Modeling the Impact of Border Crossing Bottlenecks on Supply Chain Disruption Risk

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Abstract—In order to remain competitive, companies outsource the manufacturing process to global markets. Globalization requires shipping of goods across borders. Cross border movement of goods faces diverse difficulties and creates bottlenecks in the supply chain. Complex products involve numerous parts and complications in the assembly process, resulting in multiple border-crossings with varying level of complexity across multiple countries before reaching to the customers. This activity contributes to the supply chain disruption risk. Border crossing is unavoidable in global supply chains, and how to integrate border crossing complexity in supply chain models is an unresolved issue. This paper suggests an approach to quantify the border crossing complexity and its impact on the supply chain disruption risk in the global outsourcing environment. Results show that key factors which contribute to border crossing complexity include product complexity, trade procedures, and various bottlenecks at each border-crossing. Based on results drawn from the quantitative analysis, we propose several strategies to manage the impact of border crossing bottlenecks. The focus of this research is the manufacturing companies which are involved in managing the global supply chains.

Keywords-Quantitative Analysis, Border Crossing Complexity, Supply Chain Disruption, Global Outsourcing

I. INTRODUCTION

Today, 20% of all goods cross a border. By 2020, 80% of all goods will cross a border regardless of the country [1]. Global supply chains are increasingly fragmented across a larger number of countries, each involved in the assembly process at a different stage, resulting in multiple border-crossings of parts and components before getting incorporated in the final product [2]. To facilitate such networks, the focus of trade policy has gradually shifted from traditional trade barriers to the remaining facilitation hurdles and bottlenecks because of considerable reduction in tariffs on goods crossing national borders [3].

In order to remain competitive, companies outsource the manufacturing process to international markets which results in different structure of supply chain network. However, the lack of outsourcing decision making tools for logistic activities of supply chain has made the reshoring an emerging trend [4-7]. Among the global logistics activities, border delays constitute a major bottleneck to the smooth movement of goods [8]. For example, a study related to Sub-Saharan Africa shows that the cost to transporter alone runs into hundreds of millions of US dollars annually, excluding the much larger cost to the mining, manufacturing and retail sectors due to long and unpredictable delays in the delivery of freight consignments. Long delays experienced at border posts are the single biggest contributor towards the slow average movement of freight [9]. Belzer et al. [10] estimated a cost to the region of more than US$ 1.6 billion if a border-crossing point at the Ambassador Bridge (between the United States and Canada) closes for two weeks for any reason. Roughly US$ 6 billion is spent each year by the automotive industry on inventory-carrying costs at borders. Therefore, efficient and effective border procedures have the potential to provide more benefits to international trade than the reduction of tariff barriers [11]. Unpredictable times at borders increase the supply chain disruption risk and cost. For example, border-crossing from one state to another is a regulatory event within India, consuming up to 15% of all transport time and adding 15–20% to the total cost. Even though value-added tax has been established, border permits are still required. It is clear that among the biggest challenges facing trading countries are the border processes, specifically import and export clearance [12]. Another study related to countries in the Greater Mekong Subregion highlights that nearly half of the total transit time is in fact taken at customs or border-crossings, and 43% of the transport costs are collected at customs and border-crossings. Hence, weakest links in various economic corridors remain the border-crossings [13].

In the modern supply chain practices, the practical and quantitative understanding of border crossing complexity is the least researched area due to subjective nature of the field. Existing literature highlights numerous aspects of the border crossing trade barriers. In a two-country trade model, [14] found that the number of signatures and number of trade procedures reduce country's exports volume by increasing transaction costs. In differentiated products, each signature lowers exports volume by 4–5 percent more than standard goods, resulting in further increase in transaction cost. Goodchild et al. [15] examined the variability in border crossing times, and the impact of this variability on regional supply chains. They highlighted that late arrivals can have significant economic costs for factories waiting for parts to assemble and for carriers who miss delivery times. Several other studies highlight the difficulty factors related to cross-border movement of goods [3], [16-18]. The majority of the articles about border crossing bottlenecks are either descriptive or lack the focus on the supply chain management. The issue of ignoring border crossing bottlenecks can cause adverse consequences in terms of bottlenecks in the supply chain, loss of competitiveness, and strategic failure of the business. The key aim of this paper is to analyze the impact of border crossing complexity by considering the risk of delay in the global outsourcing environment. To achieve this aim, this paper makes the following contributions to the existing literature:

- Utilizes a case study in the manufacturing industry to highlight the significance of problem.
- Identifies the border crossing complexity and its impact on the supply chain.
- Develops a methodology to quantify the border crossing complexity in manufacturing supply chain.
- Estimates the supply chain disruption risk as a function of border crossing complexity.
- Proposes several strategies to manage the impact of border crossing complexity for effective supply chain design.

The remainder of this paper is organized as follows. In Section II, a case study is described to highlight the significance of the border-crossing problem. In Section III, a seven-step model to quantify the border crossing complexity and its impact on the disruption risk is developed. In Section IV, a numerical analysis is provided to support the proposed methodology. Results and discussions based on quantitative analysis are provided in Section V. Finally, Section VI describes the conclusions and future work.

II. CASE STUDY-TOYOTA MOTOR CORPORATION

In this section, we describe a case study to highlight the significance of the problem of border crossing complexity. We choose an automotive company, Toyota Motor Corporation, because it is the most benchmarked company in the modern business practices. Also, automotive industry is more vulnerable to border crossing complexity. The case study is created based on evidence from Toyota and related literature [16], [19-24].

Toyota Motor Corporation produces more than 10 million vehicles per year in its 52 overseas manufacturing companies in 27 countries, and sells them in more than 170 countries. Parts suppliers are located everywhere in the world. There are approximately 15000 distinct vehicle parts in the World. The average number of distinct parts in a vehicle is 2200. This large number of parts/vehicles contributes to the product complexity. The product complexity can be described as number of vehicles, number of parts, difficulty in generating these parts/vehicles, degree of novelty of parts/vehicles, variety of production processes, and configuration of parts/vehicles. Moreover, the globalization amplifies the impact of product complexity due the factors such as distance between supply chain partners, number of parts suppliers, number of vehicle manufacturers, and number of border-crossings. Border-crossing difficulty makes this situation more complicated. In order to reduce the impact of this phenomenon, Toyota reduces costs and standardizes basic parts to produce multiple vehicles at the same time. In this case, if a part is assigned to a single supplier, missing one type of part can interrupt the production of several models. This circumstance can also magnify the impact of quality-related disruptions. For example, Toyota suffered the billions of dollars of lost sales and costs as a result of product recalls in 2010. The key reason of this loss was the reliance on using a single part, sourced from one supplier, in many car models. A reasonable strategy is to assign a single part to multiple suppliers, but the increased frequency of border-crossings may increase the risk of delay. In contrast, if a common part is sourced from a single supplier, it increases the supply chain disruption risk. Therefore, Toyota needs alternative strategies to deal with conflicting behavior between standardization of common parts, number of suppliers, number of manufacturers, predictable disruptions, and unpredictable disruptions.

