# Simulating severe supply chain disruptions with multiple suppliers and firms

by

**Kevin Korniejczuk**

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Dr. Gary Mirka

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this creative component. The Graduate College will ensure this creative component is globally accessible and will not permit alterations after a degree is conferred.

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## DEDICATION

I would like to dedicate this creative component to my parents, Halina and Andrzej Korniejczuk. Without their constant encouragement throughout my engineering education, this work would not have been possible.

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# ABSTRACT

Global supply chains are susceptible to disruptions. Disruptions in one part of the world can lead to supply chain problems for companies around the world. This creative component analyzes a model of severe supply chain disruptions where several suppliers encounter inoperable facilities, resulting in potential shortages for firms which purchase from those suppliers. All entities within the model are able to choose strategic initiatives to maintain operations. If an entity's facility is closed because of a disruptive event, the entity can choose to move production to an alternate facility. If an entity's facility is undamaged, the entity can experience a supply shortage but may be able to use inventory or buy from an alternate supplier in order to mitigate the disruption. A simulation based on the 2011 Japanese earthquake and tsunami, where several key companies in the automotive, electronics, gaming, and camera industries have closed facilities, is applied to the model. The results demonstrate that on average all the industries are able to meet almost 100% of demand during the simulation; however, individual firms may suffer heavily and lose customers to other firms. Sensitivity analysis is conducted to understand the impact of the probability of a facility reopening, the cost of moving production to an alternate facility, the amount of inventory available, and a firm's desire to trade off between meeting demand and maximizing profit.

# CHAPTER 1. INTRODUCTION

The Tōhoku earthquake and tsunami struck Japan on March 11, 2011, impacting over 27,000 businesses through destroying or disabling production facilities, warehouse facilities, or retail facilities. Due to the severity of the disaster, 22% of those business did not resume operations one year after the disaster (Daily Yomiuri, 2012). These entities deliver goods to nations around the world and the natural disasters directly disrupted global supply chains. Due to the disruptions, orders could not be fulfilled, production paused, and supplier inventory decreased (Nakata, 2011).

As modern supply chains become increasingly more complex, more globalized, and more efficient, managing exposure to risk in modern supply chains is an important task company executives are aiming to mitigate. Firms in one country receive raw materials from multiple suppliers in different countries. When a disruption occurs and causes an entity within the supply chain to be inoperable, shortages throughout the supply chain may happen. As efficient supply chains contain low inventory levels and few suppliers, the difficulty to mitigate a supply chain increases in difficulty if a supplier cannot fulfill their requirements.

A severe supply chain disruption is defined as a disruptive event resulting in challenges for multiple suppliers and where at least two of those suppliers produce different products or services to at least two competing firms. When these disruptions happen, entities throughout the supply chain are required to make decisions about recovery, moving production, and purchasing from alternative suppliers. Fulfillment, the ratio of total production to total demand, can be utilized to measure the effectiveness of the mitigation strategies.

Modeling and simulation tools are often used to analyze supply chain risk as supply chains are complex systems with uncertainty built in. Simulation tools provide an opportunity to showcase all scenarios to a decision maker to provide an understanding of all risks built into the system. Therefore, multiple suppliers and multiple firms can be further examined to provide insight into how the effects of certain nodes within a global supply chain can impact the network.

This paper analyzes a simulation study in which a disruption impacts several suppliers and firms, and therefore may face supply shortages. The simulation incorporates decisions made by suppliers and firms, including the decision to move production to an alternate facility, using existing inventory to meet demand, and purchasing inventory from an alternate supplier.

The simulation quantifies the response of the individual firms and the market as a whole to a disruption in terms of the fulfillment rate of demand, or the ratio of production to demand. Chapter 2 provides a literature review of supply chain disruption risk management, entailing methods to predict disruptions, methods to evaluate decision strategies, and supplier portfolio selection. Chapter 3 presents the results of the simulation of the supply chain disruption that occurred based on the 2011 Japanese Tsunami. Eight markets are analyzed as well as individual firms in the simulation. Chapter 4 adjusts parameters of the simulation to evaluate the effects of certain parameters such an inventory, cost of switching suppliers, and the expected time to reopen the facility on firm fulfillment and industry fulfillment of demand.

# CHAPTER 2. LITERATURE REVIEW

Snyder et. al. (2016) provide a good and recent review of supply chain disruption risk studies that have been conducted at the tactical level and the operational level. Tactical level qualitative studies (Chopa and Sodhi, 2004; Sheffi, 2005; Tang, 2006) categorize supply chain risk into different categories and recommend or review best practices for organizations to prepare for and ultimately prevent supply chain disruptions. Manuj et al. (2007) argue the causes of risk in supply chains include supply-side risk, demand-side risk, operational risk, and security risk. Chopra and Sodhi (2014) explain the benefit of supply chain segmentation and supplier diversification.

Scoring methods—such as risk matrices or failure mode effects analysis—have become a popular method to assess supply chain risk in a qualitative or pseudo-qualitative manner. A score method for supply chain risks typically categorizes the risks in different categories to determine which risks are of highest priority (Bradley, 2014). Risks may be further categorized into different functions of supply chain management, such as planning, sourcing, making, delivering, returning, and whether a risk appears within the organization or outside the organization (Kayis & Karningsih, 2012). Ryding & Sahlin (2013) rely on interviews with supply chain managers to incorporate performance measures supply chain risk management practices. Companies that do the best in risk management connect their key performance indicators to their risk management strategies in order to understand the effectiveness of risk management activities. Connecting key risk indicators with key performance indicators allows supply chain managers to receive warnings about future risks (Ryding & Sahlin, 2013). The ability of the workforce to identify damages and serve as resources for recovery can have a significant impact on the severity of disruptions (Santos et al. 2014).

The supply chain risk management literature also involves a wide range of quantitative models. Sawik (2017) designs a stochastic mixed integer programming model to determine how to select the best supply chain portfolio under the presence of risks. The article concludes the best strategy is to select either the cheapest suppliers or to select a single reliable supplier. Baroud et al. (2016) create a Bayesian beta kernel model (MacKenzie et al., 2014) to identify that supplier location and risk management procedures—rather than industry type and size—are stronger predictors of the likelihood of a supply disruption. Supply disruption management strategies may include adjusting scheduling (Bean et. al., 1991; Adhitya et al., 2007), utilizing different transportation modes (Mackenzie et al., 2012), and purchasing from alternative suppliers (Hopp et. al., 2008).

The supply chain risk management literature at the operational level often focuses on the amount of inventory to hold, whether or not to purchase from alternate suppliers, and other factors to mitigate risk. The traditional economic order quantity (EOQ) model can be adapted to account for supply uncertainty and disruptions (Parlar and Berkin, 1991; Berk and Arreola-Risa, 1994). Disruptions may be modeled as a Markov process where the two states are either a functional supply chain or a disrupted supply chain to determine the optimal inventory level (Song and Zipkin, 1996; Tomlin, 2006). Chang and Lin (2018) design a simulation model of a traditional retailer, warehouser, and factory supply chain model to measure how the lead time impacts the resilience of a traditional supply chain.

The 2011 Japanese earthquake and tsunami has inspired a number of models and analyses to understand supply chain disruptions and the interdependent impacts of these disruptions. Kajitani and Tatano (2014) propose a method utilizing fragility curves to consider the relationships between earthquake ground motion, production capacity, and recovery timelines. Todo et al. (2015) employ a tobit estimation to explain how supply chain networks impact the resilience of manufacturing firms to natural disasters and evaluated the estimation method using firm-level data from before and after the tsunami. Supply chain networks with more diverse and regionally dispersed suppliers and customers are more resilient to severe disruptions. Carvalho et. al. (2016) conclude that firms struggled to find viable alternatives to mitigate the impact of the Japanese tsunami. The interdependent impacts contributed to a 1.2% decrease in Japan's gross output in the year after the tsunami. However, Japanese demand for products was largely satisfied by other companies in countries outside of Japan and that inventory in the production pipeline mitigated many of the supply chain impacts of the tsunami (MacKenzie et al., 2012). MacKenzie et al. (2014) create a model and simulation of a severe supply chain disruption inspired by the disruption in the automobile sector as a result of the Japanese tsunami.

The model in this paper is also inspired by the 2011 Japanese earthquake and tsunami and seeks to replicate the complex supply chain networks that were impacted by the tsunami. MacKenzie et al. (2014) model the decision-making process of suppliers and firms during a severe disruption in which multiple suppliers are suddenly inoperable. The model contained in the paper herein follows the same decision-making process but includes multiple supply echelons and different industries (e.g., electronics, chemical) within the supply chain network. This paper increases the number of entities in the simulation to 63 from the initial number of seven in MacKenzie et al. (2014). Since the design of supply chain disruption model and the simulation are outside the scope of this paper, Appendix A (written by Dr.

MacKenzie) provides an overview of the model and simulation and the data and assumptions integrated into the simulation. This paper allows for a broader and deeper understanding of complex interactions among suppliers and firms during a disruptive event.

# CHAPTER 3. RESULTS

The results are obtained through running 1,000 trials of the simulation utilizing the baseline parameters. Eight major industries were evaluated: Automobiles, Electronics, Gaming, Camera, Semiconductor manufacturing, Telecommunications equipment, Semiconductor equipment and testing, and Chemicals.

The simulation returns the number of units produced and the number of units demanded. The effectiveness of fulfilling demand is an important factor in decision-making and therefore, will be the sole factor in performance evaluation for firms and markets since total cost is not an output within the simulation. Fulfillment is defined as the number produced divided by the number demanded. Automobiles, Electronics, Gaming, and Camera industries are the only industries that sell solely to final consumers.

## Overall Industry Performance

Table 3.1 provides the summary statistics of the fulfillment rate. All markets fulfill at least 98% of their demand. The industries perform well as a whole due to two main reasons. Firms can meet demand that another firm in the same industry fails to meet, showcasing the impact of competition form a logistics standpoint. Additionally, the simulation continues until all suppliers have reopened their facilities, allowing firms and industries to meet demand later in the simulation. This notably is shown within the two semiconductor industries (semiconductor manufacturing and semiconductor equipment and test). These industries contain the largest average fulfillment rate. These two industries both average over 100% fulfillment. These semiconductor industries are suppliers to other firms in the model, and these industries average over 100% fulfillment because the model assumes that that suppliers will attempt to replenish lost inventory. However, this replenishment of lost inventory is not considered in the denominator when calculating the fulfillment rate.  Due to these factors, timing factors in aspect of the results are also evaluated.

