Supply Chain Disruption Management: Review of Issues and Research Directions

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Abstract

Supply Chain Risk Management (SCRM) is an increasingly popular subject of research which emphasizes the goals of achieving improved supply chain robustness through development of design and operational strategies. Disruption management is one aspect of SCRM which examines the ability of the supply chain to maintain a high level of performance under the effects of major disruptions. Specifically, disruptions refer to events characterized by a low likelihood of occurrence and a large impact. Because of their limited rate of occurrence, disruptions are associated with a high uncertainty with respect to their expected impact. Improved modeling of the disruption impact is one key issue in this field. Other issues include the design of methods for supply chain performance measurement, disruption monitoring and detection, evaluation of recovery strategies, and methods of optimal supply chain design. Design features to be considered include flexibility, redundancy, and operating efficiency. The relevant literature is presented in the context of these major issues and future directions suggested by researchers in the field are discussed.

Keywords
Supply Chain, Disruptions, Risk Management, Gray Swan

1. Introduction
In his discussion of improbable events, Nassim Taleb defines the Black Swan as an outlier occurrence, falling outside the realm of expectations, having extreme impact, which after occurring causes us to come up with explanations making it explainable and predictable, although these explanations may not be correct [1]. If a Black Swan can be shown somehow to be a plausible occurrence it may then be converted into a Gray Swan. In the risk literature these Gray Swan events are often referred to as disruptions. Supply chain disruptions include issues that may not be completely obscured but for which predictive models are mainly nonexistent. Because of this uncertainty, existing research has had the tendency to focus on more frequently occurring operational risks which often have estimable likelihoods based on historical occurrence [2]. Although supply chain disruption risks have a much higher business impact than more predictable operational risks, researchers have focused largely on modeling operational risk. Typically these operational risk models focus on assessing changes in economic factors such as profit or expected cost, but for the Gray Swan disruption other performance targets may be more relevant [3].

The terms used in the field of risk management are not fully standardized and thus it is pertinent to specify a set of definitions at the outset of the presentation to be used throughout the discussion. Terms such as risk, resilience, and robustness each have been described in a number of different ways in the literature with varying degrees of similarity. A typical definition of resilience is the ability of a system to return to its original state or move to a new, more desirable state after being disturbed [4]. On the other hand, robustness is a defined more generally as a measure of supply chain strength or an ability to remain effective under all possible future scenarios [5]. Interpretations of the term risk have been more diverse but in the study of quantitative risk assessment (QRA) there is typically a specification of a set of risk triplets, where the items in the triplet reflect the risk scenario, its estimated likelihood, and the consequence of its occurrence [6]. Often this is represented as shown in equation (1).

$$R = \left\{ \langle S_i , P_i , X_i \rangle \right\},\ i = 1,2,...N \tag{1}$$

S_i represents a possible risk scenario, while P_i is the probability that the scenario will occur and X_i is a measure of the consequence should the scenario occur. Here the scenario is interpreted as an event which after occurring would cause a negative impact on the supply chain performance. In a similar manner, risk has been assessed as a series of three questions: what can go wrong? How likely is it to happen? And what are the consequences if it does happen [7]? One way to depict the likelihood and consequence visually is on a risk matrix such as the example shown in Figure 1. Although the matrix is an effective communication tool it has the weakness of presenting low impact, high likelihood events with a similar level of urgency as low likelihood, high impact events.

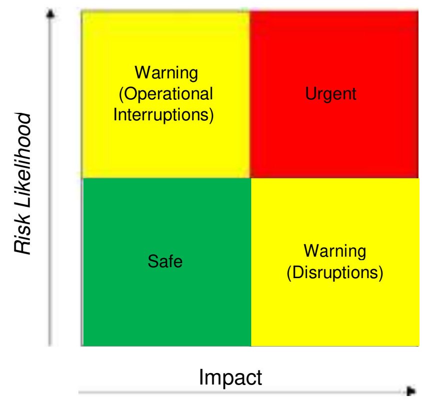

Figure 1 : Risk Matrix

As seen in Equation (1) the quantitative definition of risk distinguishes between the likelihood of an event and the consequence it may inflict on the supply chain. In some sources, the term disruption is used in a general sense to indicate the occurrence of a risk event. For example, Kleindorfer and Saad suggest a classification of disruptions into operational contingencies (includes most business-side issues), natural hazards (weather), and terrorism or political instability [8]. Although the terminology may differ from one source to the next, risk events are from this point in the presentation divided into disruptions (low probability, high impact) and operational interruptions (high probability, low impact). A significant body of research has been devoted to the study of operational interruptions. This work explores such subjects as supply and demand uncertainty [9], stochastic scheduling problems [10], and rework and machine failure disturbances [11, 12] . Modeling and analysis of disruptions is a more recent research interest and because it is such a difficult problem many open questions remain in the area. The intention of this review is to present a representative sample of the existing literature in the field of supply chain disruptions in the attempt to fit the relevant subtopics into a larger context which may lead to more exhaustive reviews in the future.