For in-house manufacturing in Japan, Toyota sources 85% of the parts suppliers located within a 50-mile radius of a plant (i.e., within a one-hour drive). Toyota has outsourced its manufacturing operations to 27 countries around the globe, and North America is Toyota's key manufacturing destination. The supplier base is spread out in North America—perhaps over 300 miles from the plant. In this case, the goal is for 80% of the parts to be delivered within three to five days lead time. About 75% of its inbound material is sourced in North America, from 660 suppliers across more than 30 states, Canada and Mexico. Toyota imports parts from overseas to North America, mainly from or via Japan. It receives about 160 full containers per day – nearly 80,000 twenty-foot equivalent units (TEUs) per year. Almost all parts from Asia are repacked and consolidated in vanning centers in Japan, then imported to North America; the exception is Brazil, from which Toyota imports directly to the port of Norfolk. Recently, Toyota exports US-assembled vehicles to 32 countries around the world including Canada, Mexico, Central America, the Caribbean, South America, the Middle East, Asia

Pacific and Europe. Therefore, the sourcing of parts and shipping of vehicles in everywhere in the world have significant impact on supply chain complexity. Fig. 1 shows a typical structure of the Toyota's supply chain network. Domestic parts supply has no border-crossing, but many other factors such as international vehicle shipping, handling the number of parts at suppliers, vehicle manufacturing complexity, and handling a great number of parts/vehicles at border-crossings can magnify the disruption risk. International parts supply involves two main kinds of suppliers, souring from neighboring countries and offshore souring. For instance, Toyota sources vehicle parts from Canada to USA, which involves one border-crossing. On the other hand, when Toyota sources parts from one country into Japan and then supplies to manufacturing destinations in another country, it results in two unique border-crossings.

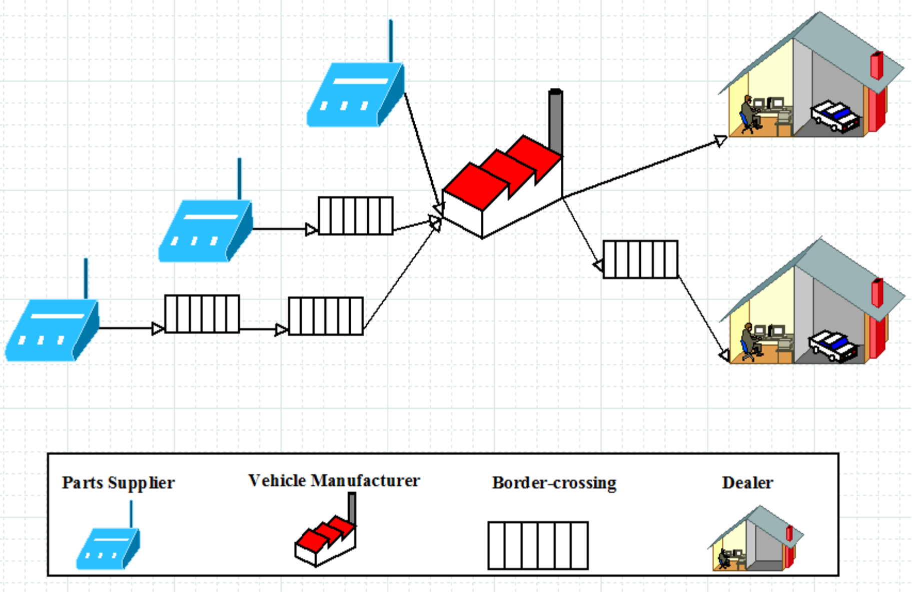

Fig. 1. Typical Structure of the Toyota's Supply Chain Network

In addition to parts sourcing based on quality and competitive prices, Toyota seeks low cost manufacturing destinations. For example, the closure of Toyota's Australian assembly plant will be completed by 2017, due to unfavorable currency and high manufacturing costs. Relocation of manufacturing facilities alters the structure of supply chain, resulting in variable impact on supply chain complexity. For instance, in the case of Toyota Europe, certain models of Corollas are outsourced to South Africa and the United Kingdom. South Africa is a low cost manufacturing destination. The time varies depending on where the car is built, six to eight weeks to ship from South Africa but only three days from the United Kingdom. Parts are sourced from Turkey, South Africa, and Thailand for both the European and South African vehicle manufacturing. Therefore, shipment of vehicles from South Africa to global market may discourage the dealers due to delays in consumer deadlines.

While border procedures are among the most troublesome links in the global supply chain, they are especially so in poor countries, where it frequently takes three times as many days to import goods as it does in more developed ones. Imports to poor countries require nearly twice as many documents and six times as many signatures. The automotive industry is especially vulnerable to any delays at the border because most assembly plants operate on a Just-in-time (JIT) system, where parts arrive only a few hours before they are needed for assembly. JIT strategy promotes the pull system with small and frequent lot deliveries. Parts procurement and shipping to customer destination is performed through several countries and multiple border-crossings. Toyota stores all parts in careful way, so ineffective handling of parts and equipment at borders could lead to degradation of the quality, increased costs or delays, or suspensions in Toyota's production and deliveries. Emergence of security fears at borders has a serious impact on Toyota's supply chain, resulting in lost production due to long delays. Toyota has incurred, and expects to incur in the future, significant costs associated with difficulty factors such as vehicle safety, environmental matters, tariffs, taxes, exchange controls, recall practices, new legislation, changes in existing legislation, and other trade barriers. Increased trade barriers have caused the increase in number of signed/stamped documents required at border. The impact on inventory levels in the supply chain can increase 600 percent compared to normal operating conditions as a result of increasing the security measures on international borders. Thus, border delays may increase the impact of predictable and unpredictable disruptions, causing expedited freight charges, downtime, and overtime premiums. In order to avoid plants shutdowns, the industry faces increased carrying cost, warehousing cost, and quality problems. Therefore, border crossing bottlenecks combined with product complexity strengthen the impact of supply chain disruptions.

III.MODEL OF BORDER CROSSING COMPLEXITY

In the following, we develop a seven-step model to quantify the border crossing complexity and its impact on the disruption risk in manufacturing supply chain. We utilize basic probability, reliability, and uncertainty principles to analyze the impact of border crossing complexity. We use following seven steps in this model:

Notation

j	Index of manufacturing destinations, $j = 1,2, \dots m$
k	Index of parts-shipments in production schedule, $k = 1,2, \dots K$
v	Index of unique borders required to be crossed by parts-shipment k, $v = 1,2, \dots V$
u	Index of product-shipments in production schedule, $u = 1,2, \dots U$
y	Index of unique borders required to be crossed by product-shipment u, $y = 1,2, \dots Y$
$F_{k,v,u,y}$	Number of physical/laboratory tests required for shipment k or u at unique border v or y
$\delta_{k,v,u,y}$	Average repetition frequency of physical/laboratory tests for shipment k or u at unique border v or y
$G_{k,v,u,y}$	Number of stamped/signed documents required for shipment k or u at unique border v or y
$\eta_{k,v,u,y}$	Average repetition frequency of stamped/signed documents for shipment k or u at unique border v or y
$E_{k,v,u,y}$	Number of remaining unique trade procedures required for shipment k or u at unique border v or y
$\epsilon_{k,v,u,y}$	Average repetition frequency of remaining trade procedures for shipment k or u at unique border v or y
$\gimel$	Index of difficulty factors, $\gimel = 1,2, \dots N$
$W_{\gimel}$	Weight of difficulty factor $\gimel$ for parts/products shipments
$\mathcal{S}_{\gimel,v}$	Strength of difficulty factor $\gimel$ at unique border v for parts-shipments
$\mathcal{S}_{\gimel,y}$	Strength of difficulty factor $\gimel$ at unique border y for product-shipments
$\mathfrak{U}$	Maximum strength of a difficulty factor
a	All types of parts in the production schedule
b	All types of products in the production schedule
$q_{k,v}$	Types of parts in the parts-shipment k that crosses unique border v
$Q_{u,y}$	Types of products in the products-shipment u that crosses unique border y
$\mathcal{F}_{k,v,u,y}$	Fraction of trade procedures that is likely to cause the disruption for shipment k or u at unique border v or y
$\mathfrak{D}_j$	Fraction of trade procedures that is likely to cause the disruption at destination j
s	Index of parts suppliers for destination j, $s = 1,2, \dots S$
$\mathbb{mm}$	Index of manufacturers at destination j, $\mathbb{mm} = 1,2 \dots \mathbb{M}$
r_s	Number of parts sourced from supplier s at destination j
r_m	Number of elements of manufacturing complexity for manufacturer $\mathbb{mm}$ at destination j
$\mho_s$	Difficulty level for parts supplier s at destination j
$\oiint_{\mathbb{mm}}$	Difficulty level for manufacturer $\mathbb{mm}$ at destination j
$p_{k,v,u,y}$	Probability of failure for each trade procedure for shipment k or u at unique border v or y
p_j	Probability of failure for each trade procedure at destination j
p_s	Probability of failure for each part for supplier s at destination j
$p_{\mathbb{mm}}$	Probability of failure for each element of manufacturing complexity for manufacturer $\mathbb{mm}$ at destination j
$t_{k,v,u,y}$	The time assigned to trade procedures for shipment k or u at unique border v or y
$\mathbb{Q}_j$	Optimal transportation lot-size without integration of border crossing complexity at destination j
H_j	Inventory holding cost per unit time at destination j
$\mathcal{L}_j$	Labor cost per unit time at destination j