Table 3.1: Industry Performance Summary Statistics

| | **Auto-mobiles** | **Electronics** | **Gaming** | **Camera** | **Semi-conductor Manufacturing** | **Telecom-munications Equipment** | **Semi-conductor Equipment and Testing** | **Chemical** |
|---|---|---|---|---|---|---|---|---|
| **Mean** | 99.53 | 99.73 | 99.93 | 99.62 | 100.75 | 99.79 | 101.07 | 98.87 |
| **Standard Deviation** | 0.58 | 0.34 | 0.21 | 0.36 | 1.73 | 2.41 | 2.33 | 2.67 |
| **Min** | 95.59 | 96.90 | 97.35 | 97.66 | 93.94 | 83.72 | 86.83 | 82.77 |
| **Max** | 100 | 100 | 100 | 100 | 110.71 | 110.46 | 114.53 | 108.09 |

The automobile industry, the electronics industry, the gaming industry, and the camera industry only produce for final consumers. From the final consumer selling industries, the gaming industry performs the best and also contains the smallest variance. Each firm in the gaming industry initially carries five weeks of inventory. Most suppliers are expected to reopen within five weeks, allowing enough existing inventory for firms to meet demand requirements. Only one firm, Sony PlayStation, has a supplier, Renesas, without other competitors. Therefore, it is likely for the other firms to have produced demand Sony could not fulfill.

The automobile industry contains the lowest mean fulfillment rate and also contains the largest standard deviation for firms that sell to final consumers. This industry relies heavily on Renesas and Merck, which are two severely disrupted firms within the simulation with their facilities expected to be closed for twelve and eight weeks respectively. Additionally, two firms (Isuzu and Mazda) are initially disrupted within the simulation, and two firms (Toyota and Honda) have a supplier with an expected 26-week disruption period. All these factors lead to a lower mean fulfillment rate due to firms lacking inventory when customers need their products.

The semiconductor manufacturing industry performs well due to only half the firms being disrupted. Those specific firms generally required less demand, while the active firms in the contained large inventory amounts or had no suppliers, implying their ability to fulfill demand the disrupted firms could not fulfill. The semiconductor equipment and testing industries have no suppliers, and although all three firms within the industry are disrupted, all firms should expect to resume operations within two weeks. This short time, its independence from suppliers, and its ability to produce large quantities over a period of time allow the semiconductor equipment and industry to perform well. However, the uncertainty of the time the facilities will reopen contributes the most to the large standard deviation.

The remainder of the results chapter will focus on individual firms within each market to compare their performance against their direct competitors. Within the chapter, the automobile market and the electronics market will be further analyzed due to their roles as firms that sell solely to final consumers

## Automobile Market

Table 3.2 indicates the performance statistics of the fulfillment rates for each firm in the automobile industry in the simulation. As indicated, all the firms fulfill at least 94% of their demand on average.  Isuzu contains the largest mean fulfillment rate, while Honda has the smallest mean fulfillment rate. Nissan, General Motors, Mazda, and Isuzu all contain mean fulfillment rates over 100%, indicating these firms are often fulfilling demand the remaining firms cannot fulfill within the simulation. General Motors has the smallest variance while Isuzu has the largest variance. Isuzu and Mazda have initially disrupted facilities, which contributes to their large variances. However, Isuzu only contains inventory from three suppliers, increasing variability due to its increased dependence on its suppliers to fulfill demand. The causes for a lower fulfillment in comparison to other firms is the disruption of two automobile suppliers, Renesas and Merck, and the 26-week disruption period of Toyota and Honda's respective main suppliers.

Table 3.2: Automobile Firm Summary Statistics: Mean Fulfillment (%)

| | **Toyota** | **Honda** | **Nissan** | **GM** | **Ford** | **Chrysler** | **Mazda** | **Isuzu** |
|---|---|---|---|---|---|---|---|---|
| **Mean** | 97.4 | 94.4 | 102.3 | 101.2 | 99.6 | 99.0 | 102.0 | 103.4 |
| **Standard Deviation** | 2.9 | 6.8 | 3.0 | 1.5 | 2.7 | 6.8 | 8.2 | 14.2 |
| **Min** | 81.1 | 54.1 | 100.0 | 100.0 | 79.6 | 51.7 | 52.0 | 17.9 |
| **Max** | 102.9 | 107.2 | 123.4 | 112.1 | 104.8 | 112.8 | 152.2 | 197.8 |

To observe Honda more closely, a histogram of Honda's fulfillment rate has been depicted (Figure 3.1). The spread of the distribution causes Honda to have a large probability of failing to meet demand due to the large variance and its natural left shew. While around 25% of trials do meet demand, few trials exists where production exceeds demand by a large amount, showcasing the reason for a left skew distribution. The reason why Honda has instances where the fulfillment rate is larger than 100% is due to firms being able to produce units of demand their competitors could not produce within each period.

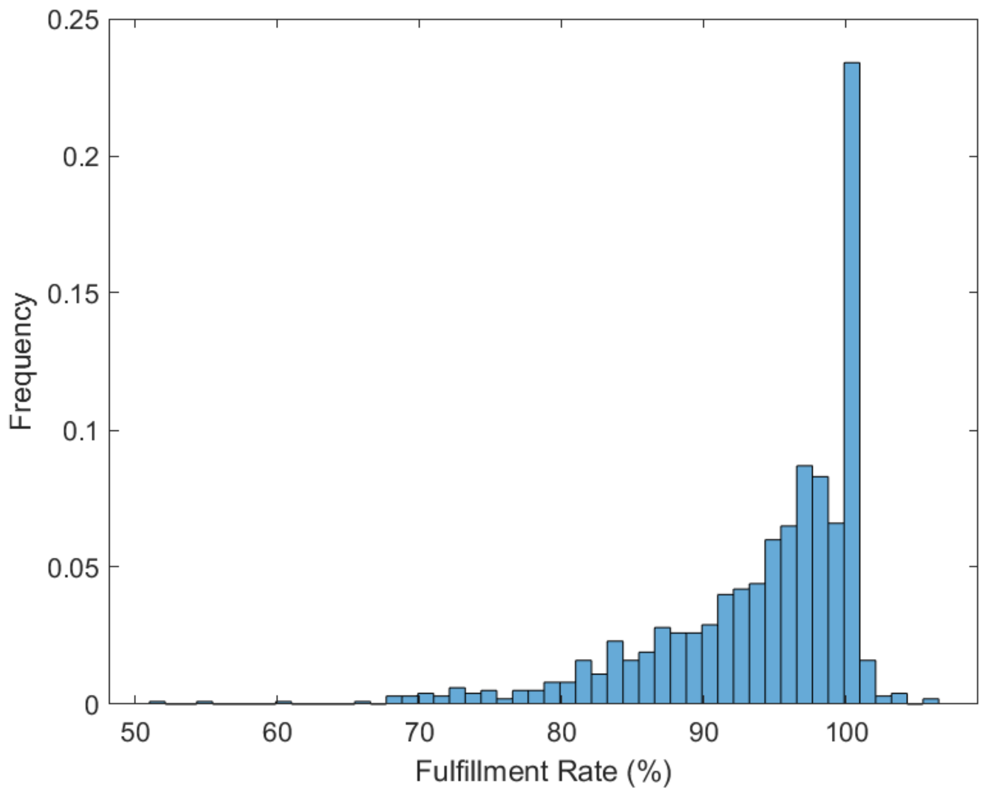



Figure 3.1: Histogram of Honda Fulfillment

The shape of the Toyota's fulfillment distribution follows similarly to Honda. However, the scale of the x-axis differs between the firms. While Toyota follows a similar distribution, it has a higher mean fulfillment rate due to more inventory being demanded and produced as well as higher inventory levels being placed. The distribution functions have a similar shape because the firms share the same suppliers except for one, but the different suppliers for Toyota and Honda are both disrupted for 26 weeks, which causes a lower fulfillment rate in comparison to the other firms. There is one difference between the firms: the initial demand. Since Toyota has almost three times more demand than Honda, which calculating fulfillment, Honda will have a larger fulfillment ratio variability as failing to meet one unit of demand causes a lower fulfillment ratio for Honda as opposed to Toyota. Since the parameters are essentially the same besides the demand and production units, these two firms will follow a similar spread in fulfillment ratios.

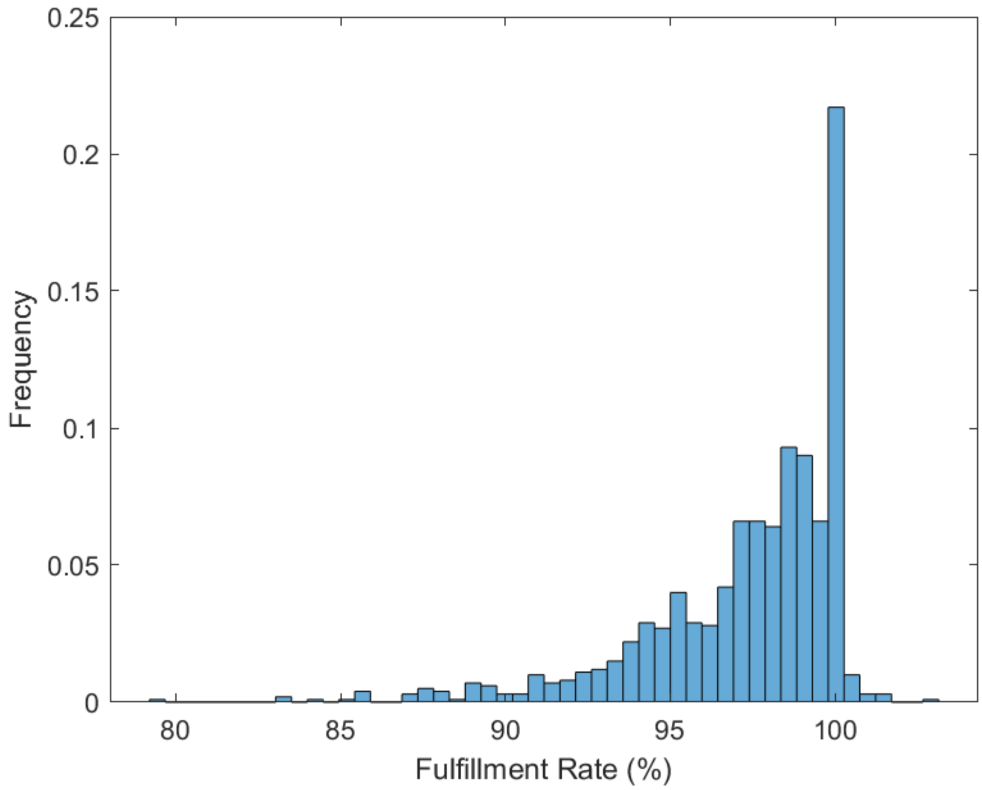



Figure 3.2: Histogram of Toyota Fulfillment

Nissan shares the same suppliers as Toyota and Honda, except for one supplier only unique to Nissan. In comparison, Nissan carries one more week on on-hand inventory and their unique supplier only expects a 13-week disruption period. These two differences explain the fact that although the firm’s characteristics are the same, Nissan has a 3% larger mean fulfillment rate.

Figure 3.3 shows a histogram of Isuzu's fulfillment rate over all 1,000 trials. As shown, the spread of its fulfillment appears symmetric. However, the fulfillment rate has a large variance. As mentioned previously, Isuzu only carries inventory from three suppliers. Therefore, since Isuzu has increased dependency as opposed to the other firms, the facility is initially disrupted for three weeks, and the demand is lower with similar inventory ratios to the competing firms, the variability is much higher as opposed to its competing firms.