Figure 2 is a framework of issues pertinent to the area of supply chain risk management, specifically those related to disruptions. A second half of the map, which would focus on operational interruptions, is not shown for the sake of space consideration and emphasis. The concepts are divided into quantification of impact, quantification of likelihood, and management operation and design strategies. Impact quantification is discussed in section 5 in terms of metrics used; however less emphasis was given to these issues. Also, literature relating to environmental or social metrics as a measure of disruption impact is a lesser emphasis in this discussion, although the importance of such matters is recognized.

The disruption framework in Figure 2 also identifies relevant issues to disruption likelihood quantification. Because disruptions are rare events which cannot typically be observed historically with any regularity, there is a de-emphasis on the quantification of disruption likelihood. However, this area is not completely unapproachable and should be explored in further detail. Finally Figure 2 demonstrates various management strategies which can be implemented in the attempt to increase risk resilience. This section of the framework represents the primary contribution of this work, formulating a structure that attempts to contextualize the various issues that have been discussed in disruption management.

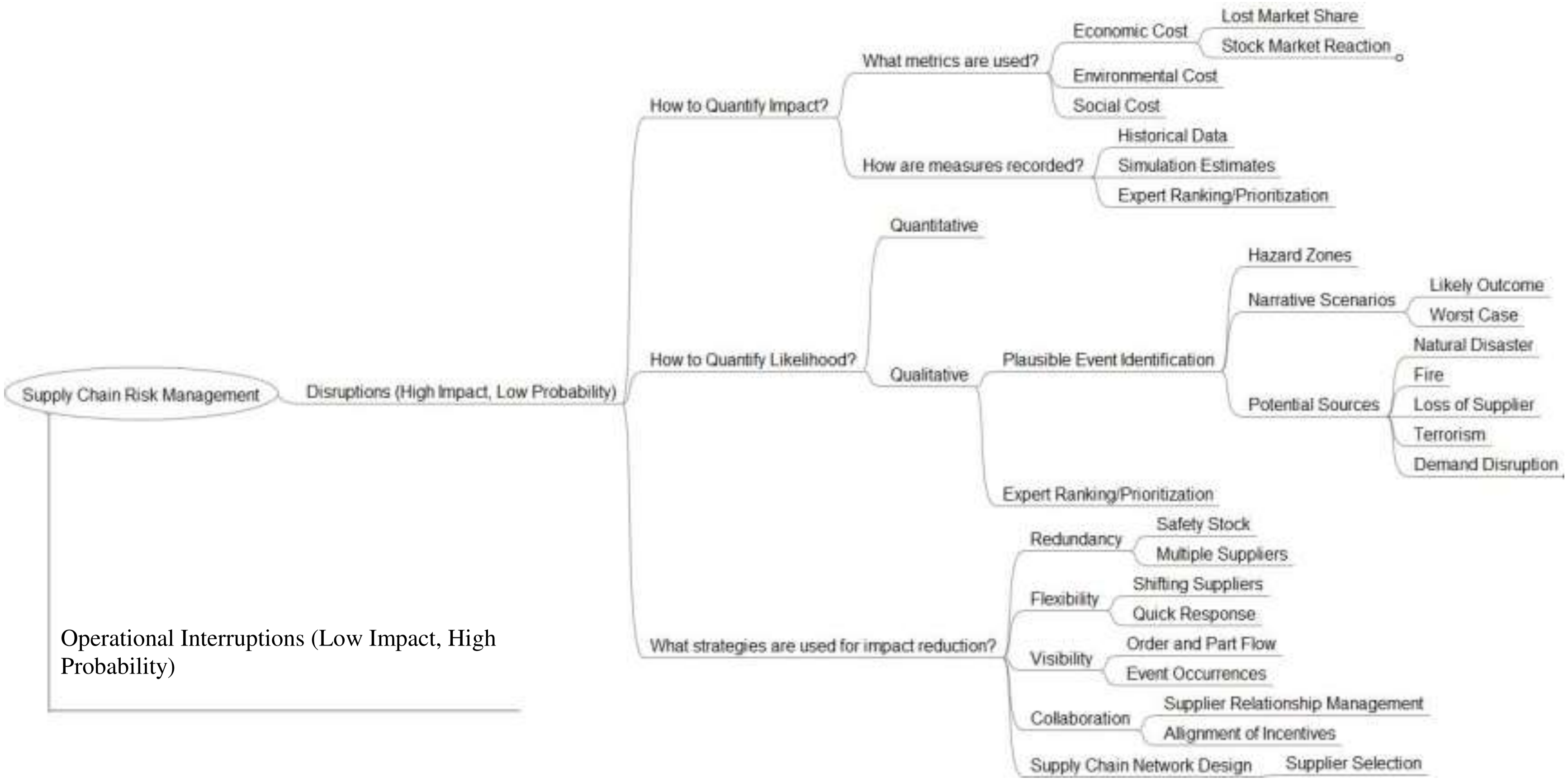

Figure 2: Supply Chain Disruption Framework

2. Research Questions

As previously stated, in the field of supply chain risk management, an extensive body of literature has been developed on the topic of operational risk. On the contrary, less work has been done on risks which are here classified as major disruptions. The questions to be addressed in this review can be categorized into the investigation of research outcomes and the analysis of research methods.

2.1 Investigation of Research Outcomes

The first questions to be addressed are associated with generalized research outcomes as reported through publications including industry surveys, case studies, and empirical studies which generally report on the needs of management in the area of supply chain risk. Primarily, the goal of this investigation is to identify any commonly reported supply chain intervention techniques or strategies which have been used to improve resilience. If a common set of strategies can be identified, then what are the results or the specific intended consequences of these interventions? What tradeoffs exist between different management strategies?

2.2 Analysis of Research Methods: Metric Selection

Many methods may exist to study the effects of various management strategies in the face of supply chain disruptions. The measure of success or failure of a strategy comes down to quantification of disruption impact. The resulting research question is then to ascertain the set of possible metrics which can be used to quantify the impact and how those metrics are then recorded. Traditional cost-based measures may not be sufficient in disruption scenarios as there may be hidden cost and other long-term effects [3].

