ABSTRACT

Title of Thesis: RESILIENCE ASSESSMENT OF SUPPLY-CHAIN NETWORK INFRASTRUCTURE

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This thesis proposes a discrete event simulation model to investigate the complex interactions among supply chain components and infrastructure (1) under normal conditions when the facility can maintain the continuity of its performance under uncertainty and (2) under disruption scenarios. The model shows the flow of the risk in the supply chain. A special focus is given to risks from both (1) the reliability of infrastructure affecting materials necessary to produce a final product and (2) failures of infrastructure that support the transportation of materials. Bayesian network provides necessary models to analyze the different types of infrastructure supporting the supply chain, including dependencies, in simplified terms. This thesis provides a quantitative assessment of supply chain resilience to characterize the impact of events that threaten supply chains due to uncertainty in infrastructure performance, including potential infrastructure failures. Results were used to demonstrate the development of mitigation plans to reduce the impact of infrastructure disruption on the supply chain to overcome the possible risks associated with infrastructure failure.

RESILIENCE ASSESSMENT OF SUPPLY CHAIN NETWORK INFRASTRUCTURE

by

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Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

Supply chain disruption due to the failure of infrastructure is a significant problem for supply chains world-wide (FEMA 2017 and Fuller 2011). The global interconnected nature of supply chains amplify the consequences of any possible disruption (Goldberg 2020). It is an inevitable reality that decision-makers must consider and address. Most of the literature reviewed focused on analyzing the performance of a facility under a disrupted infrastructure state, where the facility is incapable of performing its primary goal of satisfying the customers in the right place and at the right time.

This work is aiming to achieve an adequate understanding of the complex interaction between supply chain components and supporting infrastructure – under disruptive conditions and additionally under normal conditions when the facility can maintain the continuity of its performance, albeit with uncertainty. This uncertainty depends on the infrastructure reliability, which affects the number of materials that can be processed to a final product. Bayesian network analysis is performed to model the dependencies of the different infrastructure types that support the supply chain. Discrete Event Simulation (DES) is used to analyze supply chain performance and to characterize the risk that threatens supply chains due to the failure of infrastructure by focusing on quantifying the impact of the disturbance.

1.1 Background

Hurricanes Harvey, Irma, and Maria caused around $265 billion damage to the United States economy during the 2017 hurricane season (FEMA 2017). Failure of supply chains in various sectors caused that huge economic loss. Some supply chains have not recovered yet after Hurricane Maria (FEMA 2017). Failure of supply chains plays a fundamental role in world economies (Fuller 2011). Therefore, it is important to assure the continuity of supply chain performance. A disruption to the supply chain can lead to enormous economic losses. Natural disasters are one of the primary causes of supply chain disruption (Industry Star 2018). For the purposes of this thesis, the focus of disruption will be due to the occurrence of unpredictable events such as natural disasters. that negatively impacts people and society besides the supply chain performance (Madu and Kuei 2017).

Boeing Center (2017) indicated that 25% of the oil refiners in the United States were closed by the end of August after Hurricane Katrina hit the Gulf Cost of the United States, which caused massive disruption to the gasoline supply chain in the Southeast and the Midwest, thereby creating a rise in gas prices.

Supply chains are vulnerable to natural disasters, such as earthquakes and hurricanes, due primarily infrastructure damage. The destructive flooding and high winds that accompany hurricanes often cause closure of ports, power outages, closed roads, water shortages, and communication loss. Disruptions propagate through the supply chains causing harm to some physical parts of the supply chain and a lot of chaos to the flow of materials and information. The delivery of raw materials or final products can be delayed, and manufacturing processing required to turn the raw materials into a good or service can be halted for a while. The consequences of damage to the supply chain reach beyond the local origin of a given supply chain. Infrastructure damage sustained during hurricanes Katrina and Harvey serve as good examples of how damage to infrastructure can affect supply chain performance regardless of the distance between the point of the disaster and the supply chain. Some airports managed to resume operations in a very short time, but around 1,000 flights over a day or two were delayed. Other airports were disrupted for weeks. Ports were highly impacted by the hurricane. Port Arthur was completely flooded. Some railways and highways were shut down halting many deliveries for FedEx, and USPS.

Fuller (2011) mentioned that several floods happened in Thailand in 2011 that caused significant damage to the offices of Western Digital -- one of the pioneer companies in hard drive production. It provides around 25% of the world's computer hard drives. It took the company approximately a year to recover and reach normal levels of production. During that year, customers from all over the world noticed around a 10 percent increase in the price of hard drives.

Hochfelder (2017) published statistics from the Business Continuity Institute (BCI-Zurich) on disasters around the world in 2016: the Japanese earthquake, Canadian wildfires, hurricanes in Europe, and Hurricane Matthew in the US:

- 8%   Productivity loss
- 53% Increase in cost of working
- 38% Reputation or image damage
- 37% Loss of revenue

The magnitude of these consequences of natural disasters are unpredictable ahead of time. These unknown risks that threaten the supply chain make the supply chain more vulnerable (Christopher and Peck 2004) to disruption. Therefore, it is necessary to focus on increasing the resilience of the supply chain in addition to increasing its efficiency in order to minimize the impact of any possible risk that may impact any part of the supply chain. Resilience is the ability to withstand a potential disruption with minimal effects. A resilient supply chain can withstand those unseen disruption, or the consequences that follow on supply chain performance and recover quickly in a short period. A design plan in case of emergencies should be prepared to mitigate the risk and the consequences (Barroso et al. 2015). Other researchers believe supply chain design plays an pivotal role in supply chain resilience. Pettit et al. (2010) indicate that increasing the capability of the supply chain will enhance its resilience and decrease its vulnerability. The supply chain must be designed with a high readiness to face any disruption in an effective way to recover to its previous state before the disruption or to a better state (Ponomarov and Holcomb 2009).

1.2 Objective

The goal of the research is to develop a methodology for the resilience assessment for supply chain network infrastructure, to examine the role of infrastructure reliability on the performance and the resilience of the supply chain, and to propose mitigation plans for the impact of infrastructure failure by increasing the resilience of a supply chain under natural-hazard disruptions.

The objectives of this research are to:

1. Develop a methodology for resilience assessment for supply chain network infrastructure.
2. Identify the impact of the reliability of infrastructure on the supply chain performance.
3. Identify the failure scenarios for a supply chain with a focus on infrastructure disruption.
4. Evaluate the consequences of disruption by quantifying supply chain performance and assess the resilience of the supply chain during a certain window of time.
5. Examine potential mitigation plans to increase the resilience of the supply chain.

