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The Impact of Severe Weather and Climate Change on Lean Supply Chains

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Abstract This study examines the impact of severe weather on lean supply chains. First, this paper reviewed the literature on the disruptions and damages that severe weather events cause on supply chain. Then, several recent examples of lean supply chain disruptions due to severe weather were discussed. The results of the study indicated that the frequency of weather related disasters is increasing and extreme weather events will increase potential risks to supply chains. First, building organizational resilience will help firms look beyond efficiency and profits in managing lean supply chains. Second, the concept of sole sourcing may need rethinking to maintain a supply chain that is lean and resilient. Third, organizations must plan ahead for supply chains in unpredictable weather. Fifth, communication is a key for anticipating and avoiding the impact of severe weather. This study proposes of a set of strategies, both theoretical and practical, that business firms should develop to effectively prevent and respond to severe weather related disruptions in lean supply chains.

Key Words : Lean Supply Chains, Severe Weather, Climate Change

1. Introduction

When customers purchase products through diverse distribution channels, their purchase decisions are affected by the various elements, such as advertisements, brand loyalty, fashion, blogs, and the like [1]. Through analyzing these purchase behaviors, firms can recognize changes in demand and exercise their dynamic capabilities to efficiently perform supply management to reinforce their competitiveness [2, 3]. However, there are numerous cases where problems occur in demand and supply management plans due to unexpected environmental changes, either natural or man-made, outside the firm's control. Such events may be due to earthquakes, weather anomalies, or terrorism.

Since natural disasters affect a country, region, or even the entire world, it is imperative to develop the ability to prevent and have plans to quickly respond to possible dangers. Natural and weather related disasters have exposed weaknesses of many firms with regard to disruption of their connections with suppliers and customers in lean supply chains [4]. For effective operation of lean supply chains, firms should have plans in place to circumvent or minimize the impact of disruptions stemming from severe weather

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changes [5].

When disasters or weather changes occur, problems in distribution channels are magnified, affecting the supply chain in the entire region [5]. Since suppliers and customers may exist anywhere in the world, inventory strategies should encompass plans to support customers during disasters or volatile changes in the environment. Inventory management that is strategically planned for lean operations can expose its weakness to serve customers in distress. To improve the efficiency of supply chains, companies have implemented lean or similar systems that focus on inventory cost reduction and timely delivery through highly optimized networks [5]. Then, to prepare and respond to disasters, efficiency should be secured first in the supply chain and then risk levels should be analyzed to manage cost (e.g., transportation cost, inventory, and cycle time) in uncertainty [6].

In the March 2012 article, "Logistics 2050 A Scenario Study", DHL predicted frequent occurrence of disasters due to rapid climate change and resultant disruptions in supply chain systems [7]. The occurrence of disasters sometimes induces new distribution demand in the process of ex-post facto responses to disasters (relief-restoration-reconstruction) along with increases in distribution costs. In general, governments expend large amounts of funds for restoration of damaged infrastructure and intra-facilities, thereby creating new distribution demand [5]. For example, the recent damages caused by Hurricanes Irma and Harvey in the Gulf Coast of the United States compelled the federal government to allocate $36 billion for emergency relief efforts in the affected states [8].

After disaster events, new distribution demand would require effective handling of articles in damaged facilities and for procurement, transportation, delivery, and storage of relief goods. Therefore, the supply chain crisis management in preparation for disaster or accident cases should be approached not only at the organizational level, but also at the national level. In addition, such disasters or accidents due to severe environmental changes should be part of the organization's corporate social responsibility (CSR). DHL's GoHelp programs and the Korean Air Lines Co., Ltd disaster support team's participation in the restoration work in disaster regions with special planes for transportation of relief goods are good examples of such CSR activities [9].

Due to the extreme disasters that have occurred during the last ten years, such as Hurricane Katrina, Irma, and Harvey in the US, the tragic 2011 earthquake in Japan, Ebola virus outbreak of 2014 and the earthquake in Nepal in April 2015, the anxiety of people is heightened. With the global urbanization trend, large populations are concentrated in big cities. Thus, even a moderate scale of disasters in urban areas can cause a tremendous amount of damage in human lives and properties. The concept, "resilience", is becoming more important for restoration in disaster management. Resilience is the capability to overcome crises or adversity and return to a positive state. This concept has also become important in supply chain management [10].

