Chapter 8
Modeling Supply Risk in the New Business Era: Supply Chain Competition and Cooperation

Xiang Li, Yongjian Li, and Linghua Zhao

Abstract In the current globalized supply chains, firms are more likely to suffer from supply risks caused by various sources, including internal production default and external disasters. This chapter focuses on the operational management problem related to the supply risk within the supply chain scope. We introduce a number of recent and important research developments, including problems in vertical supply chain interaction, horizontal supply chain competition, and supply chain network with both horizontal and vertical competitions. Analytical models are presented for each problem, and the main results are elucidated. Moreover, further research directions along with big data trends are emphasized as well.

Keywords Supply risk • Supply chain model • Competition and cooperation • Reliability improvement

8.1 Introduction

Owing to the rapid information technology development and increasingly intense global competition, the traditional perspective on firm operation management has given way to a new paradigm of supply chain management in consideration of the close multi-firm relations and interactions in the modern market place. Along with this trend, the world has become increasingly variant with inherent and exogenous uncertainties. Among them, supply uncertainty has become a major concern in global supply chain management. In traditional manufacturing processes, stochastic capacity, random yield, and uncertain transportation delay are the main causes of supply uncertainty. Unexpected disruption is another type of uncertainty that

---

X. Li • L. Zhao
College of Economic and Social Development, Nankai University, Tianjin 300071,
People's Republic of China
e-mail: xiangli@nankai.edu.cn; sadallday@sina.com

Y. Li (✉)
Business School, Nankai University, Tianjin 300071, People's Republic of China
e-mail: liyongjian@nankai.edu.cn

T.-M. Choi et al. (eds.), *Optimization and Control for Systems in the Big-Data Era*,
International Series in Operations Research & Management Science 252,
DOI 10.1007/978-3-319-53518-0_8

commonly leads to a total supply default, which severely damages several supply chain operations. A well-known industrial example is Ericsson losing 400 million Euros after a fire on the semiconductor plant of their supplier in 2000, as well as Apple losing numerous customer orders during a supply shortage of DRAM chips after an earthquake hit Taiwan in 1999. A more recent incident occurred during the March 2011 earthquake in Japan triggering a massive 23-foot tsunami and a nuclear crisis, further leading to a global supply disruption. An industrial survey conducted by Protiviti and the American Production and Inventory Control Society (APICS) showed that 66% of the respondents considered supply uncertainty as one of their most significant concern among all supply chain-related risks (O'Keeffe 2006).

Conversely, the generated supply chain field data contains highly rich information caused by technological changes. Statistics and forecasts have long been recognized as useful tools in supply chain risk analysis, as well as in the corresponding decision making (Choi et al. 2003, 2006, 2008a); whereas other powerful methodologies are being developed in this area as technologies, such as data mining, machine learning, and cloud computing, are updated (Lee et al. 2014; Fan et al. 2015). Supply chain risk management can particularly, largely benefit from new data technologies and analytic methods for collecting, analyzing, and monitoring both supply chain internal and environmental data. The increasing complexity calls for increasing the attention paid to data processing and analysis, as well as in the development of new optimization models to analyze supply chain competition and cooperation and to especially enhance the robustness of the supply chain in the presence of supply risk. Such task can be realized by sufficiently using the data derived from these advanced information programs and systems.

To achieve this goal, many researchers have developed optimization models that aim at mitigating the respective supply uncertainty and the associated risk. This chapter focuses on the related supply chain problems in the complex business environment of firm competition and cooperation to provide recent research models and results. The selected papers are not comprehensive; however, they are typical and representative to instigate contemplation and illuminate future study directions. The following studies are incorporated:

- We consider three streams of research from the supply chain structure perspective.
  - The first stream is on the vertical supply chain interaction modeled by a Stackelberg leader–follower game. Different from the traditional supply chain channel game in which the upstream supplier is the Stackelberg leader, the buyer is commonly the leader under an unreliable supply, and the supplier is the follower, as shown in Keren (2009), Li et al. (2012, 2013), and Tang et al. (2014), which will be discussed in our chapter.
  - The second stream is on the horizontal supply chain competition modeled from a Nash game in which multiple firms simultaneously act under supply uncertainty. The Nash equilibrium solution derivation and analysis is the main point of this type of problems, as shown in Qin et al. (2014), Tang and Kouvelis (2011), Chen and Guo (2013), Huang and Xie (2015), and Lee and Lu (2015).

  - The third stream is of a more complex structure, with a semblance to supply chain networks. Babich et al. (2007) and Qi et al. (2015) investigated multiple suppliers competing with one another while simultaneously interacting with a downstream buyer, whereas Fang and Shou (2015) explored a chain-to-chain competition with two suppliers and two buyers. In these models, vertical channel game is explored combined with horizontal competition game, thereby creating a generally and relatively tedious solving procedure.

- We consider three major types of supply risks widely adopted in literature from the supply risk model perspective.

  - The first type, random yield, refers to an uncertain production loss that actually delivers only part of the planned production size. Hence, for input quantity q, the output quantity $S(q)$ conforms to one of the two following forms: $S(e) = e \cdot \xi$ or $S(e) = e + \xi$, where ξ is a random variable with a known distribution. The former form is called proportional random yield, which depicts the situation of finally delivering a random fraction of input; the latter is called additive random yield, which demonstrates the situation of a random disturbance fluctuating around the input quantity. This random yield model is adopted in Keren (2009), Li et al. (2012, 2013), Tang and Kouvelis (2011), and Fang and Shou (2015).
  - The second type, random capacity, implies that an uncertain upper bound on actual delivery is independent of the planned production size. Hence, for input quantity q, the output quantity becomes $S(q) = \min[q, K]$, in which K is the random capacity. This random capacity model is adopted by Qin et al. (2014) and Chen and Guo (2013). Furthermore, Wang et al. (2010) considered both random yield and random capacity risks.
  - The third type is the "all-or-nothing" random disruption, wherein the supply process is of an "on" or "off" state that includes some probabilities, with a 100% output of a planned production under the "on" state but with nothing delivered under the "off" state. Specifically, for input quantity q, the output quantity becomes $S(q) = \begin{cases} q & \textit{probability}\, a \\ 0 & \textit{probability}\, 1-a. \end{cases}$

    Mathematically, this is a special case of random yield or capacity, with the actual delivery limited by an all-or-nothing Bernoulli trial. This supply disruption model is adopted by Tang et al. (2014), Babich et al. (2007), and Qi et al. (2015). Furthermore, Lee and Lu (2015) considered a generalized random yield model while also making the all-or-nothing random disruption a special and important case.

- We should also note that the supply risk can be divided into two categories from the maneuverability perspective.

  - The supply risk is traditionally regarded as an exogenous factor that can only be statistically counted but not controlled. For example, the supply process

  is interrupted by irresistible forces, such as natural disasters, labor strikes, terrorist attacks, and government regulation changes. Thus, the random factor assumes a given probability distribution.
- Both industrial and academic fields recently regard the internal supply process to be possibly enhanced, such that, by exerting production/technology/labor efforts, the supply reliability can be improved (of course at a certain expense). Correspondingly, the probability distribution of random supply disturbance is then affected by the reliability effort, which poses new research questions. The endogenous supply effort model first used by Wang et al. (2010) is then employed by a number of recent studies, such as those of Tang et al. (2014), Huang and Xie (2015), Lee and Lu (2015), and Qi et al. (2015).

Table 8.1 presents the model features of the main papers discussed in our chapter.

