Decision (March 2019) 46(1):41–57
https://doi.org/10.1007/s40622-019-00204-x

RESEARCH ARTICLE

Supplier ratings and dynamic sourcing strategies to mitigate supply disruption risks

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Published online: 9 March 2019
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Abstract The selection of a sourcing strategy plays a vital role in managing supply disruptions. The choice regarding the number of suppliers is one of the most important decisions in mitigating supply side risks. In this paper, we analyze single versus dual sourcing strategies of a buying organization in a multi-period setting where the low-cost supplier is exposed to disruption risks. We incorporate supplier ratings based on the performance of the suppliers in a dynamic setting and use them in the sourcing decisions. We develop a stochastic dynamic programming model to formulate the dual-sourcing problem. Our results show that dual sourcing provides maximum cost–benefit under high probability of supply disruption and high-cost differential between the reliable and the unreliable suppliers. The findings of this paper will help supply chain managers formulate optimal sourcing strategies when exposed to supply disruption risks by integrating performance metrics of the suppliers dynamically.

Keywords Sourcing strategies · Dual sourcing · Supply chain risk management · Vendor rating · Stochastic dynamic programming

Introduction

Modern supply chains are complex networks made up of multiple entities spanning the entire globe. The developing economies have played important roles both as consumers and producers resulting in expanding the reach of supply chains (Avittathur and Jayaram 2016; Sodhi and Tang 2016). In these complex supply chain networks, risks exist in every link and managing these risks have become extremely critical in the context of today's globalized supply networks (Kilubi 2016; Nagurney et al. 2013; Nagurney and Li 2014). The expansion of supply chains has added new players both as consumers and as producers that add pressure on supply chains. A recent WEC-Accenture report (Bhatia et al. 2013)[1] stresses on the resilience of supply chains to deal with supply disruptions. Another report by APICS Supply Chain Council (2014)[2] investigates

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[1] Building Resilience in Supply Chains, January 2013.

[2] Uncovering Chronic Disruption In Supply Chain And Operations Management, 2014.

the chronic nature of disruption in organizations. The report identifies varying performance of the supplier as the main reason for supply disruptions. The supply chains have constant pressure to reduce the cost resulting into suppliers from emerging economies that compete on costs (Thürer and Avittathur 2017). In the vast and complex supply chain networks, the difference between the cost of an optimal and a suboptimal network can be very high (Wang et al. 2009).

There have been numerous instances where supply chains have been adversely affected because of unforeseen supply disruptions leading to irreparable damages. The change is business dynamics have resulted in emergence of new players. In March 2007, Menu Foods (a Canadian firm) recalled more than 60 million cans and pouches of dog and cat foods after many pet deaths were reported. The firm had procured from ChemNutra which in turn had outsourced it to a Chinese supplier Xuzhou Anying Biologic Technology Development Co. Ltd. The incident resulted in huge losses to Menu Food Corp., and they lost almost half of their market value (Yang et al. 2008). The catastrophic flooding in Thailand in 2011 affected the production of several key end products, electronic parts and subsystems—most notably semiconductors, cameras and hard disk drives. The disruption to the electronics supply chain had an indirect impact in turn on the production of other devices and systems, including notebook PCs, dynamic random access memory (DRAMs), cameras and set-top boxes. Japan is a vital supplier of parts and equipment for major industries such as computers, automobiles and electronics. Thus, the tsunami attack which hit Japan in 2011 shook the world economy. The automotive supply chain, especially for Japanese OEMs Toyota and Honda, took the biggest blow, with parts supplies extremely constrained for months, and production and sales levels plunging as a result. In fact, Toyota lost its position as top global car manufacturer in 2011. A number of industries were constrained by shortages of obscure chemicals that represented just a small but vital component of their manufacturing processes, and which turned out to be either only or largely sourced from Japan. As those suppliers lost production capabilities, in some cases for months, manufacturers across the globe were sent scurrying for other sources or to find alternative materials. As companies become more global in scale and dependent on emerging markets, these risks can only escalate (Nishat Faisal et al. 2006). Social and environmental issues create further vulnerability. Another recent example of a supply chain disruption attributed to climate change was the unusually prolonged drought in Russia over the summer of 2010. By early August of that year, over one-fifth of Russia's wheat crop had been destroyed and the government banned all grain exports, contributing to wheat price futures reaching their highest point in nearly 2 years. General Mills was one of the many food manufacturers that faced significant price pressure. As a result, it has to announce increases between 4 and 5% in September 2010. These are just some examples of supply disruptions that have severely impacted the global supply chains and have made it critical for supply chain managers to come up with strategies to cope with these unforeseen events that lead to huge monetary losses.

Researchers have divided supply chain risks into two broad categories, viz., *operational risks* and *disruption* or *catastrophic risks*. To deal with supply chain risks, it is essential to perceive a clear understanding of the types of risks associated with supply chains. The first category, i.e., operational risks, refers to the risks due to inherent uncertainties in a supply chain such as coordination issues, sudden decrease of supply, sudden rise in cost, technology fallout to name a few. The other category, i.e., disruption risks, refers to risks which are either man made or caused due to natural disaster. These refer to terrorist attacks, civil unrest, political uncertainty, labor strikes and natural disasters such as floods, hurricanes, droughts and earthquakes. The impact of catastrophic risks is much more than that of operational risks (Sawik 2011). Tomlin (2006) in his work has mentioned about two tactics used to counter disruption risks, viz., mitigation tactics and contingency tactics. Mitigation refers to those tactics where a firm acts way before a disruption occurs, while contingency refers to those where a firm reacts after some disruption has already occurred. In many cases, a firm may adopt a combination of these risk management strategies. Kleindorfer and Saad (2005) created a supply chain risk framework called SAM, where "S" refers to specifying sources of risk and vulnerabilities, "A" means assessment and "M" stands for mitigation. Berger et al. (2004) pointed out that there are catastrophic events that affect all suppliers, as well as unique events that affect only one single supplier and developed a decision tree-based model which determines the optimal number of suppliers for the buying firm. Ruiz-Torres and Farad (2007) extended this model to provide better understanding of the effect of the input parameters on the optimal number of suppliers.

The choice regarding the number of suppliers is one of the most important strategic decisions in mitigating supply side risks. The most frequently used approaches of sourcing can be categorized into two types (1) single sourcing and (2) multiple sourcing. Single sourcing refers to the fulfillment of the purchasing organization's need for a product by one selected supplier. During the past two decades, driven by the objective of reducing supply chain costs, firms have adopted strategies to rationalize, consolidate and streamline their supplier base. In many cases, this has led to single sourcing strategy for many commodities. The single sourcing strategy has been well proven to realize cost savings and many companies have been able to gain a competitive advantage by utilizing low-cost country sourcing. Larson and Kulchitsk (1998) indicated in a survey that single sourcing ensures higher quality at lower total cost to the buyer and improved buyer–supplier cooperation. However, at the same time, single sourcing exposes the buying firm to a high degree of supply disruption risks.