$\pitchfork_j$	Magnitude of extra time units for expedited shipment at destination j
$\mathfrak{Y}_j$	Number of employees affected by delay at destination j
$\mathfrak{x}_j$	Cost per unit time for expedited shipments at destination j

Step 1: *Find the total number of border-crossings required for parts and product shipments within a production schedule*.

A production schedule may consist of several shipments resulting in frequent border-crossings. Complex products consist of numerous parts and final product verities that require frequent border-crossings between different countries [25]. In global supply chains, a single shipment may require several unique borders between suppliers, manufactures and customers. For example, Myanmar's neighboring countries Bangladesh, India, and Thailand are quite interested in transit trade with China through Myanmar [26]. Therefore, the total number of border-crossings required by a single production schedule at destination j is

$$(KV + UY)_j, \quad \forall j \tag{1}$$

In Equation (1), first term in the parentheses shows the product of "the number of unique borders required to be crossed by a parts-shipment and the total number of parts-shipments in production schedule." The second term shows the product of "the number of unique borders required to be crossed by a product-shipment and the total number of product-shipments in production schedule."

Step 2: *Calculate number of trade procedures required at each border-crossing*.

There are a number of trade procedures including physical/laboratory tests, stamped/signed documents, and various other trade procedures that are required at the border-crossing. Unnecessary repetition of these procedures adds further complexity to the process. So, the number of trade procedures required for a shipment k or u at unique border v or y is

$$F_{k,v,u,y}\,\delta_{k,v,u,y} + G_{k,v,u,y}\,\eta_{k,v,u,y} + E_{k,v,u,y}\,\epsilon_{k,v,u,y}, \qquad \forall k, v, u, y \tag{2}$$

In Equation (2), first term shows the product of "the number of physical/laboratory tests required for a shipment and the repetition frequency of these tests." Each shipment of parts/product has its own characteristics, so the number of tests varies from shipment to shipment within a customer order. The second term shows the product of "the number of stamped/signed documents required for a shipment and the repetition frequency of these documents." In addition to physical/laboratory tests and stamped/signed documents, there are numerous other procedures that are required at borders. Therefore, the third term shows the product of "the number of these remaining procedures and their repetition frequency."

Step 3: *Calculate difficulty level with the help of difficulty factors and product complexity.*

Difficulty factors observed at individual crossings cause difficulty in cross-border movement of goods. Based on key articles mentioned in this paper and a thorough literature review in the relevant field, Table 1 shows key difficulty factors that cause bottlenecks at borders.

TABLE 1. Key Difficulty Factors That Cause Bottlenecks at Borders

Number of border-crossings required to source/ship	Lack of maintenance for long term
Number of unique trade procedures	Excessive paperwork requirements
Number of stamped/signed documents	Lack of automation of documents
Number of physical/laboratory tests	Weak telecommunication links
Excessive repetition of trade procedures	Inefficient information system at border
Lack of standardization of trade procedures	Lack of information availability
Increasingly strict safety and security measures	Lack of information reliability
Distance between inspection facilities and agencies	Unclear internal communication between agencies
Percentage of goods inspected manually	Lack of inter-agency cooperation behind the border
Lack of single-stop inspection at the borders	Lack of cooperation between agencies across the border
Congestion at inspection locations	Non-harmonized working hours
Inconsistent handling of inspections	Customs slowdowns
Lack of storage capacity/insufficient facilities	Corrupt practices in border agencies
Poor quality of roads/pathways	Level of fraud in border agencies
Difficulty in product/container identification	Unofficial fees or illegal bribes
Difficulty in cargo/container scanning	Frustrating customers
Lack of language/communication skills	Delays without any reason
Lack of sufficient staff	Time-consuming /unnecessary licenses demands
Lack of skilled staff	Excessive customs duties required
Lack of sufficient tools/equipment	Value-added tax
Obsolete equipment	Time spent on borders
Insufficient electricity	

Each difficulty factor has a different level of importance, so we assign a weight W_{λ} to each difficulty factor, where $\sum_{\lambda=1}^{N} W_{\lambda} = 1$. For a specific difficulty factor, we assume the same weight W_{λ} for any parts/product shipment at any border-crossing. Each difficulty factor has a different impact at each unique border-crossing, so we assign strength $\mathcal{S}_{\lambda,v}$ and $\mathcal{S}_{\lambda,y}$ to each difficulty factor at each unique border, v and y. Strength is adjusted based on the effect of a difficulty factor on a specific border. If a border-crossing is composed of combination of different markets, the strength is adjusted based on the aggregate effect of both markets. The difficulty index for a shipment k or u at unique border v or y is

$$\sum_{\lambda=1}^{N}\left(W_{\lambda}\,\mathcal{S}_{\lambda,v}\right) + \sum_{\lambda=1}^{N}\left(W_{\lambda}\,\mathcal{S}_{\lambda,y}\right), \qquad \forall k, v, u, y \tag{3}$$

In Equation (3), first term shows the difficulty index for a parts shipment, and second term shows the difficulty index for a product shipment. The types of parts and products in each shipment of the production schedule affect the overall difficulty at a border-crossing. Within a production schedule, a border-crossing with fewer types of parts/products has relatively low difficulty. Therefore, the fraction of total types of parts/products may be incorporated into the difficulty index. Incorporating this aspect, the difficulty index for a shipment k or u at unique border v or y is

$$\sum_{\lambda=1}^{N}\left(W_{\lambda}\,\mathcal{S}_{\lambda,v}\right)\left(1+\frac{q_{k,v}}{a}\right) + \sum_{\lambda=1}^{N}\left(W_{\lambda}\,\mathcal{S}_{\lambda,y}\right)\left(1+\frac{Q_{u,y}}{b}\right), \qquad \forall k, v, u, y \tag{4}$$

In Equation (4), we assign strength $\mathcal{S}_{\lambda,v}$ and $\mathcal{S}_{\lambda,y}$ to each difficulty factor λ at each unique border, v and y. The strength $\mathcal{S}_{\lambda,v}$ of a difficulty factor lies between two limits (e.g. 1 = least strength, and 10 = maximum strength). If $\mathfrak{U}$ is the maximum strength of a difficulty factor, the difficulty level for a shipment k or u at unique border v or y is

$$\frac{\sum_{\gimel=1}^{N}\left(W_{\gimel}\,\mathcal{S}_{\gimel,v}\ \right)\left(1+\frac{q_{k,v}}{a}\right)+\sum_{\gimel=1}^{N}\left(W_{\gimel}\,\mathcal{S}_{\gimel,y}\ \right)\left(1+\frac{Q_{u,y}}{b}\right)}{2\mathfrak{U}}, \qquad \forall k,v,u,y \tag{5}$$