The vast literature on the optimization models and techniques for the centralized production system with random supply is notable. However, few research has considered supply chain models, and much of this has been recently conducted. This chapter aims to classify and to describe the research to date regarding supply chain models under supply risk. Hence, we exclude the stream of research focusing on the centralized operations management model for facility location design, production planning, and inventory optimization. Most studies included in this paper incorporate the multi-firm interactions, with the exception of Wang et al. (2010). Nevertheless, Wang et al. (2010) considered a problem under the supply chain environment; furthermore, they are the first to explore the endogenous supply reliability improvement effort, hence, their study is incorporated into our chapter. In addition, apart from the uncertainty in supply quantity, other uncertain factors are notably observed within the area of supply risk. These factors include procurement cost (Babich 2006; Alexandrov 2015) and lead time risks (Lin 2016), as well as procurement product quality uncertainty (Cai et al. 2010). However, these studies are excluded given the required limit in scope on the quantity risk of the supply side in this chapter.

8.2 Vertical Supply Chain Interaction

8.2.1 Exogenous Supply Risk

This section investigates how the supply risk affects the downside order and the profits of firms within a vertical supply chain channel. We first consider the scenario in which the supply risk is of a random yield type and the market side is of a deterministic demand. The supply chain specifically consists of a buyer facing the known demand d and a supplier with the random production yield model introduced in the previous section. The supplier's output quantity $S(e)$ particularly conforms to either $S(e) = e + \xi$ or $S(e) = e \cdot \xi$, for the planned production quantity e.

Table 8.1 Model features of the main papers discussed in this chapter

Paper	Supply chain structure	Supply model	Demand model	Main focus
Keren (2009), Li et al. (2012)	Supplier–buyer vertical channel	Random yield (exogenous)	Deterministic demand	Relation between order and production quantities
Li et al. (2013)	Supplier–buyer vertical channel	Random yield (exogenous)	Deterministic and random demand	Supply chain coordination contract design
Wang et al. (2010)	Supplier–buyer vertical channel	Proportional random yield, random capacity (endogenous)	Random demand	Strategic choice of dual sourcing or reliability improvement
Tang et al. (2014)	Supplier–buyer vertical channel	All-or-nothing disruption (endogenous)	Random demand	Strategic choice of dual sourcing or reliability improvement
Qin et al. (2014)	Competing suppliers	Random capacity: (exogenous)	Price-setting deterministic demand	Impact of random capacity on supply chain game with competing suppliers
Tang and Kouvelis (2011)	Competing buyers	Proportional random yield (exogenous)	Deterministic demand (Cournot game)	Supplier diversification strategy with buyer competition
Chen and Guo (2013)	Competing buyers	Random capacity (exogenous)	Deterministic demand (hotelling model)	Incentives of adopting dual sourcing with buyer competition
Huang and Xie (2015)	Horizontal competition	Proportional random yield (endogenous)	Deterministic demand (Cournot game)	Price and cost reduction effects due to competition
Lee and Lu (2015)	Horizontal competition	Proportional random yield, all-or-nothing disruption (endogenous)	Random demand (newsvendor game)	Game properties and effect of reliability on order decisions and profits
Babich et al. (2007)	N competing suppliers +1 buyer	All-or-nothing disruption: (exogenous)	Deterministic and random demand	Supplier competition effect and diversification effects
Qi et al. (2015)	2 competing suppliers +1 buyer	All-or-nothing disruption (endogenous)	Random demand	Combined competition strategy of both price and reliability
Fang and Shou (2015)	Chain-to-chain competition: 2 suppliers +2 buyers	Proportional random yield: (exogenous)	Deterministic demand; quantity competition	The strategic choice of centralization or decentralization

The sequence of events is described as follows: The buyer first submits an order quantity q to the supplier at an exogenous wholesale price w; afterwards, the producer responsively determines the planned production quantity e. After realizing the random yield, the producer delivers the minimum output production quantity and the order, with the wholesale price w paid for each delivery. Other parameters include selling price p for the distributor and production cost c for the producer (incurred by each planned unit even when not converted to the final yield), as well as leftover holding costs h_1 and h_2 for the distributor and the producer (these can be negative if the leftover earns a salvage value).

The problem can be handled in accordance with the classical procedure employed for the Stackelberg game, in which the supplier's maximizing problem is initially solved as follows:

$$\pi_p(e) = E\left\{w \min\left[q, S(e)\right] - h_2[S(e) - q]^+ - ce\right\},$$

and then optimizing the buyer's objective as

$$\begin{aligned}\pi_d(q) = E\,\{&p \min\left[d, q, S\left(e*(q)\right)\right] - w \min\left[q, S\left(e*(q)\right)\right]\\ &- h_1[\min\left[q, S\left(e*(q)\right)\right] - d]^+\right\},\end{aligned}$$

where $e_*(q)$ is the optimal response from the supplier for order quantity q.

Keren (2009) analyzed this problem and derived analytical solutions to the Buyer's ordering decision, assuming that the supply random yield follows the uniform distribution. The numerical examples provided showed that under the uniform distribution assumption, the optimal ordering quantity is shown as possibly beyond the known demand. However, Keren (2009) failed to address the questions whether ordering more is consistently optimal for the distributor or when to order more. Furthermore, the scenarios of other distributions for the random yield are neglected.

Li et al. (2012) revisited this problem and further examined supply chain decisions and profits under the generalized distribution of yield randomness. They derived analytical solutions to the optimal decisions for supply chain members and provided explicit conditions under which the buyer should order beyond the demand. These conditions are found relevant in different means to the yield distribution of additive and multiplicative risks, which indicate the importance of recognizing the production yield risk type. Furthermore, analytical solutions of the profit losses caused by the random production yield are derived for the supply chain members. The performances of the buyer and the entire supply chain are shown to be constantly worse off. However, the supplier can benefit from this random yield under certain conditions, which indicates the importance of deriving a more effective risk-sharing mechanism rather than a simple wholesale price scheme.

Hence, the next question is how to design such a coordination mechanism under the random yield of the supplier's side. Note that demand is deterministic in the above model. Under this situation, Li et al. (2013) showed that a shortage penalty contract enables the supply chain coordination and the arbitrary profit allocation between buyer and supplier. In this contract, the supplier is paid with the wholesale price for each delivered unit within the deterministic demand, as well as charged a penalty for each order shortage for the demand. However, under the random demand situation, Li et al. (2013) found that an "accept-all" type of contract is required to coordinate the supply chain, which is a much more complicated situation than that with the deterministic demand. The coordination contract specifically requires the buyer to accept all yielded units from the supplier in response to the random disturbance on the demand side. The derived coordination contracts are notably applicable to extremely generalized settings, such as the nonlinear production cost $C(e)$ rather than that in the above model, ce. Hence, they can be adopted in some other specific industrial cases, such as random yield, uncertain capacity, and stochastic used product collection. Moreover, they can easily be extended into a multiple-supplier scenario, such as decentralized assembly systems with suppliers subject to random component yields.

8.2.2 Endogenous Supply Effort

The previous subsection discusses the vertical supply chain with a primary focus on using coordination mechanism to cope with supply risk. The underlying assumption under this scenario is that the supply risk is exogenous and inherent within the production system. Conversely, the supply risk can be affected by endogenous effort in some real practical scenarios. Consequently, the buyer has an incentive to invest in improving the suppliers' processes to lessen costs, enhance quality, and improve reliability. For example, companies in the automotive industry, such as Honda, Toyota, BMW, and Hyundai commonly, work with their suppliers to improve performance (Handfield et al. 2000; Krause et al. 2007).

