REDUCING DISRUPTION-INDUCED IMPACTS ON TRANSPORTATION SUPPLY CHAIN FLUIDITY

Matthew Whelen and Ata Khan, Carleton University
David Ramsey, Transport Canada

Introduction

In a competitive environment, the performance of a major trade corridor can be enhanced by a transportation supply chain whose fluidity is not severely impacted by a disruption. Potentially, a number of factors can be used to shape an efficient and resilient supply chain. However, detailed specifications of their roles remains a challenge for researchers. In this paper, we are reporting research in factors and methods that can potentially reduce disruption-induced impacts on transportation supply chain fluidity.

In the following sections of the paper, a transportation supply chain and its interrelated performance metrics of fluidity and reliability are defined. Inherent resilience and vulnerabilities to the performance of the supply chain due to disruptions are introduced, followed by resilience factors that are intended to reduce impacts of disruption on performance. This leads to linkages between resilience and fluidity. For realism, we apply these concepts to the import component of marine containerized freight flow in the Asia Pacific Gateway Corridor (APGC).

Specifically, the paper concentrates on the supply chain that moves intermodal containers inbound from Asia through Port Metro Vancouver and by rail to principal eastern destinations. The disruption caused by the 2012 railway labour strike is used to illustrate the application of fluidity and resilience models. Finally, in the concluding section, the importance of risk analysis is stressed and the role of inherent resilience and related factors in reducing disruption-induced impacts on supply chain fluidity is described.

Transportation Supply Chain and Fluidity Measures

Transport Canada defines a supply chain as a *connected network of suppliers, manufacturers, shippers, distributors and retailers where transportation plays the role of unifying link among all the actors.* Depending upon the modelling task, the level of abstraction can range from the overall system to its components.

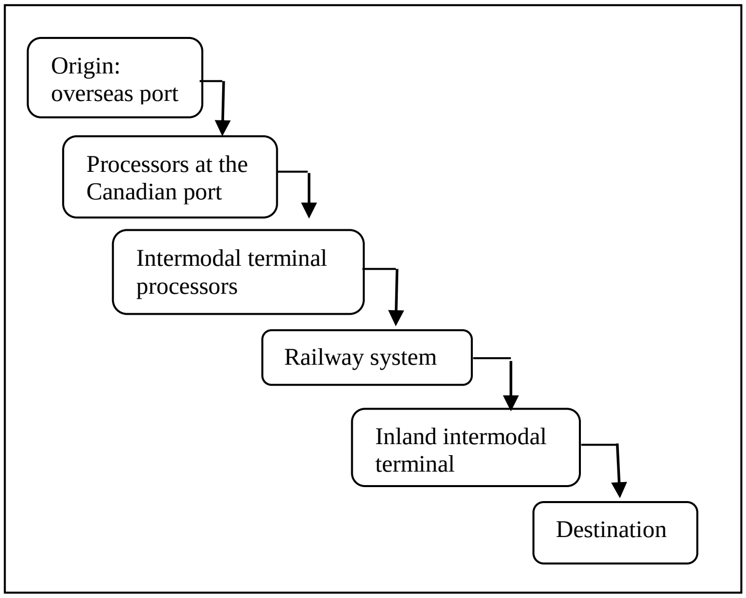
A supply chain network is shown in Figure 1. One direction and one set of modal and intermodal linkages is illustrated. In reality, even if we limit ourselves to the marine-based supply chain, two-way containerized traffic will flow between a number of overseas and North American origins and destinations. Also, Canadian and US container traffic routinely crosses the border in both directions. For the use of analysts, the challenge is to develop supply chain models characterized by links and nodes while taking into account the requirements of major trade corridors.

The marine-surface transportation part of a supply chain could include the following components (Transport Canada 2013): marine, rail/pure rail via intermodal yard-drayage, transload – rail, all-truck, and transload – truck. In this paper, we focus on the marine-rail part of the supply chain. In addition to characterizing its various parts, applicable “performance measures” are defined and quantified at the component, sub-system, and system level. Examples include dwell time and transit-time.

Risk Analysis Framework: Linking Fluidity, Vulnerabilities, Disruptions, and Resilience

Owing to the complex nature of supply chains and the socio-political, economic, and physical environment within which these operate, risk analysis is the only realistic approach to plan, operate and manage supply chains. Key factors of interest in supply chain risk analysis are: fluidity, vulnerability, risk of disruption, disruption, and resilience. Brief definitions presented in this paper are in-part sourced from Transport Canada.