In the recent past, the emergence of supply chain risk mitigation as a key issue has caused many procurement managers to reassess their reliance on single sourcing strategies. We conducted a survey of the supply chain managers in India to ascertain the important factors that contribute to risk in supply chains. The results are presented in detail in "A survey of key issues in today's supply chains." Supply disruption risk came out as one of the most challenging factors that confront supply chains of today. One of the key risk mitigation strategies adopted by procurement managers exposed to supply disruptions is multiple sourcing. Multiple sourcing has gained immense importance among purchasing organizations because of several advantages it has over single sourcing, the most important being alternative sources of materials in case of delivery disruptions from a supplier. Due to lightning in March 2000, Nokia and Ericsson lost all their essential supplies from the Philips Semiconductor plant. However, Nokia's multiple sourcing tactics mitigated the impact. Nokia responded to this disruption by increasing production at its alternate suppliers. In contrast, due to an absence of "Plan B," i.e., alternative source, Ericsson lost $400 million in potential revenue. Similarly, Chiquita was able to mitigate the impact caused by Hurricane Mitch in 1998 by practicing multiple sourcing strategies. Since Dole was dependent on its single supplier, it suffered a 4% decline in its revenue, while Chiquita increased revenues by 4%.

In this context, research efforts determining the optimal sourcing strategy and supply portfolio and diversification policies are gaining attention. Extant research has analyzed different aspects of the problem such as quantity allocation among suppliers, the trade-off between reliability and higher component costs, and the interplay between supplier diversification and flexible resources. "Literature review" section provides a detailed review of the relevant research. One key parameter that has not been extensively studied is how the performance of a supplier over multiple time periods affects the portfolio of supplier selection. Most of the extant research papers focus on single-period models, and the dynamics of supplier performance over multiple time periods and its interplay with sourcing diversification policies are largely ignored. In this paper, we contribute to this stream of research by developing a dynamic stochastic programming model that helps the decision maker develop supplier diversification strategies and split order quantities between two suppliers in a multi-period setting based on various parameters such as supplier performance, procurement costs and probability of supply disruptions.

Rating suppliers based on performance measures is an important component of production and logistics management that plays a key role in shaping supplier selection decisions and sourcing strategies of a firm. Selecting the right supplier is a complicated task as it involves considering different criteria. In today's complex supply chains, the performance of a firm does not depend solely on itself but is closely tied to the performance of its suppliers. Thus, understanding a supplier's capabilities and performance potential is crucial to the buying firm's success. Starting from Dickson's (1966) vendor selection model, researchers have focused on various critical criteria such as quality, reliability, delivery, performance history. However, how supplier performance affects the sourcing decisions and risk mitigation strategies of a firm has not been thoroughly studied in the literature. Supplier selection, in a way, is one of the key risk management strategies used to shield against potential supply disruptions. The various factors affecting a supplier's performance and its interplay with supply risk mitigation tactics are an important and potential area of research in management science. One of the primary contributions of this paper is to analyze different supplier selection criteria for evaluating supplier performance and its role in shaping sourcing decisions for mitigating possible disruption risks.

In this paper, we focus on the dynamics between single versus dual sourcing in the context of supply side disruptions. The paper considers the presence of two suppliers whose performances are judged based on two criteria—*reliability* and *technical capability*. One is a local supplier who is reliable and without any quality issues but at the same time highly expensive (high-cost supplier). The other supplier is situated in a low-cost country that is much cheaper but at the same time whose reliability and technical capability fluctuate (low-cost supplier). The low-cost supplier because of its location in a developing economy is also exposed to disruption risks. We develop a stochastic dynamic programming model to formulate the dual-sourcing problem in a multi-period setting where at each time period the performance of the suppliers is evaluated based on reliability and technical capability parameters to derive the optimal sourcing decisions.

Literature review

In this paper, we touch upon two streams of literature, viz., single versus dual sourcing methods and supplier/vendor rating. Next, we review the relevant papers in these two streams.

(i) Single versus Dual Sourcing Methods

Single versus dual sourcing strategies have been studied mostly in a single-period setting in the extant literature. Pochard (2003) used real options theory to compare single sourcing with dual sourcing and examines how buying firms should prepare for disruptions in their supply chain. Burke et al. (2007) found that single sourcing is more dominant than dual sourcing when the supplier capacity is large in comparison with product demand, and the firm does not enjoy any diversification benefits. In all other cases, dual sourcing is an optimal sourcing strategy. Empirical studies indicate that dual or multiple sourcing dominates most business areas (Goffin et al. 1997; De Toni and Nassimbeni 1999; Shin et al. 2000). A review done by Minner (2003) identifies inventory models with multiple supply options and discusses their contribution to supply chain management. Purchasing managers favor multiple sourcing over a single supplier as dependence on a single supplier invites several kinds of risks. According to the study lead by Minner (2003), the risk of increasing prices in global sourcing due to exchange rate volatility, supply disruptions due to machine breakdowns, labor strikes or political instability, capacity limitations, lead time variability can be mitigated if multiple suppliers are available. Kumar et al. (2018) jointly optimize pricing and sourcing strategies for competing retailers under disruption risk depending on a single supplier that invites agency problems such as opportunistic behavior and information asymmetries with respect to true manufacturing costs and dynamic cost development. However, these can be overcome by introducing supplier competition through multiple sourcing. Tomlin and Wang (2005) compared a single-source dedicated strategy with a single-source flexible strategy and deduce that a flexible strategy is strictly preferred to a dedicated strategy if the firm is risk neutral or if the resource investments are reliable. Anupindi and Akella (1993) pointed out various reasons for a buyer not to single source. The reasons being uncertainty in both quality and quantity of supply, price variations due to exchange rate fluctuations when sourcing from international suppliers, the habit of a single supplier to hold the buyer to "ransom," etc. Thus, industries are increasingly moving toward a smaller supplier base of two or three suppliers. According to McMillan (1990), performance is improved by creating quality competition through quantity allocations and/or price renegotiations with two/three suppliers. Constantino and Pellegrino (2010) focused on developing a quantitative model for examining the economic advantages of adopting multiple sourcing versus single sourcing in risky environments. They show that the trade-off between single and multiple sourcing depends on deterministic as well as probabilistic factors in risky environments. Another major area of research is focused on how to split orders between different suppliers. Lau and Zhao (1994) minimized the sum of annual holding and ordering costs subject to maximum allowable stock-out risk to find the optimal ratio of split of order between two suppliers. They further conclude that the split between two suppliers depends on their mean lead times. Kelle and Miller (2001) on the other hand showed that large demand and lead time uncertainty favor multiple sourcing. Sawik (2011) used a portfolio approach in a make-to-order environment to optimize the allocation of orders of custom parts among suppliers and points out that the decision is based on price, quality and reliability. These factors are self-conflicting as the supplier offering lowest price may not be reliable or provide the best quality, while the supplier providing the best quality may not be cheap. In another research effort by Berger and Zeng (2006), a study has been carried out on the optimal supply size depending on financial loss function, the operating cost and the chance of all the suppliers being down. Burke et al. (2007) suggested that one should choose single sourcing over multiple sourcing when the supplier capacity is large relative to the product demand and when there are no diversification benefits available for the buying firm. In this paper, we extend the single versus dual sourcing problem in a multi-period setting and incorporate supplier ratings in the sourcing strategies. Next, we look at the literature on supplier ratings.

