Int. J. Production Economics 175 (2016) 153–163

Contents lists available at ScienceDirect

Int. J. Production Economics

journal homepage: www.elsevier.com/locate/ijpe

Proactive cost-effective identification and mitigation of supply delay risks in a low volume high value supply chain using fault-tree analysis

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ARTICLE INFO

Article history:
Received 15 August 2015
Accepted 3 February 2016
Available online 24 February 2016

Keywords:
Supply chain
Fault-tree analysis
Supplier selection
Risk mitigation

ABSTRACT

In this paper we use a well-accepted methodology, fault-tree analysis, to identify delay risks and proactively propose a cost-effective mitigation strategy within a low volume high value supply chain. The basis for the assessment is the bill of materials of the product being studied. The top-level event of interest represents the delay in delivering a product to a customer and lower-level events represent the probabilities associated with delays caused by quality and capability deficiencies within the supply chain of the product being studied. Supply chain risk mitigation strategies have been well documented in academic literature. However, much of what has been documented addresses such topics as facility location, inventory buffers, and is generally focused on response strategies once the risk has been realized. This paper presents a robust method to reduce the likelihood of delays in material flow by representing the system of suppliers within a supply chain as a fault-tree and proactively determining the optimum mitigation strategy for the portfolio. The approach is illustrated via real-world numerical scenarios based on hypothetical data sets and the results are presented.

1. Introduction

In this paper we address the problem of proactively identifying areas of potential delay and subsequently implementing a cost-effective mitigation strategy. Delays, which have been identified as one of the primary categories of supply chain risk, have been described as being driven by poor quality, high capacity utilization, and in general, a lack of supplier capabilities (Chopra and Sodhi, 2004). Specifically, a quantitative, prevention-based methodology using fault-tree analysis is employed. The unreliability of the supply chain is modeled as a fault-tree. The top event of the fault-tree represents the critical assembly being studied. Basic events are based on the critical assembly's bill of materials. Event and gate probabilities are a function of the unreliability of delivering the particular component, subassembly, or critical assembly on-time. Fault-tree analysis methods are employed to identify opportunities, subsequently apply interdiction strategies at various points (supplier-service combinations) within the supply chain to reduce those risks, and study the consequences of implementing particular actions in advance of executing those strategies.

Industries that rely on low volume, high value, long lead time products have greater consequences when delays occur and especially if such risks are realized at the latter stages of production or downstream within the supply chain. Examples of such industries include airline manufacturing (Denning, 2013), nuclear power plant construction (Ng, 2013), and shipbuilding (Mello and Strandhagen, 2011). Further compounding the risk exposure within these supply chains is that by nature, manufacturing capability and qualified suppliers are scarce.

Manufacturing firms are always seeking better ways to mitigate risk when making decisions related to the purchase of goods and services. These decisions are quite complex and require decision makers to consider several inputs. In addition to price, considerations must be made regarding the capabilities of the suppliers as well as the probability that the goods and services are delivered on-time and meet quality and design specifications. Firms that produce standard high volume low value products (i.e., consumer electronics, household appliances, and clothing) are challenged with managing multiple sources effectively while keeping prices low. On the other hand, manufacturers that produce relatively low volume high value products (i.e., aerospace, power plant construction, energy exploration, and shipbuilding), may be constrained by the scarcity of suppliers with the requisite manufacturing capabilities to produce the product of interest. Furthermore, these industries typically have more stringent quality and regulatory requirements, which may narrow the supply

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http://dx.doi.org/10.1016/j.ijpe.2016.02.001
0925-5273/

base even further. With such few sourcing options, firms are often greatly exposed to the risks associated with a limited number of suppliers.

The supply chain associated with the manufacture of low volume high value components can be complex and lead times of critical components can be on the order of many years. Further, the unit cost of some components can exceed hundreds of thousands of dollars. Due to the large size of the components – some can weigh several tons – and subsequently the fabrication and manufacturing capability required to fulfill design requirements, a limited number of global suppliers exist. The quality and regulatory requirements placed on suppliers within these industries also increase the complexity of decision making. Hundreds of suppliers may be used in the assembly of an airline or in the construction of a nuclear power plant. In summary, suppliers with requisite capabilities are scarce, supplier development and order fulfillment lead times are long, and supply chain delays can have a significant impact on delivery, which can result in legal and financial ramifications. One estimate places the cost of delay in construction of a nuclear power plant at $2 million per day (Henry, 2014). As a result, supplier selection and proactive risk mitigating activities are critical to ensure that suppliers deliver on time. Failing to implement such an approach proactively can be costly and time consuming.

As enterprise resource planning and manufacturing execution systems have improved, firms have become more objective with planning and scheduling decisions. Likewise, site selection, inventory stocking levels, and transportation decision models have become more sophisticated within supply chains. However, a gap in common industry practice still exists with respect to providing timely and cost-effective risk interdiction activities. As a result of the regulatory scrutiny on low volume high value industries producing critical components, these interdiction strategies are typically focused on compliance to regulator standards and not necessarily or specifically targeted to the performance of suppliers. Although compliance to regulations is vital, doing so does not ensure efficient or cost effective risk mitigation. Furthermore, the use of quantitative decision making instruments that consider the cost-risk tradeoff is scarce.