Figure 1: Transportation supply chain network (marine imports)



Fluidity is a measure of how well a link or a node, or an entire network serving an origin-destination transportation market is performing. The measure of fluidity that is used frequently is transit time. Supply chain vulnerabilities are locations and associated prevailing conditions within the supply chain that are "at risk" of experiencing a service outage and there are no reasonable alternatives. Vulnerabilities represent potential disruptions. These could be:

- Man-made
- Nature induced

- System/equipment malfunction

Vulnerabilities could affect fluidity/reliability of the supply chain, impact businesses and have ripple effects in the economy. Disruptions are random events and if a disruption occurs, impacts could include lower reliability of the system (i.e., it affects performance and therefore impacts fluidity).

Various studies around the world have stressed the importance of understanding vulnerability to disruption. For example, a recent report sponsored by the New Zealand Transportation Agency favours a comprehensive approach to the study of vulnerabilities in terms of their identification, temporal characteristics, and analysis methods (Hughes and Healy, 2014). The authors emphasize the importance of developing measures to cope with both short-term shock events (e.g. earthquakes and tsunamis) and longer-term stress events (e.g. climate change-related events).

Suggested methods for analysis range widely from subjective approaches to fuzzy logic to optimization methods. However, it is clear that both breadth and depth are emphasized in understanding vulnerabilities and preparing to manage adverse effects (Hughes and Healy, 2014).

In the context of this paper, supply chain risk is the probability of events or trends that can potentially have an adverse effect on supply chain performance. The definition of supply chain disruption as used in this paper is an event or incident that results in a transportation system outage.

Resilience seems to be of growing concern because the risks and consequences of vulnerabilities are increasing, e.g., changing climate (long term), global supply chains, commodity surges, interdependencies, etc. (short term). Resilience has two components. First, inherent resilience enables the transportation supply chain, and the businesses that depend on it, to cope with the effects of a disruption. If a disruption occurs, the freight transportation component of the supply chain is impacted before the businesses are affected. Initially, the transportation component as well as the broader supply chain attempt to cope with the adverse impact with inherent resilience. If necessary, the dynamic component is initiated which involves recovery activities. The impacted businesses will do the same (i.e., they will use inherent resilience first and then, if necessary, they will use dynamic resilience involving conscious recovery actions).

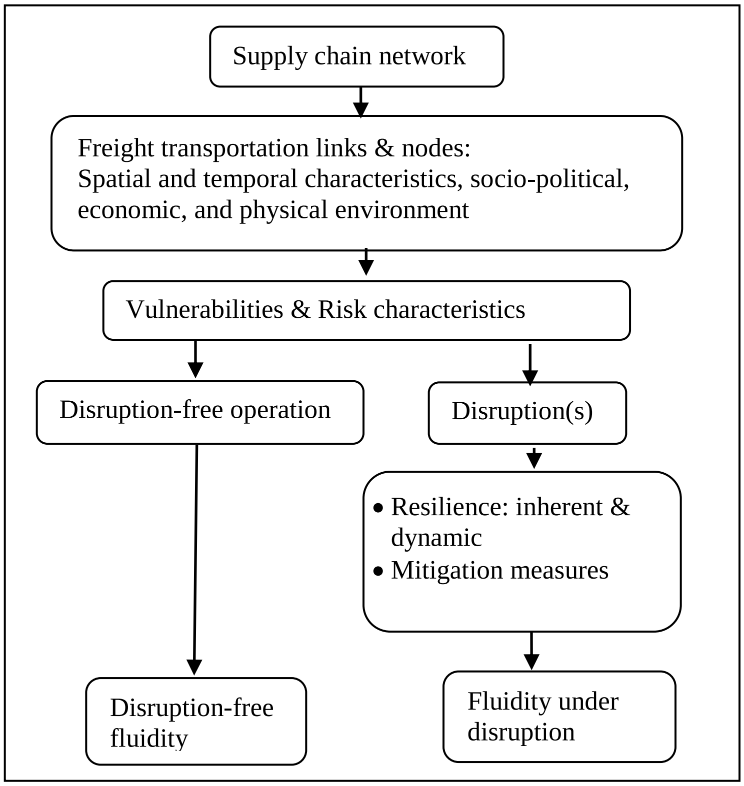
Resilience can be measured by determining the amount of service that can be maintained under the level of disruption that occurs, as well as how long it takes to return to the pre-event state of service with the help of recovery activities (Ta et al 2010).