When infrastructures, which are physical elements, are destroyed by natural disasters or terrorism, supply chains also suffer. In today's global economy, supply chains are complex and intertwined like a web, and the collapse of any one part may bring about immense ripple effects. Therefore, a collapsed supply chain is difficult to restore quickly. Establishing respond strategies in preparation for environmental changes, where supply chains

would suffer from a sudden disaster or accident, is very important considering the complexity of global supply chains. In this study, through a thorough review of literature and diverse past cases, we intend to derive lean supply chain strategies for prompt and efficient responses to disasters, accidents, and climate changes.

The rest of the paper is organized as follows: Section 2 reviews relevant literature; Section 3 presents real-world cases of lean supply chains in severe weather; and Section 4 concludes the study by articulating the results, implications, limitations of the study, and future research needs.

2. Literature Review

2.1 Lean Supply Chains in Severe Weather

Supply chain management (SCM) began in 1920 by Ford. At that time, Ford had supply chains across the mines (raw materials), rubber plantations (tire making), factories (assembly), and shipping/sales through great efforts to enhance the efficiency of the supply chains. In the mid-1960s, SCM was primarily focused on the enhancement of purchase efficiency, then from the beginning of the 1970s, firms conducted activities for minimization of distribution costs. During the early 1980s, SCM was expanded to include efficiency and optimization of the entire distribution process. By securing safe stocks at all stages such as distribution, manufacturing, and raw material suppliers, firms not only began to hold excessive inventories, but this also led to serious wasting of resources such as unnecessary facility investments and human resources. Lean supply chains are intended to resolve these structural problems [11].

Over the course of history, weather has proven to be capable of disrupting anything that was planned. Supply chains, particularly lean ones, place an emphasis on careful planning and precise execution of operations [5]. One small error or misstep can create a domino effect that can seriously derail even the most carefully designed supply chain.

Lean supply chains seek to maximize performance by minimizing waste through careful planning and execution [12]. Control over all aspects of the supply chain is key to this process. However, throughout history one constant, uncontrollable and sometimes disastrous presence has been the weather. According to estimates from the U.S. National Research Council, 46% of the United States gross domestic product is affected by the weather [13].

Today, firms are exposed to all sorts of small and large risks. Resilient firms do not agonize over how to respond to dangers, but manage various risk elements in a series of systems to effectively control crisis situations in a preemptive manner [14]. When 9-11 tragedy occurred in 2001, Morgan Stanley occupied 50 floors of the World Trade Center. However, since the company had preparations for disasters in place, its back-up site resumed activities in approximately 32 minutes, and business in all branches of the world except for the head office was normalized within 24 hours after the occurrence of the attack [15]. The case of Morgan Stanley is not a miracle. It is an expected result of smart crisis management established in advance, not after the occurrence of terrorism. Thus, Morgan Stanley drew investors' trust and attention and turned the crisis into an opportunity for growth. In rapidly changing and uncertain environments, the ability to quickly respond to crises can be achieved by implementing

contingency plans established in advance. Competitive and sustainable companies manage every small element in the supply chain to respond to disruptive events with an effective strategy.

Severe weather can greatly multiply the possible threats in supply chains. The fear of disruptions in supply chains is nothing new, but what changes when severe weather occurs is the complexity of the risk. Craighead et al. [16] (p. 132) described disruptive risks of supply chains as "unplanned and unanticipated events that disrupt the normal flow of goods and materials as a consequence expose firms within the supply chain to operational and financial risks". Kleindorfer and Saad [17] classified supply chain disruptions into three categories: operational risks (e.g., equipment malfunctions, system failures, and financial distress), natural hazards (e.g. earthquakes, landslides, wild fires, hurricanes, tornadoes, and floods); and terrorism and political instability. These threats are compounded due to today's global supply chains. Consequently, if a severe weather event occurs anywhere in the world, it can have serious effects on the rest of the planet [18]. In this regard, Rao and Goldsby [19] suggested that firms should analyze environmental risk sources (macroeconomic uncertainties, social uncertainties, and natural uncertainties), including national and world issues. Goldstein [20] suggested strategies for planning ahead to prepare for the effects of severe weather in the transportation industry.