(ii) Supplier/Vendor Ratings

Supplier selection plays a major role in mitigating supply disruption risks, and thus over the past five decades supplier rating has evolved as an important area in management science research (Dickson 1966). According to Ishikawa (1990), quality evaluation of a supplier can be done by considering the following criteria: quality, cost, delivery and service. A study by Weber et al. (1991) revealed that traditionally vendors focused on criteria such as quality, delivery speed, reliability, offered price. In case of a relationship which is longer and closer, vendors are selected based on their global performances. Global evaluations, on the other hand, range from total cost analysis (Roodhooft and Konings 1996; Ellarm 1996; Tagaras and Lee 1996), supplier's capacity in production planning (Ho and Carter 1988), their future manufacturing capability (Ellarm 1990) and continuous improvement capabilities (Choi and Hartley 1996). Rao and Kiser (1980) and Bache et al. (1987) have identified over fifty criteria for supplier selection. Gaballa (1974) formulated a single-objective, mixed-integer programming model to minimize the sum of purchasing, transportation and inventory costs by considering qualitative criteria such as vendor's quality of material, delivery and capacity. Weber and Current (1993) used a multi-objective approach for analyzing the trade-offs between conflicting criteria in supplier selection problems. Masella and Rangone (1995) and Merli (1991) divided important supplier selection criteria under different levels: Level 1—price and quality; Level 2—supplier's logistical performance such as reliability, flexibility, supply lots and lead time; Level 3—supplier's process capability such as setup time, lot size, lead time; Level 4—supplier's human resource from several points of view-design involvement, management ability, culture among others; Level 5—strategic performance like business partnership. Murlidharan and Anantharaman (2001) and Deshmukh (2001) described the importance of group decision making in vendor evaluation. They also discuss how Analytical Hierarchy Process (AHP) and multi-criteria decision-making (MCDM) tools are useful in such evaluation. An attempt had been made by Mandal and Deshmukh (1993) to study the problem of documenting factors for vendor selection using MCDM methods. A trade-off among quality, cost and delivery performance measures has been studied by Kraljic (1983), Burton (1988) and Benton and Krajewski (1990). The relative importance of supplier attributes such as quality, cost and delivery performance has been studied by various researchers such as Wagner et al. (1989), Chapman (1993) and Chapman and Carter (1990). Yu and Tsai (2008) conducted a case study on a semiconductor industry to rate supplier's performance. In our dynamic stochastic programming model, we incorporate technical capability and reliability, which are important performance and quality measures, of the suppliers in the sourcing framework.

Next, we explain a survey that we conducted among supply chain managers in India to ascertain what are the most important factors that concern them.

A survey of key issues in today's supply chains

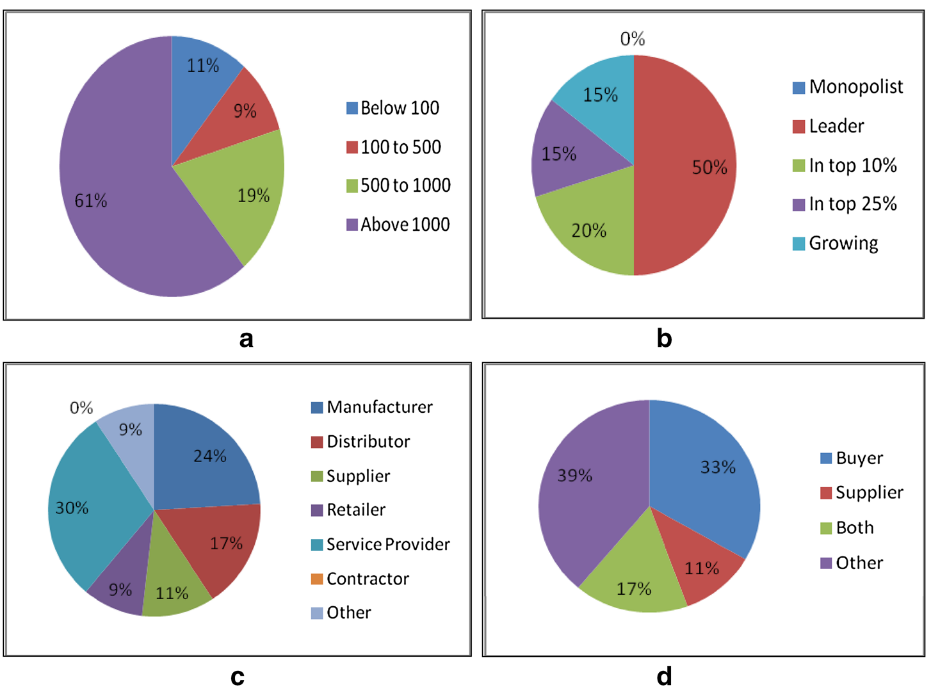
To get a first-hand view of the challenges confronting supply chains, we surveyed supply chain professionals in the Indian industry about the factors that contribute to various risks in supply chains. The survey contained questions on the company profile of the respondents and the top five most important factors that are perceived as key challenges facing the supply chain of their respective organizations. We sent out the surveys through emails to 550 professionals working in India. The total response received was 354, i.e., around 64%. The respondents were asked to select the top five concerns facing the supply chain in their company. The company profile of the respondents is reported below in Fig. 1a–d.

We analyzed the responses to determine the key challenges facing supply chains. Figure 2 highlights the results of our survey. We found that mitigating supply chain risks and more specifically supply disruptions, severe quality and technical problems are one of the most significant challenges confronting supply chains today. Motivated by the results of this survey, we focus on developing an analytical model that derives important sourcing strategies based on the technical capabilities of the suppliers to mitigate supply disruption risks.

Next, we explain the stochastic dynamic programming model in detail for identifying optimal sourcing strategies.

Stochastic dynamic programming model for dual sourcing

In order to model the choice between single and dual sourcing, we develop a stochastic dynamic programming model in a multi-period setting. We start by considering the availability of two suppliers (geographically apart from each other) to a firm. Both the suppliers possess the capability of supplying a certain required component needed by the firm, though at different prices and with varying reliability. We assume that the first supplier, say S_1, is very reliable yet costly (domestic high-cost supplier), while the second supplier, say S_2, is cheap but at the same time not that reliable (foreign low-cost supplier). Thus, the amount demanded from S_2 is not received completely and only a fraction of it is delivered to the firm. On the other hand, the buying organization receives the entire



Notes: 1(a) Percentage of respondents in terms of annual turnover (in Rs. 10 million); 1(b) organization's position in the market; 1(c) role(s) of organization in the SC; 1(d) perspectives for answering this survey