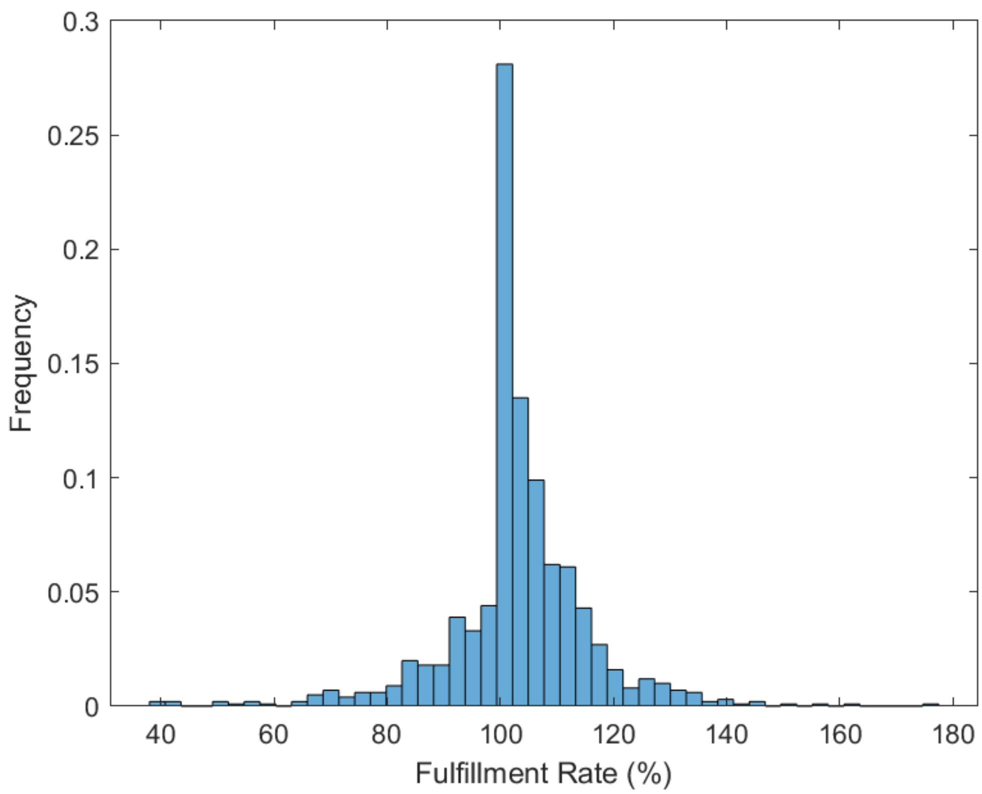



Figure 3.3: Histogram of Isuzu Fulfillment

Overall, the automobile industry performs well, but long supplier disruption periods impact the respective firms' ability to fulfill demand. As shown by Isuzu in comparison to Toyota and Honda, the length of a supplier disruption period contributes directly to the firm's fulfillment rate as well as the amount of on-hand inventory. As the number of units demanded decreases, the fulfillment rate carries more variability as failing to fulfill one unit of demand results in a larger decrease in the fulfillment rate. Therefore, there are some fallacies to comparing firms solely by their ability to fulfill their own demand.

## Electronics

The electronics market contains six firms: Apple, Sony Ericsson, Nokia, HTC, Huawei, and Samsung. Table 3.3 provides a summary of the summary statistics for the fulfillment rates of all six firms. The electronics market generally performs well with five firms allowing almost 100% of the total demand to be fulfilled. As shown, Apple has the smallest mean fulfillment rate, while HTC has the largest mean fulfillment rate. While Apple has the smallest mean, the firm also contains the largest variance. Nokia has the smallest variance.

Table 3.3: Electronics Firm Summary Statistics: Mean Fulfillment (%)

| | **Apple** | **Sony Ericsson** | **Nokia** | **HTC** | **Huawei** | **Samsung** |
|---|---|---|---|---|---|---|
| **Mean** | 88.9 | 102.2 | 100.1 | 104.4 | 103.7 | 99.7 |
| **Variance** | 10.2 | 3.8 | 0.4 | 6.0 | 5.0 | 1.0 |
| **Min** | 29.5 | 62.6 | 96.5 | 97.2 | 63.3 | 91.8 |
| **Max** | 105.6 | 134.0 | 102.5 | 160.9 | 160.9 | 101.0 |

Figure 3.4 shows the distribution of Apple’s fulfillment rate over all 1,000 trials. The distribution showcases that Apple performs poorly overall, but there is some possibility of having a high fulfillment rate. However, Apple rarely fulfills 100% of their demand. Multiple factors contribute to Apple’s low fulfillment rate. In terms on initial on-hand inventory,

Apple only carries two weeks of inventory while the remaining firms carry between four - eight weeks of inventory. The firm's suppliers have an expected disruption period between 2-16 weeks, and the single market suppliers have disruption periods from 4-12 weeks. Therefore, low inventory is Apple's pitfall in terms of satisfying demand because the firm cannot obtain the raw materials to produce more units.

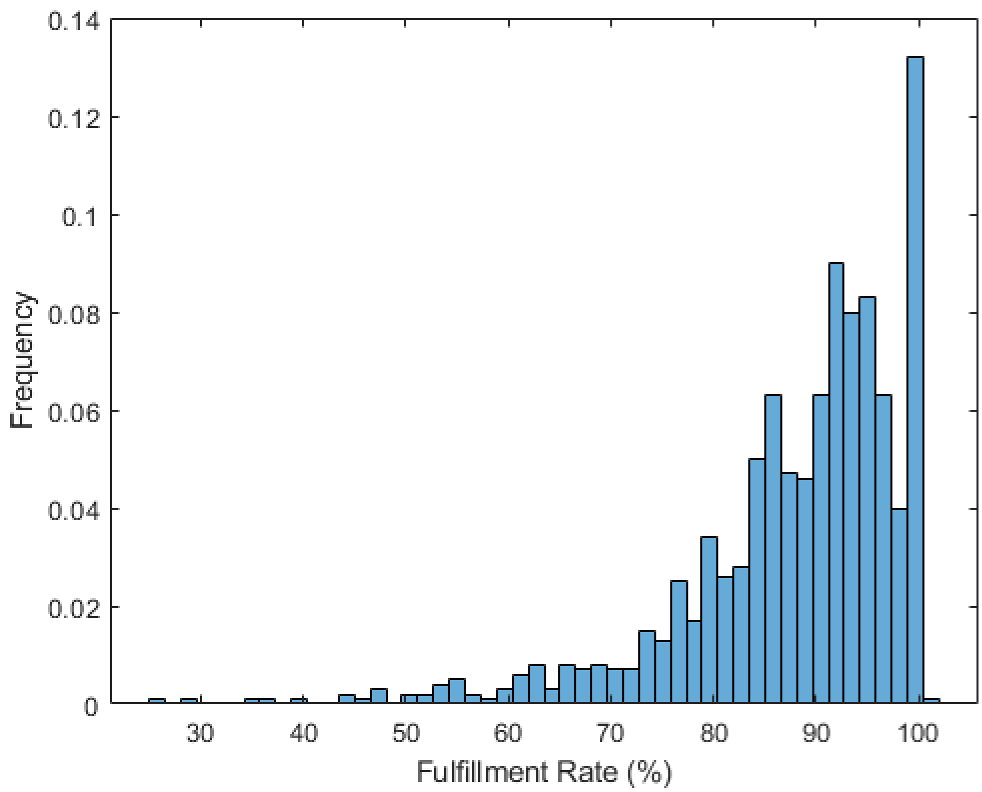



Figure 3.4: Histogram of Apple Fulfillment

Samsung has much less variability as opposed to Apple, indicating Samsung has less exposure to risk. Samsung carries five weeks of inventory as opposed to two weeks. Only three suppliers have an expected disruption period of over five weeks, and only one firm of those three suppliers is in a unique market. This places Samsung in a good condition to fulfill most of their demand. Most of the variability is likely to come from the length of the supplier disruption periods. The length of the disruption period of any organization within the simulation contains variability. Due to variability, some suppliers contain disruption periods over five weeks long, leading to inventory being unable to fully accommodate the disruption period and causing fulfillment rates to decrease below 100% in some instances.

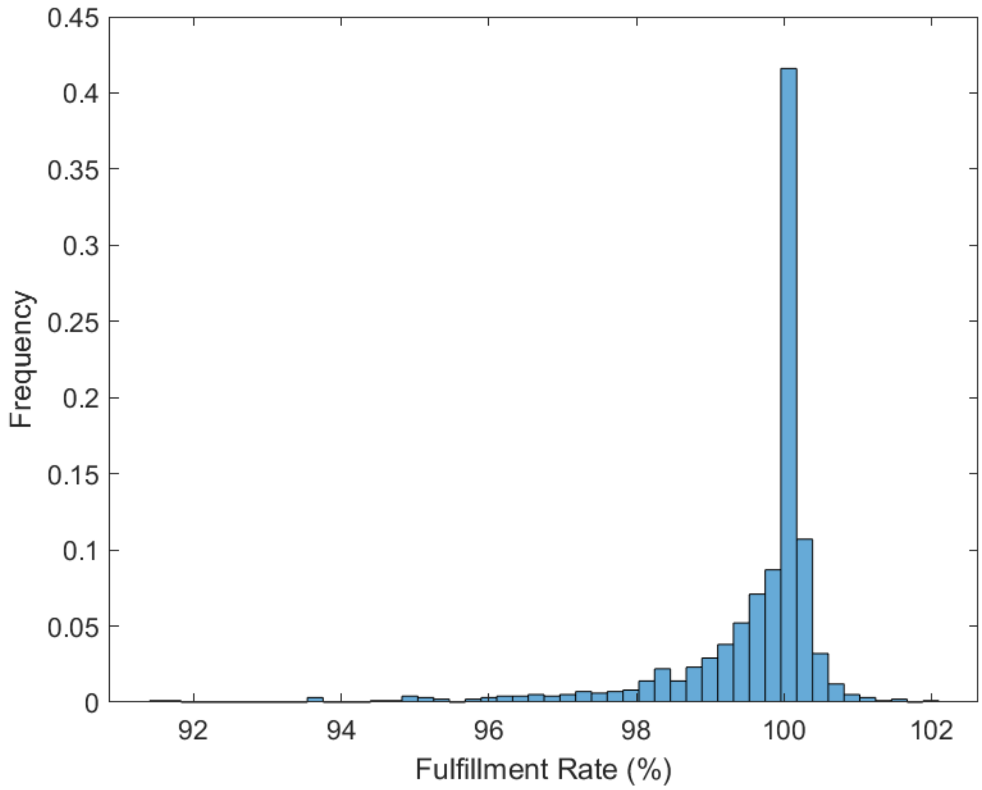



Figure 3.5: Histogram of Samsung Fulfillment

Sony Ericsson has a very interesting fulfillment distribution. As opposed to the previous histograms shown, the distribution shows that Sony Ericsson actually has demand fulfillment over 100% in the majority of the simulations. This trend also follows for HTC and Huawei. Multiple factors allow Sony Ericsson to fulfill demand. Sony Ericsson carries eight weeks of demand initially. The firm also only has one supplier in a unique industry. Therefore, Sony has enough initial on-hand inventory to survive a supplier disruption period of under eight weeks. If a supplier is still disrupted, unless that supplier is in a unique industry, other suppliers can produce more within that industry to fulfill the demand that supplier could not fulfill.