Step 4: *Integrate difficulty level and number of trade procedures to estimate strength of uncertain trade procedures.*

The difficulty level at each border-crossing is variable. If it is easy to deal with some trade procedures at the border, the difficulty level tends to diminish. For instance, if the difficulty level is zero at a border-crossing, there are a negligible number of trade procedures that are likely to cause the disruption. To estimate the approximate disruption risk, the fraction of uncertain trade procedures can be determined as the product of “total number of trade procedures (Equation (2)) at a specific border-crossing and the overall difficulty level (Equation (5)) at this border-crossing.” Therefore, the fraction of trade procedures that is likely to cause the disruption for shipment k or u at unique border v or y is

$$\mathcal{F}_{k,v,u,y}=\frac{1}{2\mathfrak{U}}\left[\left(F_{k,v,u,y}\,\delta_{k,v,u,y}+G_{k,v,u,y}\,\eta_{k,v,u,y}+E_{k,v,u,y}\,\epsilon_{k,v,u,y}\right)\times\left\{\sum_{\gimel=1}^{N}\left(W_{\gimel}\,\mathcal{S}_{\gimel,v}\ \right)\left(1+\frac{q_{k,v}}{a}\right)+\sum_{\gimel=1}^{N}\left(W_{\gimel}\,\mathcal{S}_{\gimel,y}\ \right)\left(1+\frac{Q_{u,y}}{b}\right)\right\}\right], \qquad \forall k,v,u,y \tag{6}$$

Similarly, the fraction of trade procedures that is likely to cause the disruption at destination j is

$$\mathfrak{D}_j=\frac{1}{2\mathfrak{U}(KV+UY)_j}\left[\sum_{k=1}^{K}\sum_{v=1}^{V}\sum_{u=1}^{U}\sum_{y=1}^{Y}\left(F_{k,v,u,y}\,\delta_{k,v,u,y}+G_{k,v,u,y}\,\eta_{k,v,u,y}+E_{k,v,u,y}\,\epsilon_{k,v,u,y}\right)_j\times\left\{\sum_{\gimel=1}^{N}\left(W_{\gimel}\,\mathcal{S}_{\gimel,v}\ \right)\left(1+\frac{q_{k,v}}{a}\right)+\sum_{\gimel=1}^{N}\left(W_{\gimel}\,\mathcal{S}_{\gimel,y}\ \right)\left(1+\frac{Q_{u,y}}{b}\right)\right\}_j\right], \qquad \forall j \tag{7}$$

Step 5: *Calculate risk of delay as a function of strength of uncertain trade procedures at each border-crossing.*

It is difficult to estimate the probability of some events such as disruption due to uncertain trade procedures, faulty part/product, etc. In the long term, it is much better to overestimate the probability of disruptions compared to underestimating or ignoring the likelihood of disruptions [23]. Therefore, we estimate the probability of disruption for uncertain trade procedures and faulty parts/products by using basic principles of probability and reliability. According to Wiener [27], if an experiment consists of n independent trials, each trial with probability of success p, then probability that there will be at least one success in experiment is

$$1-(1-p)^n \tag{8}$$

In Equation (8), the term $1-p$ is the probability of no success for each trial. Similarly, the function $(1-p)^n$ can be described as the probability that there will be no success in experiment. In the following, we adapt the Equation (8) in two different ways: (*i*) the probability that at least one trade procedure will cause the disruption; and (*ii*) the probability that at least one part/product will cause the disruption.

For a shipment k or u at unique border v or y, if a border-crossing consists of n independent trade procedures, each with probability of failure $p_{k,v,u,y}$, then the probability that at least one trade procedure will cause the disruption is

$$1-\left(1-p_{k,v,u,y}\right)^{\mathcal{F}_{k,v,u,y}} \qquad \forall k,v,u,y \tag{9}$$

In Equation (9), the term $1-p_{k,v,u,y}$ is the probability of no failure for each trade procedure. The function $(1-p_{k,v,u,y})^{\mathcal{F}_{k,v,u,y}}$ can be described as the probability that there will be no failure or the reliability of the trade procedures. Similarly, the probability that at least one trade procedure will cause disruption at destination j is

$$1-\left(1-p_j\right)^{\mathfrak{D}_j} \qquad \forall j \tag{10}$$

Step 6: *Estimate product complexity and resultant risk of delay for each supplier and manufacturer involved in execution of production schedule. Determine reliability for individual border-crossings, suppliers, and manufacturers.*

For the measurement of border crossing complexity, we incorporated the number of unique parts and products in a shipment at each crossing. Various types of parts and products require multiple shipments resulting in multiple border-crossings. Therefore, product complexity is directly related to border crossing complexity. Inman & Blumenfeld [25] used similar approach to estimate the probability that at least one part will cause the disruption. They argued that product complexity is related to the number of parts in a product. If it is easy to deal with a part for a supplier, then there are only a fraction of parts that are likely to cause the disruption. This fraction of parts may be calculated as the product of “number of parts assigned to a specific supplier” and “the overall difficulty level for acquiring parts from this supplier." Therefore, the probability that at least one part will cause the disruption for parts supplier s at destination j is

$$1-(1-p_s)^{\mathrm{r}_s \mho_\mathrm{s}} \qquad \forall s,j \tag{11}$$

In the Equation (11), the term $\mathrm{r}_s\mho_\mathrm{s}$ is the fraction of parts that are likely to cause the disruption. The term $(1-p_s)^{\mathrm{r}_s\mho_\mathrm{s}}$ is the reliability of parts supplier s. For a manufacturer, the product complexity can be measured by the number of elements of manufacturing complexity other than the sourced parts (e.g. number of unique processes required to manufacture the product, attributes of complexity, etc.). Therefore, the probability that at least one element of manufacturing complexity will cause the disruption for manufacturer m at destination j is

$$1-(1-p_{\mathbb{mm}})^{\mathrm{r}_{\mathbb{mm}} \oiint_{\mathbb{mm}}} \qquad \forall \mathbb{mm},\mathrm{j} \tag{12}$$

In the Equation (12), the term $\mathrm{r}_{\mathbb{mm}}\oiint_{\mathbb{mm}}$ is the fraction of element of manufacturing complexity that are likely to cause the disruption. The term $(1-p_{\mathbb{mm}})^{\mathrm{r}_{\mathbb{mm}}\oiint_{\mathbb{mm}}}$ is the reliability of manufacturer m.

Step 7: *Estimate risk index for individual paths for alternative manufacturing destinations*.

So far, we have established the measure for the probability of disruption and reliability for border-crossings, suppliers, and manufacturers. Any delay at any supplier's facilities, manufacturer's facilities, or the border-crossings results in disruptions, in the form of impact of supply chain disruption as given in Table 2.

TABLE 2. Impact of Border Crossing Complexity on Supply Chain

Cost of waiting for parts	Disturbance of schedule
Switching to costly transport modes	Price drop due to quality degradation
High inventory holding cost	Rejection at border
Excessive overtime	Loss of parts or items
Lost business opportunities	Non-optimal inventories
Missing delivery windows	Inventory obsolescence
Penalty for late delivery	Increased transaction cost
Underutilization of transportation	Loss of customer

We consider a supply chain system in which the parts supply comes from domestic as well as international suppliers. Parts from international suppliers reach the manufacturer through multiple border-crossings and multiple countries. At the manufacturing stage, various vehicles models wait for the parts. After manufacturing, the vehicles are shipped to domestic dealers without border-crossings and to international dealers through multiple border-crossings. We, then calculate the risk index for the entire system considering the impact of border crossing complexity and product complexity. We utilize the uncertainty theory in the numerical example in the next section. Detailed justification of this theory is provided in [28]. According to this theory, many real systems may be simplified to a Boolean system in which each element (including the system itself) has two states: working and failure.