1.3 Structure of the Work

The work has been divided into three parts:

Part I. Acquisition of background information

The focus herein is on linking the reliability of built infrastructure to the supply chain. This information was collected by way of a thorough literature review and interviewing workers and business owners who experienced discontinuity in their supply chain performance due to infrastructure disturbance. The literature review has focused on definition of risk in the supply chain due to infrastructure, to define the resilience of the supply chain, and to explore supply chain management decisions that may help to increase the resilience of the supply chain.

Part II. Methodology development

Once the background information was collected, the methodology was established. This methodology is focused towards analyzing the interactions among different infrastructure types and supply chains including the influence of infrastructure reliability on the supply chain and to set a quantitative performance measure to assess the resilience of the supply chain was established. This step has been completed by taking the following steps: (1) defining the system ; (2) identifying the dependency among infrastructure using Bayesian network; (3) assessing the performance of the supply chain; (4) imposing a disruption scenario as a failure of one of the infrastructure types; (4) developing a discrete event simulation model for two case studies using Extendsim; (6) calculating the supply chain resilience; and (7) assessing mitigation strategies to manage associated risks and increase the resupply chain resilience.

Part III. Evaluation and assessment of simulation results

This final part of the work consists of running the model, tracking the logical progress of the work, and finally evaluating the output with the desired goal. Extendsim can show outputs in tables and graphics. The outputs show the movement of materials and information among the supply chain entities, the impact of supply chain disruption, and the vulnerability of entities.

Chapter2: Supply Chain Risks and Infrastructure: A Literature Review

2.1 Supply Chain

Supply chains (SCs) have attracted a great deal of attention in the last few years as businesses have realized the importance of the supply chain to their success and economists have studied the wide impact of supply chains on the economy. Most economists and researchers have focused only on increasing the profitability of supply chains, which can make them more vulnerable to the negative impact of uncertain events (Oliveira et al. 2017). The focus of the researcher has been shifted to the risk that threatens the supply chain resilience due to the negative consequences that followed some events, such as the attacks of September 11, 2001, Hurricane Katrina2005, Thailand flooding, and the Japanese earthquake (Schmitt and Singh 2012) and Hochfelder (2017).

The term “supply chain” arose in the 1980s when companies realized the importance of collaboration within their surroundings and beyond (Lummus and Vokurka 1999). The concept of a supply chain has become a popular topic since the 1990s (Cooper et al. 1997). The term was originally implicitly introduced by Forrester (1958) who identified some essential management issue “there will come general recognition of the advantage enjoyed by the pioneering management who have been the first to improve their understanding of the interrelationships between separate company functions and between the company and its markets, its industry, and the national economy." Figure 2.1 provides the history of the term.

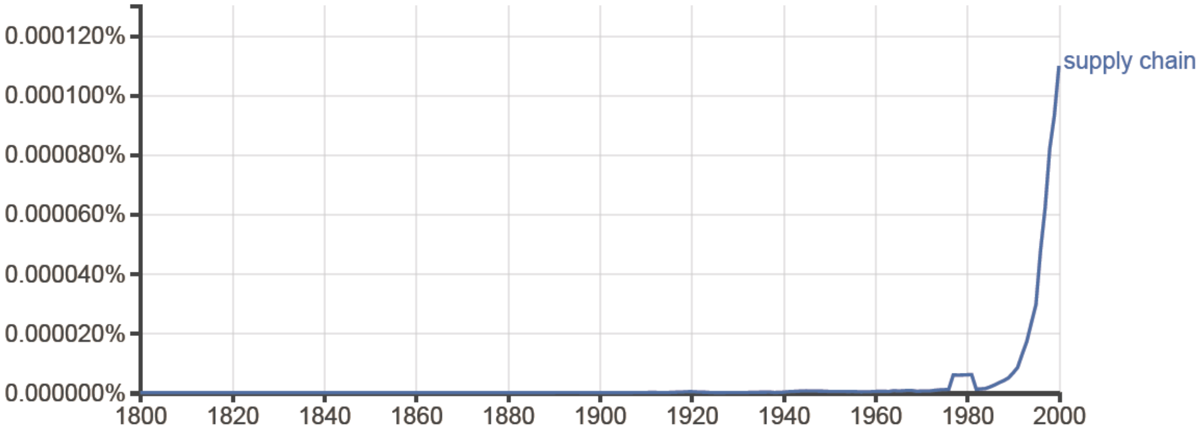


Figure 2.1 Time-series from Google Ngram Viewer to show the history of literature for the supply chain from Google Ngram site, https://books.google.com/ngrams (2020)

Several definitions of supply chains are available. The American Production and Inventory Control Society (APICS) Dictionary defines a supply chain as "the processes from the initial raw materials to the ultimate consumption of the finished product linking across supplier-user companies" (Cox III et al. 1995).

According to (Beamon) 1998, a supply chain is an organized manufacturing process to transfer raw materials into finished goods delivered to customers. Beamon considers supply chains to be global networks consisting of several organizations that team up together to assure a smooth flow of materials and information from suppliers to customers with the lowest possible cost to eventually gain customer satisfaction.

Other definitions are available, for example, Waters (2003) defined a supply chain as a collection of organizations that work together to move the materials needed for their process. The materials include raw ingredients, components, and finally finished goods. Waters (2003) pointed out that a supply chain is a group of organizations that include collecting, manufacturing, storing, distribution, and communication.

All of the previous definitions of a supply chain unanimously agree that a supply chain is a combination of all the required resources, organizations, events, and processes to deliver a final product or service to the customer. This is the definition that is used in this thesis.

2.2 Risks in Supply Chains

2.2.1 Definition of Risk

The focus on the risk that surrounds supply chains has increased since the occurrence of destructive events, such as the attacks of September 11, 2001and Hurricane Katrina (Schmitt and Singh 2012). Those events contributed to increasing attention to the ability of a supply chain to handle negative consequences. The concept of risk can be connected to uncertainty in the occurrence of an event (Ayyub 2014). Risk is about a negative effect if an event occurs. Table 2.1 shows some definitions found in the literature, all of which agree that risk relates to the following general questions:

- What can go wrong when an event occurs?
- How likely will that happen?

- What are the consequences?

