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Resilient logistics to mitigate supply chain uncertainty: A case study of an automotive company

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Abstract. Over the years, supply chain management has become more sophisticated. As supply chains become more interconnected and globalized, they also become more vulnerable, with more potential of failure and less margin of error for absorbing delays and disruptions. Since disturbances affect the normal operation of a supply chain resulting in profit loss and poor customer satisfaction, therefore, a resilient supply chain is critical to the success of an enterprise. Natural catastrophes and man-made disasters have significantly increased over the past decades. The flood in Thailand and the unexpected tsunami/nuclear leak disaster that hit northern Japan in 2011 have resulted in huge financial losses and a decline in customer satisfaction in the car manufacturing industries in Asia Pacific and North America. To overcome the increasing uncertainty which resulted from these disasters, a study to identify risk mitigation strategies for an automotive industry is timely. Our objective was to reduce the losses due to possible disasters using an automotive industry as a case example.

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1. Introduction

This study aims to mitigate supply chain uncertainty in an automobile company and develop a resilient logistics. The methodology consists of two steps. The first step is to apply the mapping process to define supply chain entities, links, material flows, operating time, and costs incurred in the logistic. The second step is to select the risk mitigation strategies to reduce the costs as a result of the disasters. Then, we suggest action plans to recover from the impact of the disasters using Program Evaluation and Review Technique (PERT) model.

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Natural catastrophes and man-made disasters have significantly increased over the past decades. According to the report of Swiss Re Economic Research and Consulting on natural catastrophes and man-made disasters, losses caused by natural catastrophes ranged from US$11.8 billion in 2006 to US$110 billion in 2011, and totaled US$71.2 billion in 2012. That was an increase of 502% in major damage caused by storms, floods, and earthquakes. Figure 1 shows the history of natural catastrophes and man-made disasters. The cost of damage caused by man-made disasters also increased from US$4.04 billion in 2006 to US$5.96 billion in 2012, with 50% of the increase caused by fires and maritime disasters. The flood in Thailand and the unexpected tsunami/nuclear leak disaster that hit Northern Japan in 2011 resulted in huge financial losses and a decline in customer satisfaction in the car manufacturing industries in Asia Pacific and North America. Researches to mitigate supply chain uncer-

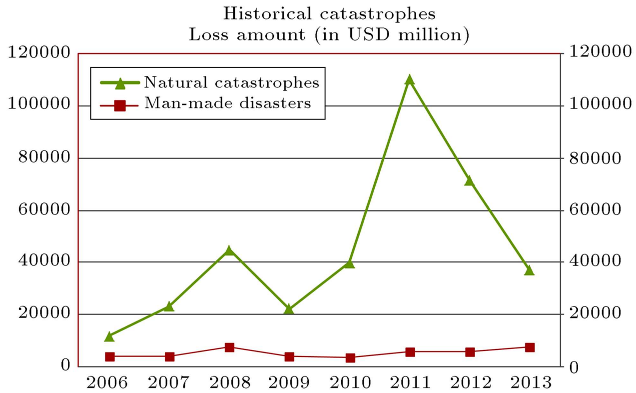

Figure 1. Historical natural catastrophes and man-made disasters (source: Swiss Re Ltd, economic research & consulting (2014) [27]).

tainty in automobile companies are lacking. Therefore, this study, using an automotive industry as a case study, seeks to build a resilient network to mitigate supply chain risks due to disasters. The objective is to reduce losses.

The contribution of this study is to facilitate automotive industries to better manage the unpredictable disasters in their supply chain through sourcing policy and global logistic strategy. The case study and user-friendly model can provide insights to other industries to better manage disruptions in their supply chains.

2. Literature review

Christopher and Peck [1] defined supply chain as "the organization networks that are involved, through upstream and downstream linkages, in different processes and activities to produce finished goods and services for ultimate consumers." An automotive industry is an elaborate network that involves moving vehicles and parts from suppliers, manufacturers, wholesalers, distributors, and retailers to the final customers. A disruption in the supply chain results in a considerable loss to the automotive company. It is crucial for the senior management team of the company to identify and mitigate the sources of supply chain disruption and build a resilient supply chain.