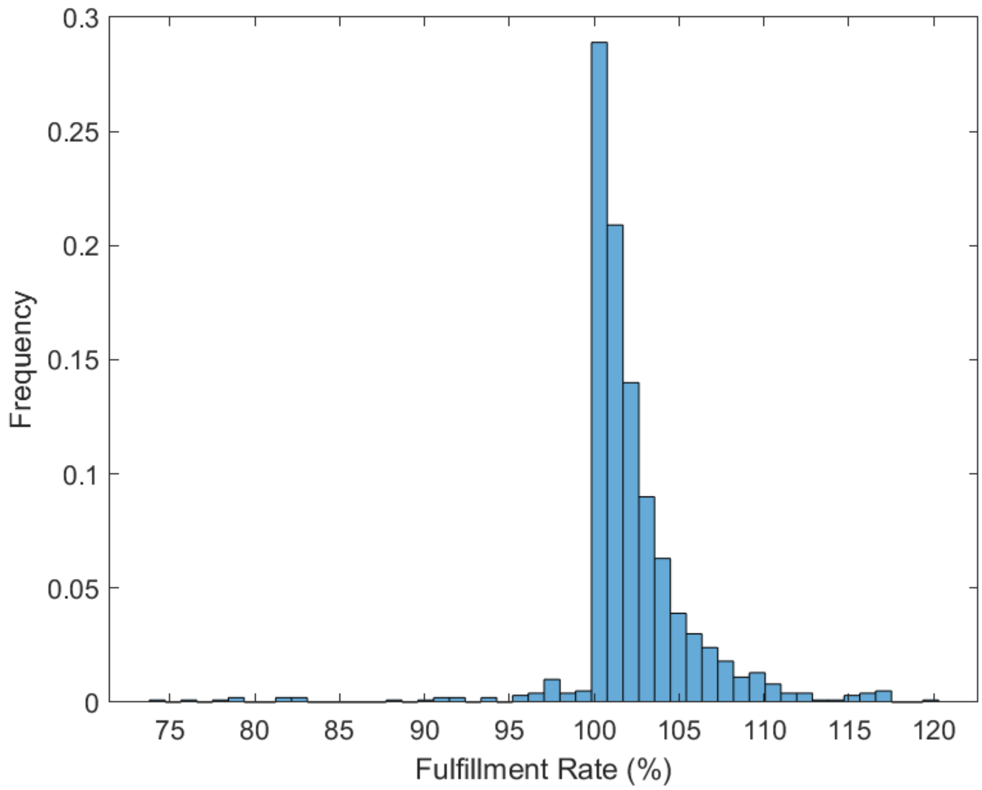



Figure 3.6: Histogram of Sony Ericsson Fulfillment Rate

Overall, the electronics firms perform well during the supply chain disruption with the exception of Apple. It is likely that most of the demand taken over the course of the simulation was demand Apple could not fulfill due to the firm’s significantly lower mean fulfillment rate. From observing this industry closely, firms are in a better situation to mitigate a severe disruption when more inventory is carried and there is increased competition within that industry.

From this section, multiple variables were determined as causes of failure to fulfill demand. Inventory levels must be sufficient to mitigate a severe supply chain disruption. Increased competition is a cause of differences in supply chain planning. Supplier disruptions appear minimal if disruption periods are small. Variability within fulfillment ratios is a result of low demand, and therefore, other metrics may tell a different story in terms of supply chain performance. The importance of these factors will be observed within the next portion of this paper.

# CHAPTER 4. SENSITIVITY ANALYSIS

Sensitivity analysis is conducted on different variables to understand how the variables impact the fulfillment rates within the firms. Throughout the chapter, the mean fulfillment rates of certain entities and industries are used as dependent variables. The effects examined include: the impact of the expected supplier facility closing period on a firm or industry, the impact of the supplier's cost of switching production to an alternate facility on a firm or industry, the effect of a firm increasing inventory, the effect of a firm closing period length on firm fulfillment, and α (the firm's desire to trade off between meeting demand and maximizing profit). The parameters have been adjusted for each iteration while keeping the parameters for the remaining firms constant.

## Supplier's Probability of Reopening

A supplier is defined in this paper as an entity who delivers products to other firms and do not sell to final consumers. A supplier can suffer supply chain disruptions either because its own facility is damaged and temporarily closed or because other entities are unable to deliver goods to that supplier. This section aims to understand how the expected number of days a supplier's facility reopens impacts the firm or the industry to fulfill their demand. The expected number of weeks the supplier's facility has been manipulated from values between one week and 100 weeks. The probability that a supplier's facility reopens in each week is the reciprocal of the expected number of weeks the facility is closed. Sensitivity analysis on the supplier's probability reopening is conducted for two suppliers: Toyota's primary supplier and Renesas, an automobile and electronic component supplier.

The primary supplier for Toyota only delivers product to Toyota, and its closure only impacts Toyota. Toyota also requires products from other suppliers in the model. Altering their supplier's expected number of weeks the facility will be closed from 0 to 100 weeks reveals Toyota's mean fulfillment rate decreases initially, and then increases with a gentle slope. This increase is likely a causality of the supplier choosing to move production to an alternate facility as the benefit of fulfilling demand for the supplier exceeds the cost of moving production to an alternate facility.

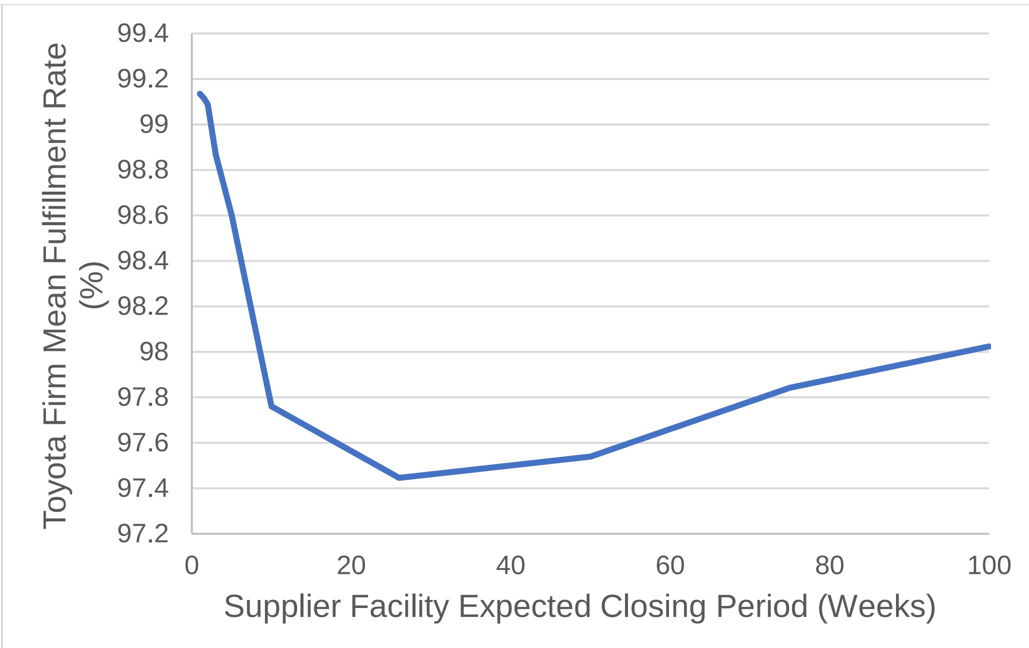



Figure 4.1: Toyota Supplier Closing Period on Firm Mean Fulfillment

Unlike the supplier for Toyota, Renesas produces electric components for each one of the automobile firms in the simulation. The effect of the expected length of time of the closing period for Renesas on the automobile industry is evaluated through evaluating the market fulfillment and the fulfillment rates of the respective automobile firms.

Figure 4.2 evaluates the effect of the expected length of time the Renesas facility is closed on the mean fulfillment rate on the automobile industry. As the expected time the facility will be closed increases, the automobile industry mean fulfillment rate initially decreases, and then increases slowly. The increase is likely a causality of Renesas choosing to move production to an alternate facility. The slope of the increase is likely decreasing due to Renesas choosing to move production sooner to an alternate facility.

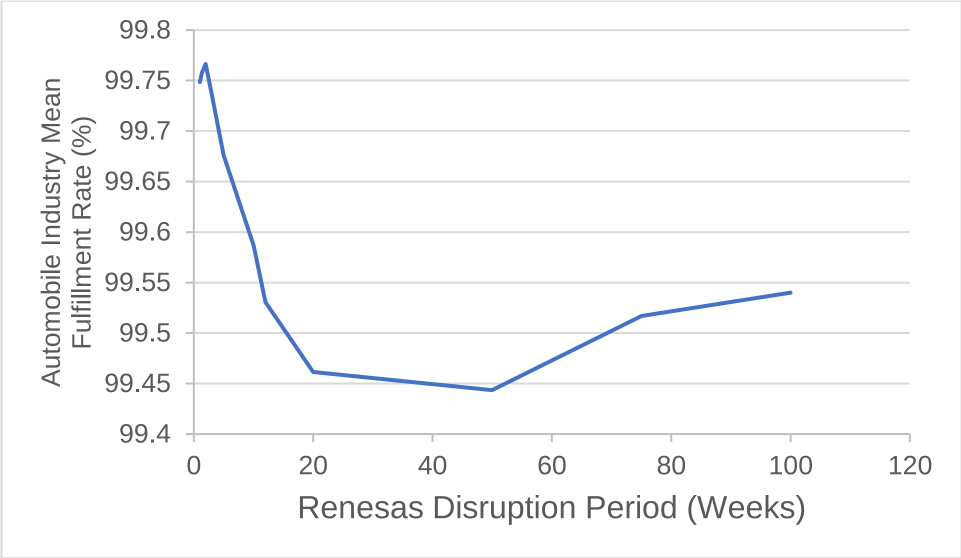



Figure 4.2: Renesas Closing Period on Automobile Industry Mean Fulfillment

Figure 4.3 examines the effects of the Renesas facility closing period on the individual automobile firms. Toyota and Honda experience the largest changes in mean fulfillment. The large changes are likely due to both firms containing more suppliers with large expected facility closing time periods. However, the plots show that although the overall industry trend is a decrease in fulfillment, some individual firms such as Isuzu and Nissan inverse to observe an increase in mean fulfillment, and then a slight decrease. The increase is due to the opportunity to fulfill demand firms such as Toyota and Honda could not fill. Once Toyota and Honda increase their mean fulfillment rates, the other firms can expect a decrease. The individual firms also seem to converge to a mean fulfillment rate, which is likely due to Renesas deciding to move production earlier to an alternative facility. Once production is moved to an alternate facility, the facility expected closing period is irrelevant.