Table 2.1 Definition of Risk

Definitions	**Reference**
"Risk is the negative deviation from the expected value of a certain performance measure, resulting in undesirable consequences for the local company."	(Wanger and Christoph 2008)
"Risk is the expected outcome of an uncertain event, i.e., uncertain events lead to the existence of risks."	(Manuj and Mentzer 2008)
"Risk is the effect of uncertainty on objectives. "	(ISO2009a)
"Risk is the potential loss resulting from an uncertain exposure to a hazard or resulting from an uncertain event that exploits the system's vulnerability."	(Ayyub 2014)

Identifying the source of risk in a supply chain is an essential step to help to take some actions that might reduce the probability of the occurrence of a negative effect.

2.2.2 Source of Risk

Based on the literature review, risk originates from one of two sources or a combination of both: (1) external and (2) internal. External sources of risk to a supply chain refer to risk that occurs due to natural disasters, such as floods, earthquakes, and hurricanes, or human-made catastrophes whether intentional or not. Internal risks to a supply chain originate from a company's supply chain and the interaction among the different parts of the supply chain. This source can be related to human activities, finances, and materials, etc.

In this work, the focus is on risk sources related to infrastructure failure as a result of natural disasters. Once the source of the risk is identified, responsive action can be taken to reduce the impacts of that risk and enhance the supply chain performance.

2.3 Supply Chains and Infrastructure

The performance of a supply chain depends on the design of the chain (Barroso et al. 2015): the components of the supply chain (suppliers, manufacturing and assembly plants, and distributors), and the connection among the different components. Infrastructure is involved in the transfer of materials, service, information, and operations. Some types of infrastructure are essential to the transfer of materials across different components of a supply chain, from the supplier to the customer. Those types of infrastructure are considered as primary parts of supply chain logistics. Supply chain logistics is about the positioning of resources or strategic management (Waters 2003), and infrastructure is involved in this change of positioning. Movement of materials and information occurs through the infrastructure from a supplier to a customer (e.g., seaport, roadways, and airports). Other types of infrastructure are very important to a supply chain operation, such as the electrical power supply, communication, water plants, and wastewater.

The availability of infrastructure is an important factor in the selection of physical locations when a company starts a business. Decision-makers typically conduct a deep analysis of geographical locations and their local climate to decide the number of suppliers, manufacturers, and distributors. Climate might affect the reliability of the various types of infrastructure, such as electrical power, water supply, transportation, and communications.

FEMA (2017) reported that during Hurricane Maria, supply chains were able to survive during the disaster because most of the businesses did not suffer major damage to their physical properties. The main challenges were caused by the damage that happened to the infrastructure. Figure 2.2 shows an example of a supply chain's dependency on infrastructure. Each physical part of the supply chain is represented as a node, a link connects the nodes that indicate the flow of information and materials. The transfer of information and services occurred through infrastructures.

Figure 2.2 shows the different types of infrastructure that are considered as primary supply chain components. The types of infrastructure in this thesis are limited to (1) electrical power; (2) communication; (3) roadways; (4) water and wastewater; (5) workforce.

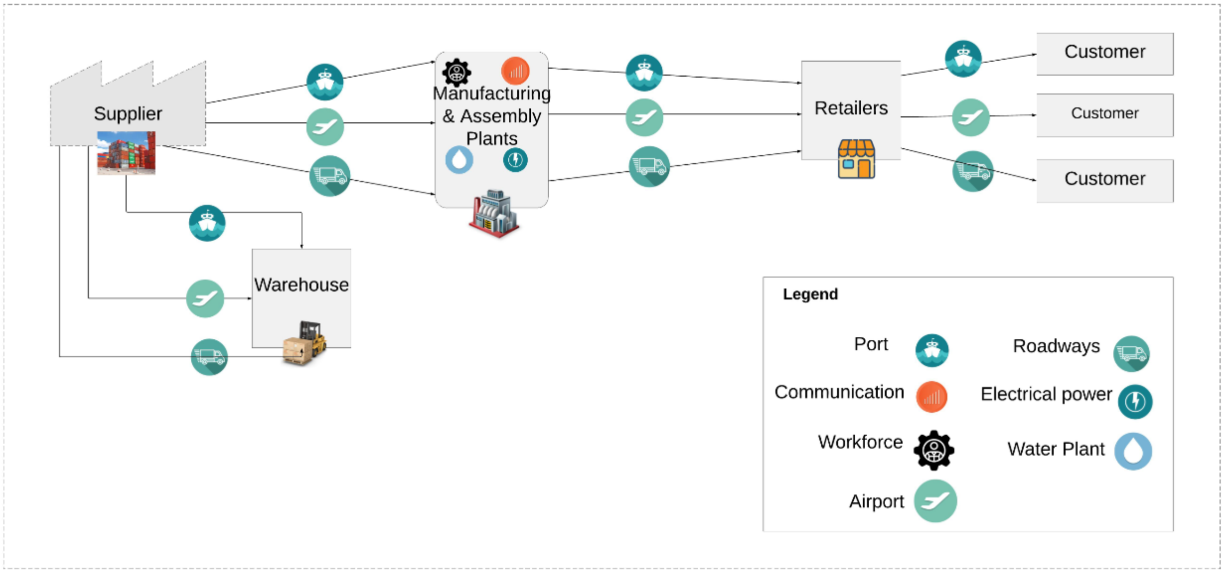


Figure 2.2 Supply chain and associated infrastructure systems

2.4. Supply Chain Resilience

The resilience of a supply chain is its capability to survive negative impacts of unseen events and to bounce back to its original state or to move to a better state (Barroso et al. 2015). Table 2.2 provides several definitions of resilience. The definition of resilience that is used in this thesis is the one introduced by (PPD-21 2013) with the focus on natural disaster.

Table 2.2 Definitions of Resilience

Definitions	**Reference**
“The ability of a system (supply chain) to return to its original state or move to a new, more desirable state after being disturbed.”	(Christopher and Peck 2004)
“The adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function.”	(Priya Datta et al. 2007)
“Resilience means the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.”	(PPD-21 2013)
“Resilience in supply chain context, defined as an ability of supply chains to recover from inevitable and unexpected disruptions.”	(Scholten et al. 2014)
“Resilience is the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions.”	(Ayyub 2015)

All the definitions above agree that resilience is about preparing for unexpected events, so that a supply chain can withstand any possible disruption with a minimum of possible loss and recover from loss as soon as possible. Some disruptive events cannot be prevented, but their consequences can be mitigated. A supply chain can be designed to be resilient and withstand any possible interruption of its performance. This performance measure will indicate how a supply chain acts under normal conditions and during a disruption. Chapter 3 explains the resilience assessment in more detail. This thesis includes the effects of reliability of infrastructure on the resilience of the supply chain under normal conditions and disturbances. The development of the methodology is shown in the next chapter.