Before building a resilient supply chain and mitigate uncertainty in an automotive network, it is vital to examine the risks prevalent in a supply chain and prioritize the risks based on intensity, vulnerability, and criticality. Deloitte and Touche [2] addressed four distinct categories of supply chain risks; they are: the macro-environment risks, the extended value chain risks, the operational risks, and the functional risks, as shown in Figure 2.

Tang and Tomlin [3] stated that operational risks refer to the inherent customer demand and cost uncertainties. The disruption risks refer to the major disruptions caused by natural and man-made disasters such as earthquakes, floods, hurricanes, and terrorist attacks; and the economic crisis refers to currency evaluation or strikes. Mason-Jones and Towill [4] addressed five categories of risk in the supply chain; internal to the firm (process and control), external to the firm but internal to the network supply chain (demand and supply), and external to the network (environment). Traditionally, enterprises focused on mitigating the operational risks and the potential disruption in the supply chains.

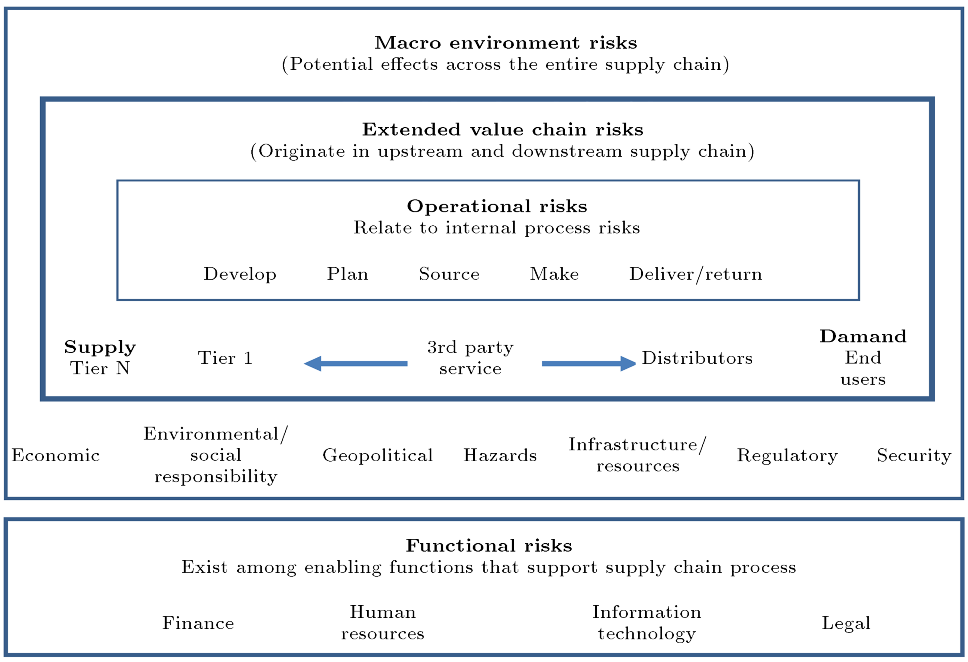

Figure 2. Risks of supply chain (source: Deloitte development LLP (2012) [1]).

A resilient supply chain enables companies to avoid risks or to recover from them quickly. Allenby and Fink [5] indicated that "resiliency is defined as the capability of a system to maintain its functions and structure in the face of internal and external change and to degrade gracefully when it must." Christopher and Peck [6] defined a resilient supply chain as "the ability of a supply chain network to return to its original state or move to a new, more desirable state after being disturbed." Sheffi [7] stated that "the resilience refers to the ability of a company to bounce back from a large disruption; this includes the speed with which it returns to the normal performance levels of production, services, and fill rate".

