Dual versus Triple Sourcing: Decision-making under the Risk of Supply Disruption

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Abstract: This paper studies three different strategies of sourcing. The whole process of this research including the problem definition is exactly based on a real case condition. This paper model sourcing process of required parts and material for a product which is manufactured under the license of Peugeot Company, the mother manufacturer in France. Based on the agreement between Peugeot and the manufacturer in Iran, all the parts should be supplied from a certified suppliers of the mother company. This paper investigates a single product setting in which a firm can source from multiple suppliers. One supplier has unreliable capacity but it is the first choice of supply because of being in partnership with Peugeot and the opportunity for future cooperation, while other suppliers are reliable but with lower product quality and not in direct relation with Peugeot. The addressed context, in which a case study has been made, is disruption due to sanctions which cause failure in the sourcing from the unreliable supplier. The main focus of current work is on defining the share of each supplier, and finding suitable sourcing policy (single, dual or triple sourcing) to apply for different probabilities of disruption. The paper is concludes in sensitivity analysis of different parameters such as set-up cost, and reveals their impact on final suggested strategy of sourcing.

Key-Words: supply chain disruption, dual-sourcing, triple-sourcing, supply disruption, sanctions, real case modeling.

1 Introduction

Regarding the complex and dynamic environment of supply chains, uncertainty (generally termed “risk”) has been raised as an important concern in literature. The reported dramatic outcomes from risky events demonstrate the importance of proactively managing supply chain risk [1].

Among the supply chain risks types are disruptions that result from natural disasters, labour disputes, supplier bankruptcy, acts of war and terrorism [2]. Naturally, different authors may suggest dissimilar sources for disruption risks, but disruption risks generally have a low probability and the potential for a large loss. Some papers refer to these as “catastrophic events” [3]. These risks can seriously disrupt or delay material, information and cash flows, any of which can damage sales, increase costs or both. How a company fares against such threats depends on the type of disruption and the organization’s level of preparedness. Supply chains can take complementary actions to be prepared for such events [4]. They can secure their supply chain or develop resiliency to perform recovery plans immediately after disruption. Both can be performed in many different ways, and there is no single best solution. The problem for managers is to choose a good strategy and to quantify the benefits of various options.

Researchers addressed different mitigation [4-7] and contingency [8] strategies to reduce the impacts of disruptions. But the problem is lethal when a single source of the firm is disrupted and cannot continue its role anymore. So, in such situation the sourcing process is not disrupted for limited time and managers of the buyer company should replace that disrupted source.

When a supplier is likely to be disrupted, it is not reasonable to work with it [8], but the working environment is dynamic and a supplier with acceptable reliability may face serious problems which prevent it from delivering the orders. For instance the global financial recession contributed to the failure of key businesses, declines in consumer wealth estimated in the trillions of U.S. dollars, substantial financial commitments incurred by governments, and a significant decline in economic activity [9] which caused bankruptcy declaration by even major companies [10]. Another specific situation caused by political issues, is when companies in different countries are banned to cooperate and run business with each other. This situation, called sanction, is the context of this paper. In the studied case of this paper, the buyer is an automotive manufacturer in Iran which supplies some of its parts from European companies. Because of political issues, some suppliers have the risk of not being allowed to be in business activities with Iranian manufacturer. But this process is not based on a sudden event; the probability of supplier failure is very low in natural situation but after the rise of unpredictable political problems, one possible reaction of countries is to impose sanction which causes serious problems in seller-buyer relationships. After occurrence of specific political problems, the probability of supplier failure due to sanction grows rapidly and buyers should make decision on how they will continue sourcing after disruption. In this case, a disruption with very low probability and tremendous impact becomes a disruption with high probability and significant influence in a short period of time, which is the critical time for decision making. It is important to mention that as the occurrence of sanctions is still a probabilistic event, even after sharp increase in its likelihood it is possible that politicians reach an agreement and the problem is solved so the probability will fall down after it was peaked. Hence the decision making becomes more crucial. Similar problem is the situation of supplier bankruptcy; before bankruptcy declaration, the probability of supplier failure can be estimated and if the buyer is aware, it can plan a substitute supply policy.

This paper studies a single product setting in which a firm can source from multiple suppliers. One supplier provides high quality product but may have the risk of failure and unreliable capacity while other suppliers are reliable with lower product quality. The buyer is more willing to work with the first one which motivates him to take certain level of risk. The addressed context is disruptions due to sanctions that cause failure for an Iranian automotive manufacturer in the supply from the unreliable European source. The important question which emerges here is how the companies should use different strategies for single/dual/multiple sourcing to handle those potential disruptions. Previous studies represented the idea of dual sourcing as a mitigation strategy [4] and rerouting as a contingency strategy [8], but in their works disruption would not last until the end of study-horizon; while in this research sanction is a rare but long disruption and influences the strategic decisions. In addition probability of sanction in routine situation is really low but in special circumstances it rises so the decision making should be done if this growth of probability occurs.

In this paper two possible strategies are addressed and compared, which are dual and triple sourcing. Dual sourcing provides the firm with the opportunity of rerouting the supply source after disruption to a lower quality Far-East supplier. However, problems of monopoly rise after the disruption and the buying firm lose bargaining power. In this situation, the remaining supplier could increase/renegotiate the prices due to the monopoly situation; previous experiences of studied case warn such possibilities. Whereas, in triple sourcing, the setup cost could be higher due to an additional supplier, but after the disruption there would still be competition between two remaining suppliers and the price would not increase unreasonably.

Further, already when asking for future prices, the buyer could screen the proposed prices offered for non-sanction and sanction scenarios and potential renegotiation closures. The scenarios of being one of two versus three suppliers would affect the suppliers' offers.