Finally, the risk of failure in a supply chain is inevitable. Some sources of risk are outside human control. With this in mind, the only way to deal with these potential risks is to be prepared for them with contingency plans in the event that such an event occurs. These plans will make the supply chain increasingly resilient.

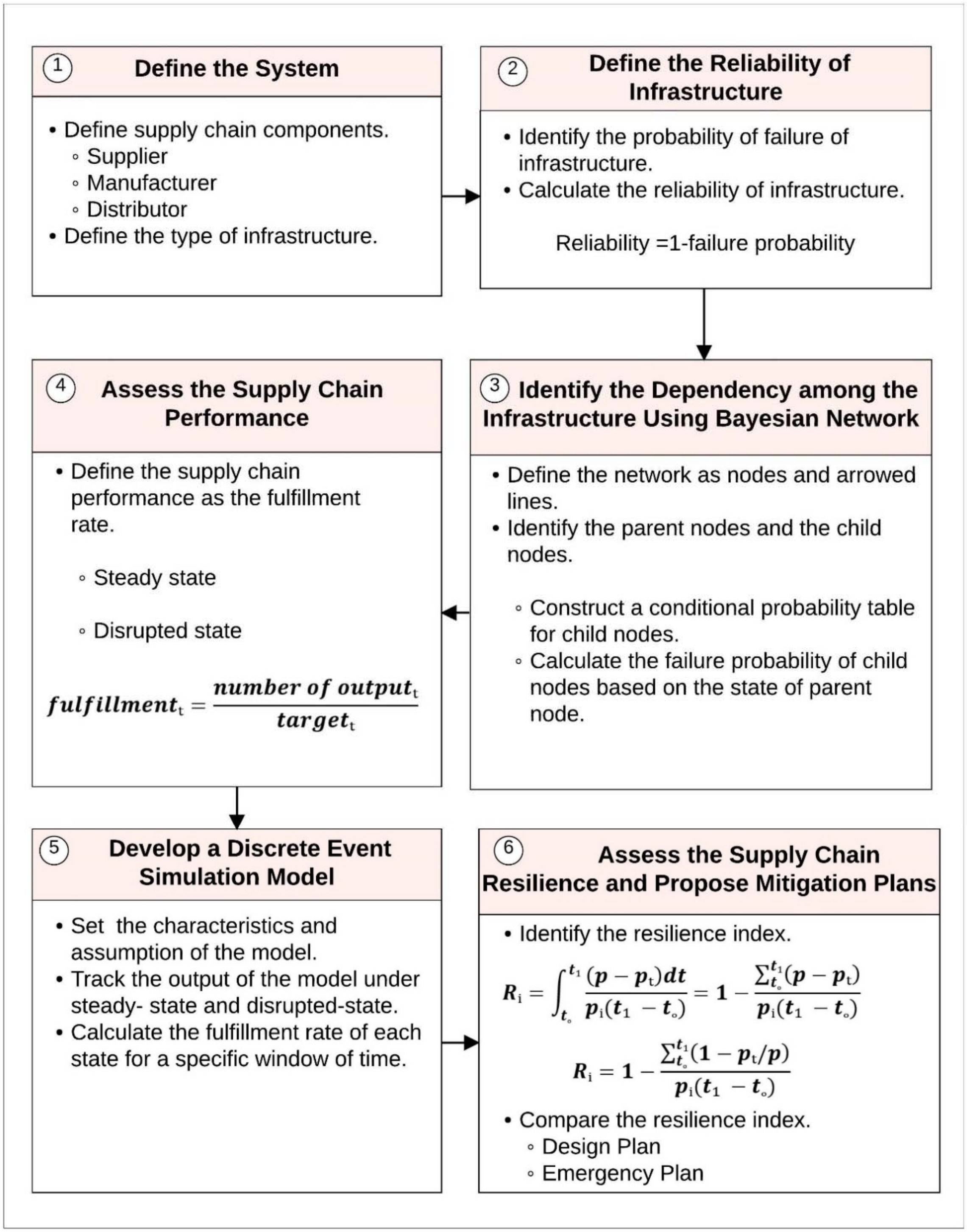
Chapter 3: Methodology

This chapter proposes a methodology to analyze the interactions among different infrastructure types and supply chains, including the influence of infrastructure reliability on the supply chain performance and to assess the resilience of the supply chain. Figure 3.1 summarizes the proposed methodology and the associated steps: (1) define the system by identifying all the supply chain components including infrastructure and associated reliabilities; (2) identify the dependency among infrastructure and the impact of the dependency on the reliability of infrastructure using Bayesian network; (3) assess the performance of the supply chain by accounting for infrastructure reliability; (4) assess the performance of the supply chain under failed states of infrastructure types; (5) develop a discrete event simulation model using Extendsim; (6) assess the supply chain resilience and assess mitigation strategies to manage associated risks.

The proposed methodology examines how infrastructure is linked to the supply chain and how variation in the reliability of infrastructure influences supply chain resilience. The results of the study propose solutions to minimize the impact including disruptions of the supply chain and to increase its resilience. The methodology depends on creating a quantitative model to analyze the interaction among supply chain components, the impact of infrastructure reliability, and disruption in the performance of the supply chain. The model has been generated using discrete event simulation. Simulation is a very effective tool to capture the interaction of system components and to test different response scenarios to lead to a more resilient performance. The different infrastructure types supporting the supply chain are interdependent. The failure of one infrastructure may lead to a disruption in another one. Therefore, a Bayesian network has been used to capture the dependency and reflect its impact on supply chain performance.

3.1 System Description

This section includes a detailed description of the supply chain components that form the system analyzed in this thesis using DES. The system of the research consists of the various components of the supply chain, the infrastructure supporting it, the failure mode, and the associated risk. In this thesis, two case studies have been examined; each case study represents a manufacturing facility. Both cases include all the primary components of the supply chain and the different types of supporting infrastructure that allow the supply chain to properly operate under normal conditions (i.e., without disruption). Chapter 4 provides further explanations of each case study.



① **Define the System**

- Define supply chain components.
  - Supplier
  - Manufacturer
  - Distributor
- Define the type of infrastructure.