Fig. 1 Company profile of the respondents

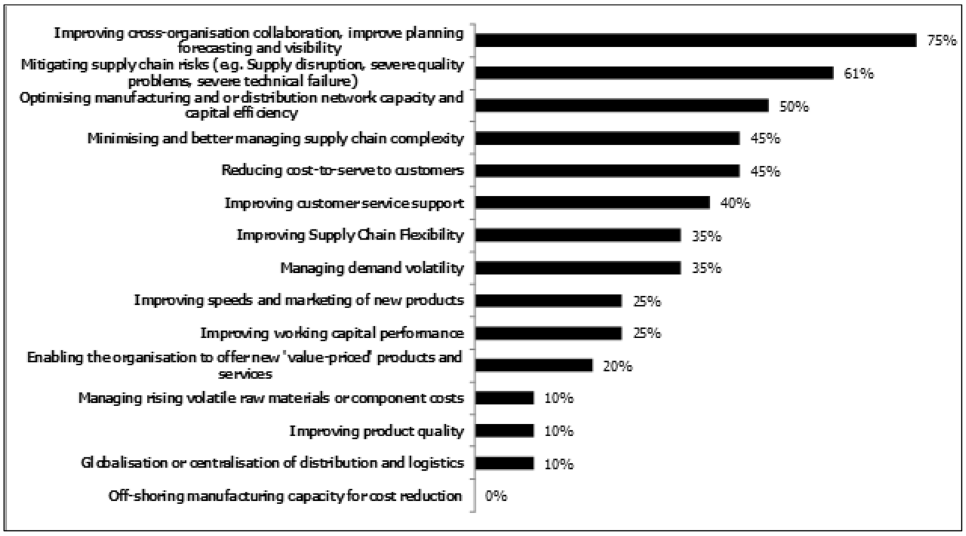


Fig. 2 Supply chain key issues

quantity that it orders from S_1. The fraction of a particular order that S_2 actually delivers in a particular time period depends on two criteria, namely its *reliability* (R_t) and *technical capability* (Y_t). Reliability and technical capability are important performance and quality measures that determine the effective yield of S_2. Reliability and technical capability of S_2 may increase or decrease from one time period to another based on its internal process improvements or decline in technological prowess. The future reliability and technical capability of S_2 are functionally dependent upon its reliability and technical capability in the current time period. This functional dependence is stochastic in nature. For example, if in current time period $S_2's$ reliability is "high" and the technical capability is "medium" then there is a probability distribution that specifies what would be the reliability and technical capability level of S_2 in the next period. This probability distribution is the transition matrix that is used in the stochastic dynamic programming model. Here, we model the future yield as a stochastic function of technical capability and reliability separately. The supplier may have high technical capability, but there could be quality issues because of faulty processes and the overall reliability and yield may be low. Just pushing for higher technical capability may not finally lead to greater reliability. The buying firm, based on past data and its previous experience with S_2, would be able to construct this transition matrix. An illustrative transition matrix is shown in Fig. 3. Here, we have shown three levels of performance criteria, viz. "High," "Medium" and "Low," but in practice there could be multiple levels for measuring performance. Our model can be scaled up based on multiple levels of performance measuring criteria.

In our model, the buying organization needs to order quantity Q in each period. c_1 and c_2 denote the cost per unit of the component charged by S_1 and S_2, respectively. We also consider the availability of spot market from where the buying organization can get the remaining product quantity in case there is some shortfall due to supply disruptions. The spot market charges c_s per unit ($c_s > c_1 > c_2$). At the beginning of each period, the supply chain manager of the buying organization checks the reliability and technical capability score of S_2 based on the previous time period's performance (R_t and Y_t) and places an order x_t with the low-cost supplier. $Q - x_t$ is ordered from the high-cost supplier, S_1. The orders are received at the end of time period t(which also marks the beginning of time period $t+1$). The effective yield ($K_{R_{t+1}Y_{t+1}}$), i.e., fraction of the order (x_t) received from S_2, depends on the reliability and technical capability score of S_2 at the start of time period $t+1(R_{t+1}$ and $Y_{t+1})$. Dual sourcing occurs when $0 < x_t < Q$. If there is any shortfall from Q, then that is arranged from the spot market. S_2 is located in a low-cost sourcing country and hence is exposed to various kinds of political and

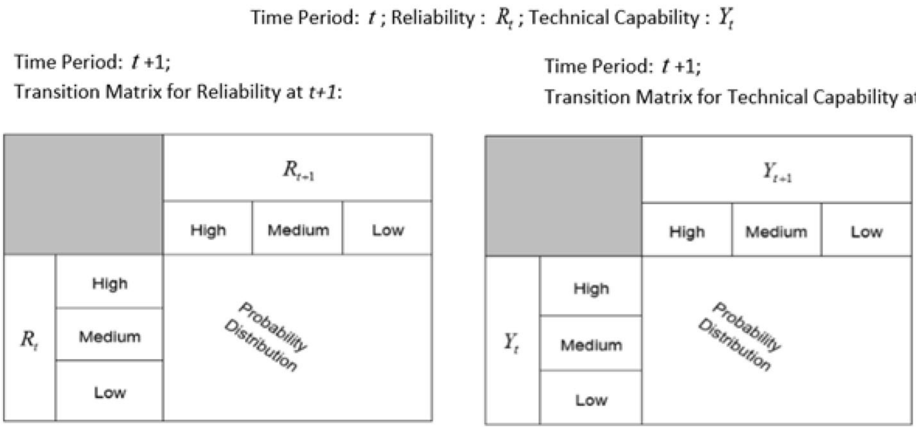


Fig. 3 Probability transition matrix depicting the reliability and technical capability of the low-cost supplier at $t + 1$

disruption risks. We assume that local disruptions may occur at S_2 at any time period leading to complete delivery disruption. Let λ denote the probability of disruption at S_2. Thus, $1 - \lambda$ is probability of no disruption at S_2. S_1 is a domestic supplier located in a developed economy, and hence we assume there is no supply disruption risk. The state of the stochastic dynamic programming model at any particular period is given by the reliability and technical capability score of S_2. The recursive relationship in our model is preserved by the transition matrix. The decision variable, i.e., the order size, is determined based on the reliability and technical capability values at any time point. The dynamics of the model is pictorially represented in Fig. 4.

Table 1 lists the variables used in the finite-horizon stochastic dynamic programming model.

The following recursive functional equation specifies the multi-period dual sourcing model:

$$
\begin{aligned}
f_t(R_t, Y_t) = \underset{x_t}{\text{Min}} \sum_{R_{t+1}, Y_{t+1}} & p(R_{t+1}, Y_{t+1} | R_t, Y_t)(1 - \lambda) \\
& \times \{c_1(Q - x_t) + c_2 K_{R_{t+1} Y_{t+1}} x_t \\
& + x_t(1 - K_{R_{t+1} Y_{t+1}}) c_S + f_{t+1}(R_{t+1}, Y_{t+1})\} \\
& + \lambda\{c_1(Q - x_t) + c_S x_t + f_{t+1}(L, L)\}
\end{aligned}
$$

The boundary condition is given by: $f_T(R_T, Y_T) = 0$ which implies that at the boundary there are no ordering decisions, and hence, there is no cost incurred at the boundary.