The main focus of current work is on defining the share of each supplier, and also which sourcing policy (dual or triple) to apply for different probabilities of disruption. In dual sourcing option, supply share should just be calculated before disruption. The problem for triple sourcing is vaster and the step of calculating supply share before disruption is followed by investigating supply share after disruption. The above decisions are made to minimize the long run average cost and in both options, the main costs are categorized into set-up cost, ordering cost, quality cost and lost order cost. Research questions are: For which probabilities of disruption the triple sourcing strategy would be more cost effective? And what is the share of each supplier under each scenario?

The remaining sections of this article are organized as follows: In section 2, supply chain disruption studies and existing methods neutralizing supplier failure are reviewed. Section 3 introduces the proposed model. Section 4 presents an empirical study which is followed by sensitivity analysis of model in section 5 to make decision on optimal disruption management strategies. Finally, the paper concludes with a brief summary in Section 6.

2 Literature Review

The occurrence of a disruptive event is an extraordinary and unusual situation. Supply chain disruption can result from an internal or external source, and can thus occur under a wide range of intrinsically different circumstances. For instance, a supplier financial fault and a natural disaster (i.e., earthquake or flood) can both affect production capacity, but these two situations are completely different in terms of their likelihood, predictability, frequency and recovery time. Because of these differences, the disruptions can have different outcomes.

While a significant amount of research has been conducted in the area of supply-chain systems, there has been relatively little research reported in the important area of understanding the system-wide or global impacts of supply chain disruptions [11]. Along these lines, Lee and Wolfe [12] presented strategies for reducing vulnerability to security losses that may cause disruptions. Kleindorfer and Saad [13] introduced a conceptual framework to estimate and reduce the effects of disruptions. Norrman and Jansson [14] studied a fire accident at Ericsson Inc.'s sub-supplier and the company's solution to mitigate the likelihood of such events as an proactive plan. Tang [5] proposed robust strategies for mitigating disruption effects, and Pochard [4] discussed an empirical solution based on dual-sourcing to mitigate the likelihood of disruptive events. Marley [6] discussed lean management, integrative complexity and tight coupling, as well as their relationships with disruption effects. Papadakis [15], based on an empirical analysis, shed light on the financial implications of supply chain design, particularly on the differences between pull- and push-type designs. The focus of their study was on risk exposure to difficult-to-foresee supply disruptions, like those resulting from natural or man-made disasters. Hendricks and Singhal [16] estimated the effect of supply chain glitches, which causes production or shipment delays, on shareholder wealth In another research, Hendricks and Singhal [17] showed that supply chain disruptions have negative impacts on financial performance measures, as well as on operating income and return on assets. Craighead et al. [7] illustrated the relationship between supply chain structure and disruption severity based on their observations from different case studies. Yu and Qi [18] presented literature related to supply chain disruptions and demonstrated mathematical models for demand disruptions while Qi et al. [19] examined quantity discount policy when demand disrupts. Xiao and Yu [20] developed an indirect evolutionary game model with two vertically integrated channels to study evolutionarily stable strategies (ESS) of retailers in quantity-setting duopoly situations with homogeneous goods and analysed the effects of demand and raw material supply disruptions on the retailers' strategies. Xiao et al. [21] investigated the coordination mechanism of a supply chain with one manufacturer and two competing retailers when the demands are disrupted and based their investigation on different scenarios for the problem and for discount strategies. Similarly, Xiao and Qi [22] studied the coordination of a supply chain with one manufacturer and two competing retailers after the production cost of the manufacturer was disrupted. Tomlin [8] suggested two different groups of strategies, mitigation and contingency, prior to a disruption and discussed the values of these two choices for managing a supply chain disruption. Chopra et al. [23] focused on the importance of decoupling recurrent supply risk from disruption risk and of planning appropriate mitigation strategies; they showed that bundling the two uncertainties leads a manager to underutilize a reliable source while over-utilizing a cheaper but less reliable supplier.

In general, because of the unpredictability and complex effects of disruption, some researchers [3, 14] choose proactive approaches. A catastrophic event has a very low probability of occurrence, but significant consequences if it does occur [3], and supply chains are increasingly vulnerable to catastrophic events such as hurricanes or terrorist attacks. This is not only true because firms are more exposed to catastrophes, but also because of investments made in recent years to operate supply chains with fewer human and capital resources, especially inventory. Consequently, there is less "slack" available in supply chains to deal with catastrophic events, and proactively planning for these types of events should be a priority for supply chain managers.

Although, single sourcing improves communication due to close buyer-seller relationship and could cause lower cost as a consequence of economy of scale [24]; the uncertainty of a specific buying-selling situation makes dual/multiple sourcing a reasonable strategy. But it is crucial to find out with which level of uncertainty supply chain should shift to dual/multiple sourcing. One of the main contributions of this paper is to answer this question which helps managers to make strategic sourcing decisions.

3 Proposed Model

As illustrated earlier, this paper is focused on decision making process of sourcing when the buyer company is located in a region which is faced global sanctions; few examples of those countries are Brazil, Argentina, South Africa, Iran and Iraq. All the assumptions of this research are based on experienced events in the investigated company to reflect real context. All the designed sanctions against the studied country have had military targets but other industries have been suffered as well. Procurement of parts in automotive industry can be mainly influenced by sanction in two ways, first is because of the limitations on banks and financial organizations of the target country which causes problems for monetary transactions, and second is because of possibility of dual usage of some parts in military and nuclear industries besides automotive industry. So, the studied buyer is not target of sanctions and its procurement activities might be immune but because of the two aforementioned reasons, there is always the risk of being hit by sanctions.