To build resilience, companies must focus on essential capabilities. Deloitte and Touche [2] identified four crucial attributes of a resilient supply chain: visibility, flexibility, collaboration, and control. In addition, they indicated that good governance, accountability, and ownership supported by strong key people, processes, and technology are critical to sustain a resilient supply chain. Sheffi [7] also indicated that "companies can develop resilience in three main ways: increasing redundancy, building flexibility, and changing corporate culture". Redundancy indicates that an organization can hold extra inventory, implement low capacity use, and retain numerous suppliers to continue operating after a disruption, however, this is a temporary, costly, and inefficient measure. A flexible supply chain allows a company to withstand disruptions and effectively responds to demand fluctuations. Resilient organizations share several cultural traits after a disruption:

1. Continual communication among informed employees;
2. Teams and individuals are empowered to take necessary actions;
3. Successful companies engender a sense of the greater good in their employees;
4. Resilient and flexible organizations are apparently conditioned.

Kim et al. [8] illustrated Graph theory to conceptualize supply network disruption and resilience by examining the structural relationships among entities in the network. Chen et al. [9] created a formal model to portray a dynamic operational performance among supply chain firms facing disruptions caused by natural and man-made disasters.

From current literature, we identified risks and the characteristics of a resilient supply chain. Then, we summarized the mitigation policy/action for the supply chain risks and the related references. The details are shown in Table 1.

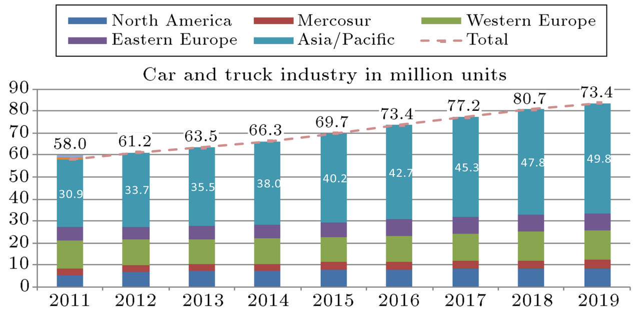

Figure 3. Car and truck industry (source: global car and truck forecast by LMC (2014) [28]).

3. The logistic strategy by PERT model

3.1. Background

The total number of cars and trucks manufactured globally in 2011 was 58 million units; it was around 66.4 million units in 2014 and will be 83.4 million units in 2019, a 43.9% increase as compared with the growth rate from 2011 to 2014. The forecast was done by LMC Automotive based on over four hundred cars and truck makers around the world. Figure 3 shows the global growth of car and truck industry from 2011 to 2019. The Asian automotive industry was 30.5 million units in 2014, 38 billion units in 2014, and will be 49.8 billion units in 2019. Being a rapid growing economy, the automobile growth in Asia is expected to account for 61% of the global growth in the auto industry over the next five years. The details are illustrated in Figures 3 and 4.

The automobile company under study has a forecast growth of 60-70% in the next 10 years. Asia Pacific is now the largest vehicle market in the world totalling 24 manufacturing and assembly facilities in eight markets. This automobile company expects vehicle sales to increase approximately 50% from 5.3 million in 2010 to about 8 million by mid-decade. It is predicted that nearly one-third of the company sales in 2020 will come from Asia Pacific.

Since 2006, over US$6 billion has been invested by this automotive company in the region (including

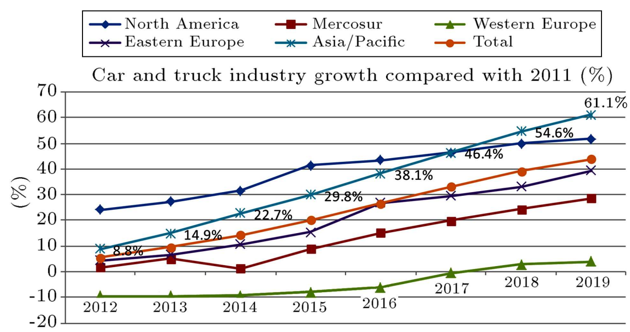

Figure 4. Car and truck industry growth compared with car industry in 2011 (source: global car and truck forecast by LMC (2014) [28]).

Table 1. Summary of mitigation policy/action vs. supply chain risks.