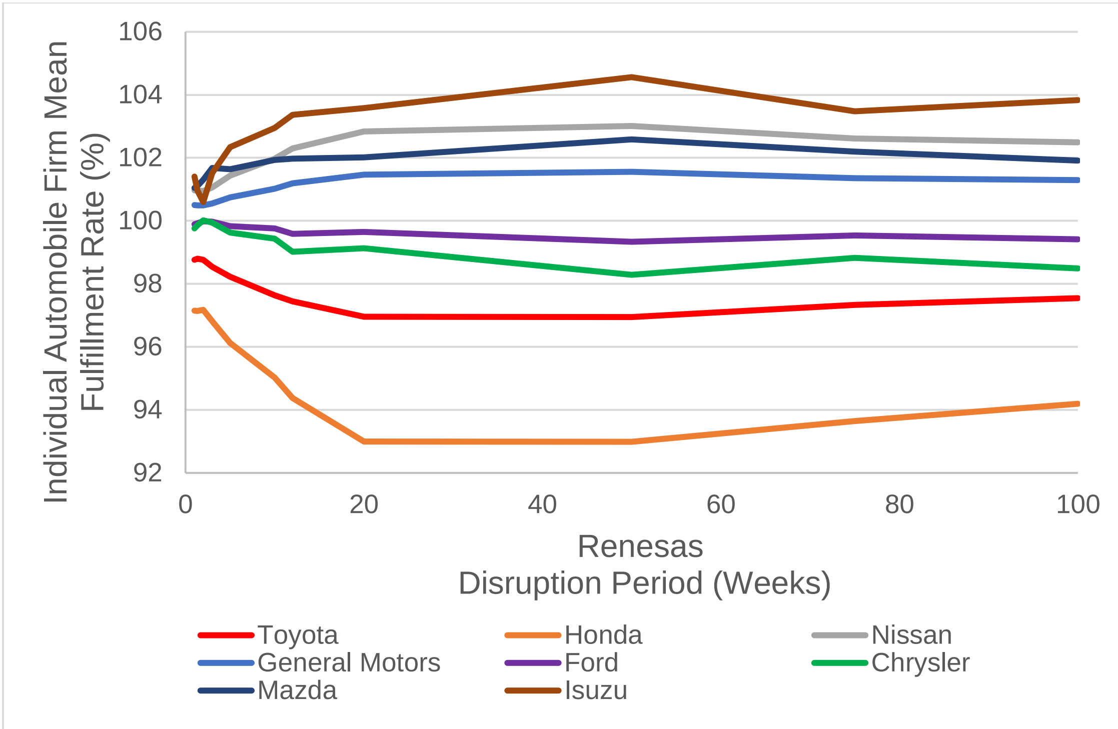



Figure 4.3: Renesas Closing Period Effect on Individual Automobile Firms

Overall, suppliers have a direct impact on the firm's ability to meet demand. The initial trend is a decrease in fulfillment as the disruption period ends, followed by an increase in fulfillment that converges to a final value due to the firm selecting from an alternate supplier outside the simulation. The increasing trend also contains a decreasing slope, converging to a final value due to an alternate supplier likely being selected early within the simulation.

**Cost of Switching**

The cost of switching refers to the fixed cost required for a supplier to move production to an alternative facility. Within the simulation, a supplier makes a decision about whether to move production based on minimizing its expected cost. The expected cost of moving production is the fixed cost of moving production to an alternate facility plus the expected cost of producing at the alternate facility. The expected cost of not moving production is the cost of producing at the primary facility once it reopens plus the expected cost of losing demand during the time the facility is closed. The cost of switching facilities is analyzed for two suppliers: a sole supplier for Honda and Merck who supplies chemicals used in paints to the automobile industry firms.

Figure 4.4 showcases the effect on Honda's mean fulfillment rate as a result of altering their direct supplier's cost of moving production. The plot indicates the cost of switching is merely a measurement of justification for the decision, and the point of indifference between moving production and keeping the facility closed is less than 100. When the cost exceeds 100, moving production to an alternate facility is not justifiable as the supplier's expected cost of moving production is larger than the cost of waiting for the facility to reopen.

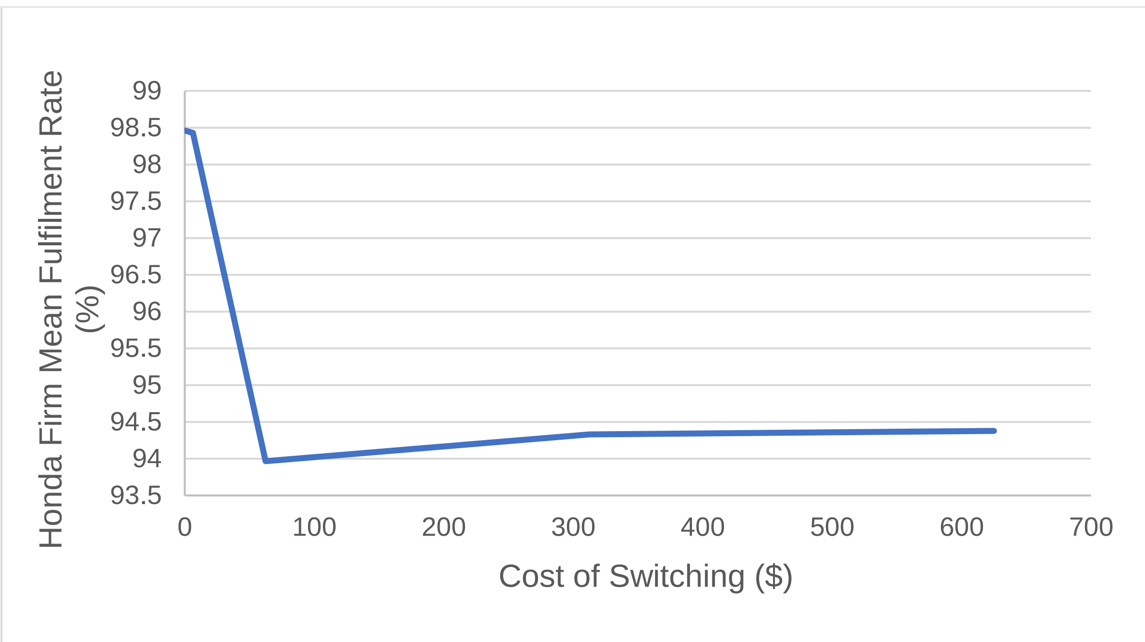



Figure 4.4: Effect of Supplier Cost on Honda Mean Fulfillment Rate

Figure 4.5 showcases the effect of the cost of moving production for Merck, an automotive supplier, to an alternate facility on the mean fulfillment rate of the entire automobile industry. The plot indicates a similar indifference point as the previous example, but the y-axis implies a small difference. The low points of indifference imply that firms do

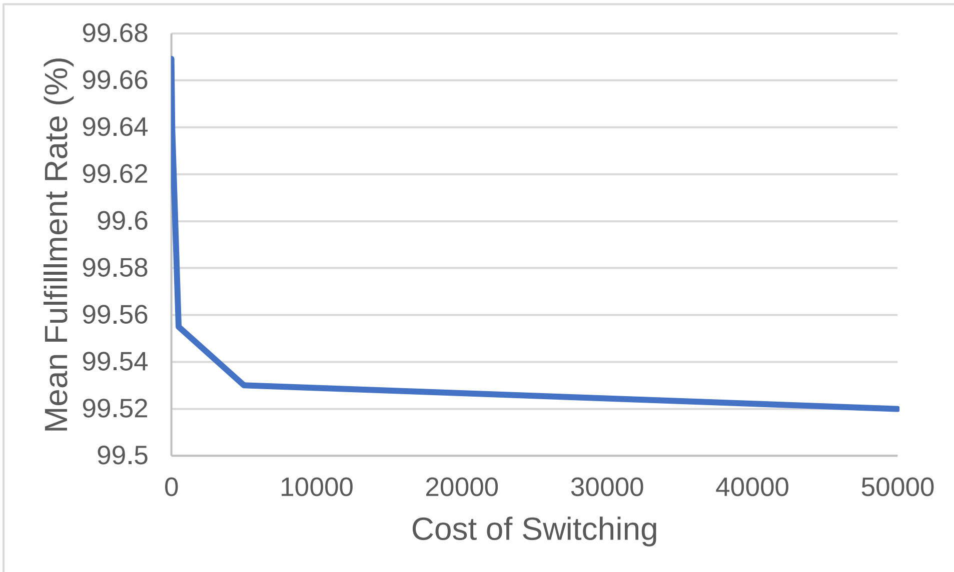



Figure 4.5: Effect of Merck Cost of Moving Production on Automobile Market

The cost to move production is a point of difference yielding plateau-like plots to the analysis. When the cost is minimal, moving production to an alternate facility is justifiable. However, when the cost is large, moving production is not justifiable. The cost containing a point of indifference reflects business behavior for firms aiming to reduce costs in global supply chains.

**Firm Inventory**

The amount of inventory a firm carries initially is manipulated while holding remaining parameters constant to evaluate the performance of the firm. The amount of inventory adjusted varies by the number of weeks of inventory the company carries to keep the comparisons at a quantifiable value per firm due to constant demand being assumed in the model. Apple and Honda inventory levels are impacted as firm parameters within this section.

Apple initially carried only two weeks of on-hand inventory, only fulfilling 82% of their demand on average. As inventory increased, Apple was significantly more likely to meet demand. Once Apple contains twelve weeks of inventory, a 100% mean fulfillment rate is expected. Twelve weeks offers a buffer over most simulations as the disruption period on average as the longest mean supplier facility closing period from Apple is twelve weeks. Therefore, the risk is mitigated during a large portion of simulations.