In the above model, we assume that when there is a supply disruption at S_2, i.e., when S_2 is unable to fulfill any orders, then the following time period, the reliability and the technical capability of S_2 become "L" that denotes the lowest possible level for technical capability and reliability. Therefore, once a supply disruption occurs at S_2, the following time period S_2 has to again start from the lowest level of reliability and technical capability score.

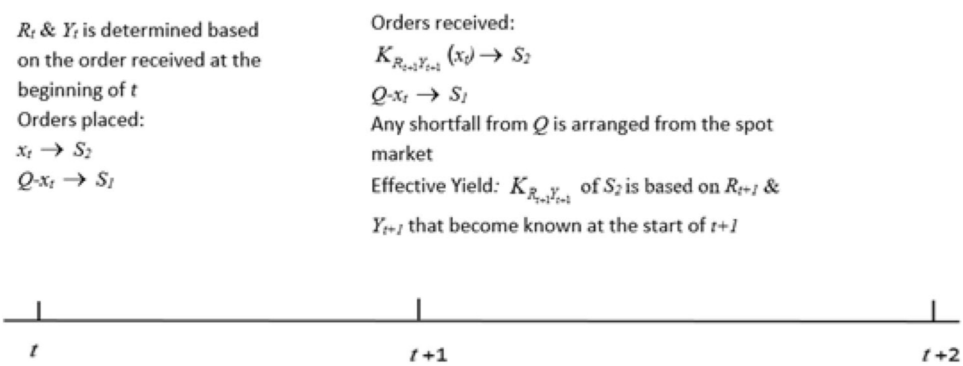


Fig. 4 Modeling framework

Table 1 Notations used in the stochastic dynamic programming model

Q	Amount ordered every time period
c_1	Cost per unit of supplier 1
c_2	Cost per unit of supplier 2
c_S	Cost per unit of spot market
x_t	Amount ordered from supplier 2
$K_{R_{t+1}Y_{t+1}}$	Fraction of order received from supplier 2
R_t	Reliability score of supplier 2 at time period t
Y_t	Technical capability score of supplier 2 at time period t
λ	Probability of disruption at supplier 2
$p(R_{t+1}, Y_{t+1} \vert R_t, Y_t)$	Probability of reliability and technical capability being R_{t+1} and Y_{t+1} at time period $t + 1$ given the reliability and technical probability is R_t and Y_t at t
f_t	Function calculating the minimum cost of procurement for the buying organization

Next, we derive important managerial insights based on numerical analysis of the above stochastic dynamic programming model.

Numerical insights and managerial implications

For the first set of numerical results, we assume that the low-cost supplier could be in any of the following five levels of reliability and technical capability states: "very high," "high," "medium," "low" and "very low." The probabilities for transitioning from any one of the above five states in a given time period to any other state in the next time period can be determined based on past performance of the supplier. The transition probability matrix used in the first set of analysis is given in the "Appendix." We first focus on the sourcing strategies under varying levels of supply disruptions from the low-cost supplier at different values of low versus high-cost sourcing and varying spot price conditions. We assume that the high-cost supplier is a reliable but costly supplier who does not face disruptions, whereas the low-cost supplier has a certain probability of supply disruption (λ).

We study three possible sourcing strategies, viz., low cost, high cost and dual sourcing. As mentioned earlier, local sourcing corresponds to high-cost sourcing and foreign sourcing corresponds to low-cost sourcing. The results of the above numerical study are provided in Fig. 5a–d. In Fig. 5a, b, we analyze the sourcing costs when the spot price of the component is high and in Fig. 5c, d we study the sourcing costs when the spot price of the component is relatively low. In Fig. 5a, b, we highlight the sourcing costs for the three sourcing strategies when the cost differential between the local and foreign supplier is high and low, respectively. We find that when the spot price of the component is high and the cost differential between low-cost and high-cost sourcing is also high, then at low probabilities of supply disruption of the low-cost supplier, dual sourcing clearly is the best strategy. However, as the probability of supply disruption of the low-cost supplier increases then high-cost sourcing becomes optimal. Implicitly, the above result means that as the probability of disruption of the low-cost supplier increases then the entire sourcing should take place from the high-cost supplier. Similar results hold when the cost differential between the low-cost and the high-cost supplier is low (Fig. 5b). From the above, we can conclude that when the spot price is high then low-cost sourcing is never optimal; dual sourcing is a dominant strategy when the cost differential is high and the probability of disruption of the low-cost supplier is low; under the other scenarios, high-cost sourcing provides maximum cost benefits. The intuition behind the above result is as follows: Here, the spot price is much higher than the price charged by the high-cost supplier and in Fig. 5a the cost differential between the high- and low-cost suppliers is also high. So, at low values of probability of disruption, dual sourcing becomes optimal and the sourcing strategy uses both low- and high-cost suppliers. However, as the probability of disruption of the low-cost supplier increases the cost associated