This paper builds upon previous work in the areas of fault-tree analysis and supply chain risk mitigation by making the following main contributions and is intended as a methodology to augment existing decision making tools used by sourcing professionals. (1) A new methodology to formulate a fault-tree using the bill of materials of a low volume high value product being manufactured is demonstrated and subsequently utilized to quantify risk (unreliability) within the firm's supply chain. The data used to formulate the fault-tree is based on real-world scenarios and hypothetical on-time delivery data that is readily available to most firms. (2) A quantitative approach is employed to identify potential sources of delay and model the trade-off between reducing these risks and the investment required to mitigate. (3) A set of computational experiments in the form of simple scenarios provides results for decision makers to better understand the tradeoffs between risk reduction and associated mitigation costs.

2. Related literature

2.1. Supply chain risk

A wide body of literature is available in the area of risk response and primarily focuses on redundancies, safety stock, inventory buffers, auditing, management intervention, and other strategies to hedge the consequences of a risk being realized (Feng et al., 2010). However, opportunities exist in the areas of (1) identifying risk sources, (2) defining risk and consequences, (3) identifying risk drivers, and (4) mitigating risks (Juttner et al., 2003). As a result, instruments that model the areas associated with risk prevention are scarce as noted in several literature surveys (Chen and Paulraj, 2004; Wagner and Bode, 2008; Schmitt and Singh, 2009; Melo et al., 2009). This paper intends to systematically and quantitatively address the gaps associated with risk identification (specifically those risks associated with delays in the supply chain) and subsequently provide practitioners with an instrument that augments other decision making tools to make better informed cost-effective mitigation decisions.

Researchers have analyzed supply chain risk management extensively from a qualitative point of view (Cooper et al., 1997). In their agenda for future research in the field, Juttner et al. (2003) proposed a basic construct for supply chain risk management and noted needs for more practical approaches to risk assessment, a supply chain and industry-specific approach, better approaches for managers to identify risk drivers, and processes to guide trade-off decision making between risk reduction and mitigation costs. Likewise, several authors have proposed strategic frameworks and approaches to supply chain risk management (Cooper et al., 1997; Christopher and Peck, 2004; Juttner et al., 2003; Giannakis and Louis, 2011; Tummala and Schoenherr, 2011; Feng et al., 2010; Manuj and Mentzer, 2008b) and some have focused specifically on mitigating such risks (Christopher and Lee, 2004; Norrman and Jansson, 2004; Manuj and Mentzer, 2008a; Giunipero and Eltantawy, 2004; Trkman and McCormack, 2009). However, empirically based published work in the area remained sparse until recently and approaches have varied (Sodhi et al., 2012; Christopher and Peck, 2004). In a review of quantitative models for managing supply chain risks, Tang (2005) suggests that it is appropriate to use cost or profit as a means to evaluate options for managing operational risks and the usefulness of "back-up" suppliers. Furthermore, he discusses demand management, product management, and information management strategies. Toward the goal of developing an approach that minimizes cost as a means to evaluate options, Aqlan and Lam (2015) propose a model to maximize risk reduction under budgetary constraints using bow-tie analysis. However, the authors use expert opinion as the basis for the likelihood and impact of the supply chain risks.

In practice, decisions related to supplier selection are often unstructured (De Boer et al., 1998). A variety of multi-criteria decision making approaches have been studied with respect to supplier selection and envelop several factors in the categories of quality, cost, delivery, and service (Lee et al., 2001). Other research incorporates order quantities and capacity constraints into the supplier selection decision making process (Ghodsypour and O'brien, 2001; Aissaoui et al., 2007). Methods include the analytical hierarchy process, goal programming, data envelopment, fuzzy set theory, genetic algorithms, and others (Ha and Krishnan, 2008; Kahraman et al., 2003; Sarkis and Talluri, 2002; Liu et al., 2000; Gencer and Gürpinar, 2007; Min, 1994; Amid et al., 2006; Bevilacqua et al., 2006). However, consideration for the impact on business objectives is lacking (Ho et al., 2010).

The area of supply chain disruption has been studied extensively. Blackhurst et al. (2005) identified discovery, recovery, and redesign as the three primary areas crucial to managing supply chain disruptions. Among other conclusions, the authors point out that tools are needed to establish a regular system of supply chain disruption predictability and that dynamic or real-time measures are important.

Disruptive threats such as terrorism (Sheffi, 2001; Brown et al., 2006), natural disasters (Stewart, 1995), sourcing decisions (Chopra et al., 2007), demand (Qi et al., 2004; Chen and Xiao, 2009; Xiao et al., 2005), and others are discussed in the literature as well as strategic frameworks and supply chain design methodologies