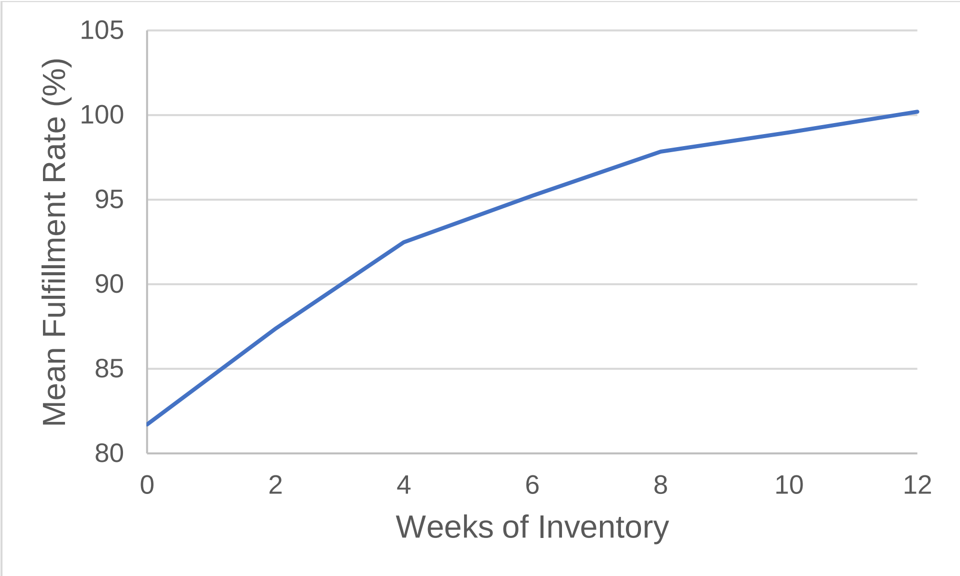



Figure 4.6: Effect of Apple Inventory on Firm Fulfillment

Honda had a similar sensitivity curve as Apple. From Figure 4.7, Honda should also carry twelve weeks of inventory to fulfill all demand on average. Both Apple and Honda share Renesas as a supplier, which is expected to be closed for twelve weeks on average. Therefore, Honda and Apple are able to use their inventory as a buffer for trials within more of the simulations, leading to a 100% mean fulfillment rate. Although Honda also has a unique supplier which is expected to be inoperable for 26 weeks, the supplier likely moved production to an alternate facility.


Figure 4.7: Effect of Honda Inventory on Firm Fulfillment

Overall, from the example firms, an increase in inventory increases the mean fulfillment rate due to its ability to be used as a buffer. However, the marginal benefit of carrying more inventory decreases significantly after more on-hand inventory is carried. While adding inventory is beneficial during a disruption, each firm must consider the marginal cost of adding more inventory, whether that involves a larger capacity, or a larger inventory holding cost.

**Firm's Probability of Reopening**

Although most entities whose facilities are closed because of the disruptive event are suppliers, a few firms who deliver directly to final consumers also experience facilities that are temporarily closed. When a firm's facility closes, the length of time it takes for a facility to reopen may impact their strategy on a corporate level. Analyzing how the expected length of time a facility is closed impacts the firm's ability to satisfy demand is important.

This type of sensitivity analysis was completed on the likelihood Mazda will reopen. The time frame ranged from one week to 100 weeks. As seen in Figure 4.8, if the firm facility closing period is shorter on average, the firm is more likely to meet demand. Since the cost of moving production to an alternate facility for Mazda is large, Mazda cannot justify moving production and therefore, the fulfillment rate continues to decrease. The firm is more sensitive to its own facility being closed rather than a supplier's facility since a firm can decide to purchase from an alternate supplier.

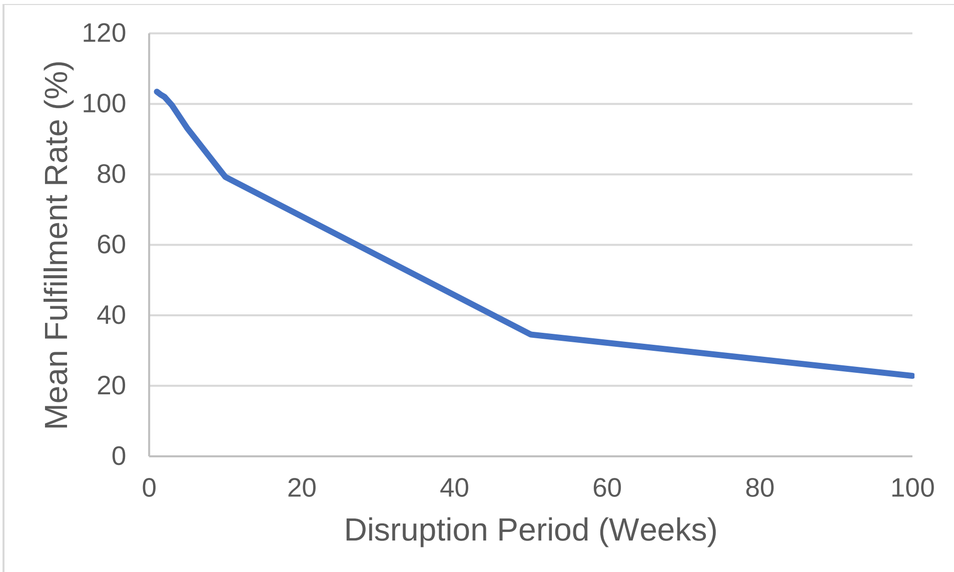



Figure 4.8: Mazda Disruption Period Length Sensitivity Analysis

**Trade-off Between Meeting Demand and Maximizing Profit**

The α parameter is a tradeoff parameter which determines whether meeting demand or maximizing cost is more important. When $\alpha = 0$, the firm's only objective is to maximize its profit in the current period. When $\alpha = \infty$, the firm's only objective is to satisfy demand in the current period; however, from a practical point of view, firms are incentivized to satisfy for $\geq 1$ because satisfying demand in the short term can lead to better customer relationships which enable long-term profit. The parameter is held constant for all firms within the regular model at 0.1. The sensitivity analysis adjusts the parameter for all firms from values between 0.0001 and 1.

Figure 4.9 describes the effect of the mean fulfillment rate for industries which sell to final consumers (automobiles, electronics, gaming, and camera industries) when altering the parameter. The mean fulfillment rate tends to converge to a 100% mean fulfillment rate with the exception of the camera industry, indicating the viability of fulfilling demand when cost is a negligible issue. The reason why the camera industry does not converge to 100% is due to all three firms being closed initially in the simulation. Therefore, the industry cannot fully meet 100% demand.

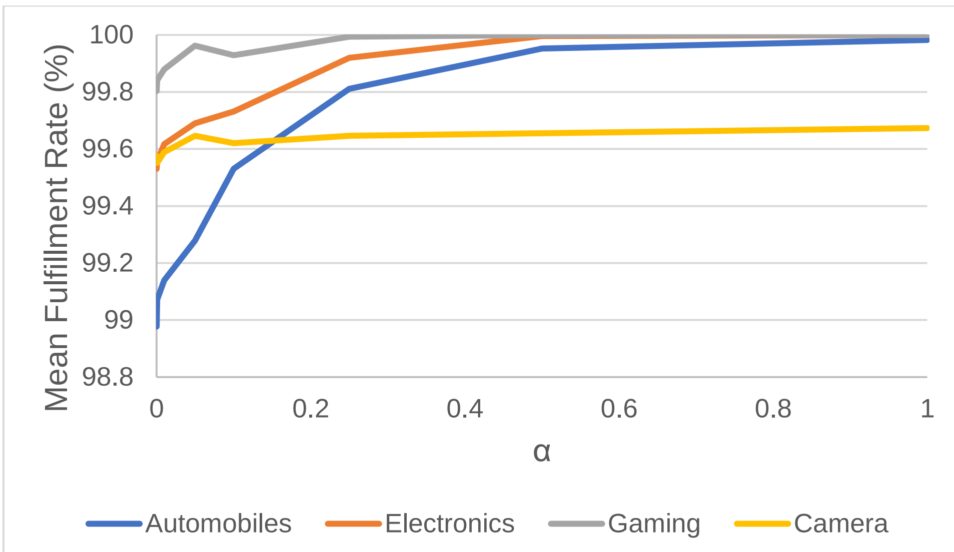
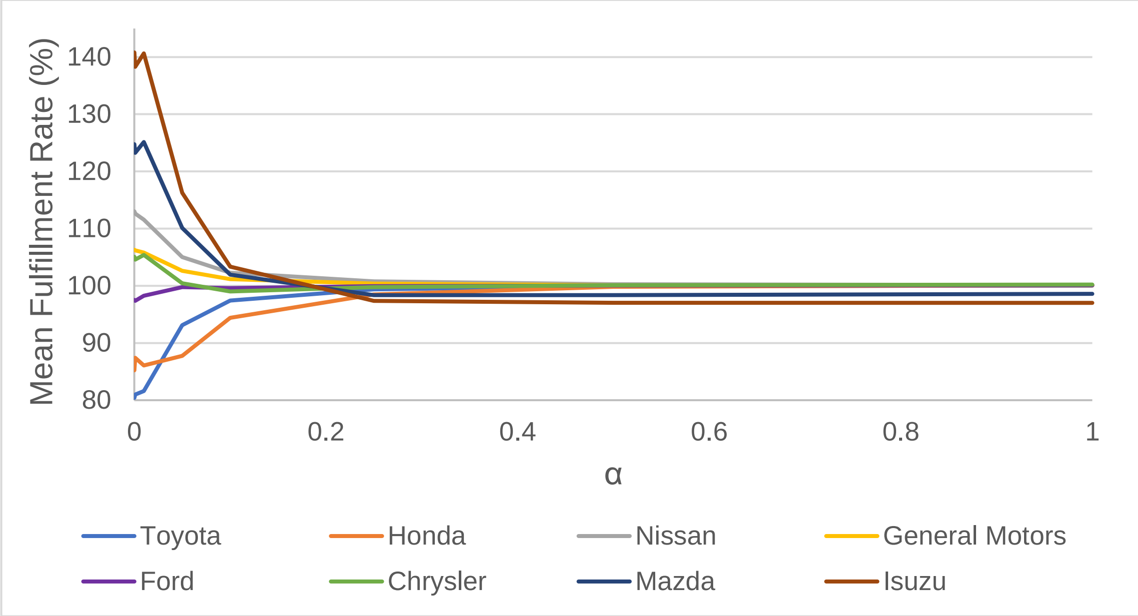



Figure 4.9: Effect of α on Final Consumer Industries

Figure 4.10 showcases the effect of the parameter on individual automobile firms. When α is small, firms have the ability to take demand from other firms. Firms such as Toyota and Honda are hurt the most because their direct suppliers have long closing periods. A low α parameter value fails to allow these firms the means to mitigate the ability to justify decisions to select alternate suppliers or their suppliers to move production to an alternate facility. This allows well-performing firms to fulfill demand poor-performing firms cannot.

When α is large, competition is minimized due to firms and their suppliers making decisions for the sole purpose of satisfying demand. Firms such as Honda and Toyota are now able to purchase from alternate suppliers and their suppliers can move production to alternate facilities, increasing the mean fulfillment rate. Mazda and Isuzu are the only firms which failed to achieve a 100% mean fulfillment rates. These two firms are also the only automobile firms initially closed within the simulation. Therefore, initially closed firms have difficulty to fulfill 100% demand. Even though Mazda and Isuzu have a lower mean fulfillment rate with a large α parameter, the demand of those firms is much less than the other firms in the industry. Therefore, the other firms still have mean fulfillment rates around 100% as there is little demand to steal.




s

Figure 4.10: Effect of α on Individual Automobile Firms

Figure 4.11 depicts the effect of α within the camera firms. Panasonic and Canon have negligible effects. The general trend of Nikon increasing its fulfillment rate is a result of the parameter's ability to focus on production. Since Nikon was capable of producing previously, the parameter allows Nikon to produce more. Once Canon is able to fulfill more of their demand as α increases, Nikon has fewer opportunities to steal. Canon's facility is expected to be closed for six weeks. Therefore, a 100% mean fulfillment rate is difficult to achieve as the high cost of moving production makes it difficult to fulfill demand. Nikon and Panasonic both have expected three-week closures. The differences in expected closing periods enable Nikon to steal demand more consistently from Canon.

