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A general framework for assessing system resilience using Bayesian networks: A case study of sulfuric acid manufacturer

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ABSTRACT

Supply chains play an important role in modern society and national economic development. In recent years, supply chains are more susceptible to variety of disruptive events, including natural disasters, man-made attacks, and common failures due to their complexity, globalization, and interconnected structures. Hence, it is important to design resilient supply chains which are capable of withstanding and recovering rapidly from disruptive events. This paper first explores the key drivers that contribute to the design of resilient supply chains based on the notion of absorptive, adaptive and restorative capacities. Second, it introduces a generic conceptual framework comprising five key phases: threat analysis, resilience capacity design, resilience cost evaluation, resilience quantification, and resilience improvement. The primary challenge to the literature of system resilience is how to measure it qualitatively. Findings from literature indicate that many of the drivers to the system resilience are qualitative such as staff cooperation and collaboration during disruptive events, level of preparation against natural disaster, among others. To fill the gap between qualitative and quantitative assessment of resilience, we employed Bayesian network to quantify the system resilience. Bayesian network is a rigorous tool for measuring risks under uncertainty, representing dependency between causes and effects, and making special types of reasoning. Additionally, it is capable of handling both qualitative and quantitative variables in terms of probability. We implemented Bayesian network for quantifying the supply chain system resilience of sulfuric acid manufacturer in Iran. Different scenarios have been defined and implemented to identify critical variables that are susceptible to the system resilience of sulfuric acid manufacturer.

1. Introduction

Nowadays, supply chains (SCs) are facing with growing number of disruptions due to their globalization, complexity, and interconnected structures. With the inception of globalization, managing supply chain risks have become more significant and challenging, and hence, it received a great deal of attentions from academics as well as supply chain stakeholders. Supply chain disruptions (*e.g.*, unpredicted failures of manufacturers, natural disaster at distribution locations, transportation systems, and labor strike) could cause significant decrease in companies' revenue and market share, inflation in suppliers' cost of product, and may even damage to the credibility of involved companies. For instance, Hsinchu Industrial Park (HIP) located in Taiwan was affected by earthquake of magnitude 7.6 on September 21, 1999. At the time of earthquake, HIP alone had 10% share of the world's production of memory chips. Several components of computers were also manufactured by HIP. This disaster imposed devastating consequences. Supply activities halted for the following few months; HIP lost roughly $1.2 billion, and many computer companies such as Dell, Gateway, IBM and Apple were adversely affected [1,2]. More recent examples of supply chain disruption due to natural disasters are Japanese earthquake and Hurricane Sandy, which devastated the east coast of Japan in 2011 and NY/NJ of USA in 2012, respectively. The high magnitude Japanese earthquake and tsunami demolished the transportation infrastructures and knocked out factories supplying high tech components, forcing automotive and electrical companies like Toyota Corp. and Sony Corp. to suspend their production [3]. These examples highlight the importance of research on supply chain resilience. Many of previous researches have focused on reducing the likelihood of devastating events using security management tools, known as pre-disaster or contingency strategy. However, contingency strategy may not be sufficient to withstand

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disruptive events, especially for highly unpredictable devastating disruptions. In addition to contingency strategy, the significance and need for timely response, preparedness, and quick recovery are inevitable. These activities commonly referred as post-disaster strategy or mitigation strategy. The aim of post-disruption strategy is to efficiently recover the disrupted performance of system (*e.g.*, production capacity of manufacturer) and reduce the potential consequences of disruption. The role of post-disaster strategy has become even more important in design of large-scale multi-layer supply chains because the devastating consequence of disruptive events could easily propagate though the layers of supply chain.

The term 'resilience' is defined as "bounce back" after a disruption. It has been studied in various disciplines including safety science [4,5], education [6–8], economic [9,10], organizations and enterprises [11,12], and infrastructures [13–15]. It has been defined extensively by many researchers. U.S. Department of Homeland Security Advisory Council [16] defined the resilience as "ability of systems, infrastructures, governments, business, and citizenry to resist, absorb, recover from, or adapt to adverse occurrence that may cause harm, destruction, or loss of national significance."