Mitigation policy/action	Supply chain risks	References
Information management for short-life cycle products	Risk of product delivery process - control system, supply, demand, manufacturing process	Mason-Jones and Towill (1998) [4]
Agile supply chain-network based, process and virtual integration, market sensitive	Risks of time-to-market, time-to-serve, time-to-react	Christopher and Peck (2004) [1]
Urban systems and network-centric organizations	Terrorist attacks, natural disasters, tsunami	Allenby and Fink (2005) [5]
Supply chain reengineering, collaboration, agility, flexibility, risk management culture	Disruption of process, control, supply and demand due to man-made or natural disaster	Christopher and Pack (2004) [1], Sheffi (2005) [7], Tang (2006) [10]
Flexibility strategies - shift order and production quantities across supplier or products and time	Supply cost risks, commitment risks, process risks, demand risks	Tang and Tomlin (2008) [3], Shao (2012) [11], Das (2011) [12], Sting and Huchzermeier (2010) [13]
Proactive planning team, mitigation plan, continuous improvement, detection, response, and recovery plan	Catastrophic events of a major terrorist, strikes, aircraft accidents, nuclear reactor, earthquake, etc.	Knemeyer et al. (2009) [14]
Flexible capacity, contingency plan, multiple sourcing strategy; promotion, customer incentive, educated customer; cost reduction in operation, lobbying	Supply risks - imports, climate, man-made disasters, natural disasters, socio-economic; Demands risks - economic, uncertainty, product hazard, outbreak, forecasting errors	Oke and Gopalakrishnan (2009) [15], Naim et al. (2010) [16]
Multiple sourcing, alternative sourcing in and out of home country, outsourcing, early supplier involvement, supply chain design, operational hedging, postponement strategy, mixed model, lean manufacturing, reduced inventory holding, efficient transportation, supplier initiatives	Material flow risk-source, make, deliver and supply chain scope; Financial flow risk-exchange rate, price and cost, financial handling; Information flow risk-accuracy, security and disruption, intellectual property	Tang and Musa (2011) [17]
Optimal backup depot, Multiple sourcing, coverage	Uncertain location-transportation	Klibi and Martel (2012) [18]
Supplier order policy (multiple suppliers, multiple-product-multiple-stage-multiple-period, lead time, capacity, and cost)	Supply and demand risks	Sawik (2013) [19], Yu et al. (2009) [20], Klibi and Martel (2012) [21], Xanthopoulos et al. (2012) [22], Kumar and Havey (2013) [23], Davarzani et al. (2011) [24], Fang et al. (2013) [25]
Build up a decision management supports for disaster relief supply chain	Natural disasters, environmental threats, financial meltdowns, surprise attacks	Boin et al. (2010) [26]

Africa). The top priority for the senior management team is to build resilient logistics to mitigate uncertainty due to vulnerable automotive industry.

3.2. Methodology and study process

Several root causes of the losses were highlighted by the target automotive company management team, deep dove. Two key reasons to prevent the risks incurred were identified as tooling source shared and inefficient communication in the region. The resilient logistics was suggested to overcome the problem in the tooling source shared and the complex automotive industry. The first step is to apply the mapping process to define supply chain entities, links, material flow, operating time, and costs incurred in the logistics. The second step is to select the risk mitigation strategies to reduce the costs as a result of the disasters. Then, we suggest action plans to recover from the impact of the disasters using Program Evaluation and Review Technique (PERT) model. The four stages in this study are illustrated as follows:

- **Stage 1.** Supply chain mapping: To quickly respond to the supply chain disturbance, supply chain mapping is described and visualized. The mapping considers:
  1. Supply chain entities;
  2. The links between supply chain entities;
  3. Material flows;
  4. Information flows;
  5. Management policies;
  6. Lead times.
- **Stage 2.** Potential disturbances identified in the supply chain: This phase focuses on the disturbances that may occur in the supply chain. Potential disturbances have a higher probability of occurring and/or high negative impact on the supply chain;
- **Stage 3.** Mitigation policy selected for potential disturbances: This stage identifies reactive or proactive policies to mitigate the disturbance in supply chain;
- **Stage 4.** Performance comparison of mitigation policies implemented: This stage examines the policies to mitigate the adverse impacts and to promote speed recovery.