3. Strategies for Supply Chain Disruption Management

Blackhurst et al. present an empirical study performed to identify key variables and relationships in dealing with supply chain disruptions [13]. Three focus areas identified were disruption discovery, recovery, and supply chain redesign. It was discerned that enabling the rapid discovery of disruptions necessitated various forms of visibility. These forms of visibility include real time information sharing between supply chain nodes, shared knowledge of capacity both at suppliers and at transportation hubs between suppliers, and specification and reporting of risk indices which incorporate global issues that may be pertinent to supply chain partners. Recovery after disruption is facilitated through reconfiguration capability and an assessment strategy referred to as Reachability Analysis which carefully delineates the extent of the effects of a disruption throughout the supply chain. Finally, supply chain redesign strategies should be developed which incorporate the hidden costs of global sourcing. This point reinforces the previously stated notion that it may be necessary to extend beyond cost-based metrics as models are developed for improved supply chain redesign. Also needed in the design field are optimization tools which provide robust solutions over a range of possible operating scenarios.

An alternative set of strategies are outlined by Guojun and Caihong for increased efficiency and resilience in the face of supply chain disruptions [14]. Definitions are cited from Tang [2] as (1) resilience: ability to operate during a disruption and to recover quickly after it occurs and (2) efficiency: ability to manage operational risks regardless of the occurrence of a disruption. Strategies identified are categorized as supply, demand, product, and information management. First, supply management can be achieved through dealing with multiple suppliers or through forms of redundancy in the form of excess capacity or inventory on hand. Demand management is an approach of controlling customer demand through responsive pricing, wherein the demand is shifted with pricing incentives to other products which may not be subject to the same level of disruption. Alternatively, demand postponement controls demand through pricing incentives for customers to accept delayed delivery of orders, or in the service industry an offer of different prices at different times in order to shift demand from heavily saturated periods to less busy times. Disruptions are also controlled with product management in the form of part interchangeability and postponement of customization. Together these methods increase the chances that disrupted parts may be replaced with similar ones with better availability. Finally, information management facilitates collaborative problem solving in the supply chain, ensuring that the information needed to recover from the disruption is immediately available and accurate.