A risk analysis framework and constituent models/methods were developed for systematic studies of supply chain fluidity (Figure 2). Highlights of the framework and application are presented in this paper. This framework integrates the key factors of fluidity, vulnerability, risk, disruption, and resilience. It provides outputs of disruption-free fluidity as well as under-disruption fluidity. A key feature of the framework is the Monte Carlo simulation-based risk analysis model which enables an analyst to take into account the random nature of performance variables. The fluidity data collected by Transport Canada in association with the Monte Carlo simulation model enabled us to estimate the most likely transit time from origin to destination as well as the variability in the estimate.

As applied to fluidity, the Monte Carlo simulation method samples probability distribution functions of transit time in the applicable components of the supply chain, and it creates a composite distribution of the total transit time from an origin to a destination. The statistics of this composite distribution are provided as well (i.e. both the expected mean and the variance).

This risk analysis framework and constituent models overcome the limitations of examining average value and variance of a performance function for each link (e.g. a mode) in the supply chain in isolation. For realism, in addition to examining the performance of each link, the performance of the entire chain from origin to destination should be assessed. This cannot be done without the Monte Carlo model-based risk analysis framework.

Figure 2: Risk analysis framework



As opposed to the current practice, the fluidity method used relaxes the assumption of certainty in the quantification of the performance factors for components of the supply chain. Risk analysis serves an important function in studies on how to protect and enhance supply chain fluidity whether in disruption-free condition or under disruption.

The subject of reducing variability in supply chain performance is drawing much attention around the world. The World Economic Forum (WEF) (2012, 2013), the International Transport Forum (2013) and many other agencies are calling for research on improving concepts and methods that can ultimately lead to “risk mitigation”. A study by the International Transport Forum highlighted the importance of future policy focus on reducing variability in supply chain performance.

In the risk analysis framework presented in Figure 2, we can quantify fluidity under disruption-free conditions as well as under-disruption conditions. These two estimates of fluidity can be expressed as an index as suggested by the Texas Transportation Institute (Texas Transportation Institute 2010). The fluidity index (FI) is the ratio of transit time in the disruption condition to the disruption-free transit time.

Fluidity is closely aligned with the performance metric of reliability of a transportation supply chain (Gillen and Hasheminia 2013, Tardif 2013). Fluidity and reliability are stochastic as they cannot be estimated or predicted with certainty. For this reason, a standard deviation is frequently cited in fluidity databases, in addition to the most likely estimate (i.e., the average). If two supply chains have equal or nearly equal transit time, a high-reliability system will exhibit a lower variance while a low-reliability system will exhibit a high variance.

Mathematical models of resilience have been reported by Miller-Hooks et al. (2012) and Nair et al. (2010). A modified version is used in this study. Please see below.

α resilience index of a link or a node or a network; α is stochastic (i.e. probabilistic). It is not known with certainty.

d_w demand that can be served by a link w post-disruption while maintaining a prescribed level of service

D_w pre-disruption demand that can be served by link w, using specific resources

β dummy variable representing connectivity. If a link or node is not operational, $\beta = 0$. Otherwise $\beta = 1.0$.

For one link w, the resilience index is

$\alpha = E[d_w/D_w]\beta$

E expected value of the ratio, given that d_w and D_w are stochastic Variables (i.e. their values cannot be predicted with certainty.

For a network

d_w demand that can be served by a link w after disruption while maintaining a prescribed level of service

D_w predisruption demand served that can be served by link w, using specific resources

β_w a dummy variable representing connectivity of link/node w. If a link/node is not operational, $\beta_w = 0$. Otherwise $\beta_w = 1.0$.

The resilience index α is shown below.

$\alpha = E\ [\Sigma_{w\varepsilon W}\ d_w/\Sigma_{w\varepsilon W}\ Dw]\ \beta_w$

The pre-disruption capacity cannot be known with certainty. Likewise, the effect of recovery activities cannot be predicted with certainty. Therefore, Dw and d_w should be treated as stochastic variables, and consequently the resilience index, α, is also stochastic. From the amount of post-disruption capacity available, dw, and the amount of capacity needed, Dw, we can find α. The Monte Carlo method can be used to find the expected resilience of the supply chain.

The resilience and fluidity of the supply chain are integrated in the risk analysis-based methods. These methods can be applied to any disruption with the potential for producing appreciable damage. As an illustration of their application, a preliminary analysis of a major disruption (i.e. Rail labour strike of 2012) is presented in this paper.