3.3. Case study

The target Automotive Company selected five manufacturers including Thailand j_1, Taiwan j_2, South Africa j_3, Vietnam j_4, and Australia j_5 in the Asian region for study. These manufacturers share the same auto parts tooling mold in these countries; consequently, they will encounter risks if the supply chain disasters occur. Valuable lessons were learnt from the great East Japan Earthquake in March 2011 and the severe floods in Thailand in May 2012. A resilient network can mitigate the losses due to supply chain disruptions. The network of an automotive company includes several key activities, events, immediate predecessor, and crash activities. They are shown in Table 2.

3.3.1. Logistic description

The supply chain was defined by seventeen entities: 5 manufacturers, 1 component's kitting, 6-tier I supplier, 1-tier II supplier, and 4 port's handling. The 1st manufacturer provided X product to itself and four other manufacturers in Asia Pacific. X product included A and B parts. A part was produced by 1st assembler who owned the jig tooling of A parts

Table 2. Mapping process of an automotive supply chain.

Activity	Description	Immediate predecessor	Crash activity	Process flow				
				O	**T**	**I**	**S**	**D***
1	Consignment assembly	-	Over time/2nd shift/increase capacity	O	T		S	D
2	Component part supplying	A	Over time/2nd shift/increase capacity	O	T		S	D
3	assembler	B	Over time/2nd shift/increase capacity	O	T	I	S	D
4	Packaging	C,B	Over time/increase facility	O			S	
5	Kitting	D	Over time/increase facility	O			S	
6	Truck from warehouse to port	D,E	Over time/increase frequency		T			
7	Sea freight	F	Premium freight		T			
8	Truck from port to warehouse	G	Over time/increase frequency		T			
9	Unboxing	H	Over time /increase facility	O				
10	Consignment parts assembled	H	Over time/2nd shift/increase capacity	O	T		S	
11	Material handling	I,J	Over time/increase facility	O				
12	Assembler	I,K	Over time/2nd shift/increase capacity	O		I	S	D

*O: Operation (value added); T: Transportation (value added); I: Inspect (non-value added); S: Storage (non-value added); D: Delay (non-value added).

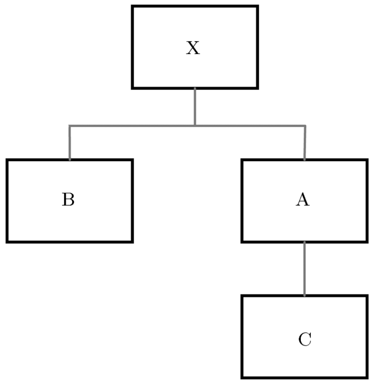

Figure 5. BOM list of X product.

(tier I supplier), while raw material C was from tier II supplier. A parts were then delivered to the kitting center by truck; B parts (tier I supplier) together as X product were packed for shipping by sea to other 4 manufacturers where they were unloaded and unboxed into X product. X product and local parts are then delivered to production line for vehicle production. X product's Bill Of Materials (BOM) tree is illustrated in Figure 5. All material flow was handled by Material Requirements Planning (MRP).

The 1st Tier A produced part A daily; the quantity produced depended on the order placed daily by 1st assembler; the production lead time was 4 days; 2nd Tier C produced part C daily; the quantity produced depended on the order placed daily by 1st Tier A (production lead time was 2 days). The installed maximum capacity of 1st manufacturer was 12,000 units monthly. The normal lead time to ship X product to 2nd manufacturer and 3rd manufacturer was 45 days; to 4th and 5th manufacturers, it was 46 days. The supply chain flow is illustrated in Figure 6.

This study analyzed the supply chain resilience and flexibility in term of response time and costs. Management teams around the Asia region aim to build a robust process to quickly mitigate disturbances in the auto industry supply chain.

3.3.2. Performance measures

In order to develop a resilient and proactive supply chain, key performance index is essential to assess current states and potential future state. After implementing the mitigation policies, compare the performances of the current state and the potential future states in term of supply chain cost and lead time.

The measurement applies PERT (Program Evaluation and Review Technique) using Lingo software and Excel sheet.