Wang et al. (2010) explored a model in which a buyer can source from two suppliers and/or exert effort to improve supplier reliability. For both random capacity and random yield types of supply uncertainty, a modeling framework of process improvement is established in which improvement efforts (if successful) increase supplier reliability by demonstrating that the delivered quantity (for any given order quantity) is stochastically large after the improvement. The specific model is presented as follows:

A buyer faces a newsvendor style random demand X for a product over a single selling season. Let r, v, and p denote the product's per unit revenue, salvage value, and penalty cost (for unfilled demand), respectively. The firm can source from two suppliers, $i = 1, 2$. Suppliers are unreliable in that the quantity y_i delivered by supplier i is less than or equal to the quantity q_i ordered by the buyer. The incurred procurement cost is $(\eta_i q_i + (1 - \eta_i) y_i) c_i$, where c_i is the supplier i's unit cost, and $0 \leq \eta_i \leq 1$ is the supplier i's committed cost. The supply risk is the random capacity model introduced in Sect. 8.1. Thus, for a given order quantity q_i, supplier i's delivery quantity is then given by $y_i = \min\{q_i, (K_i - \xi_i)^+\}$, where K_i is the supplier i's design capacity, and ξ_i is the supplier i's random capacity loss.

The model also incorporates a reliability index a_i with supplier i. A higher a_i implies a lower ξ_i, which increases reliability relative to the stochastic order. Let supplier i's initial reliability index be given by a_i^0. A feature of this problem lies in the buyer's capacity to exert effort to increase supplier i's reliability index. However, improvement efforts can and do fail. If the firm exerts an effort level $z_i \geq 0$, then supplier i's capability improves to $a_i(z_i) \geq a_i^0$ with probability θ_i and remains at a_i^0 with probability 1 - θ_i. The reliability improvement cost is linear in its effort and denoted as $m_i z_i$ for improving supplier i. The core problem for the buyer is deciding its improvement efforts $z = (z_1, z_2)$ first followed by determining the order quantities,$q = (q_1, q_2)$ after observing the success or failure of these efforts. Therefore, the process can be formulated as the following two-stage stochastic programming:

$$\begin{aligned}\prod\nolimits_1(a) = \sum\nolimits_{i=1}^{2} -m_i z_i(a_i) + \theta_1\theta_2\prod\nolimits_2^*(a_1, a_2) + \theta_1(1-\theta_2)\prod\nolimits_2^*\left(a_1, a_2^0\right) \\ + (1-\theta_1)\theta_2\prod\nolimits_2^*\left(a_1^0, a_2\right) + (1-\theta_1)(1-\theta_2)\prod\nolimits_2^*\left(a_1^0, a_2^0\right),\end{aligned}$$

where $\prod_2^*(a^r) = \max_{q\geq 0}\left\{\mathrm{E}_{\xi(a^r),X}[\pi(q)]\right\}$ and

$$\begin{aligned}\pi(q) = -\sum\nolimits_i(\eta_i q_i + (1-\eta_i)y_i)c_i + r\min\left\{x, \sum\nolimits_i y_i\right\} \\ + v\left(\sum\nolimits_i y_i - x\right)^+ - p\left(x - \sum\nolimits_i y_i\right)^+.\end{aligned}$$

The above modeling framework facilitates the examination of two typical supply risk mitigation strategies, namely single sourcing with process improvement or dual sourcing without improvement. A number of typical supplier attributes, such as cost and reliability, are considered as factors influencing the strategy preference of the buyer. The benefits of both strategies are more pronounced with the growth of the heterogeneity of the cost or of the reliability between the two suppliers. However, comparison results indicate that improvement is increasingly favored over dual sourcing as the supplier cost heterogeneity increases; however, dual sourcing is favored over improvement if the supplier reliability heterogeneity is high. Furthermore, if both improvement and dual-sourcing strategies can be jointly used, then its value is more significant if the suppliers are extremely unreliable or if they have low capacities relative to demand.

A similar model can also be proposed to analyze the random yield model situation, which is consistent with the modeling approach discussed in Sect. 8.1. The result is quite interesting. In the random yield model, increasing cost heterogeneity can reduce the attractiveness of improvement. Furthermore, improvement can be favored over dual sourcing if the reliability heterogeneity is high, which sharply contrasts with the situation of random capacity.

The above model guides when the dual-sourcing approach is favored relative to the process improvement approach. This comparison assumes that the buyer has developed a close relationship with the supplier, thereby enabling the adoption of a particular production process in the production facility of the supplier. In reality, such close partnership between supply chain members may not constantly be easily achieved. In some cases, each member has autonomy over its operational decisions, such as process and technology choices, as well as production and order quantities. Tang et al. (2014) investigated such a problem in which the buyer may provide incentives to influence supply reliability; however, the supplier firm makes process/technology choices and production decisions. The study by Tang et al. (2014) differed from that of Wang et al. (2010) in the adoption of the random disruption model instead of random capacity or random yield of the former along with the assumption of a deterministic demand in the base model. The sequence of event is as follows: the supplier first proposes an incentive contract consisting of the order quantity and the sharing fraction of reliability improvement cost incurred by the supplier; then, the supplier exerts the reliability improvement effort accordingly.

For the all-or-nothing disruption model, the buyer is shown to prefer using the subsidy option only, which removes the need to inflate order quantity. However, both incentives, namely subsidy and order inflations, may be simultaneously used in the partial disruption model. Another central issue is the comparison between the effectiveness of process improvement and dual-sourcing strategies, which is also the core research question in Wang et al. (2010). However, in this case, the improvement effort is undertaken by the supplier and can only be indirectly induced by the buyer, such that, it is exerted anyway even under the dual-sourcing strategy. Hence, the basic tradeoff for the buyer is different with that in Wang et al. (2010). If the buyer places the entire order in a single supplier and possibly offers subsidy to reduce supply risk, the buyer ensures great supplier effort, high reliability, and a good chance of meeting the demand. In contrast, if the buyer diversifies, it lowers supply risk because both suppliers have no tendency to experience disruption simultaneously. However, a potential downside of supply diversification exists in endogenous reliability choice; this implies that a lower order allocation to each supplier may reduce the incentive of the supplier to invest in the reliability-improving effort. The results indicate that despite the benefit of a large order in the single-sourcing mode, dual sourcing may lead to higher expected profit for the buyer under the same wholesale price. This phenomenon can be accounted to the benefit of risk diversification together with the savings from the lower overage cost that can outweigh the loss resulting from less supplier reliability in some cases. Conversely, cases in which dual sourcing is attractive only if wholesale price is low are observed when sourcing from two suppliers. The above insights are also verified to be valid in the newsvendor type random demand situation. In conclusion, although single sourcing provides great indirect incentive to the selected supplier because order splitting is avoided, the buyer may prefer the diversification strategy under certain circumstances.

8.3 Horizontal Supply Chain Competition

8.3.1 *Exogenous Supply Risk*

8.3.1.1 Supplier Competition

In this section, we turn our attention to the horizontal competition within the supply chains. A supplier competition issue is investigated by Qin et al. (2014) using a model with the following features: first, suppliers are competing on the wholesale price w in the supply chain, which sharply contrasts with the previous models in which the wholesale price(s) is assumed exogenous; second, the supply risk is a random capacity type, that is, supplier i has a stochastic delivery capacity K_i with a known distribution; third, the market price is endogenous and determined by the buyer, which influences market demand. Specifically, the price-dependent market demand is assumed as a linear function of price p, i.e., $D(p) = \alpha - \beta p$.

The sequence of events is as follows: first, supplier i sets the unit wholesale price w_i; second, the buyer sets the order quantity q_i; third, the supplier i plans to produce quantity q_i. Supply capacity k_i is realized at value k_i, and the supplier produces and ships $z_i = \min(q_i, k_i)$ to the buyer; finally, the buyer receives shipments and sets retail price p, with demand materialized and all revenues and costs incurred.