The frequency of severe weather events has been increasing in recent years [21-23]. The European Environment Agency (EEA) [24] believes there will be more serious situations caused by frequent severe weather events, such as river flooding, heat waves, earthquakes, hurricanes, wild fires, tornadoes, and droughts. These situations affect supply chains locally and globally [25]. In fact, the number of weather events that caused over $1 billion in damages has increased in recent years. In the US alone, 20 such events occurred in the 1980s, followed by 47 in the 1990s, and 48 in the 2000s [26]. Some believe this trend can be attributed directly to climate change. The World Bank reported that the average global temperature has increased by 0.8°C from the pre-industrial level. Over the past two decades, weather related events have cost an average of tens of billions of dollars annually [18]. Climate change is often ignored or overlooked as a stand-alone risk, but it complicates and amplifies existing threats ranging from raw material supplies to transportation. Due to this impact, climate change should be viewed as a risk multiplier [18].

Modeling research suggests that climate change tend to occur gradually and linearly over an extended period of time. Hence, there is time to effectively adapt infrastructure, settlement patterns, and economic systems [27]. A common conclusion reached suggests that the climatic tolerance to which a majority of the transportation infrastructure was built will need to be modified to accommodate the impact of global warming. McKinnon [27] presented an analysis that what was once thought as a hundred-year floodplain may soon become a ten-year floodplain. For this reason, flood protection efforts will need to be reinforced, and in some cases, transportation arteries will need to be elevated to higher grounds to avoid the impact of floods. Natural disasters (e.g., earthquakes, landslides, wild fires, volcanic eruptions, avalanches, etc.) and climate events (flooding, heat waves, droughts, tornados, and typhoons) are increasing as uncertain hazard

situations in the supply chain [23, 28-32]. Thus, for rapid response to severe weather and climate events, SCM executives should develop appropriate approaches to identify, analyze, and mitigate strategies for local and global supply networks [25].

The automobile industry is especially susceptible to supply chain disruptions caused by severe weather. As supply chains are very interdependent in this industry, a severe weather event can completely shut down the flow of supplies and components, which in turn would interrupt assembly lines for days or weeks at a time. Such production interruptions can easily cost auto companies over $1.25 million per hour [26].

As reported in Severe Weather and Manufacturing in America, published by the U.S. Environmental Protection Agency, the costs associated with supply chains account for 75% of auto-makers' total expenses [26]. Given the many risks and possibilities for disruptions in the supply, companies stand to lose money and customers if supply chain is derailed. These risks are amplified by the threat of severe weather. In today's lean supply chain environment, the odd of a severe weather event disrupting a firm's supply chain can be magnified. There are several factors that affect the negative impact of severe weather on SCM as follows [26]. 1) Many key suppliers are located in regions of the world that are at high risk of severe storms, rising sea levels, and extreme temperatures; 2) As supply chains grow, they become less transparent, increasing unknowns and making threats more difficult to identify and measure; 3) The lower level of the manufacturing industry supply chain is comprised mainly of small businesses, which are less likely to survive and recover from the impact of severe weather events; 4) The infrastructure is aging while congestion is increasing; and 5) Many manufactures have eliminated excess plants in an effort to become leaner, and as a result they have many plants that run two or three shifts. A disruption at a plant that is running at or near full capacity can have a much greater impact than at a plant that only runs one shift in the event of severe weather problems.

3. Examples of Lean Supply Chains in Severe Weather

The Center for Epidemiology of Disasters uses two metrics to measure the impact of natural disasters: death toll and economic cost [27]. We should focus on the latter. With supply chains increasingly becoming a worldwide network of importers and exporters, the effects of a single event in one corner of the earth can cause ripple effects throughout the global supply chain.