In order to fight against potential risks of sanctions, the buyer company has two choices either to contract a local supplier or a reliable source in one of the ally countries. The first option is not usually available because of high investment cost and impossibility to launch production line due to limitation on import of technology and equipment to the sanctioned country. This condition brings up the second option as a viable strategy. In this context, if the buyer chooses to have more than one supplier, appropriate share for each of them is the matter question. This question is being answered by proposed model in this section. According to the possibility of occurring monopoly problems after disruption, triple sourcing strategy is also being considered. More detailed reasoning behind this strategy has been presented in introduction section. Main goal of the buyer in this study is to reduce the expected cost and keep the procurement process running. Goal function of this model either in dual or triple sourcing is divided into four main categories of costs:

- C_1- Ordering cost: The cost of buying parts from suppliers based on different unit-price of each supplier. Unit-price is defined as the price for one unit of a purchased product.
- C_2- Quality cost: one of the characteristics of the alternative suppliers of the studied buyer in Far East Asia is their lower quality in comparison to the main supplier in Europe which imposes additional quality cost. So we assume if the whole demand is supplied from the first source, the base quality cost is zero, otherwise this cost will be calculated based on the amount of supplied parts from alternative suppliers. The effect of low quality is generally on the amount of broken parts and reworks so it has a linear relation with the amount of production.
- C_3- Lost order cost: Based on the assumption of this work, all the unmet demand is lost and will not be backordered. So, by losing every single customer order, the company loses the opportunity of earning revenue which is called “lost order cost” in this paper. Lost orders are two types, (a) unmet demand due to the under-estimation of demand, (b) lost order caused by lack of required material due to the problems of disruption. The first type is the same in all sourcing policies and is based on the ordering policy and decision on amount of order in each period, so it would not be considered in the proposed model. But the expected cost of the second scenario is calculated.
- C_4- Set up cost: The more suppliers, the more set-up cost will be imposed. In this paper, set-up cost has a linear relation with the number of suppliers so adding a new source/supplier imposes a fixed cost as set-up cost. This cost includes but is not limited to negotiation and transaction costs.
- C- Total cost: sum of C_1, C_2, C_3 and C_4.

In this model the firm operates in an infinite horizon, with complete lost order for unmet demand where there is not any capacity constraint for suppliers. In both sourcing strategies (dual or triple sourcing) following parameters exist:

F: Fixed cost of starting a relation with a supplier and placing orders

D_t: Demand in period t

b: Lost order cost at the end of a period per unit of unsold product

p: The rate of quality cost per unit if firm buys from alternative suppliers

z_i: Amount of lost orders due to lack of required material at the beginning of period *i* because of sanction problems

π_1 : Probability of disruption in a period

$\pi_0 = 1 - \pi_1$: Probability of having a period without disruption

$[x]^+$: The first integer number which is greater or equal to *x*

The firm has one unreliable supplier which may fail down due to a disruption caused by sanction and if it goes down it will never be available in the time horizon of long term planning. Before presenting two models of dual and triple sourcing, single sourcing as the basis plan will be illustrated in next section. Currently the buyer has single sourcing relation with the supplier in Europe which makes it valuable to estimate expected average cost of this strategy in comparison to the suggested two other sourcing strategies.

3.1 Single sourcing

Part prices supplied from each supplier is defined as follows:

c_u : Part price, supplied from first source (which is the unreliable supplier)

c_r: Part price, supplied from second source (which is the reliable supplier with lower quality)

If the firm chooses single sourcing strategy with the main supplier, the total long-run average cost includes (1) ordering cost based on the part price which is calculated for the periods without disruption, (2) lost order cost based on the expected amount which cannot be supplied during disruption, and (3) set-up cost for the periods without disruption. As the negotiation and transaction costs are included in set-up cost, these cost are imposed just in the periods without disruption in which buyer is working with the supplier. In this situation the long-run average cost would be:

$$C^{av} = D^{av} c_u \pi_0 + bD^{av} \pi_1 + F\pi_0 \quad (1)$$

But if the firm chooses single sourcing from the alternative supplier, total long-run average cost includes (1) ordering cost based on the part price, (2) quality cost, and (3) set-up cost, calculated as follows:

$$C^{av} = D^{av} c_r + pD^{av} + F \quad (2)$$

3.2 Dual sourcing

Based on the primary assumption, there are two alternative sourcing strategies: dual and triple sourcing; and each of them has specific parameters and decision variables. The dual sourcing variables and parameters are as follows:

w: Supply share of second supplier before disruption

c_u : Part price before disruption, supplied from the first source (which is the unreliable source)

c_r: Part price before disruption, supplied from the second source (which is the reliable source with lower quality)

c_f: Part price after disruption, supplied from the second source

q_u^i: Supplied quantity from the first source during period *i*

q_r^i: Supplied quantity from the second source during period *i*, based on its regular supply share

q_f^i: Supplied quantity from second source during period *i*, from its flexible capacity

Experiences of studied buyer show the second source may evade providing parts with c_r price after disruption even for its regular share and insist to set the contract terms in a way that part price increases to c_f after disruption for all the demand. So, according to the second supplier's price for the parts after disruption, two different assumptions can be made which divides the modelling into two scenarios:

(I) D-A- second supplier keeps the price for the share of *w*, on c_r even after disruption and delivers the additional demand with the price of c_f

(II) D-B- second supplier increases the price of whole demand to c_f after disruption

Two sub-scenarios of (D-A-1) and (D-B-1) would emerge when $b < c_f$; while (D-A-2) and (D-B-2) would be the result of having $b \geq c_f$. The two scenarios of (D-A-1) and (D-B-1) are the same; because in the condition of $b < c_f$, lost order cost is less than imposed cost of rerouting and the buyer prefers to lose the order rather than supplying from the flexible capacity of the second supplier. Hence, the question is on determining the share of each supplier before disruption which will remain fixed after disruption for the alternative supplier. In both (D-A-1) and (D-B-1), the decision is similar and average ordering quantity to alternative supplier is:

$$q_r^{av} = wD^{av} \quad (3)$$

where, D^{av} is the average demand per period. In similar way the long-run average ordering quantity to the main supplier is:

$$q_u^{av} = (1-w)D^{av}\pi_0 \quad (4)$$

If the lost order cost is less than the imposed cost due to using flexible capacity of alternative supplier (in D-A-1 and D-B-1), amount of the rerouted parts would be zero and lost orders increase, so:

If $b < c_f$ then

$$q_f^{av} = 0 \; and \; z^{av} = (1-w)D^{av}(1-\pi_0) \tag{5}$$

Hence,

$$C^{av} = C_1^{av} + C_2^{av} + C_3^{av} + C_4^{av} = wD^{av}c_r + (1-w)D^{av}\pi_0 c_u + wD^{av}p + (1-w)D^{av}\pi_1 b + [1-w]^+ F\pi_0 + [w]^+ F \tag{6}$$

Moreover, when the second supplier keeps the price of share of w, on c_r and supplies additional demand with the price of c_f (D-A-2) the order quantities is calculated as below:

$$q_u^{av} = (1-w)D^{av}\pi_0 \tag{7}$$

$$q_r^{av} = wD^{av} \tag{8}$$

and $q_f^{av} = (1-w)D^{av}\pi_1$ (9)

So, all the demand will be rerouted to the alternative supplier and there is not any lost order due to sanction and the long-run average costs would be:

$$C^{av} = C_1^{av} + C_2^{av} + C_3^{av} + C_4^{av} = wD^{av}c_r + (1-w)D^{av}\pi_0 c_u + (1-w)D^{av}\pi_1 c_f + \left((1-w)D^{av}\pi_1 + wD^{av}\right)p + [1-w]^+ F\pi_0 + [w]^+ F \tag{10}$$

The second possible option of parts pricing is to increase the price of whole demand to c_f after disruption (D-B-2). Under this circumstance, the average supplied parts from the main supplier (q_u^{av}) is $(1-w)D^{av}\pi_0$; q_r^{av} and q_f^{av} as the average amount of supplied parts from routine and flexible capacity of alternative supplier are $\pi_0 wD^{av}$ and $D^{av}\pi_1$ respectively. Hence, the average long-run costs would be:

$$C^{av} = C_1^{av} + C_2^{av} + C_3^{av} + C_4^{av} = w\pi_0 D^{av}c_r + (1-w)D^{av}\pi_0 c_u + D^{av}\pi_1 c_f + \left(\pi_1 D^{av} + \pi_0 wD^{av}\right)p + [1-w]^+ F\pi_0 + [w]^+ F \tag{11}$$

The illustrated model can calculate the average expected cost under the threat of disruption based on its probability and cost related parameters e.g. part price and set-up cost. It is reasonable to choose the strategy with the minimum cost; but decision makers may add some tacit parameters which influence final decision. Process of decision making will be discussed in later sections.

3.2 Triple sourcing

While there are numerous papers on single/dual sourcing [4, 24-26] to find the proper answer for the best number of suppliers, only few researchers have worked on multiple sourcing [27, 28] and its mathematical formulations [29]. Most of the companies prefer to reduce number of suppliers to decrease the material supplying cost by omitting the unnecessary set-up and negotiation costs. Hence the dominant strategies are single and dual sourcing. When the risk of supplier failure is high, companies tend to dual sourcing but what if one supplier goes down and the remained one causes serious problem due to its position as a single source. Problems of monopoly are crucial when because of political instability or high bargaining power of the seller, the buyer firm should accept special contract conditions to receive the parts, e.g. the supplier may put the statement of continuing relationship based on stability of environmental and political issues in contract, which let them to renegotiate or terminate the contract in the case of mentioned situations due to sanctions. One possible solution for this problem is to set sourcing strategy on triple sourcing which causes competition between two alternative suppliers and bring down the probability of renegotiation. In addition, this strategy leads to price competition to prevent price increase. Consequently, even if triple sourcing increases the set-up cost, it reduces the risk of monopoly problems and as a part of strategic decision making on number of suppliers, this option should also be explored. In addition to overall defined variables and parameters, the triple sourcing parameters and variables are listed below:

w_{r1}: Supply share of the first alternative supplier before disruption

w_{r2}: Supply share of the second alternative supplier before disruption

c_{r1}: Part price before disruption, supplied from the first alternative source (which is the reliable source with lower quality)

c_{r2}: Part price before disruption, supplied from the second alternative source (which is the reliable source with lower quality)

c_{f1}: Part price after disruption, supplied from the first alternative source

c_{f2}: Part price after disruption, supplied from the second alternative source

q_u^i: Supplied quantity from the main source during period i

q_{r1}^{i}: Supplied quantity from the first alternative source during period *i*, based on its regular supply share

q_{r2}^{i}: Supplied quantity from the second alternative source during period *i*, based on its regular supply share

q_{f1}^{i}: Supplied quantity from the first alternative source during period *i*, from its flexible capacity

q_{f2}^{i}: Supplied quantity from the second alternative source during period *i*, from its flexible capacity

Similar to the previous option (dual sourcing) alternative sources may evade supplying with their normal price after disruption even for their regular share, so the problem should be divided into two scenarios with an additional assumption:

(1) scenario T-A: alternative suppliers supply the share of w_{r1} and w_{r2} before disruption with the price of c_{r1} and c_{r2} respectively which remains fixed after disruption and additional demand is supplied with a higher price (c_{f1} and c_{f2});

(2) scenario T-B: alternative suppliers will not supply with their base price after disruption and increase the price to c_{f1} and c_{f2}. Furthermore, relation of lost order cost and part prices after and before disruption emerge four sub-scenarios as follows:

- T-A-1 and T-B-1: if $b < c_{f1}, c_{f2}$
- T-A-2 and T-B-2: if $b \geq c_{f1}, c_{f2}$
- T-A-3 and T-B-3: if $c_{f1} \leq b < c_{f2}$
- T-A-4 and T-B-4: if $c_{f2} \leq b < c_{f1}$