A basic model of single supplier and single buyer can be first analyzed as a benchmark for the supplier competition problem, which should be solved in a chronologically reverse order. Thus, the first optimization problem determines price p to maximize the expected revenue of the buyer as follows:

$$\underset{p}{Max}\mathrm{Re} = E(ps), \quad s.t. \;\; s = \min\left(D(p), z\right).$$

The second problem is deciding the order quantity q to maximize the expected profit of the buyer as follows:

$$\underset{q}{Max}\prod_{B} \equiv E\left(\mathrm{Re}^{*} - wz\right), \quad s.t. \;\; z = \min\left(k, q\right).$$

Finally, the (single) supplier's problem is determining an optimal wholesale price to maximize the profit as follows:

$$\underset{w}{Max}\prod_{s} \equiv E\left[(w - c)\, z\right], \quad s.t. \;\; z = \min\left(k, q^{*}\right), w > c.$$

Solving the above problems yields the result that the introduction of risk to a decentralized supply chain does not alter the relationship between the buyer's order size and wholesale price; instead, it leads to the supplier charging a high wholesale price, sequentially decreasing the order quantity of the buyer. Consequently, both the supplier and the buyer suffer from low profits under the supply capacity risk. Consumer surplus and welfare are also low because of the increased retail price.

Consistent with the above modeling framework, the dual-sourcing case can be analyzed under supplier competition. Two cases of dual sourcing can be considered. One case suggests that one supplier is perfectly reliable, whereas the other is unreliable. The other case indicates that both suppliers are subject to random capacities. In the dual-sourcing case, random capacity risk clearly affects wholesale pricing differently than in the single sourcing because of the suppliers' competition for the buyer's order. Reducing capacity uncertainty may not constantly benefit a supplier competing for a monopolistic buyer's orders; the benefit of the reduction fundamentally depends on the cost heterogeneity between the suppliers.

Moreover, a supplier-duopoly case, in which both suppliers directly sell to the market without the monopolistic buyer, is explored. In this case, the unreliable supplier is proven to constantly benefit from reduced capacity variability, which deviates from the result under the two suppliers selling through a buyer. These findings highlight the role of the buyer's diversification strategy in distorting a supplier's incentive for reducing capacity uncertainty under supplier price competition.

8.3.1.2 Buyer Competition

The above work investigates unreliable suppliers competing in wholesale prices. Another issue on horizontal competition is the competition between downstream buyers given an uncertain supply. The strategic sourcing decision of a firm can initiate the chain effect to the demand-side competitor under supply risk. Consequently, the effect of supply uncertainty on firm profitability should be evaluated in the context of the vertical buyer–supplier relationship and the horizontal buyer market competition.

Tang and Kouvelis (2011) investigated this issue by adopting the supply risk model as random yield type. Thus, for an order of size q received by supplier i, the actual quantity delivered is $Y_i * q$, where Y_i is a random variable with support on [0, 1]. The supply chain structure forms a two-echelon configuration, where competing buyers order a critical component from outside suppliers and use it to produce substitutable products for the end market. A buyer's procurement cost for an order of size q includes a fixed ordering cost f and a variable cost proportional to the quantity of the item being ordered at an agreed wholesale price w. The assumption that the buyer pays for the ordered item is slightly different from the previously introduced model; however, it is plausible and possibly observed in actual practices, such as agricultural industries. The buyer also incurs unit production cost c to produce one unit final product to satisfy demand.

The market demand is price sensitive. For a monopolist buyer, the inverse demand function is given by $P(Q) = a - bQ$, where P is the market price determined by the total available-to-sell quantity Q. In the duopoly model, the competition between buyers is modeled as the Cournot quantity competition. The inverse demand function faced by firm i is assumed to be $P_i(Q_i, Q_j) = a - b(Q_i + Q_j)$, where Q_i and Q_j are the available-to-sell quantities by buyers i and j, respectively. This downside demand competition model particularly fits a limited end-market situation, where the market prices for buyers are highly influenced by their output.

Industrial examples include the electronic chip manufacturers of Xilinx and Alter, who use different sourcing strategies and the personal computer firms HP and Dell, who utilize various sourcing channels.

A benchmark is the monopoly model, in which a single-sourcing buyer determines the order q to maximize the expected profit as follows:

$$\pi_{ms} = E_Y\left[(a - bq\gamma) - cq\gamma - wq\right] - f.$$

If the buyer adopts dual sourcing, the quantities q_1 and q_2 from Suppliers 1 and 2 should be determined, respectively, to maximize the expected profit as follows:

$$\begin{aligned}\pi_{md}(q_1, q_2) = E_{\gamma_1,\gamma_2}\big\{ &[a - b(q_1\gamma_1 + q_2\gamma_2)](q_1\gamma_1 + q_2\gamma_2) \\ &- c(q_1\gamma_1 + q_2\gamma_2) - w(q_1 + q_2)\big\} - 2f.\end{aligned}$$

Solving the above two problems and comparing their results indicate that dual sourcing can bring value to the monopolist buyer by reducing the variability in market output, thereby diminishing the market output inefficiency caused by the random yield. This benefit is defined as the diversification effect. Furthermore, a more diverse supply base leads to a larger diversification benefit.

Under the duopoly model of buyer competition, the buyers simultaneously choose the order quantity to be placed with their supplier(s). The end-market price is determined by the total quantity delivered by suppliers after yield realization. Three cases are under consideration, namely, *Case 1*: both buyers with a sole source; *Case 2*: both buyers with dual sources; *Case 3*: one buyer with a sole source and the other with dual sources. The Nash equilibrium solutions of order quantities can be derived for the competing buyers. Dual sourcing is proven to improve the expected profit over sole sourcing when the fixed ordering cost and the supplier correlation are relatively low. Therefore, buyer competition does not change the logic of choice between sole versus dual sourcing. However, the variability reduction in market output is an inconsistent desirable target in terms of supplier selection and order allocation caused by its occasional failure to increase expected buyer profit, which differs from the monopoly case. For example, the buyer equally splits the order between two identical suppliers regardless of their supply process correlation in the monopoly model, which is not the optimal response for a buyer competing with a sole-sourcing opponent using a common supplier.

The above work mainly focuses on the benefits of supplier diversification in the context of dual-sourcing duopolies, as well as the related effects of supplier correlation. Chen and Guo (2013) studied competing buyers under supply risk from another angle, i.e., considering the incentives of firms in choosing a dual-sourcing strategy from both risk mitigation and strategic-sourcing perspectives. They examined how different sourcing strategies affect firm performance given both supply uncertainty and retail competition. Their model assumed that the yield uncertainty interdependently affects the order fulfillment of competing firms, which is also different from the findings by Tang and Kouvelis (2011).

We specifically consider a supply chain model consisting of a common supplier selling an essential input at unit wholesale price w to two buyers, labeled as Firms A and B; these firms transform the essential input into differentiated retail products and sell them at unit retail price p_i, for $i = A\,, B$, at the end of the consumer market. The two firms differ in their sourcing options. Although Firm A relies solely on the common supplier for the essential input, Firm B has an alternative supplier that can provide unlimited supply at unit price S. Thus, Firm A adopts a single-sourcing strategy, whereas Firm B uses a dual-sourcing strategy. This representative supply chain structure captures a class of real-world scenarios in which competing firms adopt distinct sourcing strategies (in relation to a common supplier), similar to the case of Nokia and Ericsson in the famous fire event that occurred in early 2000 at the Philips Electronics plant, a major microchip supplier for the two cell phone producers.

This model has two issues that require clarification. First is on the demand side. The two buyer's competition is supposed to be a Hotelling's horizontal product differentiation model, which yields simple linear demand functions with a pricing competition for both firms. On the supply side, the common supplier is subject to a random yield, which causes uncertain supply to the two firms. More specifically, the supplier has high (infinite) capacity with the probability $\alpha\,, \alpha \in (0, 1)$, as well as a realized finite capacity Q with the probability $1 - \alpha$. In the latter, the common supplier adopts a uniform allocation rule because of its desirable properties, such as fair and strategy-proof.