② **Define the Reliability of Infrastructure**

- Identify the probability of failure of infrastructure.
- Calculate the reliability of infrastructure.

Reliability =1-failure probability

③ **Identify the Dependency among the Infrastructure Using Bayesian Network**

- Define the network as nodes and arrowed lines.
- Identify the parent nodes and the child nodes.
  - Construct a conditional probability table for child nodes.
  - Calculate the failure probability of child nodes based on the state of parent node.

④ **Assess the Supply Chain Performance**

- Define the supply chain performance as the fulfillment rate.
  - Steady state
  - Disrupted state

$$fulfillment_t = \frac{number\ of\ output_t}{target_t}$$

⑤ **Develop a Discrete Event Simulation Model**

- Set the characteristics and assumption of the model.
- Track the output of the model under steady- state and disrupted-state.
- Calculate the fulfillment rate of each state for a specific window of time.

⑥ **Assess the Supply Chain Resilience and Propose Mitigation Plans**

- Identify the resilience index.

$$R_i = \int_{t_0}^{t_1} \frac{(p - p_t)dt}{p_i(t_1 - t_0)} = 1 - \frac{\sum_{t_0}^{t_1}(p - p_t)}{p_i(t_1 - t_0)}$$

$$R_i = 1 - \frac{\sum_{t_0}^{t_1}(1 - p_t/p)}{p_i(t_1 - t_0)}$$

- Compare the resilience index.
  - Design Plan
  - Emergency Plan

Figure 3.1 Proposed methodology to understand the interaction between infrastructure and supply chain including the influence of infrastructure reliability on supply chain resilience

3.1.1 Supply Chain Components

The main components of a supply chain are suppliers, manufacturing processes, and distributors. For each case, a specific number of suppliers and the type of infrastructure they use to transfer the real materials to the facilities (i.e., roadways, airports, and seaports) are stated. Therefore, the infrastructure used in transferring the materials is critical to the continuity of the supply chain performance. Supply chain components are modeled using discrete event simulations as nodes connected by links – where links are responsible for the movement of materials and information.

Manufacturing processes are specific to the supply chain analyzed and depends on the study case under consideration. Each case study represents a different sector. The facility consists of multiple plants, where each plant is responsible for a specific step of the manufacturing process. The facility can also have a storage space/warehouse to keep the inventory. The number of outputs represents the final product of each facility. The distribution of the final product is divided into two markets: domestic and global. The percentage for each one is included in the model, but the distribution process is disregarded.

3.1.2 Infrastructure

Multiple components fall under the definition of supply chain infrastructure. The definition contains some physical aspects like the buildings of the manufacturers and distributors, and the informational aspects that are essential to run the supply chain (Fallon 2020). Supply chain infrastructure includes the infrastructure used to move the products across the supply chain components and the other types of infrastructure that are essential to run the facility.

Supporting infrastructure is one of the main components of supply chain logistics. That means it is responsible for the movement of materials and information from suppliers to intermediary manufacturers and customers by way of seaports, ports, and airports, etc. Infrastructure is also critical to manufacturing operations. The facility requires water, electrical power, and communication. Therefore, it is crucial to understand the role of infrastructure in the supply chain and the impact of potential disruption.

Figure 3.2 shows how the different types of infrastructure are important to the interaction among supply chain components.

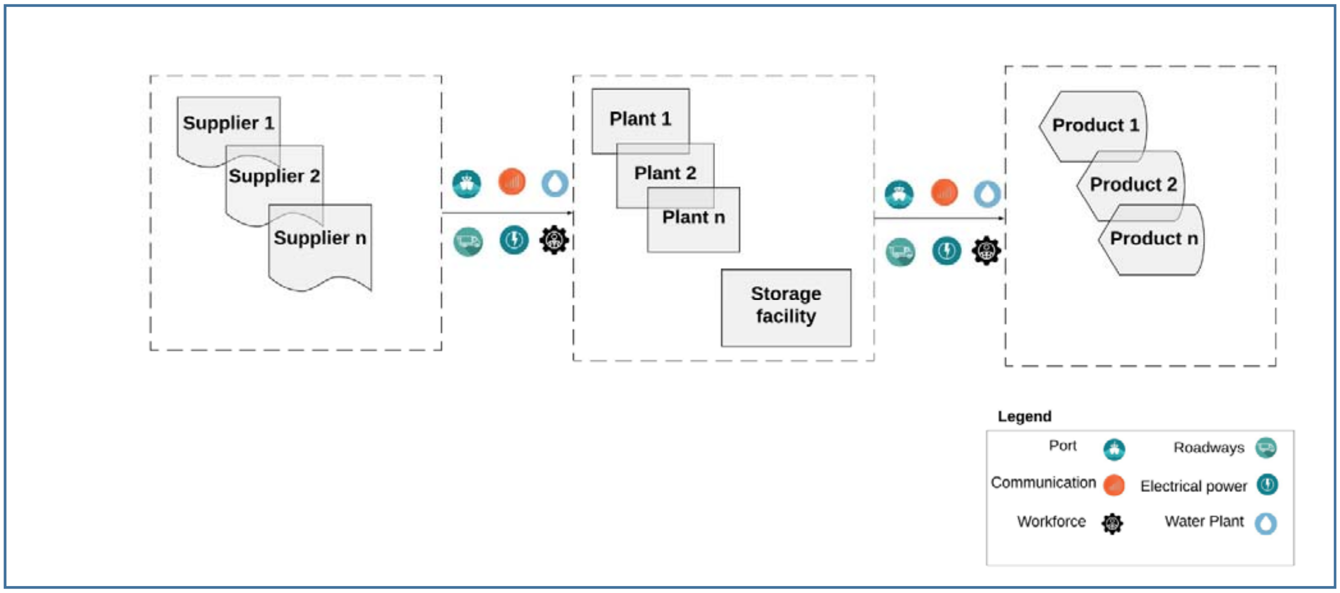


Figure 3.2 Supply chain and the different types infrastructure supporting the supply chain

Infrastructure performance under the stress of a disruption will highly impact the whole supply chain. The performance as a general term considers “the capability of a system to fulfill the need of its functional requirements” (Ayyub 2014). Performance can be measured based on the problem of interest. The performance of infrastructure in this thesis is measured through the reliability of the infrastructure.