The average ordered quantity to each supplier in T-A-1 and T-B-1 sub-scenarios is as follows:

$$q_{r1}^{av} = w_{r1} D^{av} \tag{12}$$

$$q_{r2}^{av} = w_{r2} D^{av} \tag{13}$$

$$q_{u}^{av} = w_{u} D^{av} \pi_0 \tag{14}$$

where,

$$q_{f1}^{av} = q_{f2}^{av} = 0 \tag{15}$$

So the lost order due to disruption is equal to:

$$z^{av} = w_u D^{av} \pi_1 \tag{16}$$

As a result, the long-run average costs would be:

$$\begin{aligned} C^{av} &= C_1^{av} + C_2^{av} + C_3^{av} + C_4^{av} = \\ & w_{r1} D^{av} c_{r1} + w_{r2} D^{av} c_{r2} + w_u D^{av} \pi_0 c_u \\ & + (1 - w_u) D^{av} p + w_u D^{av} \pi_1 b \\ & + [1 - w_{r1} - w_{r2}]^{+} F \pi_0 + [w_{r1}]^{+} F + [w_{r2}]^{+} F \end{aligned} \tag{17}$$

In the same way as previous sub-scenarios, the assigned share and quantity to each supplier can be formulated. So the total long-run average cost for each scenario would be:

$$\begin{aligned} & \text{Total long-run average cost for T} - \text{A} - 2 = \\ & w_{r1} D^{av} c_{r1} + w_{r2} D^{av} c_{r2} + w_u D^{av} \pi_0 c_u \\ & + w_{f1} D^{av} \pi_1 c_{f1} + w_{f2} D^{av} \pi_1 c_{f2} \\ & + [1 - w_u + (w_{f1} + w_{f2}) \pi_1] D^{av} p \\ & + [1 - w_{r1} - w_{r2}]^{+} F \pi_0 + [w_{r1}]^{+} F + [w_{r2}]^{+} F \end{aligned} \tag{18}$$

$$\begin{aligned} & \text{Total long-run average cost for T} - \text{A} - 3 = \\ & w_{r1} D^{av} c_{r1} + w_{r2} D^{av} c_{r2} + w_u D^{av} \pi_0 c_u \\ & + w_u D^{av} \pi_1 c_{f1} + [1 + (\pi_1 - 1) w_u] D^{av} p \\ & + [1 - w_{r1} - w_{r2}]^{+} F \pi_0 + [w_{r1}]^{+} F + [w_{r2}]^{+} F \end{aligned} \tag{19}$$

$$\begin{aligned} & \text{Total long-run average cost for T} - \text{A} - 4 = \\ & w_{r1} D^{av} c_{r1} + w_{r2} D^{av} c_{r2} + w_u D^{av} \pi_0 c_u \\ & + w_u D^{av} \pi_1 c_{f2} + [1 + (\pi_1 - 1) w_u] D^{av} p \\ & + [1 - w_{r1} - w_{r2}]^{+} F \pi_0 + [w_{r1}]^{+} F + [w_{r2}]^{+} F \end{aligned} \tag{20}$$

$$\begin{aligned} & \text{Total long-run average cost for T} - \text{B} - 2 = \\ & w_{r1} D^{av} \pi_0 c_{r1} + w_{r2} D^{av} \pi_0 c_{r2} + w_u D^{av} \pi_0 c_u \\ & + D^{av} \pi_1 \left[\min \left\{ \begin{array}{l} (w_{f1} c_{f1} + w_{f2} c_{f2}), \\ (w_{r1} c_{r1} + (1 - w_{r1}) c_2), \\ ((1 - w_{r2}) c_{f1} + w_{r2} c_{r2}) \end{array} \right\} \right] \\ & + D^{av} (1 - w_u \pi_0) p + [1 - w_{r1} - w_{r2}]^{+} F \pi_0 \\ & + [w_{r1}]^{+} F + [w_{r2}]^{+} F \end{aligned} \tag{21}$$

$$\begin{aligned} & \text{Total long-run average cost for T} - \text{B} - 3 = \\ & w_{r1} D^{av} \pi_0 c_{r1} + w_{r2} D^{av} c_{r2} + w_u D^{av} \pi_0 c_u \\ & + (1 - w_{r2}) D^{av} \pi_1 c_{f1} + [1 + (\pi_1 - 1) w_u] D^{av} p \\ & + [1 - w_{r1} - w_{r2}]^{+} F \pi_0 + [w_{r1}]^{+} F + [w_{r2}]^{+} F \end{aligned} \tag{22}$$

$$\begin{aligned} & \text{Total long-run average cost for T} - \text{B} - 4 = \\ & w_{r1} D^{av} c_{r1} + w_{r2} D^{av} \pi_0 c_{r2} + w_u D^{av} \pi_0 c_u \\ & + (1 - w_{r1}) D^{av} \pi_1 c_{f2} + [1 + (\pi_1 - 1) w_u] D^{av} p \\ & + [1 - w_{r1} - w_{r2}]^{+} F \pi_0 + [w_{r1}]^{+} F + [w_{r2}]^{+} F \end{aligned}$$

In order to determine the appropriate value for each variable, "total long-run average cost" should be minimized. But it is notable that the probability of disruption is not fixed and pre-determined. In addition, suppliers may offer different part prices. So, in the remainder parts of this paper, a case study experience will be discussed which illustrates the way of finding applicable solution in real-case decision makings.

4 Empirical Study

In this section, an empirical study is presented to clarify the proposed model. Disruptions mostly originates from natural disasters, labours dispute, war, terrorism and different political/social problems. Disruptions are unpredictable and due to nature of their resources, they are mainly uncontrollable or partially controllable. They are mostly rare events with huge impacts so there is not any special distribution function and history data for them. One example of such risks is disruptions which are caused by sanctions.