3.3.3. Formulating the PERT model

Before describing the model, the following notations are defined:

- **Parameters:**
  ND_{ij}: Normal days caused by the ith activity and jth assembler; i Logistic activity, $i = 1, 2\cdots, m$,

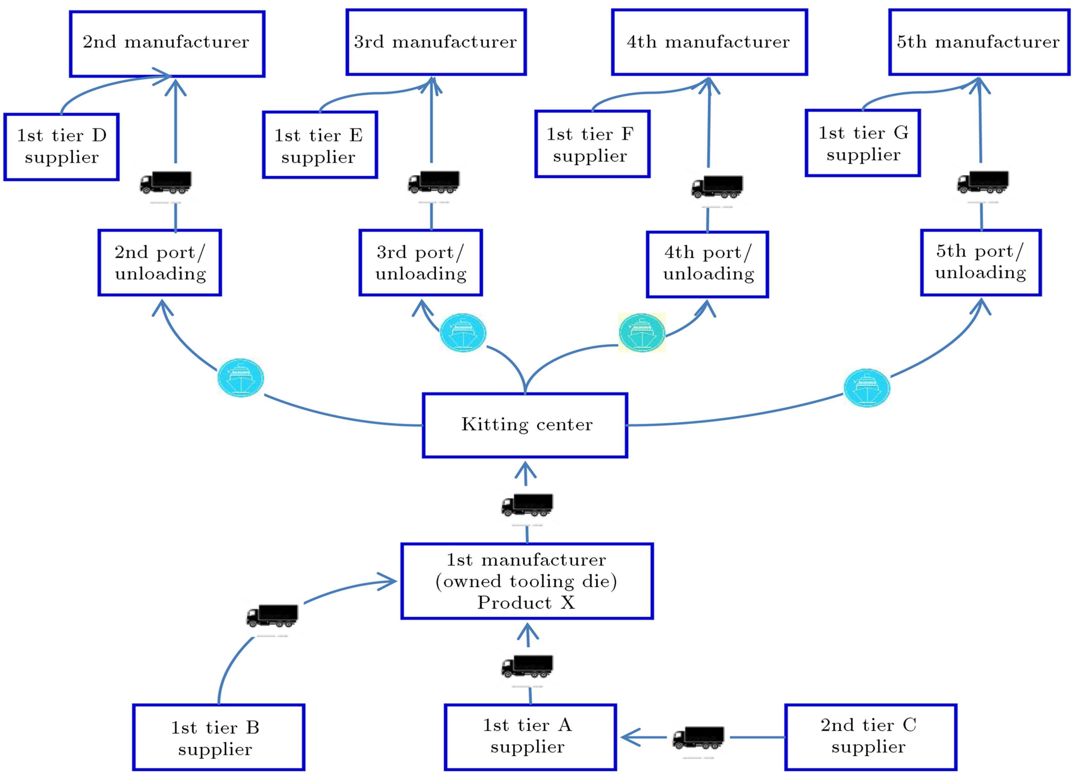

Figure 6. Auto industry supply chain.

$i \in \mathbb{N}$, and j Manufacturer, $j = 1, 2, \cdots, n$, $j \in \mathbb{N}$;
CD_{ij}: Crash days by the ith activity and jth manufacturer;
$RD_{ij} = ND_{ij} - CD_{ij}$: Maximal reduction days caused by the ith activity and jth manufacturer;
TFD_j: Maximum total finish days for jth assembler in region;
CND_{ij}: Normal logistic costs caused by the ith activity and jth manufacturer;
$CND_j = \sum_{i=1}^{m} CND_{ij}$: Normal logistic costs caused by jth manufacturer;
CCD_{ij}: Crash logistic costs caused by the ith activity and jth manufacturer;
$CCDD_{ij} = (CCD_{ij} - CND_{ij})/RD_{ij}$: Crash logistic costs per day caused by the ith activity and jth manufacturer;
$CCDD_{ij} = (CCD_{ij} - CND_{ij})/RD_{ij}$: Crash logistic costs per day caused by the ith activity and jth manufacturer;
PU_j: Upper bound production volume by jth manufacturer;
PL_j: Lower bound production volume by jth manufacturer;