3.1.3 Failure Modes and Associated Risks

Supply chain resilience is the ability of the supply chain or any of its components to rebound from a setback in the occurrence of disruption (Schmitt and Singh 2012). Supply chain components must be prepared to face the risk of failure to maintain supply chain performance.

One of the major steps in performing this work is to develop a strong understanding of how the risk flows across the system components. In other words, how the failure of one component can transfer to other components and eventually affect the outputs of the supply chain? In this research, the focus is on the risk that threatens the supply chain due to the variation of the reliability of infrastructure and the total failure of the infrastructure responsible for the logistics of materials/goods.

Risk is embedded in the supply chain even under normal conditions due to the variation of the ability of infrastructure to provide the supply chain with services required by the supply chain to maintain its operations. For example, ports and roadways are responsible for the movement of materials; electrical power, water supply, and communication are susceptible to a disturbance at any time. This variation can affect all the various parts of a system, and it will be reflected in the number of outputs. Another cause of risk is the total failure of the infrastructure that is critical to transportation can cause a loss of a supplier. Figure 3.3 shows different kinds of risk.

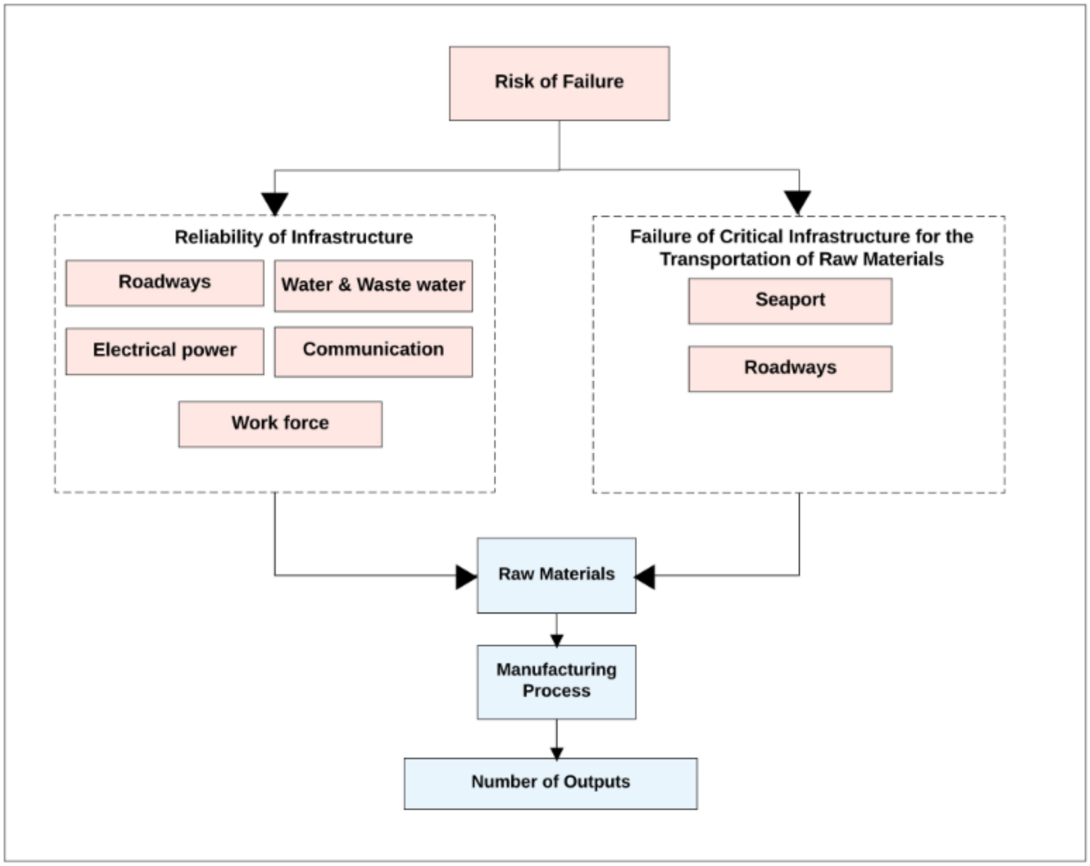


Figure 3.3 Risk flow in the supply chain – generalized representation

3.1.3.1 Infrastructure Reliability

The reliability of the infrastructure is identified as the performance of infrastructure. It measures its ability to serve the supply chain. This uncertainty potentially affects the services provided by the infrastructure of the supply chain. As a result, the type of materials and the relative magnitude of each sent by the supplier to the manufacturing facility of a supply chain will change due to infrastructure reliability. Probability is a common way to describe the ability of the system (Ayyub 2014). Reliability is measured as the probability of the complementary event to failure. The reliability of infrastructure is calculated based on equation 3.1.

$$\text{Reliability } = 1 - \text{failure probability} \tag{3.1}$$

This type of risk is captured in the model by reducing the value of critical raw materials by multiplying them by the reliability of infrastructure. Consider x_i as a random variable that represents the amount of critical raw material required by a facility at a specific time, and y_i is the random variable that represents the provided material to the facility based on the reliability of infrastructure.

$$y_\mathrm{n} = a_\mathrm{n} x_\mathrm{i} \tag{3.2}$$

where,

a_n: Reliability of infrastructure, $0 \leq a_\mathrm{n} \leq 1$

x_i: The amount of required raw materials by the facility at time i

y_n: The amount of provided raw materials by infrastructure n at time i, $0 \leq y_\mathrm{n} \leq 1$

Thus, each infrastructure type that supporting the supply chain produces a different amount of materials. The minimum amount of materials provided by infrastructure controls the raw materials delivered to the facility.

In the discrete event model, the materials provided by each type of the supporting infrastructure will be presented as a random variable z_n uniformly distributed with a minimum value of y_n and a maximum value of x_i.

$$z_\mathrm{n} = U(y_\mathrm{n}, x_\mathrm{i}) \tag{3.3}$$

$$z_i = min\begin{cases} z_1 \\ z_2 \\ . \\ . \\ z_n \end{cases} \tag{3.4}$$

where,

z_i: The minimum amount of provided raw materials by infrastructure at time i

3.1.3.2 Total loss of Suppliers Due to Failure in the Logistics Infrastructure

The supply chain is highly influenced by the state of infrastructure, whether it is available or not. This controls the movement of materials from one component to another. Losing one component of the infrastructure responsible for logistics will negatively impact the supply chain. This is what usually occurs during a natural disaster when seaports can be shut down and roadways can be blocked.