Rose [17] defined resilience as "the ability of an entity or system to maintain function (*e.g.*, continue producing) when shocked." Gunderson et al. [18] defined the engineering resilience as the speed of returning to normal operating conditions following a perturbation. U.S. Department of Homeland Security Risk Steering Committee [19] defined the resilience as "ability of systems, infrastructures, government, business, and citizenry to resist, absorb, recover from, or adapt to an adverse occurrence that may cause harm, destruction, or loss of national significance."

2. Related literature on supply chain resilience

Despite the extensive researches on resilience, the concept of supply chain resilience is still in its infancy. Supply chain resilience is a new concept with multidimensional phenomena. A multidisciplinary perspective of supply chain presented by Ponomarov and Holcomb [20] defines the supply chain resilience as "the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function". The definition presented by the authors points out that adaptive capability, response, and recovery are the main elements of supply chain resilience. Van der Vorst and Beulens [21] state that reduction of uncertainty and complexity is the most effective way of improving supply chain resilience, while Lee [22] highlighted collaborative partnership as the main arm of supply chain resilience. Ponomarov [23] introduced a framework that addresses the relationship between logistics capabilities and supply chain resilience. Supply chain resilience was considered with three phases: event readiness, efficient response, and recovery. Deloitte LLP [24] proposed five steps to build a resilient supply chain. These include (1) assess supply chain resilience, (2) determine risk exposure, (3) evaluate and prioritize resilience strategies, (4) address supply chain resilience opportunities, and (5) monitor supply chain resilience, shown in Fig. 1.

Fig. 1. Five steps of building resilient supply chain [24].

There are several recent works that address quantitative modeling of supply chain resilience. Soni et al. [25] modeled supply chain resilience as digraph of its enablers including supply chain agility, collaboration among players, information sharing, and sustainability in supply chain, risk and revenue sharing, trust among players, supply chain visibility, creating risk management culture, adaptive capability, and supply chain structure. The resilience digraph captured the interdependencies of enablers. Finally, the resilience is quantified using a single index. Although their proposed approach is novel; however, it is not practical to quantify the components of supply chain resilience like collaboration among players and supply chain visibility. Carvalho et al. [26] used discrete event simulation (DES) tool to investigate the resilience of automotive supply chain. Two strategies of redundancy and flexibility were considered to be the elements of resilience in their simulation model. Redundancy is defined as stocking extra capacity to sustain against disruption, while flexibility is defined as substituting disrupted transport system with an alternative one. Finally, six scenarios are investigated through DES tool. The authors did not consider the likelihood and impact of natural disasters that are very common to the components of supply chains. Bode et al. [27] noted that firms could improve disruption response by cultivating a strong supply chain disruption orientation.

Based on the findings from the literature related to supply chain resilience, it is noticeable that one of the main challenges is to identify the sources of disruption because of its novelty in nature such as ecological disasters, global economic disasters, unpredictable natural disasters, and marketplace changes. Even though we may have little or no historical records in these cases, there is often an abundance of expert (subjective) judgements, as well as various data and information indirectly related to disruptions. These types of situations can be successfully addressed by Bayesian network tool, even when classical data-driven approaches to risk evaluations are not possible [28]. Bayesian network can be very useful for such cases where disruptive events cannot be expressed easily in terms of likelihood of occurrence. BN can handle those cases by using linguistic variables (e.g., low, medium, high). In addition, Bayesian networks are capable of modeling both qualitative and quantitative variables and also capable of updating beliefs in the light of new evidence which is central to many disciplines (engineering, finance, business).

The main contributions of this paper can be outlined as below:

- Proposing a new conceptual framework for designing the resilient supply chain systems. The conceptual framework deserves generality and can be used for designing resilient infrastructure systems.
- Classifying the drivers of supply chain systems with respect to the notion of absorptive, adaptive and restorative capacities.
- Developing probabilistic graphical model, known as Bayesian network for measuring and assessing the resilience of supply chain systems.