The sequence of events is as follows: (1) Given the price pair $(w; s)$, both firms decide on their retail prices $(p_A; p_B)$ and place orders $(q_A; q_B)$ to the common supplier. (2) The common supplier fully fulfills the orders of both firms under the situation of high capacity, whereas the supplier rations the orders from the two firms in accordance with the uniform allocation rule under the situation when capacity Q is realized, and firm B can temporarily acquire additional supply from its alternative source. (3) The market clears based on the realized delivery of products from the two firms. The firms are risk neutral, and the supply chain structure is common knowledge. Each firm optimally chooses its retail price and order quantity, anticipating the action of its rival. A Nash game is consequently induced, with the objective functions of the two firms as

$$\max_{p_A, q_A} E\pi_A = \left[\alpha q_A + (1 - \alpha)\, g_A\right] (p_A - w)\,,$$

and

$$\max_{p_B, q_B} E\pi_B = \left[\alpha q_B + (1 - \alpha)\, g_B\right] (p_B - w) + \left[\alpha\, (D_B - q_B) + (1 - \alpha)\, (1 - g_A - g_B)\right] (p_B - s)\,.$$

Chen and Guo (2013) solved the above model by considering two scenarios. One scenario is $w \leq s$, i.e., the wholesale price is lower than the alternative supply price for Firm B. In this scenario, the price of Firm B is shown to be higher than that of Firm A, which in turn is priced higher when both firms adopt a single-sourcing strategy. This finding is accounted for by the following: with the option of dual sourcing, Firm B obtains a “monopoly” of power over the residual demand and induces it to raise its retail price. Consequently, this price increase by Firm B reduces the pressure on Firm A’s pricing. Firm A then raises its retail price as well, but not to the extent that Firm B does because of Firm B’s competitive advantage over the residual demand. Furthermore, by comparing the firm’s expected profits with the single-sourcing benchmark, Firm B’s dual-sourcing strategy is shown to probably benefit itself, as well as Firm A. This result is expected for Firm B, given that an alternative supply secures more for its order fulfillment. However, such result is relatively interesting for Firm A because under Firm B’s dual-sourcing strategy, Firm A charges a relatively lower price than Firm B, which yields higher demands and expected sales, compared with the single-source benchmark case. The increased price and sales lead to a higher expected profit for Firm A. Thus, the alternative sourcing of one firm creates a positive externality for its rival.

Another scenario under consideration is $w \leq s$, i.e., when the wholesale price is lower than the alternative supply price for Firm B. In this scenario, as long as the wholesale price is within a certain interval, Firm B has an incentive to order from the common supplier even at a relatively higher cost compared with the alternative supply. Accordingly, Firm B limits its rival’s supply to the market in the event of a supply shortage, the benefit of which can outweigh the extra cost paid to the common supplier. This finding indicates a strategic sourcing incentive for other effective retail completion. Under this scenario, both firms charge higher prices and earn higher expected profits in the dual-sourcing environment than in the single-sourcing benchmark, and Firm B still charges a higher price than Firm A does. These insights are similar to that in the former scenario.

8.3.2 *Endogenous Supply Effort*

8.3.2.1 Cournot Quantity Competition

The previous subsection discusses vertical competition under supply uncertainty; however, the random factors in the supply side are exogenous. We currently investigate the problems through which the supply reliability can be improved with endogenous effort. In this aspect, Huang and Xie (2015) considered two unreliable firms who endogenously exert effort to improve their reliability through a Cournot quantity game competition.

Consider two symmetric firms, i and j, who produce identical products in a market characterized by Cournot competition. The production process is unreliable in terms of the quantity of qualified output for either firm $i(j)$. Suppose the input quantity is $q_i(q_j)$ for manufacture $i(j)$; then, the output quantity is $q_iy_i(q_jy_j)$, where y_i and y_j are random yield rates independent and identically distributed over support $[0, 1]$. Dropping the subscripts because of symmetry, the yield rate for each firm is assumed to be a uniform distributed random variable $y\ \ \mathrm{U}(0, a(e))$. Here, $a(e)$

is a concave function that increases in e with $a(0)=a^0$ and $\lim_{e\to\infty}a(e)=1$. a measures the reliability after improvement over (0, 1), and a^0 is the initial reliability without improvement. Furthermore, the disutility of effort e is denoted by an increasing convex function $z(e)$. On the demand side, the inverse demand function is $p=d-bQ(b>0)$, where Q is the total quantity supplied to the market, d is the market potential, and b is the sensitivity parameter. The total production cost is given by $c_i=(1-(1-\eta_i)(1-y_i))q_iw$, where w is the unit production cost, and $\eta\in(0\,,1]$ measures the loss associated with the defective product.

The sequence of the events is as follows: (1) The two firms simultaneously determine the reliability improvement efforts; (2) The firms decide the input quantities after observing the realized reliabilities; (3) The firms engage in quantity competition on the market with output quantities. Suppose that the firm is unaware of the opponent's realized yield when making input quantity decision, hence, a two-stage dynamic game is established.

The game can be solved using a backward approach, such that, the second-stage game should be considered first. For firm i, given q_j, the second-stage profit can be maximized by inputting q_i as follows:

$$\begin{aligned}&\prod\nolimits_{d2}\left(q_i;q_j,a_i^r,a_j^r\right)\\&\quad=E_{y_i\left(a_i^r\right),y_j\left(a_j^r\right)}\left[\left(d-b\left(q_iy_i+q_jy_j\right)\right)q_iy_i-\left(1-\left(1-\eta_i\right)\left(1-y_i\right)\right)q_iw\right].\end{aligned}$$

The problem can be solved with analytical solutions of Nash equilibriums for the firms' input quantities under the following four possible scenarios after firms exert efforts: both firms succeed, both firms fail, firm i succeeds, but j fails, and firm i fails whereas j succeeds. The comparison results of firm input quantities under two scenarios (firm success versus failure) are closely related to market potential. When the market potential is low, the successful firm inputs additional quantities than the failed firm; however, when the market potential is high, the successful firm inputs less quantities. On the relationship between optimal input and realized reliability, the firm's optimal input quantity decreases in the competitor's realized reliability. Furthermore, the firm's optimal input quantity increases in its own realized reliability when the market potential is low, although its realized reliability decreases when the market potential is high. This phenomenon is explained by the possible two contradictory effects when the realized reliability of the firm increased, namely the price reduction (negative effect) and cost reductions (positive effect). Under low market potential, the firm prefers to exploit the cost reduction effect and inputs additional quantity expecting to lower average cost. In contrast, under large market potential, the firm inputs less quantity to diminish the price reduction effect and to maintain high margins on products sold.

For the first-stage problem, the problem of choosing an optimal effort is converted into that of choosing an optimal reliability. Thus, the firm determines reliability a to maximize the first-stage profit function as follows:

$$\begin{aligned}\prod\nolimits_{d1}(a) =&\theta^2\prod\nolimits_{d2}^{*}(a,a)+\theta\left(1-\theta\right)\prod\nolimits_{d2}^{*}\left(a,a^0\right)\\&+\left(1-\theta\right)\theta\prod\nolimits_{d2}^{*}\left(a^0,a\right)+\left(1-\theta\right)^2\prod\nolimits_{d2}^{*}\left(a^0,a^0\right)-z\left(e_d(a)\right)\end{aligned}$$

Two aspects of results can be obtained by analyzing the Nash equilibrium solution for this problem. First, on the effect of quantity competition on reliability improvement, the optimal effort the firm exerts in the duopoly case is less than that in the monopoly case, and the difference between the optimal efforts under the two cases increases with the probability of improvement success. Second, on the effect of reliability improvement on quantity competition, the endogenous behavior of reliability improvement intensifies competition by making firms increase inputs under the low market potential in terms of expectation, while weakening competition under the high market potential. This insight is similar to the relationship presented in the second stage as follows: when the market potential is small, firms tend to use the cost reduction effect from reliability improvement by increasing the input quantity; when the market potential is large, firms depend more on the price reduction effect than saving costs, and thus input a smaller quantity.