- **Variables:**
XST_{ij}: Expected start logistic day related to the ith activity for jth manufacturer; i logistic activity, $i = 1, 2, \cdots, m$, $i \in \mathbb{N}$, and j manufacturer, $j = 1, 2 \cdots, n$, $j \in \mathbb{N}$;
XST_{ij}^{-}: Expected start logistic day related to the immediate predecessor by the ith activities for jth manufacturer;
XRD_{ij}: Expected reduction crash day by the ith activity and jth manufacturer;
$XRD_j = \sum_{i=1}^{m} XRD_{ij}$: Expected reduction Crash day by jth manufacturer;
$XFD_{ij} = XST_{ij} + ND_{ij} - XRD_{ij}$: Total finish days by the ith activity and ith manufacturer;
$XTFD_j$: Expected finish logistic days related to the jth manufacturer;
P_j: Optimal production volume for the jth manufacturer;
$TCCD_j = \sum_{i=1}^{m} CND_j + \sum_{i=1}^{m} CCDD_j \times XRD_j$: Total crash logistic costs by the jth manufacturer.

Based on the above definitions, PERT can be represented formally as the following liner integer program:

Objective: Minimize total regional logistic costs:

$$\sum_{j=1}^{n} TCCD_j \times P_j = \left(\sum_{i=1}^{m} CND_j + \sum_{i=1}^{m} CCDD_j \times XRD_j\right) \times p_j. \qquad (1)$$

where:

i Logistic activity, $i = 1, 2, \cdots, m$, $i \in \mathbb{N}$;
j manufacturer in region, $j = 1, 2, \cdots, n$, $i \in \mathbb{N}$.

Subject to:
$XTFD_j \leq TFD_j$: Expected total finish logistic days less than the maximal total finish days for jth manufacturer;
$XTFD_j \geq XFDL_j$: Expected total finish logistic days greater than the last logistic activity of L for jth manufacturer;
$XRD_{ij} \leq RD_{ij}$: Expected reduction crash days less than the maximal total finish days caused by the ith activity and jth manufacturer;
$XST_{ij} \geq XST_{ij}^{-}$: Expected finish logistic days related to the logistic activities j greater than the immediate predecessor by the ith activity and jth manufacturer;
$PL_j \leq P_j \leq PU_j$: Optimal production volume of jth manufacturer greater lower bound production volume of jth manufacturer and less than the upper bound production volume of jth manufacturer.

3.3.4. Identified actions and scenarios to mitigate the disturbance

In this case study, 1st manufacturer suffered from flooding and X product was delayed. The loss impact was huge due to components delay. The management team was forced to make mitigation actions. The mitigation actions taken were working overtime, more shifts production, and changing the mode of transportation from sea to air. A total of 6 actions were identified and evaluated.

- **Mitigation Action 1 (MA1):** Raw material C of tier II shipped through air freight;
- **Mitigation Action 2 (MA2):** 1st manufacturer worked overtime to increase production capability;
- **Mitigation Action 3 (MA3):** Kitting through overtime increased production capability;
- **Mitigation Action 4 (MA4):** 2nd∼5th manufacturers worked overtime to increase production capability;
- **Mitigation Action 5 (MA5):** 2nd∼5th manufacturers, supplier D∼G, and material handling through overtime increased production capability;
- **Mitigation Action 6 (MA6):** Component parts were shipped by air freight instead of shipping by sea.

A total of 10 scenarios were listed for different mitigation actions taken for this case study. They were measured by using PERT.

- **Scenario 1:** The normal lead time to ship X product to 2nd and 3rd manufacturers was 45 days, and to 4th and 5th manufacturers was 46 days; a total logistic cost was $569.95 million;

- **Scenario 2:** MA1 action taken to mitigate the disruption;
- **Scenario 3:** MA2 action taken to mitigate the disruption;
- **Scenario 4:** MA3 action taken to mitigate the disruption;
- **Scenario 5:** MA4 action taken to mitigate the disruption;
- **Scenario 6:** MA5 action taken to mitigate the disruption;
- **Scenario 7:** MA6 action taken to mitigate the disruption;
- **Scenario 8:** MA1 and MA2 actions taken to mitigate the disruption;
- **Scenario 9:** MA1, MA2 and MA3 actions taken to mitigate the disruption;
- **Scenario 10:** MA1∼MA6 actions taken to mitigate the disruption.