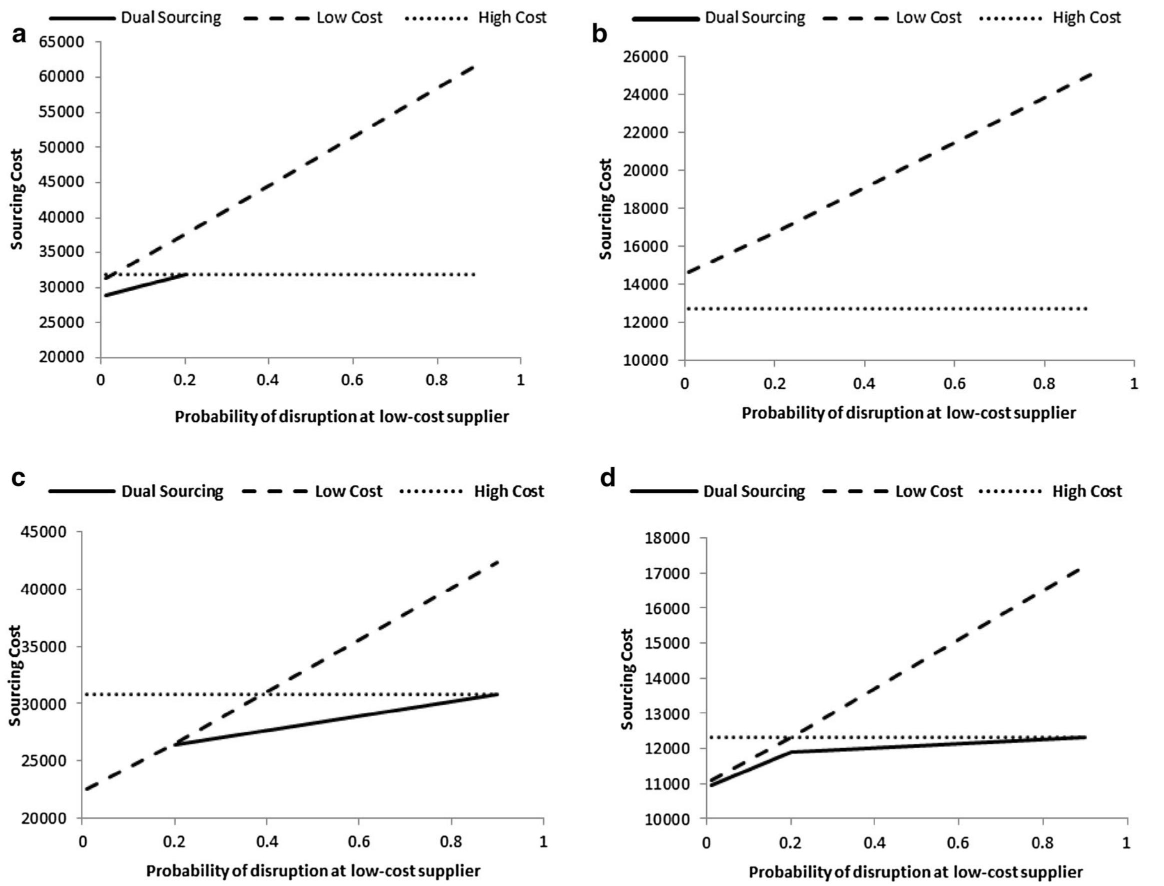


Fig. 5 Sourcing costs at different levels of supply disruption of the low-cost supplier under varying conditions of low- versus high-cost sourcing and spot price differentials

with using the low-cost supplier also increases as disruption is linked with using spot purchase, and hence, high-cost sourcing becomes cost beneficial. In Fig. 5b, the cost differential between the high- and low-cost suppliers is low, and therefore even at low values of probability of disruption of the low-cost supplier, high-cost sourcing clearly dominates.

Next, in Fig. 5c, d we analyze the sourcing costs when the cost differential between the suppliers is high and low, respectively, and spot prices are low. We find that when the spot price of the component is low and the cost differential between low- and high-cost sourcing is high then at low probabilities of disruption of the low-cost supplier, low-cost sourcing and dual sourcing provide the best options. On the other hand, as the probability of disruption increases then dual sourcing clearly is the best strategy (Fig. 5c). When the cost differential between low- and high-cost suppliers is low then dual sourcing clearly dominates the other two sourcing strategies (Fig. 5d). From the above, we can conclude that when the spot price is low and the cost differential between the local and foreign supplier is high then at low probability of disruption of the low-cost supplier, low-cost sourcing is optimal, whereas dual sourcing is clearly a dominant strategy under other scenarios, viz., low spot prices and low-cost differentials between low-cost and high-cost sourcing. The intuition behind the above results is as follows: Here, the spot price is not significantly higher than high-cost sourcing, so when the cost differential between the high and low-cost supplier is high (Fig. 5c), at low values of probability of disruption of the low-cost supplier, low-cost sourcing dominates. As the probability of disruption increases, high-cost sourcing becomes an important component of dual sourcing which dominates low-cost sourcing. In Fig. 5d, the cost differential between the high- and low-cost suppliers is low, so here even at low values of probability of disruption of the low-cost supplier, the high-cost supplier is used in the dual sourcing portfolio.

In the next set of results, we analyze the sourcing problem under different scenarios where the reliability and the technical capability of the low-cost supplier change from one state to another. In one scenario, we assume that the low-cost supplier's reliability and the technical capability changes drastically from one state to another, i.e., the probability of transitioning to another level of reliability and technical capability is very high. We call this the high-variance condition because the variance of the states in the transition matrix for this scenario is high. In the other scenario, we assumed that the variance between the different states is low, i.e., the reliability and the technical capability of the supplier do not change drastically. We compare the sizes of the order that the firm places to the low-cost supplier when variance between the future states of reliability and technical capability is high and when variance is low under different probabilities of supply disruption. The results are highlighted in Fig. 6.

We observe that when variance is low, the firm orders everything from the low-cost supplier at low probabilities of supply disruption. As the probability of disruption increases, the percentage of total order given to the low-cost supplier gradually decreases. When variance is high, the percentage of total order given to the low-cost supplier shows a much steeper fall and becomes zero at low probability of supply disruption. The above analysis leads to the conclusion that when the performance of the low-cost supplier is stable in terms of reliability and technical capability, then even at relatively higher probabilities of supply disruption, percentage of sourcing from the low-cost supplier is significant. However, if the performance of the low-cost supplier drastically changes from one state to another, then the percentage of sourcing from the low-cost supplier under dual sourcing falls strikingly.

Next, we analyze the order quantities given to the low-cost supplier under varying conditions of technical capability and reliability. Here, we assume that the low-cost supplier can be at any one of the following three levels of technical capability and reliability, viz., "high," "medium" and "low." We consider two cases: one where the probability of moving to another state, viz., technical capability and reliability, is high in the transition matrix and second where the probability of transitioning to another state is low. We denote the first condition as "variance high" state because in this case the probability of transitioning to another state is high and denote the second condition as "variance low." For example, in the "variance high" case if the low-cost supplier is currently at "high" levels of reliability and technical capability the probability of transitioning to "medium" and "low" states is 0.3 each, whereas in the "variance low" case if the low-cost supplier is currently at a "high" levels of reliability and technical capability the probability of transitioning to "medium" and "low" states is 0.1 each. The probability distributions used for this study are given in the "Appendix." We focus on the low-cost supplier's order size under the above two scenarios and varying levels of cost differential between the low cost and the spot market. We took five levels of cost differentials between the low cost and the spot prices starting with "very low" (denoted by "VL") where the spot prices are 20% more than the low-cost supplier's price and then increasing the cost differential by 10% (which we represent by "L" denoting low, "M" denoting moderate and "H" denoting high) and reaching a difference of 60% in the cost differential "very high" case (which we denote by "VH").

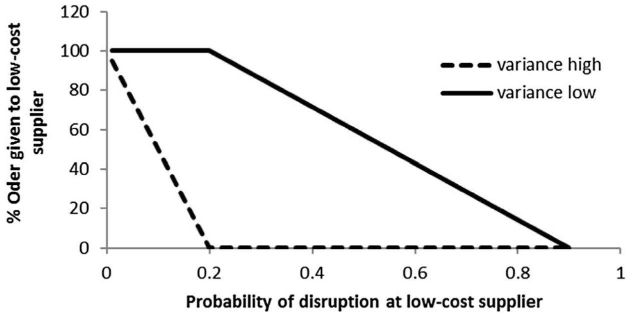


Fig. 6 Percentage of total order given to low-cost supplier under varying levels of reliability and technical capability conditions and probabilities of supply disruption

Our findings are presented in Fig. 7a–d. In Fig. 7a, the current technical capability and reliability scores of the low-cost supplier are both "high" based on past performance. Here, we find that when the variance is low, i.e., the probability of transitioning to another technical capability and reliability score is low, it is optimal to place 100% of the order to the low-cost supplier even when the cost differential between the low cost and the spot prices is very high. However, when the variance is high, the probability of transitioning to another technical capability and reliability score is high. In that case, the percentage of the total order given to the low-cost supplier reduces as the cost differential between the low cost and the spot prices increase and when the cost differential is high, nothing is ordered from the low-cost supplier. In the first case when the variance in the transition probability matrix is low, the probability that the low-cost supplier stays at high levels of technical capability and reliability is also high, and hence, 100% of the total order quantity is given to the low-cost supplier. On the other hand, when the variance in the transition probability matrix is high, the probability that the low-cost supplier moves to "medium" or "low" levels of technical capability and reliability from the current "high" level is also high, and hence, total order quantity given to the low-cost supplier reduces as the cost differential between the low cost and the spot prices increases.