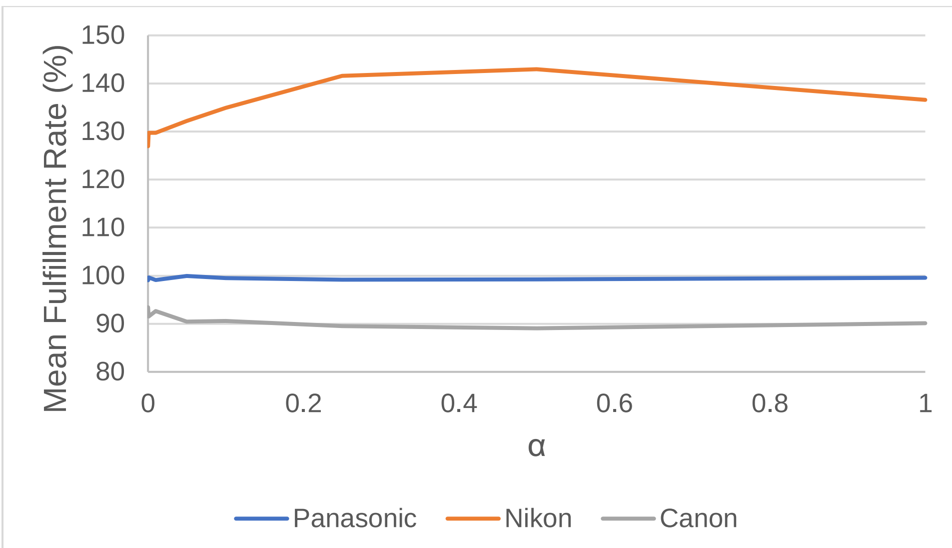



Figure 4.11: Effect of α on Individual Camera Firms

Overall, the α parameter is the most sensitive parameter to the results. This parameter drives the justification behind decisions firms make to satisfy demand, whether to purchase goods from an alternative, or to move production to an alternate facility. When the parameter is low, firms are not incentivized to make decisions to fulfill more demand to maximize profit. This causes firms within an industry to not fulfill demand, but also for well-performing firms to steal demand from poor-performing firms. Additionally, parameters altered at the firm level impact the firm more than supplier parameters as firms can make decisions to purchase from alternate suppliers and use existing inventory. Closed facility reopening at the firm level only impact the ability to fulfill demand if the cost of moving production to an alternate facility is too large. The cost of moving production to an alternate facility is the least sensitive parameter as the cost must only be lower than the cost of waiting for the facility to reopen to justify the decision.

# CHAPTER 5. CONCLUSION

The 2011 Japanese tsunami showed many firms how disasters can directly impact supply chain operations on a global scale in today's age. The simulation aims to showcase how certain variables impact the firms' ability to meet demand. The industries perform well as a whole as all industries fulfilled at least 98% of their demand on average. The excellent performance is due to individual firms fulfilling demand other firms cannot, and the fulfillment rate captures backlogged demand, allowing industries that do not sell to final consumers to have a mean fulfillment rate of over 100%.

Within the simulation, the α parameter is set equal to 0.1, indicating that firms care more about maximizing profit than fulfilling demand. Therefore, entities are less likely to justify moving production to alternate facilities or purchase from alternate suppliers. Therefore, firms such as Apple, Toyota, and Honda perform poorly within their respective industries as their suppliers have long facility closing periods.

Firms which carry larger amounts of inventory perform better than firms which carried small amounts of inventory due to its role as a buffer within supply chain disruption periods. As shown through the sensitivity analysis, inventory acts as a buffer when suppliers have closed facilities. When Apple carries twelve weeks of inventory, the firm achieves a 100% mean fulfillment rate as their unique suppliers have a maximum expected closing period of twelve weeks, enabling Apple to carry enough inventory to mitigate the disruption through most trials. The variability of the closing period causes Apple to not fulfill 100% of their demand in a small number of trials within the simulation.

The α parameter was the most sensitive variable as the parameter dictate the decisions firms make to justify supply chain disruption management strategies. When α is large, entities prefer to prefer to fulfill demand, causing entities to mitigate their risks through selecting alternate suppliers and move production to alternate facilities. When α is small, firms prefer to maximize profit, therefore increasing competition between firms within industries due to well-performing taking demand from poor-performing firms.

Firm parameters directly impact the firm more than supplier parameters due to firms having the option to make more decisions with respects to the suppliers. Firms can select a supplier when the supplier facility is closed, but a firm can only move production to an alternate facility if their own facility is disrupted. As α is equal to 0.1, firms have difficulty justifying moving production, causing firm closing period lengths and inventory to have large impacts on firm capabilities to meet demand.

Overall, firms that perform well within supply chain disruption periods contain less unique suppliers, carry more inventory, and prefer fulfilling demand over maximizing profit. However, these strategies come at a cost to the firm. To advance the model, assuming constant demand over each period should be relaxed as well as cost. These relaxations would allow the simulation to provide increased realistic outputs with increased variability in decisions made throughout each trial within the simulation. Additionally, carrying inventory is also expensive and should be factored into decision-making processes, and warehousing facilities can also be added to increase the complexity of the model. While this model does provide opportunities to explore risk mitigation techniques in a severe supply chain disruption, there are more uncertainties not being reflected within the simulation that will improve the decision making processes within the simulation.

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## APPENDIX A. [MODEL EXPLANATION AND DATA]

The model in this paper is based on MacKenzie et al. (2014) and contains the same elements and decision-making processes. A supply chain contains $N$ entities. Some entities receive no supplies from any other entities; some entities receive supplies from other entities and supplies product to other entities; and some entities receive supplies from other entities and sell finished goods to final consumers. Figure A.1 outlines the decision-making framework and the relationships between entities in this supply chain.

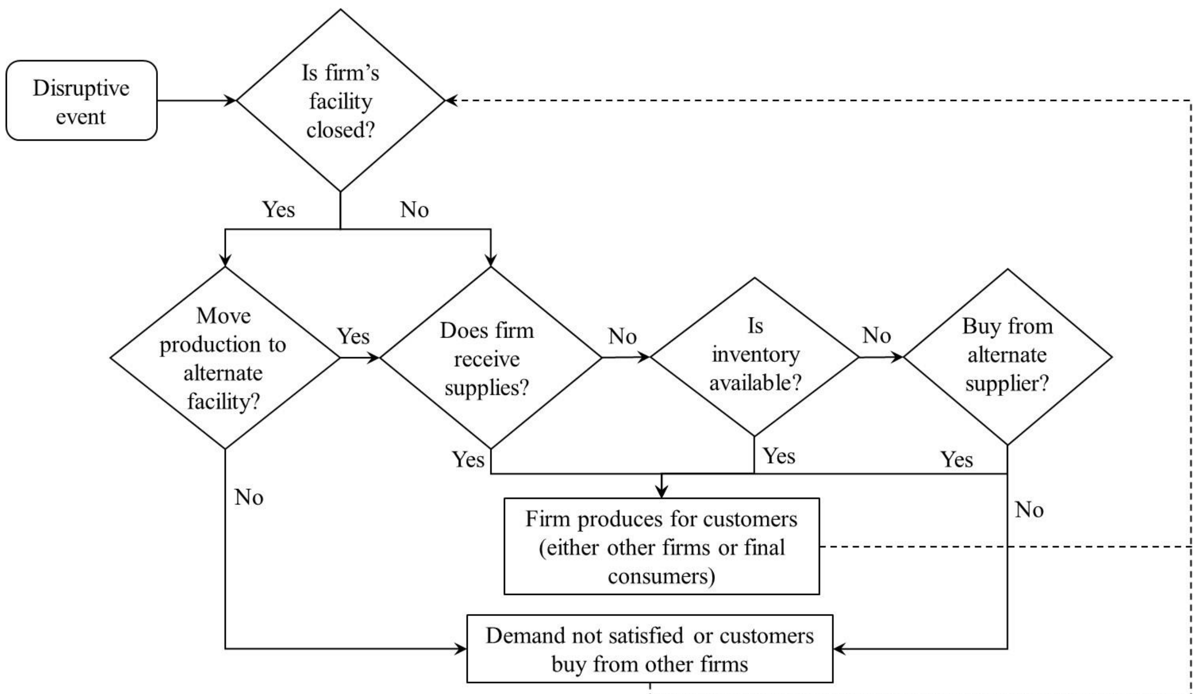


Figure A.1. Decision-making Framework for Supply Chain Disruption Simulation

The disruption begins when an event disrupts the facilities of $M$ entities in the supply chain where $M \leq N$. These facilities are temporarily closed. Facility $m = 1,2, \ldots, M$ has a $p_m$ probability of reopening in each period following the disruptive event. An entity with a closed facility may choose to move production to an alternate facility each period. If the entity moves production to an alternate facility, the entity will incur a fixed cost of moving production but the entity will be able to produce as if it was not disrupted. If an entity does not move production during the period, the entity will not be able to produce. Consequently, that entity may lose demand if the entity's customers choose to purchase those products from alternative suppliers. An entity will choose to move production to an alternate facility if the expected cost of moving production is less than the expected cost of not moving production, which includes the cost of losing demand.

If an entity chooses not to move production, each entity that usually receives product from that entity must deal with the lack of supplies. Assuming that the latter entity's facility is open, the entity may have a few alternatives available to it. First, if the entity has supply inventory, the model assumes the entity will use whatever supply inventory it has in order fill the loss in supply. If the entity does not have supply inventory, the entity can choose to purchase from an alternate supplier. The model assumes that the alternate supplier is exogenous to the model and is always at least as costly as the primary supplier who is not producing. The entity decides how much to produce in a period based on two objectives: maximize its profit and meet customer demand in the current period. If no disruption occurs, meeting customer demand and maximizing profit will result in the same production. If a disruption occurs and a firm's supplier is not able to produce, the firm will need to purchase from an alternate supplier. Since the alternate supplier costs more than the primary supplier, the firm will need to sacrifice profit it wants to meet customer demand. A parameter $\alpha$ enables the firm to trade off between maximizing profit and meeting demand. If $\alpha = 0$, the firm will focus exclusively on maximzing its profit. If $\alpha = \infty$, the firm will focus exclusively on meeting customer demand in the current period.

If a firm does not produce as much as it normally does in the current period, the firm's customers may either purchase from the firm's competitors or some demand is not satisfied in the current period. Any demand not satisfied in the current period is added to the demand in the subsequent period. Since firm's can sell to customers who normally purchase from the firm's competitors, firms may be able to increase their market share during a disruption.

At the end of each period, every entity's facility who is closed may reopen. Each facility has a probability of reopening at the end of the period, and this probability remains constant over time. Different facilities have different probabilities of reopening. If the facility reopens, the entity can produce as it was producing before the disruption began. The disruption ends when all of the facilities that have been closed reopen.