3.1 Example 1: the American Auto Industry

Severe weather events can shut down both transportation routes of parts and materials as well as production facilities for automobile firms. In some cases these interruptions can last for days or even weeks. The cost of these shutdowns has been estimated to be over one million dollars per hour. Just-in-time (JIT) delivery practices further complicate this situation, because under JIT as little as two to four hours' worth of inventory is typically stored on site. To remedy this, some companies often hire helicopters to deliver materials when other methods of transportation are compromised [26]. Some of the most notable recent examples of lean supply chain

disruptions due to severe weather are reviewed.

During the period from 2010 to 2013, typhoons in Thailand, hurricanes in the Gulf of Mexico, tornadoes in Kentucky, droughts in Texas and California, floods in the northeast United States, and falling water levels in the Great Lakes disrupted American auto plant operations [26, 33]. The results were that highways were subject to more delays, cargo ships carried less cargo, ports prepared for more hurricanes, and train cars full of materials were significantly delayed. All of these effects seriously hampered the efficiency of the auto industry and created financial hardships [26].

3.2 Example 2: the Thailand Flood of 2011

During the summer of 2011, Thailand experienced devastating flood as a result of increased rainfall and regional tropical storms. The impact of this flooding was felt worldwide as the supply chains of an estimated 14,000 companies were disrupted. Specifically, in the United Kingdom a Honda plant reduced production by 50% due to a lack of motor and electronic parts produced in Thailand [33]. In the United States, the production of consumer electronics was reduced by 33% [26]. The worldwide impact of weather related disruptions on specific products has led to concerns over the geographic clusters of companies [33]. By solely sourcing these products to specific areas, companies have made themselves vulnerable to the impact of weather events.

3.3 Example 3: Russian Drought

In 2010, Russia experienced a severe drought and wild fires brought on by prolonged periods of extreme heat. These wild fires destroyed many crops nationwide, most notably the wheat crop. Due to the large amount of wheat grown and exported from Russia, it was estimated that worldwide economic losses associated with this drought were $15 billion. Additionally, due to the short supply of wheat in Russia, export restrictions were placed on the product, which caused a global price increase that trickled down from the producers to consumers [18].

3.4 Example 4: Hurricane Sandy

In October 2012, Hurricane Sandy hit the east coast of the United States. While cities from Virginia to Massachusetts felt the impact, most seriously affected were the ports of New York and New Jersey, the world's major consumer market. As a result, cargo ships were diverted to other ports until the Port Authority of New York and New Jersey (PANYNJ) was back in full operation [34].

The silver lining of this devastating event was that it forced all the ports in the area to implement emergency plans to prepare for and deal with the effects of such an event. Specific changes in PANYNJ resulting from the hurricane were as follows [34]; 1) Future construction will be designed to minimize the impact of such events; 2) Equipment was raised to an elevation that would be safe from flood waters; 3) Electrical controls were placed at least two feet above the flood line so that facilities would not lose power; backup generators were purchased; 4) PANYNJ made arrangements for fuel to be supplied from companies located further inland in the event that it is not available locally; 5) Finally, communication was stressed; phone networks,

as well as Internet pages and social media were all updated as critical players to handle severe weather in the area.

However, while severe weather affects everyone in the area, certain companies and industries are more vulnerable than others. According to Assessing and Managing Climate Change Risks in Supply Chains published by the United Kingdom Environmental Agency, vulnerability depends on the following: company size; geographic location; whether or not supplies are climatically sensitive; transportation distance and method; whether suppliers are JIT or stockpiling systems [35]. The report noted that in a lean supply chain it only takes one weak link to derail the entire system. As a result, lean supply chains are more susceptible to upstream supply shocks [33]. Interestingly, companies that maintain a surplus of materials are in a better position to weather both a figurative and literal storm.

The type of industry may be the most critical factor in determining a firm's vulnerability to severe weather. Historically, industries dealing with food, water, energy, or ecosystem services have felt the greatest impact of severe weather events [18].