Following a similar pattern of thought, further research explains how resilience is built into the supply chain through some combination of redundancy and flexibility [15-17]. Redundancy involves the procurement of excess capacity to be used in the event of a disruption, and flexibility redeploys existing capacity, requiring a tradeoff decision because the capacity must be taken from elsewhere. Flexibility may be achieved by cross-training the work force or adapting equipment or tooling so that it is capable of producing multiple variations of a product. To support improvement strategies the business case must be made which requires somehow quantifying the impact of a disruption, possibly by looking back at past experiences if they exist.

Table 1 presents a summary of the management strategies presented as well as some of the advantages and disadvantages associated with each. The information in the table provides a preliminary response to the main research question, being what interventions and techniques have been used by organizations to increase supply chain resilience. Strategies are organized according to risk management of the four main categories of product, demand, information, and supply management as suggested by Tang [2]. Although this framework was originally developed with a focus on operational risk, the same categories can used effectively in support of analysis of disruption management. The trade-offs which exist between the identified strategies are also identified in Table 1 in the form of advantages and disadvantages of implementation of each.

Table 1: Summary of Management Strategies

Supply Chain Risk Management Strategy	Methods of Implementation	Advantages	Disadvantages	References
Product/Process Management	Interchangeability	Simplification	Design Requirements	[14]
	Postponement of Customization	Inventory Control	Design/Planning Requirement	[14]
Demand Management	Pricing Incentives	Maintain Customer Base	Alternate Products must be Available	[14]
Information Management	Real Time Information Sharing	Collaborative Problem Solving	Intellectual Property Risk	[13, 18, 19]
	Risk Indices	Increased Transparency	Conflicting Interests Impede Reporting	[13]
Supply Management	Strategic Redesign	Long-Term Solution	Expense, Modeling Complexity	[13, 20, 21]
	Redundant Capacity	Enables Quick Response	Loss of Operating Efficiency	[14, 15, 22]
	Safety Stock	Flexible Solution	Holding Cost	[13, 14]
	Multiple Suppliers	Leverage	Relationship Management	[14, 17, 19, 22]
	Flexible Deployment of Capacity	Quick Response with Less Efficiency Loss	Capacity Taken From Another Process	[13, 15]
	Cross-Training	Skill Development	Time/Cost	[15]
	Efficiency/Lean Operation	Cost Savings	Increased Risk Exposure	[23]

Common themes across the reported studies include the desire for increased visibility, flexibility in supply base, multiple suppliers/redundancy, and product flexibility each of which can be achieved through a number of practices. The approach toward real-time data management and visibility is needed to facilitate the rapid response after disruption occurs [18, 19]. However, it is important to note that these strategies are not implemented without difficulty and can lead to extra cost in the supply chain. The empirical studies provide a good introduction into the types of variables and relationships which can be manipulated in the search for increased resilience. Advanced modeling techniques should be used to fully consider the variable trade-offs and complete cost/benefit and sensitivity analyses of various actions in pre-defined operational scenarios. For example, facility location and other supply chain network design problems can be considered under the effects of disruptions such as those caused by transportation failures [20]. During such strategic design stages the recurring argument between efficiency of operation and robustness against risk should be noted [21]. Further research is needed in the development and validation of these tools.

4. Supply Chain Management Strategy Trade-offs

Before the amplification of interest in supply chain resiliency, organizations were taking actions to improve quality, reduce cost, and increase response times to the customer [23]. In fact, management paradigms have been developed in the attempt to improve performance in different combinations of these areas. For example, the Lean manufacturing paradigm blends cost and quality through its focus on waste reduction, which facilitates quality adherence at a reduced cost. The concept of agility blends the goals of time and cost by ensuring systems can adapt quickly to provide a product or service even when faced with volatile demand and supply. Finally, responsiveness blends the goals of quality and time by focusing efforts on developing the ability to respond quickly to the customer and satisfy unanticipated requirements. In some cases, such as with the Lean supply chain, there is a trade-off that becomes apparent between the increased efficiency of operations and reduced risk. Figure 3 provides a visual representation of this goal overlap.