Theorem 1: (Liu [28], Risk Index Theorem for Boolean System). Assume that $\xi_1, \xi_2, \dots \xi_n$ are the independent elements with reliabilities $\Re_1, \Re_2, \dots, \Re_n$ respectively. If a system contains $\xi_1, \xi_2, \dots \xi_n$ uncertain elements and has the truth function f, then the risk index is

$$Risk = \begin{cases} \underset{f(x_1,x_2,\dots x_n)=0}{\sup} \quad \underset{1\le i\le n}{\min} \; v_i(x_i), \\ \\ \quad if \quad \underset{f(x_1,x_2,\dots x_n)=0}{\sup} \quad \underset{1\le i\le n}{\min} \; v_i(x_i) < 0.5 \\ \\ 1- \underset{f(x_1,x_2,\dots x_n)=1}{\sup} \quad \underset{1\le i\le n}{\min} \; v_i(x_i), \\ \\ \quad if \quad \underset{f(x_1,x_2,\dots x_n)=0}{\sup} \quad \underset{1\le i\le n}{\min} \; v_i(x_i) \ge 0.5 \end{cases} \tag{13}$$

Where x_i take either 0 or 1, and v_i are defined by

$$v_i(x_i) = \begin{cases} \Re_i, & x_i = 1 \\ 1 - \Re_i, & x_i = 0 \end{cases} \qquad \text{for } i = 1,2,\dots,n, \text{ respectively.}$$

We use the Equation (13) estimate the risk index for two general supply chain systems, where each system is the combination of series and parallel systems.

IV. NUMERICAL EXPERIMENTS

In this section, we perform numerical experiments to illustrate the effectiveness of the proposed method. Where possible, we use the real data from relevant literature. However, we did not perform full scale empirical data collection. To this end, we use the example dataset to analyze the problem. We consider two comparable supply chain systems "System A" and "System B", which are according to Toyota's real supply chain networks. In system A, the manufacturing destination is USA (see Fig. 2). In system B, the manufacturing destination is South Africa (see Fig. 3).

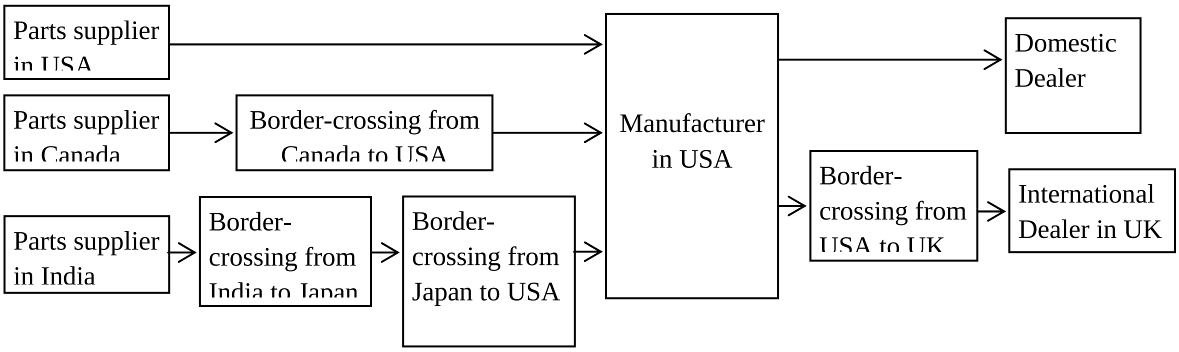

Fig. 2. System A: Manufacturing Destination is Located in USA

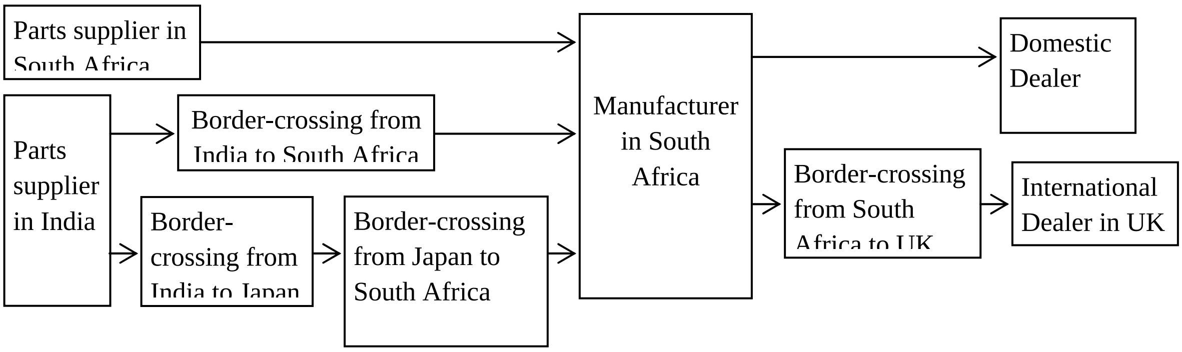

Fig. 3: System B: Manufacturing Destination is Located in South Africa

A production order for manufacturing 50 unique types of vehicles is scheduled for both systems. For both systems, there are 35 unique types of vehicles for local dealers and 15 unique types of vehicles for international dealers. There are total 2200 unique types of parts involved in manufacturing the vehicles at each system. Quantity of parts from the local suppliers in both systems is 1000 (Path 1). Quantity of parts from international suppliers is 600 for each of the other two paths (Path 2 and Path 3). Three parts shipments cross a unique border containing 300, 200, and 100 parts respectively. One product shipment with 15 vehicles crosses a unique border. In both systems, assume that the individual suppliers, manufacturers, and border-crossings are 14 independent uncertain elements $\xi_1, \xi_2, \dots \xi_{14}$ whose states are denoted by $x_1, x_2, \dots, x_{14}$. There are three paths from the input to the output. We consider these paths as 3 separate series paths of the both systems. Table 3 shows the description of uncertain elements in each path of each system. If any one of the uncertain elements on a single path fails, the entire path fails.

Path 1 $input - \xi_1 \rightarrow \xi_{13} \rightarrow \xi_{14} - output$
Path 2 $input - \xi_2 \rightarrow (\xi_4, \xi_5, \xi_6) \rightarrow \xi_{13} \rightarrow \xi_{14} - output$
Path 3 $input - \xi_3 \rightarrow (\xi_7, \xi_8, \xi_9) \rightarrow (\xi_{10}, \xi_{11}, \xi_{12}) \rightarrow \xi_{13} \rightarrow \xi_{14} - output$

TABLE 3 Description of Uncertain Elements in Three Paths of Both Systems

Name of element	**Uncertain elements**	**System A**	**System B**
Product complexity	ξ_1	USA supplier	South Africa supplier
Product complexity	ξ_2	Canada supplier	India supplier
Product complexity	ξ_3	India supplier	India supplier
Border crossing complexity (3 shipments pass through each unique border-crossing)	ξ_4, ξ_5, ξ_6	Canada to USA Border	India to South Africa Border
	ξ_7, ξ_8, ξ_9	India to Japan Border	India to Japan Border
	$\xi_{10}, \xi_{11}, \xi_{12}$	Japan to USA Border	Japan to South Africa Border
Product complexity	ξ_{13}	Manufacturing facility in USA	Manufacturing facility in South Africa
Border crossing complexity	ξ_{14}	USA to UK Border	South Africa to UK Border

We start from the general analysis of the impact of trade procedures on the risk of delay in supply chain. The number of trade procedures increases with the addition of each border-crossing. As a result, even if the probability of failure for each procedure is 0.10%, the overall disruption risk is higher. If the probability of failure for each trade procedure is 0.50% and 1.00%, the risk of delay approaches to 100%. Fig. 4 shows this phenomenon.