3.3.5. Data analysis

After implementing the mitigation actions for the disturbance in the logistics, improvement in supply chain cost and lead time was summarized in Table 3. For the mitigation actions of Scenario 2, 3, and 7, the lead time was shortened from 46 days to 43 days, a 3-day reduction, but the total logistic costs for the implemented actions were $584.74 million for action of MA1, $586.46 million for action of MA2, and 605.34 million for action of MA6. Supply chain costs per day for action implemented were $4.93 million for action of MA1, $5.51 million for action of MA2, and $11.8 million for action of MA6.

As a result of mitigation actions for Scenarios 3, 4, and 5 shown in Table 3, the total logistic cost of Scenario 3 (overtime) conducted by 1st manufacturer (mitigation action of MA2) was $586.46 million, and the total logistic cost of Scenario 5 was $590.59 million for the mitigation action (overtime) taken by 2nd∼5th manufacturers (MA5). We found that the total logistic cost, due to the action taken by the 1st manufacturer, was lower than the total logistic costs (overtime action) taken by the 2nd manufacturer.

In Scenario 2, where raw materials were shipped by air freight, the lead time was shortened from 46 days to 43 days; total supply chain cost was $584.74 million, $14.79 million higher than Scenario 1. For the mitigation action Scenario 7 (MA6), the total logistic cost was $605.34 and the logistic cost per day was $11.8 million; it was higher than the other mitigation actions. The total cost of raw material delivered by air freight was around 18.88 million lower than the cost of component parts shipped by air freight. If all mitigation policies were taken, the lead time would

Table 3. Performance measurement summary.

Scenario	Characterization		Performance measures			
	Disturbance	Mitigation action	Total logistic cost (US$ million)	Max (lead time) (days)	Response lead time (days)	Additional logistic cost per day (US$)
1	-		$569.95	45/46	-	-
2	V	MA1 (supplier overtime)	$584.74	43	3	$4.93
3	V	MA2 (assembler 1 overtime)	$586.46	43	3	$5.51
4	V	MA3 (kitting overtime)	$573.26	45	1	$3.31
5	V	MA4 (assembler 2 ∼ 5 over time)	$590.59	44	2	$10.33
6	V	MA5 (supplier, material handling and assembler 2 ∼ 5 overtime)	$590.59	44	3	$10.33
7	V	MA6 (air freight instead of sea freight)	$605.34	43	3	$11.80
8	V	MA1 plus MA2	$604.71	40	6	$5.79
9	V	MA1 plus MA2 plus MA3	$611.69	39	8	$5.96
10	V	All MA	$722.81	30	16	$9.55

be shorten to 30 days, but the cost was escalated to \$722.81 million; \$152.86 million higher than the normal logistic cost for Scenario 1.

3.3.6. Findings and contributions
The significant findings and contributions of this study are as follows:

- One auto parts manufacturer in Asia Pacific region was identified to supply the additional resource for the automobile company during emergency needs. The assessment criteria included logistics costs, supply flexibility, production capacity, and overall investment;
- Analyzing and mapping out of the process in the supply chain network helped the automobile company to quickly respond to the risks incurred in the supply chain. We proposed the use of PERT (Program Evaluation and Review Technique) to mitigate any losses and damage through assessing time-cost and trade-offs.

This study facilitates the automotive industry to better manage unpredictable disasters in the supply chain through sourcing policy and global logistic strategy. Finally, this user-friendly model can provide an insight for other industries to better manage disruption in their supply chains.

4. Conclusion

Two key root causes of the target automotive company losses were highlighted by the management team. The first reason of losses was due to single tooling source shared by the auto parts manufacturers, and the second reason was due to the inefficient communication in the region. This study, using an automotive industry as a case study, has suggested answers to these two key root causes. Through comprehensive mapping process and efficient mitigation actions, the impacts caused by the disasters were reduced. PERT (Program Evaluation and Review Technique) was used to improve the communication in the region. These analytic tools gave the company a better perspective to resolve complex supply chain problems. The results in this study are consistent with several published literature. The user-friendly model can provide managerial insights for other industries to mitigate losses and quickly respond to any disruptions in their supply chains.

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