## Data Sources

Data is collected to represent the 2011 Japanese earthquake and tsunami. The primary set of data sources comes from news articles in the weeks and months following the Japanese tsunami. A search on Lexis Academic produces more than 1,000 news articles on companies impacted by the Japanese tsunami. Some companies were directly impacted by having facilities that were destroyed or damaged by the tsunami. Other companies were indirectly impacted because they might not have operated any facilities closed by the tsunami, but their suppliers or suppliers' suppliers operated facilities that were closed by the tsunami. Thus, those companies suffered supply shortages.

The review of news articles enables us to identify and include 63 entities in the simulation of the supply chain disruption. Although more than 63 companies were directly or indirectly impacted by the Japanese tsunami, including 63 entities in the simulation provides a reasonable picture of the complexity in modern supply chains and how the complex nature of supply chains exacerbated the impacts of the disruption caused by the supply chain. The news articles provide a way to estimate some of the numbers required for the model of the supply chain disruption. Google searches were conducted in order to obtain the relationships between suppliers and firms and to understand which firms sell to other firms. If the Google search brought up results that seemed to indicate that one company sells to another company, then the model connects them so that one of them supplies product to another. Since data were not available for many parameters, we estimate many parameters by assigning values that were reasonable. For example, the cost of the alternative supplier is always twice as much as the cost of the primary supplier.

Fifty-three entities are divided into eight different markets. The market is important because an entity is able to capture demand from another entity if both entities are in the same market. Ten entities did not fit into a market although these entities play an important role in providing supplies to other markets.

| **Industry** | **Firm** | **Facility closed?** | **Suppliers** | **Customers** |
|---|---|---|---|---|
| Auto-mobile | Toyota | No | Toyota supplier, Renesas, Merck, Hitachi, Freescale, Kuraray | Final consumers |
| | Honda | No | Honda supplier, Renesas, Merck, Hitachi, Freescale, Qualcomm | Final consumers |
| | Nissan | No | Nissan supplier, Renesas, Merck, Hitachi, Freescale, Qualcomm | Final consumers |
| | General Motors | No | Renesas, Merck, Mitsui Chemicals, Hitachi, Freescale, Maruzen Petrochemicals, Nippon Peroxide | Final consumers |
| | Ford | No | Renesas, Merck, Mitsubishi Chemicals, Teijin DuPont, Mitsui Chemicals, Hitachi, Texas Instruments, Adeki-Fuji, Qualcomm | Final consumers |
| | Chrysler | No | Renesas, Merck, Mitsubishi Chemicals, Toray, Mitsui Chemicals, Hitachi, Freescale, Texas Instruments, Nippon-Peroxide, Qualcomm | Final consumers |
| | Mazda | Yes | Renesas, Merck, Hitachi, Freescale, Nippon Peroxide | Final consumers |
| | Isuzu | Yes | Renesas, Merck, Freescale | Final consumers |
| Elec-tronics | Apple | No | Renesas, Samsung supplier, Hynix, China Foxconn, TSMC, Kureha PVD, Asahi Glass, Asahi Kasei, Sumitomo, Teijin DuPont, Toshiba NAND, Texas Instruments, Elpida, Adeki-Fuji, ON Semiconductor, Qualcomm, Applied Materials | Final consumers |
| | Sony Ericsson | No | Renesas, Samsung supplier, Fujistu, TSMC, Texas Instruments, Elpida, ON Semiconductor, Qualcomm | Final consumers |
| | Nokia | No | TSMC, Asahi Glass, Anritsu, Sony Sendai, | Final consumers |

| | | | | |
|---|---|---|---|---|
| | | | Freescale, Texas Instruments, ON Semiconductor, Qualcomm | |
| | HTC | No | Asahi Glass, Qualcomm | Final consumers |
| | Huawei | No | TSMC, Asahi Glass, Rudolph Technologies, Anritsu, Freescale, Qualcomm | Final consumers |
| | Samsung | No | Renesas, Fujitsu, Asahi Glass, Asahi Kasei, Sumitomo, Anritsu, Freescale, Texas Instruments, Maxim Integrated, Qualcomm, Applied Materials | Final consumers |
| Gaming | Sony Playstation | No | Renesas, Fujitsu, TSMC, Texas Instruments, Elpida, ON Semiconductor, Qulacomm | Final consumers |
| | Nintendo | No | Fujitsu, TSMC, Hitachi, Freescale, Texas Instruments, ON Semiconductor, Qualcomm | Final consumers |
| | Sega | No | TSMC, Freescale, Texas Instruments, Qualcomm | Final consumers |
| Camera | Panasonic | Yes | Renesas, Elpida, ON Semiconductor, Advantest Corp, Applied Materials | Final consumers |
| | Nikon Group | Yes | Renesas, Toshiba NAND, Sony Sendai | Final consumers |
| | Canon | Yes | Rensas, ON Semiconductor | Final consumers |
| Semi-conductor manu-facturing | Samsung supplier | Yes | Shin Etsu, Toray, Mitsui Chemicals, Nippon Peroxide, JSR Corp, MEMC | Apple, Sony Ericsson, Qualcomm |
| | Hynix | No | | Apple |
| | Fujitsu | Yes | Mistubishi Chemicals, Rudolph Technologies, Teijin DuPont, Toray, Applied Materials | Sony Ericsson, Sony Playstation, Samsung, Texas Instruments, Nintendo |
| | TSMC | No | Shin Etsu, Rudolph Technologies, Tokyo Electron, SUMCO, Adeki-Fuji, JSR Corp, MEMC | Renesas, Apple, Sony Ericsson, Nokia, Huawei, Sony Playstation, Texas Instruments, Nintendo, Sega |
| | Toshiba NAND | Yes | Shin Etsu, Rudolph Technologies, SUMCO, | Apple, Nikon Group |

| | | | | |
|---|---|---|---|---|
| | | | Adeki-Fuji, Amkor Technology | |
| | SUMCO | No | | TSMC, Toshiba NAND |
| | Freescale | Yes | Advantest Corp, Kyocera | Toyota, Honda, Nissan, General Motors, Ford, Chrysler, Mazda, Isuzu, Nokia, Huawei, Samsung, Nintendo, Sega |
| | Elpida | Yes | | Apple, Sony Ericsson, Sony Playstation, Hitachi, Panasonic |
| | ON Semiconductor | No | Amkor Technology | Apple, Sony Ericsson, Nokia, Sony Playstation, Nintendo, Panasonic, Canon |
| | MEMC | Yes | Nippon Peroxide | Samsung supplier, TSMC, Texas Instruments |
| Telecom-munications equipment | Rudolph Technologies | Yes | | Fujitsu, Huawei, TSMC, Toshiba NAND, Texas Instruments |
| | Anritsu | Yes | | Nokia, Huawei, Samsung |
| | Hitachi | Yes | Renesas, Elpida, Maxim Integrated, Rohm Co | Toyota, Honda, Nissan, General Motors, Ford, Chrysler, Mazda, Nintendo |
| | Texas Instruments | Yes | Renesas, Fujitsu, TSMC, Rudolph Technologies, Amkor Technology, Applied Materials, MEMC, Kyocera | Ford, Chrysler, Apple, Sony Ericsson, Sony Playstation, Samsung, Nokia, Nintendo, Sega, Maxim Integrated |
| | Maxim Integrated | No | Texas Instruments, Adeki-Fuji | Samsung, Hitachi |
| | Qualcomm | Yes | Samsung supplier, Mitsubishi Chemical, Amkor Technology | Toyota, Honda, Nissan, Ford, Chrysler, Apple, Sony Ericsson, Nokia, HTC, Huawei, Sony Playstation, Samsung, Nintendo, Sega, Kyocera |
| | Rohm Co | Yes | | Honda supplier, Nissan supplier, Hitachi |
| | Kyocera | Yes | Qualcomm | Freescale, Texas Instruments |
| Semi-conductor equipment and testing | Advantest Corp | Yes | | Renesas, Freescale, Panasonic |
| | Amkor Technology | Yes | | Toshiba NAND, Sony Sendai, Texas Instruments, ON Semiconductor, Qualcomm |

| | | | | |
|---|---|---|---|---|
| | Applied Materials | Yes | | Apple, Fujitsu, Samsung, Texas Instruments, Panasonic |
| Chemical | Shin Etsu | Yes | | Toyota supplier, Honda supplier, Nissan supplier, Samsung supplier, TSMC, Toshiba NAND |
| | Mitsubishi Chemical | Yes | | Toyota supplier, Renesas, Ford, Chrysler, Fujitsu, Asahi Glass, Qualcomm |
| | Asahi Kasei | Yes | | Renesas, Apple, Samsung |
| | Sumitomo | Yes | | Apple, Samsung |
| | Teijin DuPont | Yes | | Toyota supplier, Honda supplier, Nissan supplier, Ford, Apple, Fujitsu |
| | Toray | Yes | | Toyota supplier, Honda supplier, Chrysler, Samsung supplier, Fujitsu, Sony Sendai |
| | Mitsui Chemicals | Yes | | Toyota supplier, General Motors, Ford, Chrysler, Samsung supplier |
| | Maruzen Petrochemicals | Yes | | Toyota supplier, Honda supplier, General Motors |
| | Kuraray | Yes | | Toyota supplier |
| | Adeki-Fuji | No | | Honda supplier, Ford, TSMC, Toshiba NAND, Maxim Integrated, JSR Corp |
| | Nippon Peroxide | No | | General Motors, Chrysler, Mazda, Samsung supplier, MEMC |
| | JSR Corp | Yes | Adeki-Fuji | Honda supplier, Samsung supplier, TSMC |
| No industry group | Toyota supplier | Yes | Shin Etsu, Mitsubishi Chemical, Teijin Dupont, Toray, Maruzen Petrochemicals, Qualcomm | Toyota |
| | Honda supplier | Yes | Shin Etsu, Teijin DuPont, Toray, Maruzen Petrochemicals, Adeki-Fuji, Rohm Co, JSR Corp | Honda |
| | Nissan supplier | Yes | Shin Etsu, Teijin DuPont, Rohm Co | Nissan |
| | Renesas | Yes | TSMC, Mitsubishi Chemical, Asahi Kasei, Advantest Corp | Toyota, Honda, Nissan, General Motors, Ford, Chrysler, Mazda, Isuzu, Apple, Sony Ericsson, Sony Playstation, |

| | | | | |
|---|---|---|---|---|
| | | | | Samsung, Hitachi, Texas Instruments, Panasonic, Nikon Group, Cannon |
| | Merck | Yes | | Toyota, Honda, Nissan, General Motors, Ford, Chrysler, Mazda, Isuzu |
| | Tokyo Electron | Yes | | TSMC |
| | Sony Sendai | Yes | Toray, Amkor Technology | Nokia, Nikon Group |
| | China Foxconn | No | | Apple |
| | Kureha PVD | Yes | | Apple |
| | Asahi Glass | Yes | Mistubishi Chemical | Apple, Nokia, HTC, Huawei, Samsung |