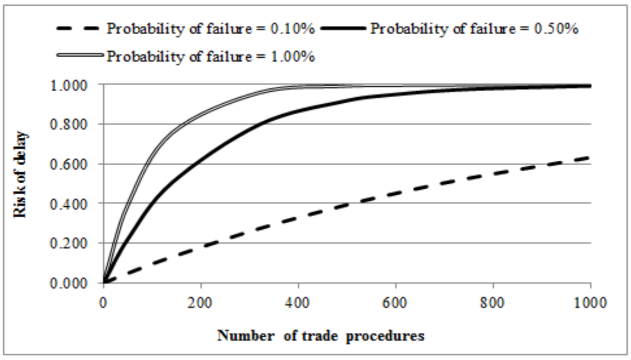

Fig. 4. Risk of Delay as a Function of Trade Procedures

In the Fig. 5, we evaluate the risk of delay for three unique border-crossings as well as whole Path-3. We incorporate number of trade procedures and impact of three parts shipments and one vehicle shipment. It is clear that the number of trade procedures is clearly higher for South Africa, but overall risk of delay for Path-3 for USA is very close to South Africa. This is due to the successive increase in trade procedures by the addition of each border-crossing.

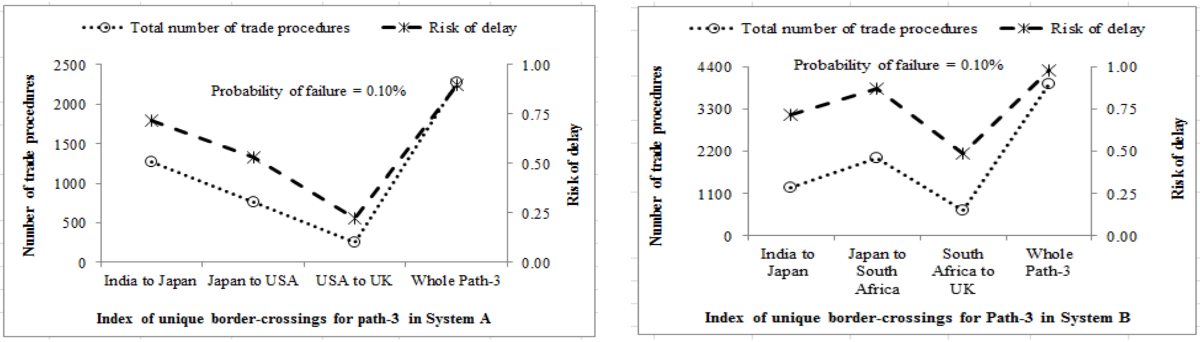

Fig. 5. Border Crossing Complexity for Unique Borders in Path-3 of System A and System B

The total number of border-crossings is seven (see Fig. 6). When we integrate the difficulty level at each of the seven crossings, impact of trade procedures tends to decrease. Incorporation of difficulty level increases the accuracy of the strength of uncertain trade procedures at each border-crossing and affects the risk of delay for complete path. The risk of delay for complete Path-3 remains higher due to multiple border-crossings.

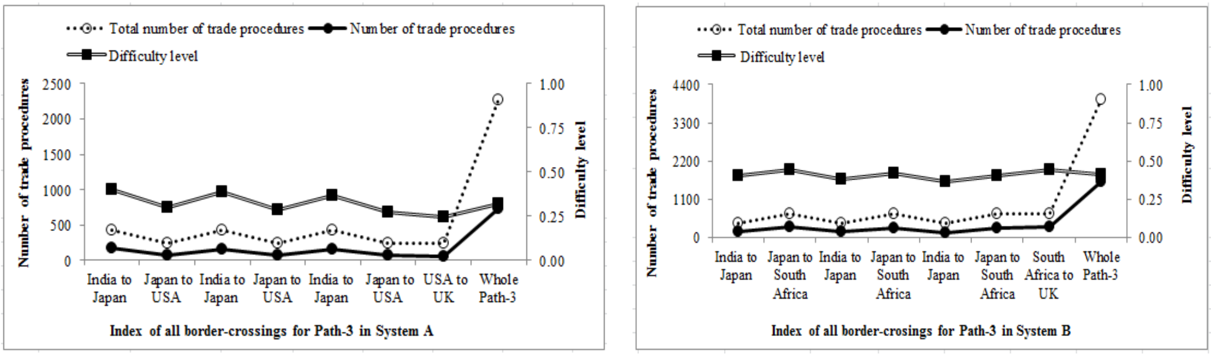

Fig. 6. Border Crossing Complexity for Each Crossing Considering Difficulty Level in Path-3

In the Fig. 7, we evaluate the risk of delay for three unique border-crossings as well as whole Path-2. The overall risk for manufacturing in the USA is smaller due to the fact that parts are sourced from neighboring country and vehicles are shipped with less border crossing complexity. In the case of Path-1, there is no border-crossing for parts shipments and one border-crossing for vehicles shipment. But, the strength of uncertain trade procedures and the difficulty level for border-crossing for vehicles is equivalent to parts suppliers in Path-2 and Path-3 because the multiple models of vehicles in one shipment are transported towards dealers in the UK.

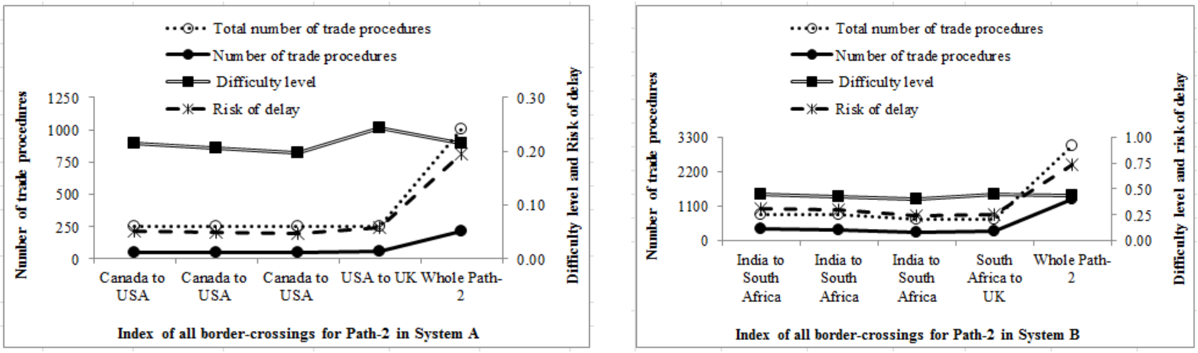

Fig. 7. Border Crossing Complexity for Each Crossing Considering Difficulty Level in Path-2

We calculated the risk of delay for the suppliers, manufacturers, and border-crossings in each of the three paths. The resultant risk of delay is used to calculate the reliabilities of the uncertain elements $_{1}$, $_{2}$, …, $_{14}$ at each path (Table 4). Now, we calculate the Truth function and Risk index for three paths and both systems based on Theorem 1 described as in [28]. The truth function for individual paths is

$$Path\ 1 = f(x_1, x_{13}, x_{14}) = x_1 \wedge x_{13} \wedge x_{14} \quad (14)$$

$$Path\ 2 = f(x_2, x_4, x_5, x_6, x_{13}, x_{14}) = x_2 \wedge x_4 \wedge x_5 \wedge x_6 \wedge x_{13} \wedge x_{14} \quad (15)$$

$$\begin{aligned} Path\ 3 &= f(x_3, x_7, x_8, x_9, x_{10}, x_{11}, x_{12}, x_{13}, x_{14}) \\ &= x_3 \wedge x_7 \wedge x_8 \wedge x_9 \wedge x_{10} \wedge x_{11}, \wedge x_{12} \wedge x_{13} \wedge x_{14} \end{aligned} \quad (16)$$