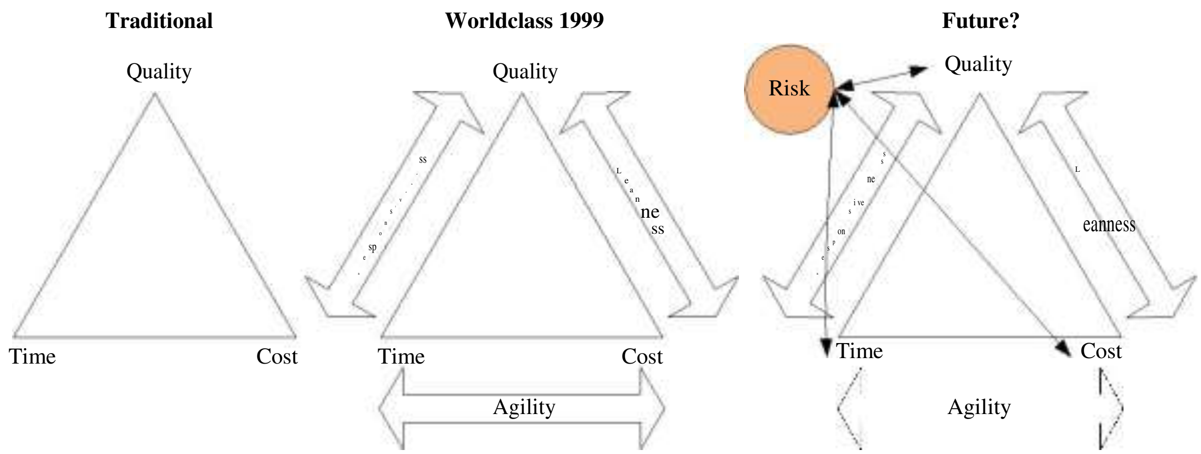

Figure 3: Overlapping Supply Chain Management Goals, adapted from [15]

Carvalho and Machado discuss the development of supply chain management paradigms including Lean, Agile, Resilient, and Green approaches [24]. The focus of the agile supply chain is rapid response to changing market conditions, and some capacity may be reserved to cope with the volatility of demand. This differs from Lean which seeks to operate according to a steady demand rate. This trade-off has led some practitioners to pursue “Leagile” supply chain techniques which combines principles from both techniques. It is noted that Green management practices can achieve increased profit and market share through improved ecological efficiency, but this may be hindered as the need for redundancy reduces efficiency. Resilience comes only with added cost. In order to perform the necessary cost/benefit analyses the impact of potential disruptions must be considered. Preliminary study was also completed in the realm of impact assessment, which should aid in the development of such a measure or measures. Potential metrics identified for impact assessment included stock price, time to recovery after disruption, and business value interrupted, and market share.

5. Metric Selection: Quantification of Disruption Impact

As discussed by [13] hidden costs may be present in the supply chain as complexity increases. Issues such as market share, sales targets, inventory levels, and holding cost may be better indicators of supply chain performance [3]. Hendricks et al. observed stock market reactions to firms undergoing disruptions with varying levels of operational slack (less negative reaction), business diversification (no effect), geographic diversification (more negative reaction), and vertical relatedness (less negative reaction) [22]. There is little empirical evidence to support the effectiveness of certain disruption management strategies and this study provides an interesting look at the relationship between strategic variables and the indirect impact measure of stock response. From the standpoint of impact assessment, Ericsson has developed a system for resilience which highlights the use of "Business Recovery Time" and "Business Interruption Value" as a way of discussing disruption impact [23]. After experiencing severe setbacks from a fire at one of their major suppliers, Ericsson was able to learn first-hand the importance of these measures.

In terms of methods which may be used to study the impacts of various strategies, agency theory may prove to be a viable option [25]. Agency theory applies to situations when one party (the principal) delegates work to another party (the agent). Problems that arise when there is a difference in goals between the principal and the agent are studied. Transparency between the two may not be possible and problems from differences in risk tolerance between principal and agent may arise. Strategies for increased resilience should help to alleviate these problems.

6. Conclusions and Future Research Directions

As defined, Black Swan events are highly disruptive and cannot be predicted. This may be referred to as the "unknown unknown" [26]. If the events can be converted to the Grey Swan "known unknown" then the study of these problems drive the need for interdisciplinary cooperation and consideration of an increasing number of variables as compared to what would be necessary to study more predictable events. Conversion of Black Swans into Gray Swans is one issue which remains open in the field of disruption research. Also of continued interest is the study of trade-off which exists between supply chain operating and design strategies. Certain strategies have been proven in various contexts but it is desired to uncover a robust policy which can perform to the desired specifications under a variety of operating scenarios. Before this can be realized, the performance indicators must be properly defined.

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