using a mixed integer linear program. Market players' efforts to maximize profits, such as minimizing costs for buyers or maximizing sales for suppliers, along with their focus on risk management, and fluctuations in demand and supply are presented as reasons why achieving the ideal equilibrium is challenging. The study introduces the concept of differential costs into the supply chain optimization model, as opposed to the traditional focus on financial costs. This model, based on accessible data from the cation reagent industry, is also applicable to other oligopolistic and mature industries. In addition, the model incorporates a technique to reflect buyers' risk-hedging tendencies. The experimental results highlight the importance of cooperation among market players to enhance the overall competitiveness of the industry. Buyers increase their risk hedge tendency to ensure supply chain stability by establishing business relationships with various suppliers, which makes trade networks among market players more complex and significantly influences each other. In this situation, multilateral concessions and collaborations between market players results in a significant reduction in TDCs of the cation reagent industry and an increase in the competitiveness of the entire industry. Managers in relevant industries can leverage the proposed model to minimize costs, diversify procurement, and ensure the sustainability of their business during market downturns. Policymakers can develop effective policies that encourage cooperation among market players while protecting fair competition based on insights of this study. Supply chain players are encouraged to adopt cooperative strategies to enhance the overall benefits of an industry and prepare for changes in market demand. Researchers can extend the proposed model in both academic and industrial contexts, as illustrated in the following paragraph.

Further studies investigating how the level of acquired information (specifically, the quantity and accuracy of information [57]) affects TDCs could be valuable. The effect of the extent of supply chain integration has been actively studied from various perspectives [58] and their application to the proposed model could also be considered. Furthermore, the proposed model can be enhanced by individualizing buyers' risk hedge tendencies, segmenting the market, considering logistics environments, and accounting for additional costs. While this paper considers costs of the entire industry in the objective function to emphasize cooperation among market players, scenarios and strategies can be further extended by developing a multi-objective model that also includes profit maximization of each player in the objective function.

#### CRediT authorship contribution statement

**Joohang Kang:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Byoungil Choi:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chae Hong Lim:** Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Joonyup Eun:** Writing – review & editing, Validation, Supervision, Software, Project administration, Investigation, Conceptualization.

#### Declaration of competing interest

The authors have no conflicts of interest to disclose.

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#### Data availability

Data will be made available on request.

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