The risk index is defined as the uncertain measure that some specified loss occurs [28]. It follows from the risk index theorem that the risk Index for Path-1 is

$$(1 - \mathfrak{R}_1) \vee (1 - \mathfrak{R}_{13}) \vee (1 - \mathfrak{R}_{14}) \quad (17)$$

Risk Index for Path-2 is

$$(1 - \mathfrak{R}_2) \vee (1 - \mathfrak{R}_4) \vee (1 - \mathfrak{R}_5) \vee (1 - \mathfrak{R}_6) \vee (1 - \mathfrak{R}_{13}) \vee (1 - \mathfrak{R}_{14}) \quad (18)$$

Risk Index for Path-3 is

$$(1 - \mathfrak{R}_3) \vee (1 - \mathfrak{R}_7) \vee (1 - \mathfrak{R}_8) \vee (1 - \mathfrak{R}_9) \vee (1 - \mathfrak{R}_{10}) \vee (1 - \mathfrak{R}_{11}) \vee (1 - \mathfrak{R}_{12}) \vee (1 - \mathfrak{R}_{13}) \vee (1 - \mathfrak{R}_{14}) \quad (19)$$

If system works if and only if there is at least one path of working elements, truth function for entire system is

$$f(x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{12}, x_{13}, x_{14}) = (x_1 \wedge x_{13} \wedge x_{14}) \vee (x_2 \wedge x_4 \wedge x_5 \wedge x_6 \wedge x_{13} \wedge x_{14}) \vee (x_3 \wedge x_7 \wedge x_8 \wedge x_9 \wedge x_{10} \wedge x_{11}, \wedge x_{12} \wedge x_{13} \wedge x_{14}) \quad (20)$$

We set this problem in MATLAB to compute the risk index for three paths in both systems with the help of the uncertainty theorem proposed as in [28].

TABLE 4 Reliabilities of Each Path in Each System

Description	**Uncertain elements**	**States of uncertain elements**	**Failure rate = 0.10%**					
			Reliability of System A			**Reliability of System B**		
			Path-1	**Path-2**	**Path-3**	**Path-1**	**Path-2**	**Path-3**
Product complexity	ξ_1	x_1	0.85	-		0.80	-	-
	ξ_2	x_2	-	0.89	-	-	0.86	-
	ξ_3	x_3	-	-	0.88	-	-	0.86
Border crossing complexity	ξ_4	x_4	-	0.95	-	-	0.69	-
	ξ_5	x_5	-	0.95	-	-	0.70	-
	ξ_6	x_6	-	0.95	-	-	0.76	-
	ξ_7	x_7	-	-	0.84	-	-	0.84
	ξ_8	x_8	-	-	0.85	-	-	0.85
	ξ_9	x_9	-	-	0.86	-	-	0.86
	ξ_{10}	x_{10}	-	-	0.93	-	-	0.74
	ξ_{11}	x_{11}	-	-	0.93	-	-	0.75
	ξ_{12}	x_{12}	-	-	0.93	-	-	0.76
Product complexity	ξ_{13}	x_{13}	0.92	0.92	0.92	0.90	0.90	0.90
Border crossing complexity	ξ_{14}	x_{14}	0.94	0.94	0.94	0.74	0.74	0.74
Risk index for each path			**0.15**	**0.11**	**0.16**	**0.26**	**0.31**	**0.26**
Risk index for each system			**0.11**			**0.26**		

Risk index for Path 3 of both systems and Path 2 of the system B is higher (Table 4). However, the risk index of Path 2 for North America is much less than South Africa. In Path 2, the parts are sourced from Canada which is a neighboring country. Therefore, offshore sourcing and shipping of the parts and vehicles has the highest risk of disruption. Also, offshoring the manufacturing process to the developing markets has the highest risk of disruption. This is obvious from the overall risk index of both systems. We can say that higher number of unique parts/vehicles in a production schedule requires more number of border-crossings, resulting in higher risk of disruption. For example, there is only one border-crossing for shipping the vehicles in the Path-1. But, risk index is still higher due to the fact that greater number of parts is sourced, even from domestic suppliers. Therefore, product complexity is the single most important factor which alone can increase the risk of disruption without any border-crossing.

V. RESULTS AND DISCUSSIONS

Border crossing complexity is an important variable that must be taken into account for outsourcing decision making in the manufacturing supply chain. In this section, we propose following strategies to deal with border crossing bottlenecks based on the results drawn from the previous sections.

Results show that as the number of border-crossings increases, the number of trade procedures also increases. Similarly, as the number of trade procedures increases, the related disruption risk also increases. For a given supply chain network, even if the probability of disruption of each procedure is small, the overall disruption risk for this network increases as the number of trade procedures increase. One strategy to decrease the impact of trade procedures is to eliminate the intermediate bottleneck border-crossings except the trading countries. There are various unique borders within a country as well as between the countries. Companies would try to eliminate the bottleneck crossings between different regions by switching to sea freight. In the case of emergency, air freight may be used to eliminate the bottleneck border-crossing.

We found that as the number of unique border-crossings increases, the supply chain disruption risk also increases. This is due to different nature of trade procedures and difficulty level at borders of different countries. Several strategies may be adopted to decrease the difficulty level at border-crossings. First strategy to deal with this problem is to manage the relative complexity for each border-crossing. We can use Relative Complexity Index for individual border-crossings to detect the border-crossings that are bottlenecks in the supply chain network. Once the bottleneck border-crossings are identified, we could make strategic decisions to deal with the root causes of the problem and discover the mitigation techniques. From Equation (6) and (7), the Relative Complexity Index (RCI) for shipment k or u at unique border v or y is

$$\text{RCI} = \frac{\mathcal{F}_{k,v,u,y}}{\mathfrak{D}_j} \qquad \forall k,v,u,y \tag{21}$$

Second strategy is to collaborate with other companies that share the same border-crossing. If trucks from several other companies arrive at the same time, it adds the difficulty to trade procedures resulting in high risk of disruption. We could identify the major companies which share a same border, and establish strategic collaboration with them in order to plan the border-crossing in an efficient way. Then, different participants could maintain a strict interval between different shipments across the various companies. Third strategy is to train the supply chain personnel for dealing with border-crossing bottlenecks. Companies could train the human resources in the supply chain to communicate with border official in a common language, to understand the technical language of the documents, to understand the physical inspection at borders and testing facilities, and protection of documents, products, and other important resources. Fourth strategy is to ensure completeness and protection of required documents before moving towards borders. Each border-crossing requires unique trade procedures. Companies should maintain good relations with custom officials, border agencies, and relevant trade agencies to prepare in advance of any disruption at border-crossings. Carelessness and misplacement of any document results in the disruption. Standardization of documents and trade procedures throughout the globe would greatly improve the efficiency of the global economy. With increased concerns about security and safety, each country is continuously introducing new rules and regulation, so no tolerance must be expected at the border if any document is missing. Therefore, we should make sure that all documents are available and each document is complete. Companies should make suitable strategies to keep the documents in a safe place.