In Fig. 7b, the current reliability score of the low-cost supplier is "high" and the technical capability score is "low." Whereas in Fig. 7c, the current technical capability score of the low-cost supplier is "high" and the reliability score is "low." Here, we find that as the cost differential between the low cost and the spot prices increases, the percentage of total order given to the low-cost supplier decreases. One interesting result unfurls as we compare Fig. 7b, c with a. In Fig. 7a, when the current reliability and

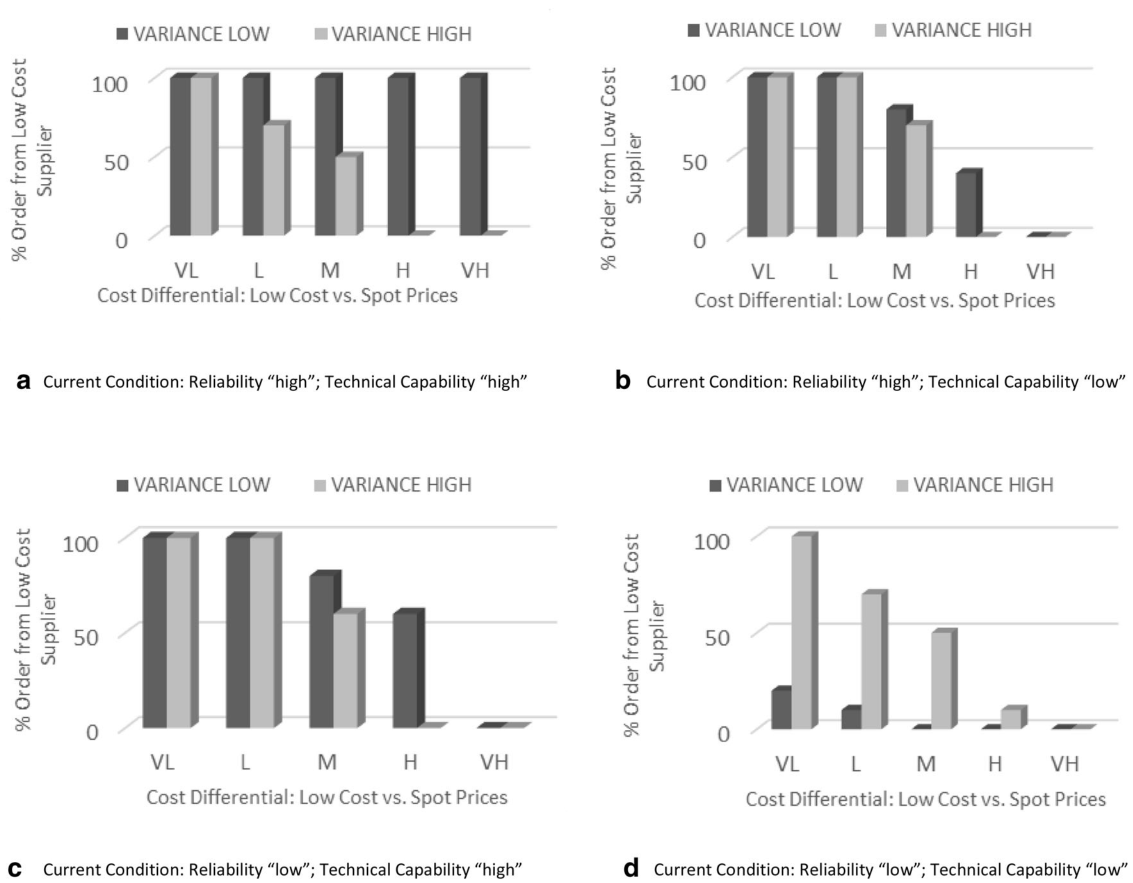


Fig. 7 Percentage of order quantity given to the low-cost supplier under varying transition probabilities and cost differentials between the low cost and spot prices

technical capability scores are high and the variance of the transition matrix is high then 70% and 40% of the total order quantity is given to the low-cost supplier when the cost differential between the low cost and spot prices is low and medium, respectively. In Fig. 7b, when the current reliability score is high and technical capability score is low and the variance of the transition matrix is high, then 100% and 70% of the total order quantity is given to the low-cost supplier when the cost differential between the low cost and spot prices is low and medium, respectively. So, the low-cost supplier's order quantities increase comparatively between Fig. 7a, b at similar levels of cost differentials when the variance between the states of the transition matrix is high. The interpretation of the above result is as follows. In Fig. 7a, the current reliability and technical capability scores are high; also, the variance in transition probabilities is high, and hence, there is a high probability that the reliability and technical capability scores transition to "medium" or "low" levels in future time periods. On the other hand, in Fig. 7b, the current reliability score is "high" and the technical capability score is "low" and the variance in transition probabilities is high, and hence even though there is a high probability that the reliability scores transition to "medium" or "low" levels, there is a high probability that the technical capability score transitions to "medium" or "high" in future time periods. In Fig. 7a, there is a high probability that the reliability and technical capability scores worsen in the future, whereas in Fig. 7b even though the probability that the reliability score worsens is high, the probability that the technical capability scores improve is also high. So, this explains why order quantities increase comparatively between Fig. 7a, b at similar levels of cost differentials when the variance between the states of the transition matrix is high. Similar results are observed in Fig. 7c when the current technical capability is high, and the reliability score is low and the variance between the states of the transition matrix is high.

In Fig. 7d, the current technical capability and reliability scores of the low-cost supplier are both "low" based on past performance. Here, we find that when the variance is low, i.e., the probability of transitioning to another technical capability and reliability score is low, the order quantity for the low-cost supplier is quite minimal. However, when the variance is high, i.e., the probability of transitioning to another technical capability and reliability score is high, the order quantities for the low-cost supplier are significantly higher. When the variance is low, the probability that the reliability and technical capability score remain at the current low level is also high. Hence, the order quantity for the low-cost supplier is minimal. On the other hand, when the variance in transition probabilities is high, there is a high probability that in future the technical capability and reliability score of the low-cost improve from the current low scores. Therefore, the low-cost supplier's order quantity significantly increases.

The above results will help the supply chain manager of a buying organization to formulate optimal sourcing strategies under probable supplier disruptions and stochastic conditions that determine performance metrics of the supplier.

Strategic sourcing decisions

In this section, we summarize the sourcing decisions presented in Fig. 5a–d under varying levels of supply disruption risk, spot price and cost differential between the suppliers. Based on the results, we construct Table 2 that identifies sourcing strategies that minimize total procurement cost for the buying organization.