Different papers and textbooks have referred to sanctions in divergent ways, e.g. trade sanctions [30], economic sanctions [31] and international sanctions [32]. Although, the first meaning which comes to mind is the barrier on import and export but this is only the first and immediate effect of sanction where after a while other effects will appear which are financial-related problems. In this situation, firms cannot perform their financial transaction through most of the local banks, in addition obtaining letter of credits becomes impossible most of the time and they should transfer money instead which causes serious difficulties in business activities. Furthermore, investment limitations will be imposed to the sanctioned country which cut down the cooperation of foreign companies. Sanctions have a unique attribute regarding the probability of happiness which does not obey any pre-determined rule and distribution function; the probability is tremendously low in normal circumstances but due to some political affairs it may rise sharply. Consequently, companies do not tend to invest on alternative solutions in regular conditions but during the period of augmentation of its likelihood, taking credit on possible options is wise.

The empirical case study of this paper has been done in this context while there are several trade barriers and sanctions in seller-buyer relationships. The investigated case is in automotive industry in Iran which buys some of the required parts from foreign suppliers, especially European producers. During recent years due to some political problems, Iran has been sanctioned by UN and EU several times. Imposed sanctions have followed different purposes each time with the aim of putting pressure on specific industries; while automotive industry has not been among them but it has suffered a lot, e.g. some foreign suppliers could not continue working with Iranian companies and lack of single-sourced parts led to reduction of production rate and even production line of one of the products stopped for a period of time. These critical parts can also be supplied from other lower quality suppliers which are not acceptable in normal situations because of imposed extra quality-cost and additional set-up cost. But when the company faces serious difficulties in sourcing from the main supplier, one of the most conventional and operational decision is to shift to dual/multiple sourcing. Figure 1 shows chronological order of events in the studied case.

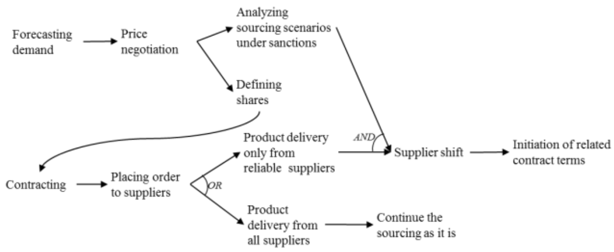

Figure 1. Chronology of events

In this section, the procedure of decision making is explored based on the probability of sanctions. Assume a critical part is supplied from the main source with the price of $c_u = 1.5$ where there is also an alternative supplier with the offer of $c_r = 1.2$, but it imposes additional quality cost of $q = 0.5$ per part. The other parameters are $c_f = 1.4, b = 3, F = 50$ and $D^{av} = 100$. These parameters represent D-A-2 scenario. Figure 2, exhibits the estimated long-run average costs based on the probability of disruption and share of alternative supplier. If the final goal of managers is to minimize the expected cost, when the perceived probability of disruption is π_1, they can make proper decision which determines the amount of w (alternative supplier share) to reach the lowest cost.

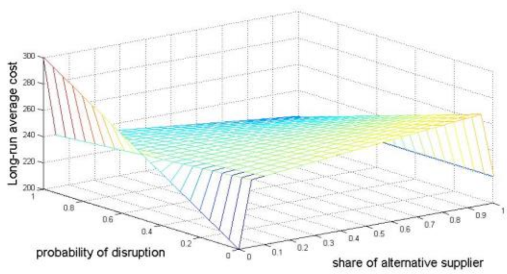

Figure 2.Results for D-A-2

For instance, based on the defined parameters in figure 2, when the probability of disruption is less than 0.3 or more than 0.7, the absolutely best strategy is remaining single sourced with the main supplier and alternative supplier respectively. Because the single sourcing strategy for these probabilities has significantly lower cost in comparison to dual sourcing. Based on this figure, if the disruption does not occur and firm remains single sourced by the main supplier, the expected cost would be 200, and if it shifts to single sourcing from the alternative supplier, the expected cost would be 220. So the company always believes that additional 20 units cost will be imposed if it shifts to single sourcing from alternative supplier and disruption does not occur.

In addition if the company chooses second supplier as its sole source where disruption does not occur and it wants to return to the main source, the renegotiating cost and time should be added to regular cost. This cost in most of the time a percentage of the fixed cost; assume this ratio is 45%, so the expected additional cost would be the summation of these two cost which is equal to 42 in this example, called “shifting cost”. Consequently, *w*=1 dominates *w*=0, when the difference of expected cost for *w*=0 and 1 is more than 42. But for the probabilities between 0.3 and 0.7 there is no significant difference between the costs of single and dual sourcing; and decision makers should decide with regards to tacit befits of each strategy which is completely different case by case. In order to clarify this issue, assume the probability of disruption is $\pi_1 = 0.6$. In this situation the optimized cost based on the model is achieved when *w*=1, but if the company shifts to single sourcing from the alternative supplier and disruption does not occur, the opportunity of future cooperation with the main supplier might be lost. In this case when the buyer wants to come to a decision on its sourcing strategy while being single sourced from the main supplier is far more risky with high expected future cost, it is wise to reserve an alternative supplier for future; and the imposed cost of hiring second supplier should be considered as an insurance charge. For instance in the illustrated example, when the probability of disruption is $\pi_1 = 0.6$, the more share for the alternative supplier results in the less expected cost but if disruption does not occur, it is reverse. Consequently, it is based on the limitation of the buyer on how much it can pay to reduce the risk of losing its main supplier. We assumed that the shifting cost is 42 and the minimum, acceptable by the main supplier, is 0.3. So the company should choose dual sourcing strategy if there are options of different share with the expected cost of less than 242 and minimum share of 0.3 for main supplier. Under this probability of disruption, the expected average cost would be between 220 and 260 based on different allocated share to the alternative supplier. Based on the illustrated limitation on shift cost and minimum share of the main supplier, the company can choose dual sourcing with *w*=0.7 and expected cost of 241.2.