8.3.2.2 Newsvendor Inventory Competition

Inventory competition, also commonly referred to as newsvendor game, is a commonly observed phenomenon in a competitive market initially studied by Parlar (1988). Lee and Lu (2015) investigated this horizontal inventory competition under yield uncertainty, in which two firms with random yields compete for a substitutable demand as follows: If one firm suffers a stock-out, which can be caused by yield failure, its unsatisfied customers may switch to its competitor. On the supply side, each firm is subject to a random yield, with the modeling similar to that in the Cournot competition problem. The stochastic yield rate y_i of firm $i = (1, 2)$ is related to the yield reliability a_i, which can be endogenously enhanced by the firm. Let q_i denote the input ordering quantity of firm i; then, the output stocking quantity is $q_i y_i$. On the demand side, let D_i denote the initial demand share of firm i. If firm i suffers a stock-out, that is, $q_i y_i$ turns out to be less than D_i, then a fixed fraction of the excess demand will switch to its competitor, firm j ($j \neq i$). Let D_i^s denote the effective demand of firm i; and it can be expressed as $D_i^s = D_i + \gamma_{ji}\left(D_j - q_j\right)^+$, where γ_{ij} $(0 \leq \gamma_{ij} \leq 1)$ is the switching rate of the unsatisfied customers of firm i going to purchase from firm j.

The sequence of event is also similar to the Cournot competition as follows: first, the firms select reliability levels (a_1, a_2) to improve and to incur the improvement costs. Afterwards, these reliability levels are observed, and the firms decide the initial order quantities (q_1, q_2). The actual output is then realized, and unsatisfied customers switch to the other firm. A two-stage game is hence established and can be solved in a reverse order.

Given a fixed pair of reliability index, $a = (a_1, a_2)$, the expected profit of firm i in the quantity game can be written as

$$\pi_i^q\left(q_i|q_j, a\right) = E\Big[p_i \min\left(D_i^s, q_i y_i\right) + s_i y_i - D_i^s\Big]^+ - c_i q_i + \delta_i c_i q_i \left(1 - y_i\right)\Big].$$

This stage of game is proven to be a submodular game, which means that a firm will reduce its order quantity if its competitor increases the order. Random supply yield noticeably gives rise to multiple equilibria, which differs from the traditional result of unique equilibrium without yield uncertainty (shown in Parlar 1988). Nevertheless, a unique equilibrium does exist if the random yield follows a Bernoulli distribution. Quantity and yield reliability also serve as complementary instruments for the competing firms. The firm can increase its expected profit with a higher reliability level, through which its competitor's profit is simultaneously reduced.

Let $\left(q_1^*(a), q_2^*(a)\right)$ be the equilibrium quantities in the second stage, then, firm $i$maximizes the first-stage profit by choosing a reliability level a_i. The first-stage optimization problem of firm i can be written as

$$\max_{a_i \geq a_i^0} \ \pi_i^r\left(a_i|a_j\right) = \pi_i^q\left(q_i^*(a)|q_j^*(a), a\right) - z_i\left(a_i\right),$$

where $z_i(a_i)$ is an increasing convex cost function of exerting effort to raise the reliability level to a_i. This first-stage reliability game can be analyzed if the firm's initial demand is deterministic and if the random yield follows a Bernoulli distribution. Under this situation, this reliability game is also submodular. Furthermore, competing firms are found to be possibly reluctant to pursue a high-reliability level as a monopoly does. This result indicates that the competition weakens the incentive to improve yield reliability. This finding is explained by the fact that the potential market share of a competitive firm is smaller than that of a monopoly; thus, the marginal gain from improving reliability is relatively small for the competitive firm. Furthermore, the equilibrium reliability levels are also sensitive to the customer-switching rate. The firm would exert a higher reliability level if more customers can switch to this firm from its competitor and vice versa. Hence, raising the reliability level is preferred if more of its competitor's customers regard itself as a backup vendor.

8.4 Supply Chain Networks

8.4.1 Supplier Competition + Buyer Diversification (N Suppliers + One Buyer)

The previous sections have provided preliminary models on one buyer dealing with multiple-competing suppliers, who may fail to deliver order quantities because of supply disruptions. However, those models exclusively focus on horizontal supplier competition. In this subsection, we incorporate both horizontal supplier competition and vertical channel competition between suppliers and their downstream buyer. Consider a simple supply chain model with one buyer and N suppliers perfectly producing substitutable products. The suppliers are unreliable because they are subject to random defaults modeled as "all-or-nothing" disruptions. Let δ_i be a binary random variable denoting the disruption of supplier i with a joint distribution of $\delta_1, \ldots, \delta_N$ determined by the probabilities $p_{d_1 d_2 \ldots d_N} = P[\delta_1 = d_1, \ldots, \delta_N = d_N]$, $d_i \in \{0, 1\}, i = 1, \ldots, N$. This modeling approach is adopted because it highlights the correlation among the disruptions of these risky suppliers.

Demand D can be deterministic or random, with unit retail sales price s as the predetermined parameter. The event sequence is similar to the typical supplier–buyer interaction within a supply chain channel as follows: The suppliers first determine their wholesale prices w_i, and then, the buyer responds by choosing order quantities q_i. Thus, the suppliers compete with one another for the buyer's business, and collectively, they serve as the Stackelberg leaders in a game where the buyer is the Stackelberg follower. The per unit production cost for supplier i is c_i.

The optimization problem of the buyer placing orders with N suppliers is

$$\max_{q_1 \geq 0, q_2 \geq 0, \ldots q_N \geq 0} \left(sE \left\{ \min \left[D, \sum_{i=1}^{N} (1 - \delta_i) q_i \right] \right\} - \sum_{i=1}^{N} c_i q_i \right),$$

whereas the suppliers compete with one another for the buyer's business and solve the following optimization problems:

$$\sup_{w_i \geq 0} (w_i - c_i) z_i (q_i, \ldots, q_N), \qquad i = 1, 2, \ldots, N.$$

Babich et al. (2007) analyzed the above model by considering the codependence among the suppliers' random disruptions. For the two-supplier problem with deterministic demand ($N = 2$ and D is deterministic), the buyer is shown to prefer suppliers with highly positive correlated disruptions. This result contradicts the intuition that negative correlation generates a diversification advantage to the buyer. With competition, the positive correlation between supplier disruptions leads to lower wholesale prices, thereby compensating the buyer for losing diversification benefits. Conversely, all things being equal, each supplier prefers a highly negative correlation between their own default processes and those of their competitors, leading to less competition and more profits extracted from the buyer. Alternately, simultaneously obtaining diversification benefits and low wholesale prices with over two suppliers ($N \geq 3$) is possible for the buyer. For example, if two competing suppliers are highly correlated and the third supplier being negatively correlated with the others, the buyer can benefit from the low wholesale price induced by the competition between the two highly codependent suppliers and use the third supplier to hedge against disruption risk.

The analysis increases in difficulty when considering models of random demand (D is a random variable); however, the overall direction of the results remains unchanged. Thus, contrary to the initial intuition regarding the advantages of diversification, positive default correlation can benefit the buyer, which outweighs the losses from a weak diversification. Simultaneously, a negative disruption correlation benefits the suppliers and the channel in general. Therefore, the preferences of the buyer and the channel for default correlation are misaligned.