From Table 2, we conclude that when the spot price is high and the cost differential between the high- and the low-cost supplier is high, then at low values of probability of disruption at the low-cost supplier, it is optimal for the buying organization to go for dual sourcing. However, as the probability of disruption at the low-cost supplier increases, high-cost sourcing becomes optimal. The reason for this is spot price is high, and hence, if there is supply disruption from the low-cost supplier then the shortfall has to be bought from the spot market and this increases the cost exorbitantly. Therefore, as the probability of disruption at the low-cost supplier increases, it is better to opt for the less-risky yet expensive high-cost sourcing. We also find that when the cost differential between the suppliers is low, then it is better to go for high-cost sourcing under high values of spot price. Here, since the spot price is high and the cost differential is low, there is no incentive to use the low-cost supplier.

Next, we focus on the scenarios where spot price values are low. When the cost differential is high,

Table 2 Strategic sourcing decisions under different probabilities of supply disruption, spot prices and cost differential between the suppliers

	Spot price			
	High		Low	
	Cost differential			
	High	Low	High	Low
Prob. of disruption at low-cost supplier				
Low	Dual sourcing	High-cost sourcing	Low-cost sourcing	Dual sourcing
High	High-cost sourcing	High-cost sourcing	Dual sourcing	Dual sourcing

under low values of probability of disruption at the low-cost supplier, it is optimal to go for low-cost sourcing. Here, since the probability of disruption at the low-cost supplier is low and the spot price is also low, the buyer can take the risk of low-cost sourcing. However, as the probability of disruption at the low-cost supplier increases, it is better to opt for dual sourcing. On the other hand, if the cost differential is low, then it is optimal to go for dual sourcing even at lower values of probability of disruption at the low-cost supplier. Since the cost differential is low, the cost of involving the high-cost supplier is not much compared to the risk of only employing the low-cost supplier, and hence, dual sourcing becomes optimal.

The above table provides important strategic sourcing decisions for the buying organization under different practical scenarios.

Conclusions and future research directions

Modern supply chains are complex networks made up of multiple entities spanning the entire globe. In these complex supply chain networks, risks exist in every link and managing these risks have become extremely critical in the context of today's globalized supply networks. There have been numerous instances where supply chains have been adversely affected because of unforeseen supply disruptions leading to irreparable damages. The selection of a sourcing strategy plays a vital role in managing supply disruptions in global supply chains. The choice regarding the number of suppliers is one of the most important decisions in mitigating supply side risks. In the recent past, the emergence of supply chain risk mitigation as a key issue has caused many procurement managers to reassess their reliance on single sourcing strategies. Despite the benefits cited in the literature for single sourcing, there is enough evidence that provides justification for using dual sourcing as a risk mitigating policy. Supplier rating based on performance measures is an important component for shaping supplier selection decisions and sourcing strategies of a firm. Selecting the right supplier is a complicated task as it involves considering different criteria. In this paper, we first conducted a survey among supply chain managers in India to identify key supply chain issues. We find that supply disruption risk is one of the most challenging factors that confront supply chains of today. Motivated by these findings, we develop a stochastic dynamic programming model to formulate the sourcing problem and derive various managerial insights under different scenarios of supply disruptions. We integrate the supplier rating mechanisms in our supplier selection and sourcing choice problem. We analyze sourcing decisions under different scenarios based on changing spot prices, cost differential between the low- and high-cost supplier and varying levels of probability of disruption at the low-cost supplier. We find that when spot prices are high and the cost differential between the low- and the high-cost suppliers is low, high-cost sourcing is the optimal choice. However, when the cost differential is high then it is better to go for dual sourcing at low values of probability of disruption at the low-cost supplier and switch to high-cost sourcing as the probability of disruption at the low-cost supplier increases. Therefore, under high values of spot prices, sourcing strategies are driven by risk mitigation rather than low-cost objectives and the focus is more on high-cost sourcing. On the other hand, for low values of spot prices, we find that dual sourcing plays a dominant role except at low values of probability of disruption at the low-cost supplier and high-cost differential between the suppliers, wherein low-cost sourcing becomes optimal. Under low values of spot price, the buyer opts for dual sourcing hedging the risks of supply disruption with the associated costs and under high-cost differential the buyer is ready to take supply disruption risks and focus on minimizing cost.

We also derive the optimal split of the order size between the low-cost and the high-cost supplier under dual sourcing and analyze the ordering decisions as the performance of the low-cost supplier varies. We measure performance of the supplier in terms of reliability and technical capability. We further study the split of order quantities given to the low-cost supplier under varying levels of technical capability and reliability. We believe our analysis will help the supply chain manager(s) of a buying organization formulate optimal sourcing strategies under the threat of supplier disruptions and performance metrics of the supplier that change stochastically with time.

In the present paper, we have not considered any capacity constraints at the supplier end. In the future, we would like to analyze the sourcing problem in a dynamic setting with supplier capacity constraints. Here, we have only looked at the problem from the buying organization's perspective. In a future research project, the supply chain implications under a game theoretic setting may be analyzed where the suppliers can be strategic and can determine their selling prices under dual-sourcing mechanisms. Incorporating learning into the dual-sourcing decisions based on the order fulfillment at each time period can be another interesting future research endeavor.

Appendix

Transition matrixes

	Transition matrix: technical capacity				
	Very high	High	Medium	Low	Very low
Very high	0.3	0.2	0.2	0.15	0.15
High	0.2	0.3	0.2	0.15	0.15
Medium	0.15	0.2	0.3	0.2	0.15
Low	0.15	0.15	0.2	0.3	0.2
Very low	0.15	0.15	0.2	0.2	0.2

	Transition matrix: reliability				
	Very high	High	Medium	Low	Very low
Very high	0.3	0.2	0.2	0.15	0.15
High	0.2	0.3	0.2	0.15	0.15
Medium	0.15	0.2	0.3	0.2	0.15
Low	0.15	0.15	0.2	0.3	0.2
Very low	0.15	0.15	0.2	0.2	0.2

Effective yield					
	Technical capability				
	Very high	High	Medium	Low	Very low
Reliability					
Very high	90%	80%	70%	40%	20%
High	80%	65%	55%	30%	15%
Medium	70%	55%	45%	25%	10%
Low	40%	30%	25%	20%	8%
Very low	20%	15%	10%	8%	5%

Transition matrix: Variance "High"

Transition matrix: reliability			
	High	Med	Low
High	0.4	0.3	0.3
Med	0.3	0.4	0.3
Low	0.3	0.3	0.4

Transition matrix: technical capability			
	High	Med	Low
High	0.4	0.3	0.3
Med	0.3	0.4	0.3
Low	0.3	0.3	0.4

Transition matrix: Variance "Low"

Transition matrix: reliability			
	High	Med	Low
High	0.8	0.1	0.1
Med	0.1	0.8	0.1
Low	0.1	0.1	0.8

Transition matrix: technical capability			
	High	Med	Low
High	0.8	0.1	0.1
Med	0.1	0.8	0.1
Low	0.1	0.1	0.8

Effective yield			
	Technical capability		
	High	Med	Low
Reliability			
High	90%	80%	40%
Med	80%	70%	30%
Low	40%	35%	20%

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