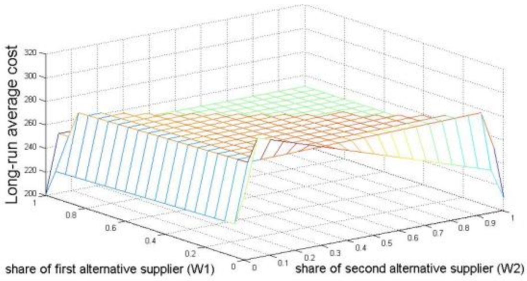

Figure 3. Results for T-A-4(π_1=0.6)

Because of special condition of monopoly for the alternative supplier after disruption, buyer may hesitate to be dependent to it. So, the other option is to investigate whether triple sourcing is an acceptable solution. This approach creates competition between substitute suppliers and leads to reduction of the offered unit-prices (before and after disruption). Assume $c_{r1} = 1, c_{r2} = 1.1$, $c_{f1} = 1.1, c_{f2} = 2$. In this case, having two competitive alternative suppliers causes reduction of unit-price and total expected cost. The defined parameters in this empirical example implies to T-A-4. While the expected cost of $\pi_1 = 0.6$ for D-A-2 (dual sourcing) is between 260 and 220; and regarding the shift cost, the acceptable option is dual sourcing with the expected cost of 241.2, possible triple sourcing solutions should be investigated to find if there is any better option. Based on the defined parameters in this example, there is not any triple sourcing option with less cost, so the final answer for this problem would be double sourcing with the share of *w*=0.7 for the alternative supplier.

5 Sensitivity Analysis

Based on the defined parameters in previous section, there is not any acceptable triple sourcing option with less cost. But the results are very sensitive to set-up cost. Changing the value of this parameter leads to completely different outcomes. For instance, reducing the set-up cost to 15, conducts the shift cost of 27 and expected cost of dual sourcing with *w*=0.7 on 192. Hence, there are different comparable options in triple sourcing with lower expected cost from 188.8 to 192. Table 1, exhibits the better sourcing strategy among dual and triple sourcing for different set-up costs with the probability of disruption being $\pi_1 = 0.6$. So, based on different cost parameters, there might be cost-effective options in triple sourcing which can be chosen by decision makers to reduce the risk derived by the alternative supplier monopoly. Considering table 1, lower set-up cost results in different sourcing strategy on triple sourcing. In all these circumstances, the proposed model can find the best cost effective solutions and help decision makers to decide on the way they are going to manage the risk of supplier failure.

Table 1. Impact of set-up cost on sourcing strategy

Set-up cost	10	15	30	50	70
Sourcing strategy	Triple sourcing	Triple sourcing	Dual sourcing	Dual sourcing	Dual sourcing

The proposed model assumes that the buyer firm can accurately estimate the probability of disruption. We conducted a numeric study to investigate the impact of over/underestimation of this probability on long-run average cost. Table 2 reveals the results of this examination for three probability of disruption (0.1, 0.6, 0.8) when the buyer firm under-estimates or over-estimates this parameter.

Table 2. Impact of over/underestimation of the disruption probability on long-run average cost

Actual Probability (*p*)	**Estimated Probability**	**Changes in Cost**	**Percentage of Change**
0.1	0.3	0	0
	0.4	40.6	19.33
	0.5	42.2	20.1
	0.6	50.2	23.9
0.6	0.3	18.8	7.79
	0.4	2.4	1
	0.5	2	0.83
	0.7	1.3	0.54
0.8	0.3	60	27.27
	0.4	20.8	9.45
	0.5	19.6	8.91
	0.6	13.6	6.18

According to table 2, misestimating the disruption probability with less than an error of 0.1 does not have significant impact on the chosen sourcing strategy and the expected long-run average cost. The more difference between actual and estimated probability results in the more imposed cost and different sourcing decision. When the likelihood of disruption is low (0.1) and it is over-estimated to 0.4, the imposed cost is very high because the sourcing strategy would be changed completely. This additional cost would be more for higher estimation but the differences between extra cost of different higher estimations is not significant. On the contrary, when the actual probability is high (0.8) and the firm under-estimates it to 0.3, the imposed cost is far much higher than over-estimation of 0.1 to 0.6; and it has significant differences with lower under-estimations. This impact is due to tremendous change in sourcing strategy for each estimated probability. The other investigated probability is 0.6, for probabilities between 0.3 and 0.7 the strategy is not changed so the extra cost is not as high as previous situations.

6 Conclusion

Decision making on sourcing strategies is one of the main steps in procurement process. This paper investigates a new setting of problem for sourcing under risk. All the assumptions and modelling parameters are based on a real case experience where the focus is on procurement of material for one product with the possibility to contract multiple suppliers. One supplier has unreliable capacity while other suppliers are reliable but with lower product quality. The addressed context is disruptions due to sanctions which causes failure in the supply process from unreliable source. The important question which emerges here is how the companies should use different strategies of single/dual/triple sourcing to handle those potential disruptions.

In this study dual and triple sourcing strategies are addressed and compared; the former with lower setup cost but high probability of future problems due to monopoly and the latter with higher setup cost but price competition after disruption.

Based on the illustrated empirical study, minimum long-run average cost is achieved with different sourcing strategies according to the probability of disruption. In addition single sourcing is a better solution when the probability of disruption is very low or very high but this supplier is different for each probability of disruption. Furthermore, sourcing from the alternative supplier is more cost-effective if the probability of disruption is higher than a specific amount. But in this case the manufacturer may lose its main supplier even if disruption does not occur and if they want to renegotiate with the main supplier it causes additional cost, which is called “shift cost” in this paper. Consequently, decision makers should consider extra cost of second source as an insurance cost and based on different factors e.g. the amount of money they afford to pay, minimum acceptable share by each supplier and shift cost, the final decision would be made. Moreover, based on the proposed model, practitioners can find expected cost of possible triple sourcing policies under determined probability of disruption. So, when the maximum affordable additional cost (as insurance) is predetermined, the optimized decision can be made. If there is any triple sourcing option with less cost than what is accepted in dual sourcing, this choice should be considered in final decision.