Sager [36] reported that droughts, floods, typhoons, hurricanes, and other forms of severe weather have had a devastating impact on crops since the dawn of time, long before anyone even knew what a supply chain was. In these industries, as well as all others, the impact will vary depending on the severity of the storm, the impact of climate change on the commodity, and the concentration of suppliers in relation to the location of the storm [18].

3.5 Summary of Case Examples

The impact of severe weather on supply chains, especially on lean supply chains is far reaching. A review of the literature suggests that supply chains dependent on agriculture are most vulnerable, everything from cultivating crops to the transportation of finished products to the consumer can be derailed by a storm (see Table 1).

The recent events such as the Thailand floods of 2011, Hurricane Sandy of 2012, the 2011 earthquakes in Japan, and Russian drought in 2010 have proven the global impact of regional severe weather. Trends show that the frequency of these disastrous events is increasing and many scientists attribute this trend to climate change.

In sum, extreme weather events will increase potential risks to supply chains as shown in Table 2. It is important for managers to understand supply chain risks associated with severe weather events so that the firm can develop effective strategies for corporate risk management.

To reduce the demand-supply variation, artificial intelligence (AI) has been applied to support operational processes through reducing delivery time and establishing capacities for risk management in supply chains.

Accurate information exchange across the supply chain to ensure competitive advantages reduce under unexpected disruption risks [41, 42]. For example, IBM has recently launched Watson Supply Chain, which is aimed for supporting 'supply chain visibility and gaining supply risk insights' using weather forecasts data (IBM homepage).

Table 1 Summary of Case Examples

	Examples of lean supply chains in severe weather			
	American Auto Industry	Thailand Flood	Russian Drought	Hurricane Sandy
Country	USA	Thailand	Russia	USA
Period	2010 to 2013	2011	2011	2012
Damage	• Highways were subject to more delays • Cargo ships carried less cargo • Train cars full of materials were delayed	• Supply chains of about 14,000 companies were disrupted. • A Honda plant reduced production by 50% in the Kingdom United • The production of consumer electronics was reduced by 33% in the United States,	• The wild fires destroyed most notably the wheat crop. • worldwide economic losses associated with this drought were $15 billion • Global the wheat crop price increases due to limited exports to products	• The ports of New York and New Jersey, the major consumer markets in the world, have been destroyed. • The cargo ships were diverted to other port.

4. Conclusions

The risks associated with severe weather events greatly intensify the complexity of managing lean supply chains. This study reviewed the relevant literature and examined several major weather related disasters and their impact on supply chain management.

The results of this study provide several theoretical and practical implications. First, building organizational resilience will help firms look beyond efficiency and profits in managing lean supply chains. McKinnon [27] suggested a five-stage procedure for improving supply chain resilience: identify risks; conduct a threat and risk analysis; develop continuity strategies; implement the strategies and adjust business policies, infrastructure, and material assets, accordingly; and review and update the continuity plan.

While this strategy can be implemented to safeguard against the effects of severe weather, even the most thoroughly planned and well executed activities cannot completely eliminate the impact of devastating weather.

Our study reinforced this point and suggests that firms must be agile and resilient to stay ahead of storms.

Second, we suggest that the concept of sole sourcing may need rethinking to maintain a supply chain that is lean and resilient. Events such as the 2011 Thailand floods have caused companies to reconsider the merit of sole sourcing, from only one supplier or one geographic region. The grim reality is that one storm can seriously affect a company's production operation when it purchases all materials from one source or suppliers clustered closely together. In order to avoid this, businesses are now considering multiple sources in dispersed locations. Toyota in particular has diversified its suppliers geographically, while some companies such as Apple are reshoring some operations to local supply chains, intending to increase production domestically versus abroad [43].

Similarly, some auto manufacturers are moving toward supply chains in which all components are from suppliers located within 100 kilometers of the assembly plant. As of 2010, approximately 25% of manufacturers had

adopted this idea [44].

Some suppliers are emphasizing redundancy by operating out of several locations across the United States. Doing so allows them to ship from secondary locations when the primary location is offline [45].