Another key result is that a unique border-crossing may be used for several shipments within a production schedule. Each shipment has different types of parts/products, which results in variable difficulty level at each border-crossing. If the types of parts, types of products, and the number of elements of manufacturing complexity are higher in a production schedule, then the disruption risk may cross a specific limit without any border-crossing. As the difficulty level for border-crossing decreases, the impact of trade procedures decreases. This phenomenon shows that only a fraction of trade procedures has the potential to contribute to supply chain disruption risk. One strategy to decrease the impact of product complexity at borders is to synchronize the inventory lot-sizing decisions with border-crossing features. In the international pipeline, the order fulfilment cycle time is dependent on the cycle and safety inventory levels as well as the different delays including consolidation points and border-crossing processes [29]. Companies should determine the ideal lot-size that is efficient and easy to handle at the border. We would adjust the inventory lot-size for each item by incorporating the risk of delay at the border-crossings. We should ensure efficient packaging, easy identification, and complete information that can help the border officials to quickly understand the characteristics of the products. Here, we propose some basic ideas to incorporate border crossing complexity into practical decision making tools. We intend to provide initial directions concerning how long the system takes to recover from disruptions related to border-crossing bottlenecks. We determine time of delay, disruption cost, and transportation lot-size as a function of border crossing complexity. If scheduled number of trade procedures for shipment k or u at unique border v or y is

$$F_{k,v,u,y} + G_{k,v,u,y} + E_{k,v,u,y} \qquad \forall k,v,u,y \tag{22}$$

Then, the average time per procedure for shipment k or u at unique border v or y is

$$\frac{t_{k,v,u,y}}{F_{k,v,u,y} + G_{k,v,u,y} + E_{k,v,u,y}} \qquad \forall k,v,u,y \tag{23}$$

Integrating repetition frequency of procedures, the total time required for shipment k or u at unique border v or y is

$$\frac{t_{k,v,u,y}\left(F_{k,v,u,y}\,\delta_{k,v,u,y} + G_{k,v,u,y}\,\eta_{k,v,u,y} + E_{k,v,u,y}\,\epsilon_{k,v,u,y}\right)}{F_{k,v,u,y} + G_{k,v,u,y} + E_{k,v,u,y}} \qquad \forall k,v,u,y \tag{24}$$

The delay time for shipment k or u at unique border v or y is

$$\frac{t_{k,v,u,y}\left(F_{k,v,u,y}\,\delta_{k,v,u,y} + G_{k,v,u,y}\,\eta_{k,v,u,y} + E_{k,v,u,y}\,\epsilon_{k,v,u,y}\right)}{F_{k,v,u,y} + G_{k,v,u,y} + E_{k,v,u,y}} - t_{k,v,u,y} \qquad \forall k,v,u,y \tag{25}$$

Any delay at border-crossing results in disruption cost in the form of inventory holding cost, expedited freight charges, and downtime cost. Each manufacturing destination results in different magnitude of disruption cost due to variations in labor cost, distance, border-crossings, transportation modes, etc. The disruption/delay cost as a function of border crossing complexity for shipment k or u at unique border v or y for any path or the whole system is

$$\sum_{k=1}^{K}\sum_{v=1}^{V}\sum_{u=1}^{U}\sum_{y=1}^{Y}\left(\frac{t_{k,v,u,y}\left(F_{k,v,u,y}\,\delta_{k,v,u,y}+G_{k,v,u,y}\,\eta_{k,v,u,y}+E_{k,v,u,y}\,\epsilon_{k,v,u,y}\right)}{F_{k,v,u,y}+G_{k,v,u,y}+E_{k,v,u,y}}-t_{k,v,u,y}\right)_j\left(H_j+\mathcal{L}_j\mathfrak{Y}_j\right.$$
$$\left.+\pitchfork_j\ \mathfrak{x}_j\right)_j\quad\forall j \tag{26}$$

The transportation lot-size by incorporating the border crossing complexity at destination at destination j is

$$\frac{\mathbb{Q}_{\mathrm{j}}\sum_{k=1}^{K}\sum_{v=1}^{V}\sum_{u=1}^{U}\sum_{y=1}^{Y}\left(\frac{t_{k,v,u,y}\left(F_{k,v,u,y}\,\delta_{k,v,u,y}+G_{k,v,u,y}\,\eta_{k,v,u,y}+E_{k,v,u,y}\,\epsilon_{k,v,u,y}\right)}{\left(F_{k,v,u,y}+G_{k,v,u,y}+E_{k,v,u,y}\right)}\right)_j}{\left(\sum_{k=1}^{K}\sum_{v=1}^{V}\sum_{u=1}^{U}\sum_{y=1}^{Y}t_{k,v,u,y}\right)_j},\quad\forall j \tag{27}$$

Another strategy is to synchronize the shipments schedules with the border-crossing timings. We would find out and avoid the times when the border agencies and custom officials are unavailable and less efficient or when there is highest congestion on the border. We may develop the trust between the manufacturing company and the border officials, and contact key personnel before planning to cross the border. For example, if there is a situation that may cause disruption at the border, then the company can think about the alternative ways to move the shipments to the destination. Another strategy is to increase the interval between different shipments that cross the border: Border-agencies and customs have limited resources to manage the movement of goods. If many trucks from the same company arrive at the border-crossing simultaneously, it results in a blockage of the crossing. We could maintain a strict interval between different shipments in the company.

We also found that the offshore sourcing/shipping has higher disruption risk compared to sourcing/shipping in neighboring countries. The supply chain network involving border-crossing from developing countries has higher impact of trade procedures. But, successive increase in trade procedures and border-crossings increases the overall disruption risk regardless of countries involved in the trade. To decrease the impact of global sourcing and offshoring, one strategy is to change the manufacturing destination based on the lowest risk of delay: First, we should estimate the total cost of manufacturing at each existing destination (e.g. unit production cost; transportation cost; transaction cost; and cost collected by customs and border agencies). Second, we can determine the all possible manufacturing destinations across the globe that can decrease overall cost and risk in the supply chain for the long term in the future. Then, we could find a tradeoff between total cost of manufacturing and risk of delay for existing and prospective destinations to select the manufacturing destinations that are likely to produce the highest revenues in the long term.

VI. CONCLUSIONS AND FUTURE WORK

This research is an effort to deal with border crossing bottlenecks in manufacturing supply chain. Key factors that contribute to the border crossing complexity are the number of trade procedures, the difficulty level of the cross-border movement of the goods, and number of border-crossings involved in the supply chain. The difficulty level can be measured by the number of unique borders that are crossed by a single shipment and the frequency of the different shipments in a production schedule that cross a unique border. Therefore, the risk of delay at border crossings is caused by product complexity, number of trade procedures, and difficulty level of crossing. Complex products with pull supply chains are more affected by border crossing bottlenecks. An increase in border crossing complexity results in high cost of disruption. We perform a risk analysis practice based on a case study in an automotive company that is involved in motor vehicle production and distribution in various countries around the world. Results show that an increase in the number of trade procedures has a direct effect on the risk of supply chain disruption. A successive increase in number of border-crossings for a manufacturing destination adds further complexity. However, low difficulty level of the cross-border movements of the goods tends to moderate the impact of uncertain trade procedures at a border-crossing. Manufacturing destinations in developed markets have a low risk of delay compared to the manufacturing destinations in the emerging markets and the developing markets. Sourcing from the offshore suppliers has more risk of delay than sourcing from neighboring countries. Domestic sourcing has a negligible impact on border crossing complexity. However, product complexity is the single most important factor which alone can increase the risk of disruption without any border-crossing. In the case of domestic sourcing, the shipping of vehicles to international markets has some exposure to border crossing bottlenecks. Also, recall practices are exposed to border crossing complexity. In order to stay competitive, manufacturing companies should implement strong disruption prevention strategies. This paper offers some useful strategies to manage the border crossing bottlenecks in the manufacturing supply chain. The following are some directions for future research:

- To estimate the supply chain disruption cost as a function of border crossing complexity.
- To develop inventory models by incorporating the border crossing complexity, product complexity, and risk of delay.
- An empirical study to elaborate the factors identified in this paper.
- Empirical studies to measure the border crossing complexity for each border across the countries.
- Models of border crossing complexity for supply chains with different nature of products.

ACKNOWLEDGMENTS

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2014R1A1A2056338 and 2012R1A1B3000631).

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