The Asia-Pacific Gateway and Corridor (APGC)

Transport Canada has identified the following gateways and trade corridors (Transport Canada 2011; Gibbons 2010): Asia–Pacific Gateway and Corridor (APGC), Ontario–Quebec Continental Gateway, and Atlantic Gateway and Trade Corridor. Among these, because of growing and high value trade trends, special attention is accorded to the APGC (Government of British Columbia 2012). The APGC is used here as a case study. Specifically, the Shanghai to Toronto containerized freight movement through Port Metro Vancouver is used for risk analysis.

The APGC is a major gateway corridor that serves the Asia-Canada trade via the west coast ports of Prince Rupert and Port Metro Vancouver. Capacity expansions are planned for both ports (Gibbons 2010, Port Metro Vancouver 2015). The Port Metro Vancouver is served by CP Rail, CN Rail, and BNSF Rail. Scheduled daily double stack container trains are operated by both Canadian railways to major destinations in Canada and to Chicago. The Prince Rupert port is served by CN Rail's double stack scheduled container service.

Supply Chain Disruption: Example of 2012 CP Rail Strike

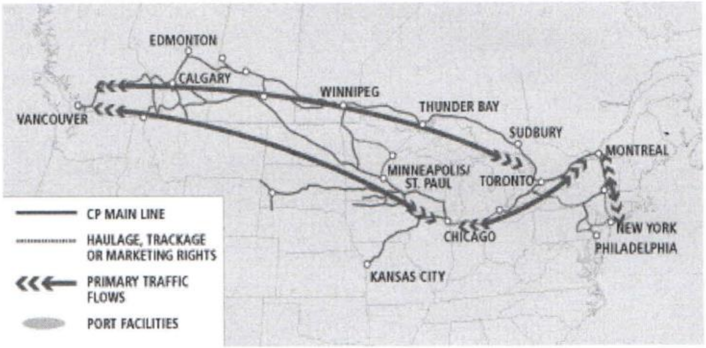
The application of the risk analysis framework is illustrated by using the Shanghai-Toronto container traffic for 2012, served via Vancouver. Disruption-free fluidity was modelled first in order to establish the baseline conditions against which the effect of a disruption could be studied (Table 1). The transit times of the marine mode, port and intermodal processors, rail movement, and destination terminal are treated as random. A normal (Gaussian) probability distribution is assumed for all input variables. Simulation results show that the pre-strike expected total transit time for the Shanghai-Toronto container traffic was 22.4 days and the standard deviation was 3.2 days.

Next, the effect of a major labour disruption on fluidity was modelled. The 2012 CP Rail's labour strike of nine days (that lasted in effect for 11 days) was a major disruptive event that impacted service throughout the network (Figure 3).

Table 1 Disruption-free fluidity: Shanghai-Toronto Traffic

Supply Chain Component	Data, Assumptions and Results
System	Base case, average conditions, no disruption, effect of CP Rail strike removed.
Marine	13.96 days x 24 = 335.04 hrs
Port + Intermodal	2.41 days x 24 = 57.84 hrs
Rail + Destination Terminal	5.90 days x 24 = 141.6 hrs
Monte Carlo Simulation	Assume normal probability distribution and st. deviation = 20% for all variables
Results:	
Expected total transit time	537.4 hrs (22.4 days)
St. dev.	75.9 hrs (3.2 days)

Figure 3: CP Rail network (Courtesy: Web source)

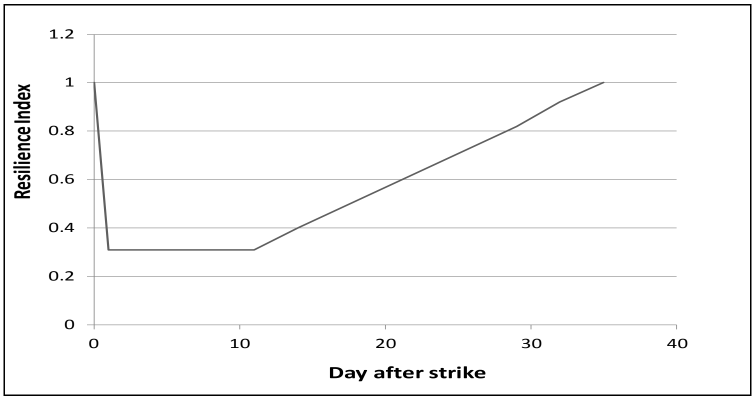


According to the media, the labour strike lasted for 9 days and it took CP Rail another two days to start serving the backlog of traffic. During the strike the Port Metro Vancouver suffered 70% capacity loss and this resulted in a major impact on containerized freight service. The case study traced the combined effect of inherent and dynamic resilience on the fluidity of the Shanghai-Vancouver-Toronto containerized freight traffic.