Banham [43] states in Weathering the Weather that shortening supply chains reduces the likelihood of being impacted by a severe weather event and improves supply chain flexibility to quickly change orders which are already in transit. We found that the general movement is toward a balance between sole sourcing, which reduces cost, and multi-sourcing, which reduces risk. Reaching a good balance is the key to maintain a supply chain that is lean, but also resilient to the global effects of severe weather.

Third, organizations must plan ahead for supply chains in unpredictable weather. Although weather is unpredictable, it rarely comes completely without warning [46, 47].

Goldstein [20] notes that one of the most surprising aspects of a storm's impact is that despite all of the resources dedicated to forecasting the weather, people and businesses seem to be caught off guard. Thus, planning ahead for the transportation aspect of SCM and implementing a proactive plan would be the best way to prepare for the devastating effects of severe weather.

Fourth, communication is a key for anticipating and avoiding the impact of severe weather. This is particularly true in the transportation part of supply chains. In today's environment of social media and instant access to local, national and global news and weather, there is no excuse for poor communication [49, 50]. Thanks to modern technologies for forecasting weather, shipping companies can anticipate where storms will strike in relation to their supply chains and current vehicle traffic. By staying ahead of the storm, shippers can reroute trucks or arrange for supplies to be shipped out of a different location. Additionally, by maintaining open communication with customers they will know whether or not a storm has shut down production at a destination plant, thus avoiding delivering supplies to manufacturers that may not be able to receive them [51].

Lastly, a key element of lean supply chains is the utilization of JIT where idle time is considered waste and sought to be eliminated. The negative side of JIT is that there is little contingency when a disruptions occurs in the well-oiled machine of lean supply chain. In order to mitigate this and soften the blow of disastrous events, companies have begun utilizing just-in-case (JIC) suppliers.

Table 2 Potential Risks in Supply Chain

Possible impact	Possible strategy	References
• Rising storms, floods, • wild fires, earthquakes • Rapid climate change • Ecosystem destruction • Increasing financial risk • Increasing SCM risk • Increasing terrorism • and political issues	• Develop appropriate lean SC • Risk management • Build strong partnership • Supplier development program and knowledge utilization • Investigate Information technology system and AI • Expand global environmental protection	Stern [37], Hinkel and Kiein [22], Kleidorfer and Saad [17], Wagner and Bode [38], Manuj and Mentzer [39], Zsidisin et al. [40], Craighead et al. [16], Kim and Song [48]

These JIC suppliers serve as a backup plan to primary suppliers and can be called upon to temporarily keep the production lines moving until the primary suppliers are once again operational [43, 49]. Adding a redundant shipping method to a supply chain can also pay dividends in the long run. As with all of these practices, the cost of diversifying a supply chain and keeping JIC suppliers on retainer must be balanced against the cost-effectiveness of sole source suppliers.

5. Discussion and Implications

Although the weather cannot be controlled or sometimes even predicted, businesses can take steps to prepare for serious weather events so as to limit their impact. With the increasing attention being paid to climate change and severe weather conditions that can accompany it, many firms are starting to examine their strategic options to lessen the impact of such events. There is a breaking point in all of this planning. At some point, the redundancy will overtake the efficiency and the supply chain will cease to be lean. For this reason, the cost of planning and preparing for severe weather events must be weighed against potential loss in profits [27, 47, 51].

Since the present study theoretically presented application plans for lean SCM centering on weather anomalies and natural disaster cases, it has a limitation that the theoretical proposal cannot be verified. In additions, as real-world cases discussed (e.g., Thailand floods of 2011, Hurricane Sandy of 2012, the 2011 earthquakes in Japan, and Russian drought in 2010), these represent the tip of an iceberg for all possible effects according to industry types. Thus, generalizability of this study's results may be limited.

Future research should consider the limitations discussed above. Additionally, examining through real-world examples, the necessity of effective respond strategies of firms against weather anomalies and climate change should be examined. Second, the increasing terrorism and weather changes, such as earthquakes and floods that are becoming more frequent, should lead to partnership efforts of firms, governments, countries, and the entire world. Thus, guidelines for preventing or responding strategies for natural or man-made disasters should be established. Third, the validity of application plans for lean supply chain management for fast and efficient movement of goods should be examined more systematically in the future.

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