The above model assumes that the supplier competition is on wholesale pricing under exogenous supply disruption risks. Qi et al. (2015) considered the situation in which the suppliers' reliabilities are endogenous and can be enhanced at some expenses. Thus, a buyer procures a product from two suppliers competing not only through pricing strategy but also through reliability improvement efforts. The framework is approximately similar to Babich et al. (2007), with some differences on supply and demand modeling. For example, the demand is assumed to be a newsvendor random one, D. The reliability of supplier i is assumed to be q_i when the market is on and $a_i\ q_i$ when the market is off, in which q_i is the reliability decision of supplier i, and the market state is shared by both suppliers with either "on" or "off," with given respective probabilities. The sequence of events is as follows: (1) The suppliers simultaneously decide on their reliabilities; (2) The suppliers observe the reliability decisions made by their competitors, respectively, and then determine the wholesale prices; (3) Based on the suppliers' wholesale prices and reliabilities, the buying firm places orders to the suppliers; (4) All uncertainties are resolved, and the transactions are completed.

Studies have shown that the reliability of suppliers, as an endogenous decision variable, frequently plays a more important role than the wholesale price in supplier competition. In fact, maintaining the reliability and wholesale price both high is the ideal strategy for suppliers with multiple options. Noticeably, when the demand uncertainty is relatively high or when the supply reliability is low, the competition among suppliers on both price and reliability may render the sole-sourcing strategy optimal in some cases, depending on the format of suppliers' cost functions. This phenomenon is a counterintuitive result opposed to the conventional wisdom that low supply reliability and high demand uncertainty motivate dual sourcing. Moreover, a supplier's profit and that of the buyer may unnecessarily decrease under supplier competition as the cost or vulnerability of this supplier increases.

8.4.2 Chain-to-Chain Competition (Two Suppliers + Two Buyers)

Chain-to-chain competition is regarded as the current business conception replacing the traditional model of firm-to-firm competition. Combined with supply uncertainty, this problem may require a more complex analysis. Fang and Shou (2015) systematically examined how to design and operate supply chains to deal with supply uncertainty effectively by considering the interaction between two competing supply chains. Each chain consists of one buyer and an exclusive supplier. Both chains are subject to supply uncertainty, which is modeled by a random yield a_i between 0 and 1. On the demand side, the market demand of chain i is determined by $p_i(Q_i, Q_j) = A - a_i Q_i - \gamma a_j Q_j$, where A is the market base, and $\gamma \in (0, 1)$ is the competition intensity, whereas Q_i and Q_j are the buyers' order quantities in chains i and j, where $i, j \in \{1, 2\}, i \neq j$.

Three types of competition games are explored, namely centralized, hybrid, and decentralized games. In the centralized game, central planners for both supply chains simultaneously determine the order quantities Q_i and Q_j to maximize their own expected profits. In the decentralized game, each supplier announces its contract term consisting of a wholesale price per unit of successful delivery and a penalty paid to the buyer per unit of unfilled order, and then, the respective buyer accordingly chooses the production quantity. The hybrid game is a mix of the centralized and decentralized chains, with the supplier in the decentralized chain making contract term before the quantity competition commences.

The obtained equilibrium solutions for the above three games provide the following observations: first, the expected order quantity and profit of a supply chain increase if its competing supply chain becomes less reliable or if its own supply becomes more reliable. Thus, a supply chain with a reliable supply can significantly maximize the high supply risk of its competing chain. Second, higher competition intensity results in lower equilibrium order quantities and expected profits for both supply chains. Third, order quantities are upper-bounded by those in the standard monopoly game without uncertainty.

Another question of interest on the strategic level is whether supply chain centralization provides a competitive advantage when dealing with competition and supply uncertainty. The answer is not necessarily. In fact, a supply chain is consistently better off by choosing to centralize, which implies that centralization is a dominant strategy. However, if the supply risk is low and the chain competition is intensive, centralization can actually decrease the supply chain profit compared with the case of the decentralized game. This phenomenon leads to a prisoner's dilemma. Alternatively, if the supply risk is high and/or the competition level is low, centralization constantly increases the supply chain profit. Hence, the desirability of supply chain centralization is enhanced by high supply uncertainty or low chain competition.

8.5 Potential Research Directions

Supply risk management has grown in importance because of the need for designing, coordinating, and operating extended supply chains. The risk can be the consequence of a host of random factors; it can also severely damage the supply chain firms. This chapter discusses supply chain models under supply risks, followed by these three classes of problems:

- First, a wholesale price contracts the risk allocation imbalance among supply chain members; thus, the channel coordination contract design under supply uncertainty is an important yet complicated problem. The strategic choice of dual-sourcing or reliability improvement is also vital for the firms within a supply chain, given that the supplier's process reliability can be endogenously improved.
- Second, the effect of supply uncertainty on firm profitability should be evaluated in the context of the horizontal market competition. With supplier competition, supply uncertainty affects the retailer's diversification strategy for replenishment and changes the suppliers' wholesale price competition and the incentive to reduce capacity uncertainty. With buyer competition, the strategic choice of single or dual sourcing is crucial for both the buyer under consideration and its competitor. The effect of reliability competition and its relation with pricing competition is also a hot topic when the supply effort is endogenous.
- Third, under a more complex system of N suppliers plus one buyer, the diversification and the price competition effects should be carefully weighed as they are closely related to the number of the supplier and the correlations among their disruptions. For a chain-to-chain network system, channel centralization inconsistently offers a competitive advantage. Thus, the choice of channel centralization also depends on system parameter.

A number of other issues require further exploration for future research directions:

- Information asymmetry: A common assumption in the above research is the existence of information symmetry within the supply chain system, i.e., both supplier and buyer share common knowledge. However, this finding may not apply in reality. For example, the suppliers may be vaguely aware of the market state, whereas the buyers may have incomplete information of the suppliers' attributes, such as costs and reliabilities. Hence, incentive theory, including adverse section and moral hazard, can be adopted to establish and analyze such models. Some studies such as those of Yang et al. (2012) and Huang et al. (2016) have looked into this research domain, which suggests a promising future direction.
- Firms' behavior: Behavior operations management has recently been in the spotlight. Hence, incorporating the features of supply chain firm behavior is another interesting topic. A major subject concerns the risk attitude of firms toward supply uncertainty. In this aspect, possible modeling tools include expected utility theory, mean-variance theory, VaR and CVaR, and prospect theory (Choi et al. 2008b; Choi and Ruszczynski 2011; Choi and Chiu 2012; Liu et al. 2013). For example, Li and Li (2016) studied a lot-sizing problem in the presence of random yield supply under loss aversion, whereas Madadi et al. (2014) investigated a centralized supply network design problem with an unreliable supply under both risk neutrality and aversion. On the supply chain interaction, other behavior characteristics can be adopted. For example, Chen et al. (2015) studied a supply chain-contracting problem with yield uncertainty and horizontal fairness concerns. We believe the study of supply chain model is potentially great by considering firms' behavior toward supply uncertainty.

- Channel power and cooperation: The above research fails to investigate specifically the issue of channel power. In fact, the effect of channel member power on the supply chain decisions and profits are interesting problems worth investigating. For example, Hwang et al. (2016) showed that the simple wholesale price contract leads to different performances under different channel power structures. Another future research issue, the supply chain cooperation and profit allocation in the presence of supply risk, is linked to the channel power problem.
- Supply risk assessment in the big data era: In our present supply chain modeling papers, the probability information of supply risk should be provided. In the real industry, such information comes from the risk assessment process, which integrates all identified knowledge of experts' opinion, historical data, and supply chain structure. Thus, measuring and quantifying supply chain risk has proven to be an enormous challenge in both the industry and the academe. According to a literature survey by Tang and Musa (2011), of the 138 papers they identified within this research domain, less than a quarter are empirical or quantitative. This finding corresponds with the comment by Wagner and Neshat (2012), "ways of measuring and quantifying supply chain risk are just beginning to emerge." Along with today's big data trend, the current process of maximizing more transparent information and revolutionary big data approach to more accurately identify and evaluate the likelihood of supply risk becomes a problem of substantial significance and interest. Innovative supply risk modeling frameworks using big data analytics are regarded extremely valuable, considering that integrating big data in operations and supply chains aids firms in improving intra- and inter-firm efficiency and effectively manages risks as well (Sanders and Ganeshan 2015).