As explained below, the containerized freight service network witnessed an increase in transit days from the base case of 22.4 days to 41.4 days as a result of the labour strike disruption.

For illustration purposes, the effect of labour disruption on Shanghai-to-Toronto container traffic was quantified in terms of network level resilience and fluidity by using models described above. The temporal profile of resilience during and following the event is shown in Figure 4.

Figure 4: Temporal profile of resilience during and following CP Rail strike



By way of an explanation of the effect of disruption on resilience and fluidity, Table 2 can be viewed as a sample of the analysis carried out using the Monte Carlo method. The result shows that with a resilience index of 0.31, the expected mean transit time between Shanghai and Toronto during the strike is 41.4 days and the standard deviation is 4.5 days. For this same traffic under disruption-free conditions, the stochastic fluidity analysis shows a mean of 22.4 days and standard deviation is 3.2 days (Table 1).

These results show that a supply chain’s resilience affects its fluidity. If there is a low level of available capacity during a disruption relative to the capacity actually needed, the likely consequence is an increase in transit days. This implies a lower fluidity level.

Table 2 Effect of resilience on fluidity: Shanghai-Toronto Traffic

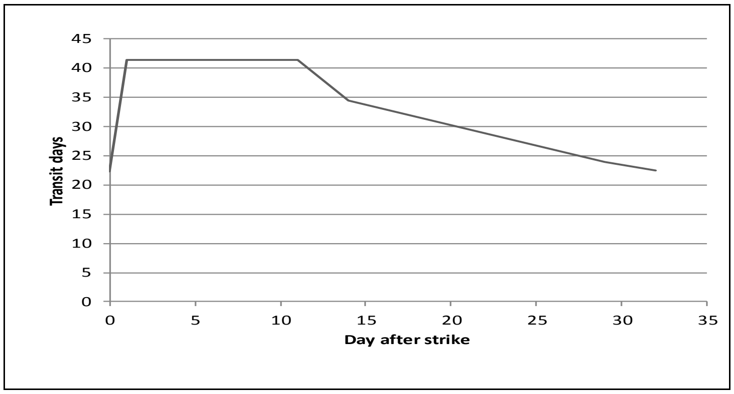
Supply Chain Component	Data, Assumptions and Results
System	CP Rail strike days 1-11 conditions & with resilience index of 0.31.
Marine	13.96 days x 24 = 335.04 hrs
Port + Intermodal	[2.41 days x 24]/0.31= 186.58 hrs
Rail + Destination Terminal	[5.9 daysx24]/0.31= 456.77 hrs
Monte Carlo Simulation	Assume normal probability distribution and st. deviation = 20% for all variables
Results:	
Expected total transit time	993.4 hrs (41.44 days)
St. dev.	109.0 hrs (4.5 days)

The temporal profile of transit days (i.e. fluidity) is presented in Figure 5. During the strike (days 1 to 11 conditions), the expected total transit time became 41.4 days and the standard deviation was 4.5 days. Following the strike, the resilience index started to rise and the transit days followed a downward profile (Figure 5). After 32 days, the transit time returned to the pre-strike level.

Inherent Resilience and Related Factors

The inherent resilience plays a role in reducing the effect of a disruption and if a supply chain’s resilience is favourable, the fluidity will not be adversely affected. On the other hand, if there is a low level of available capacity during a disruption relative to the capacity actually needed, the likely consequence is an increase in transit days. This implies a lower fluidity level. The effect of resilience on fluidity of origin-destination intermodal traffic can be investigated within the risk analysis framework described in this paper.

Figure 5: Temporal profile of fluidity of Shanghai-Toronto-Container Traffic (CP Rail Strike)



Conclusions

The risk analysis approach and models covered in this paper treat variability in fluidity and are in line with international policy trends.The case study results are intuitively logical and illustrate the usefulness of the risk analysis-based methodology for the integrated study of resilience and fluidity.

Both inherent and dynamic resilience are important in reducing disruption-induced impacts on supply chain fluidity. In the case of the labour disruption study presented in this paper, the availability of 30% capacity during labour strike prevented the inherent resilience to drop to zero. Of course with a dynamic resilience component (e.g. carrier agreement), a sharp drop in the fluidity could be prevented.

Further research is required on (a) measures to enhance short term resilience, (b) methods for seeking optimality in strategies for enhancing resilience as well as in recovery tactics, and (c) building long term resilience.

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