References

[1] S. Chopra and M. S. Sodhi, "Managing Risk to Avoid Supply Chain Breakdown," *MIT Sloan Management Review,* vol. 46, pp. 53-61, 2004.

[2] S. Chopra and P. Meindel, *supply chain management - strategy, planning & operation*, 3rd ed.: Pearson Prentice Hall, 2007.

[3] A. M. Knemeyer, W. Zinn, and C. Eroglu, "Proactive planning for catastrophic events in supply chains," *Journal of Operations Management,* vol. 27, pp. 141-153, 2009.

[4] S. Pochard, "Managing risks of supply-chain disruptions: dual sourcing as a real option," Master in Science of Technology and Policy, Engineering Systems Devision Massachusette Institute of Technology, 2003.

[5] C. Tang, "robust strategies for mitigating supply chain disruptions," *International Journal of Logistics: Research and Applications,* vol. 9, pp. 33-45, 2006.

[6] K. A. Marley, "Mitigating supply chain disruptions; essays on lean mangement, integrative complexity and tight coupling," Doctor of Philosophy, The Ohio State University, 2006.

[7] C. W. Craighead, J. Blackhurst, M. J. Rungtusanatham, and R. B. Handfield, "The Severity of supply Chain disruptions: design characteristics and mitigation capabilities," *Decision Science,* vol. 38, pp. 131-156, 2007.

[8] B. Tomlin, "On the value of mitigation and contingency strategies for managing supply chain disruption risks," *management science,* vol. 52, pp. 639-657, 2006.

[9] M. N. Baily and D. J. Elliott, "The US Financial and Economic Crisis: Where Does It Stand and Where Do We Go From Here?," The Initiative on Business and Public Policy2009.

[10] J. Y. Lin, "The Impact of the Financial Crisis on Developing Countries," The World Bank, Korea Development Institute, Seoul2008.

[11] T. Wu, J. Blackhurst, and P. O. Grady, "Methodology for supply chain disruption analysis," *International Journal of Production Research,* vol. 45, pp. 1665-1682, 2007.

[12] H. L. Lee and M. Wolfe, "Supply chain security without tears," *Supply Chain Management Review,* vol. 1, pp. 12-20, 2003.

[13] P. R. Kleindorfer and G. H. Saad, "Managing disruption risks in supply chain," *Production and Operations Management,* vol. 14, pp. 53-68, 2005.

[14] A. Norrman and U. Jansson, "Ericsson's proactive supply chain risk management approach after a serious sub-supplier accident," *International Journal of Physical Distribution and Logistics Management,* vol. 5, pp. 434-456, 2004.

[15] I. S. Papadakis, "Financial performance of supply chains after disruptions: An event study," *Supply Chain Management: An International Journal,* vol. 11, pp. 25-33, 2006.

[16] K. Hendricks and V. R. Singhal, "The Effect of Supply Chain Disruptions on Long-term Shareholder Value, Profitability, and Share Price Volatility," 2005.

[17] K. B. Hendricks and V. R. Singhal, "The effect of supply chain glitches on shareholder wealth," *Journal of Operations Management* vol. 21, pp. 501-522, 2003.

[18] G. Yu and X. Qi, *Disruption management: Frameworks, models and applications*. New Jersey, London, Singapore: World Scientific, 2004.

[19] X. Qi, J. F. Bard, and G. Yu, "Supply chain coordination with demand disruptions," *Omega,* vol. 32, pp. 301-312, 2004.

[20] T. Xiao and G. Yu, "Supply chain disruption management and evolutionarily stable strategies of retailers in the quantity-setting duopoly situation with homogeneous goods," *European Journal of Operational Research* vol. 173, pp. 648-668, 2006.

[21] T. Xiao, X. Qi, and G. Yu, "Coordination of supply chain after demand disruptions when retailers compete," *Intenational Journal of Production Economics,* vol. 109, pp. 162-179, 2007.

[22] T. Xiao and X. Qi, "Price competition, cost and demand disruptions and coordination of a supply chain with one manufacturer and two competing retailers," *Omega,* vol. 36, pp. 741-753, 2008.

[23] S. Chopra, G. Reinhardt, and U. Mohan, "The Importance of Decoupling Recurrent and Disruption Risks in a Supply Chain," *woley-interscience,* vol. 54, pp. 544-555, 2007.

[24] A. Z. Zeng, "A synthetic study of sourcing strategies," *Industrial Management & Data Systems,* vol. 100, pp. 219-226, 2000.

[25] S. M. Wagner, C. Bode, and P. Koziol, "Supplier default dependencies: Empirical evidence from the automotive industry,"

European Journal of Operational Research, vol. 199, pp. 150-150, 2009.

[26] P. D. Berger, A. Gerstenfeld, and A. Z. Zeng, "How many suppliers are best? A decision-analysis approach," *Omega* vol. 32, pp. 9 - 15, 2004.

[27] R. Tullous and L. Utecht Richard, "Multiple or Single Sourcing?," *The Journal of Business & Industrial Marketing*, vol. 7, pp. 5-19, 1992.

[28] X. Zhou and H. Fang, "Response to the supply chain disruptions with multiple sourcing," *2009 IEEE International Conference on Automation and Logistics*, pp. 136-139, 2009.

[29] V. Martínez-de-Albéniz and D. Simchi-Levi, "Competition in the Supply Option Market," *Operation research*, vol. 57, pp. 1082-1097, 2009.

[30] C. Steve, "Rethinking WTO Trade Sanctions," *American Journal of International Law,* vol. 95, pp. 792-832, 2001.

[31] R. Eyler, *Economic Sanctions: International Policy and Political Economy at Work*: Palgrave Macmillan, 2007.

[32] H. K. William and D. L. Anton, "International Sanctions," *Journal of Economic Perspectives,* vol. 17, pp. 233-235, 2003.