The occurrence of a natural disaster can lead to complete loss of a primary part of the logistics system of the supply chain. Failure of infrastructure prevents suppliers from providing a facility with the required materials. The loss of a supplier starts at one component, preventing the facility of producing the required product during the disruption. The impact of the risk propagates through the supply chain components and eventually affects the number of outputs. This loss of infrastructure was modeled in the discrete simulation model under the imposed scenarios. Equation 3.5 represents this kind of risk in the model.

$$x_i = 0 \tag{3.5}$$

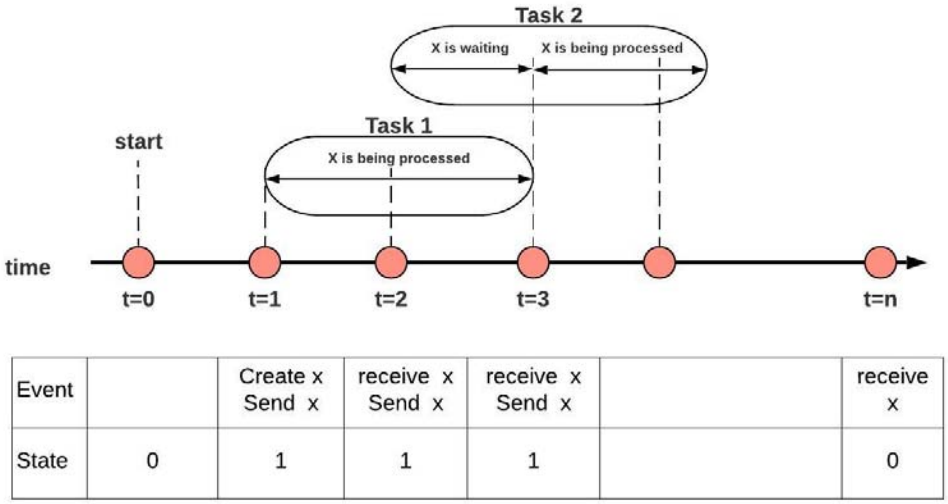
where,

y_i is the amount of provided raw materials at time i

3.2 Discrete Event Simulation

3.2.1 Background

In this section DES will be defined and the associated terms will be introduced and defined. Discrete event simulation is a technique to represent real-life problems as a system by building a model to track the behavior of system components and evaluate the system performance (Banks 2014). DES is defined by a series of events. The event is any cause possibly leading to a change in the state of any components of the system that will produce different outputs during a defined unit of time. Figure 3.4 provides a graphical presentation of the DES process.



Event		Create x Send x	receive x Send x	receive x Send x		receive x
State	0	1	1	1		0

Figure 3.4 Discrete event simulation (de Lara et al. 2014)

Discrete event simulation (DES) is widely accepted as a tool to analyze manufacturing systems. It is based on Monte Carlo methods (Brailsford et al. 2014).
To understand discrete event simulation, several terms are introduced herein. A system is a group of components interacting with each other over time to perform certain goals that are dependent on the field of interest.

The state of a system is defined as a collection of variables that contain all the necessary information that describes the system in terms of the impact of an event over a certain entity at a certain time. Model is a descriptive representation of a system by using mathematical, logical, and physical relationships that describe the interaction between the entities that form the model.

An entity is any component/part of the system that requires representation and will cause an event to happen. So, the entity usually represents a physical object in real life.

Finally, the event is the change that happens to an entity at a specific time which will affect the state of the entity.

According to the previous definitions, the DES method examines the flow of materials/ information among supply chain components caused by the occurrence of an event that leads to the movement of an entity through many queues and services, once the service is available. Each component of the supply chain has specific attributes. These attributes account for the logic behind the flow of the entity from the queue to a specific service -- whether it is the time needed to serve the entity or a priority of one service over another like the sequences of a manufacturing process where specific tasks must be done before others.

3.2.2 Methods and Software

The DES model was built using a discrete event simulation software (Extendsim power tools for simulation ©by Imagine That Inc). ExtendSim is a powerful simulation tool allowing to build dynamic models of real-life from building blocks to represent the components of the system. It is user-friendly software with a graphical drag-and-drop block. This helps through the research to visualize the supply chain. The software has a very wide range of blocks with different roles in the model included in a specific library for discrete event simulation. It is easy to track the movement of information through the different blocks. Most of the blocks can be defined by the use to provide statistical information about the associated data. Blocks are connected through lines called *connectors* which direct the movement of entities from one block to another. The behavior of the model strongly relies on the inputs. Therefore, setting the input values and associated relationships was challenging to relate to real-world functioning as closely as possible. Tracking errors in the model was the responsibility of the user. Excel was used to extract some of the graphical presentations based on the need for the research.

Simulation is a time-dependent process for the movement of entities as a part of a system. The movement of the entities depends on time; the link between the blocks represents the movement of the entities between the supply chain components. In this thesis, simulation was used as a tool to gain knowledge of a supply chain in order to make decisions that will help to increase the resilience of a supply chain. Extendsim allows flexibility to change the model based on the problem requirements. The model deviates from real life due to some of the assumptions and simplifications that have been done. An ideal system should experience a very small accumulation of queues, with a delay time for the activity block within the assumed range.

Simulation as a tool has some limitations. The model of the two cases is built based on research specific to each of the modeled manufacturing facility. Simplifications have been made so that the discrete event simulation serves the purpose of the research to investigate risks that threaten supply chains due to the uncertainty of the reliability of infrastructure.

3.2.2.1 Model Terminology

Each software has specific terminology related to the specific method emplyed. This section provides the main terminology for the DES model developed using Extendsim. Figure 3.5 shows what the terminology used in the discrete event represents in the real-life system. Understanding the terms helps to develop the discrete event model.

- *Model* is a group of blocks and links to represent a system. Each block represents one of the supply chain components.
- *Entity* is the item that is being transferred through the whole model. It is being processed in blocks and, eventually, it will be terminated from the model as an output.

- *Attributes* are characteristics to describe the entities as they move from one block to another; they can be changed as they move from one to another. For example, raw materials will be measured in a unit weight at the initial stage of the model when being moved from supplier to facility. Once the raw materials are processed to a final product, the materials can be described in a different unit (e.g., box, can).