Acknowledgment This work is supported by National Natural Science Foundation of China (NSFC) Nos. 71372002 and 71372100.

References

A. Alexandrov, When should firms expose themselves to risk? Manag. Sci. **61**(2), 3001–3008 (2015)

V. Babich, Vulnerable options in supply chains: effects of supplier competition. Nav. Res. Logist. **53**(7), 656–673 (2006)

V. Babich, A.N. Burnetas, P.H. Ritchken, Competition and diversification effects in supply chains with supplier default risk. Manuf. Serv. Oper. Manage. **9**(2), 46–123 (2007)

X.Q. Cai, J. Chen, Y.B. Xiao, X.L. Xu, Optimization and coordination of fresh product supply chains with freshness keeping efforts. Prod. Oper. Manag. **19**(3), 78–261 (2010)

J. Chen, Z. Guo, Strategic sourcing in the presence of uncertain supply and retail competition. Prod. Oper. Manag. **23**(10), 1748–1760 (2013)

J. Chen, X. Zhao, Z. Shen, Risk mitigation benefit from backup suppliers in the presence of the horizontal fairness concern. Decis. Sci. **46**(4), 663–696 (2015)

T.M. Choi, C.H. Chiu, Mean-downside-risk and mean-variance newsvendor models: Implications for sustainable fashion retailing. Int. J. Prod. Econ. **135**(2), 552–560 (2012)

S. Choi, A. Ruszczynski, A multi-product risk-averse newsvendor with exponential utility function. Eur. J. Oper. Res. **214**(1), 78–84 (2011)

T.M. Choi, D. Li, H.M. Yan, Optimal two-stage ordering policy with Bayesian information updating. J. Oper. Res. Soc. **54**(8), 846–859 (2003)

T.M. Choi, D. Li, H.M. Yan, Quick response policy with Bayesian information updates. Eur. J. Oper. Res. **170**(3), 788–808 (2006)

T.M. Choi, D. Li, H.M. Yan, Mean–variance analysis of a single supplier and retailer supply chain under a returns policy. Eur. J. Oper. Res. **184**(1), 356–376 (2008a)

T.M. Choi, D. Li, H.M. Yan, Channel coordination in supply chains with agents having mean-variance objectives. Omega Int. J. Manage. Sci. **36**(4), 565–576 (2008b)

Y. Fan, L. Heilig, S. Voss, Supply chain risk management in the era of big data design, user experience, and usability: design discourse. Lect. Notes Comput. Sci. **9186**, 283–294 (2015)

Y. Fang, B. Shou, Managing supply uncertainty under supply chain Cournot competition. Eur. J. Oper. Res. **243**(1), 156–176 (2015)

R.B. Handfield, D.R. Krause, T.V. Scannell, R.M. Monczka, Avoid the pitfalls in supplier development. Sloan Manage. Rev. **41**(2), 37–49 (2000)

H. Huang, T. Xie, Reliability improvement and production decision under Cournot competition. Int. J. Prod. Res. **53**(15), 4754–4768 (2015)

H. Huang, X.Y. Shen, H.Y. Xu, Procurement contracts in the presence of endogenous disruption risk. Decis. Sci. **47**(3), 437–472 (2016)

W. Hwang, N. Bakshi, V. DeMiguel, *Simple Contracts for Reliable Supply: Capacity Versus Yield Uncertainty Reliability*. Working paper (London Business School, London, 2016)

B. Keren, The single-period inventory problem: extension to random yield from the perspective of the supply chain. Omega Int. J. Manage. Sci. **37**(4), 801–810 (2009)

D.R. Krause, R.B. Handfield, B.B. Tyler, The relationships between supplier development, commitment, social capital accumulation and performance improvement. J. Oper. Manag. **25**(2), 528–545 (2007)

H. Lee, S.G. Kimm, H. Park, P. Kang, Pre-launch new product demand forecasting using the bass model: a statistical and machine learning-based approach. Technol. Forecast. Soc. Chang. **86**(1), 49–64 (2014)

C.Y. Lee, T. Lu, Inventory competition with yield reliability improvement. Nav. Res. Logist. **62**(2), 107–126 (2015)

X. Li, Y.J. Li, On lot-sizing problem in a random yield production system under loss aversion. Ann. Oper. Res. **240**(2), 415–434 (2016)

X. Li, Y.J. Li, X.Q. Cai, A note on the random yield from the perspective of the supply chain. Omega Int. J. Manage. Sci. **40**(5), 601–610 (2012)

X. Li, Y.J. Li, X.Q. Cai, Double marginalization in the supply chain with uncertain supply and coordination contract design. Eur. J. Oper. Res. **226**(2), 228–236 (2013)

H.J. Lin, Investing in lead-time variability reduction in a collaborative vendor–buyer supply chain model with stochastic lead time. Comput. Oper. Res. **72**, 43–49 (2016)

W. Liu, S.J. Song, C. Wu, Impact of loss aversion on the newsvendor game with product substitution. Int. J. Prod. Econ. **141**(1), 352–359 (2013)

A.R. Madadi, M.E. Kurz, K.M. Taaffe, J.L. Sharp, S.J. Mason, Supply network design: risk- averse or risk-neutral? Comput. Ind. Eng. **78**, 55–65 (2014)

P. O'Keeffe, *Understanding Supply Chain Risk Areas, Solutions, and Plans: A Five-Paper Series* (APICS, The Association of Operations Management, Alexandria, VA, 2006)

M. Parlar, Game theoretic analysis of the substitutable product inventory problem with random demands. Nav. Res. Logist. **35**(3), 397–409 (1988)

L. Qi, J.J. Shi, X. Xu, Supplier competition and its impact on firm's sourcing strategy. Omega Int. J. Manage. Sci. **55**, 91–110 (2015)

F. Qin, U.S. Rao, H. Gurnani, B. Ramesh, Role of random capacity risk and the retailer in decentralized supply chains with competing suppliers. Decis. Sci. **45**(2), 255–279 (2014)

N.R. Sanders, R. Ganeshan, Special issue of production and operations management on "big data in supply chain management". Prod. Oper. Manag. **24**(5), 852–853 (2015)

S. Tang, P. Kouvelis, Supplier diversification strategies in the presence of yield uncertainty and buyer competition. Manuf. Serv. Oper. Manage. **13**(4), 439–451 (2011)

O. Tang, S.N. Musa, Identifying risk issues and research advancements in supply chain risk management. Int. J. Prod. Econ. **133**(1), 25–34 (2011)

S. Tang, H. Gurnani, D. Gupta, Managing disruptions in decentralized supply chains with endogenous supply process reliability. Prod. Oper. Manag. **23**(7), 1198–1211 (2014)

S.M. Wagner, N. Neshat, A comparison of supply chain vulnerability indices for different categories of firms. Int. J. Prod. Res. **50**(11), 2877–2891 (2012)

Y. Wang, W. Gilland, B. Tomlin, Mitigating supply risk: dual sourcing or process improvement? Manuf. Serv. Oper. Manage. **12**(3), 489–510 (2010)

Z. Yang, G. Aydin, V. Babich, D. Beil, Using a dual-sourcing option in the presence of asymmetric information about supplier reliability: competition vs. diversification. Manuf. Serv. Oper. Manage. **14**(2), 202–217 (2012)