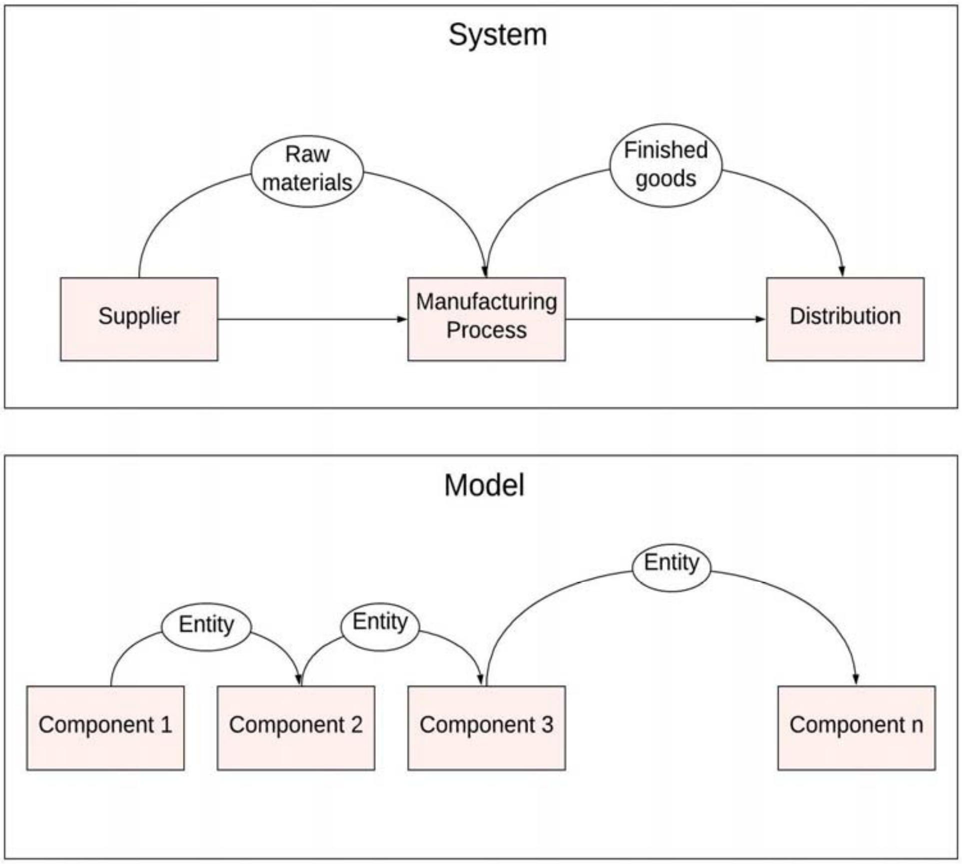


Figure 3.5 Discrete event simulation terminology

3.2.2.2 Blocks

The software provides a wide range of blocks. The model was built using a group of blocks connected by links. Links are referred to as connectors; they transfer entity and information from one block to another. Table 3.1 shows the most commonly used blocks in the research provided by the discrete event-specific library.

Table 3.1 Used blocks in the discrete event simulation model

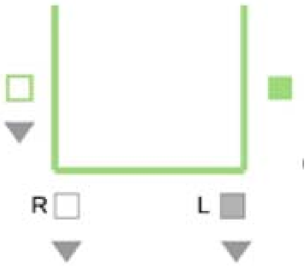
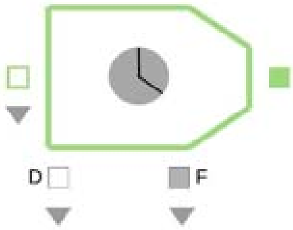
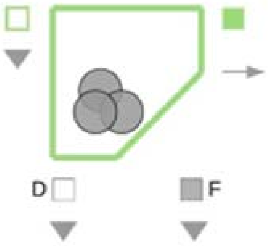
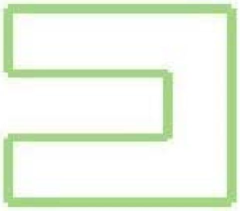
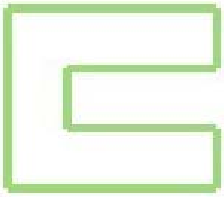
Number	Block name	Block symbol	Use definition
1.	Create block		Generates (entities) randomly, or by a schedule by setting the time between the arrival of items. This is the initial start that leads to a change in the state of the model causing the movement of generated items.
2.	Queue block		Keeps the entities until the next block is available. All blocks in this work are FIFO (first in-first out). The first entity that arrives is the first one to leave.
3.	Activity block		Executes a specific task with a predetermined amount of time. Time can be constant or random.

Table 3.1 Used blocks in the discrete event simulation model (cont.)

Number	Block name	Block symbol	Use definition
4.	Batch block		Assembles different entities into one entity. It serves the purpose of the assembly line in the model.
5.	Select item in		Controls the path of entities going into a block
6.	Select item out		Controls the path of entities going out of a block.

3.2.3 Simulation Limitations

The work has been done to make the model as logical as possible. However, there are certain issues that we cannot control. We also should be aware of all the assumptions and simplifications that have been done to build the model. Many of the faced challenges have been solved by adding blocks. It is impossible to reach the perfect model; thus, it is helpful to point out the most basic limitations.

Queues are important to the simulation model. This refers to It is the block where an entity is held when the activity block is unavailable. Therefore, it is helpful to include queues wherever there is a chance for the activity block to be occupied. This will prevent the accumulation of entities in the create block. Then the create block can keep generating items according to the original plan. In real-life, different actions would be taken, such as increasing the number of workers or rescheduling.

The reliability of the services provided by infrastructure is presented in a create block at the beginning of the model showing the number of critical materials that are served by the infrastructure. The variation in infrastructure efficiency makes the model more realistic. The resulting amount of materials would thus include in real life the impact of infrastructure on each separate step.

3.3 Bayesian Network

3.3.1 Background

Bayesian Network (BN) theory is considered an effective approach to represent risk flow in a supply chain (Schmitt and Singh 2012). As mentioned earlier in section 3.2, infrastructure forms a primary component of the supply chain logistics. Therefore, the BN can be used to model the risk propagation in supporting infrastructure due to the variation in the reliability of services that infrastructure can provide to the supply chain.

As mentioned in Section 3.1, the performance of all components of infrastructure is interdependent. The state of some infrastructure components depends on the state of others, which will eventually impact the reliability of infrastructure. For example, the failure of electrical power has a high impact on the water supply because most high elevation areas get their water through water pumps run by electrical generators. Other examples of the interdependency of different infrastructure components are workforce, communication, and roadways. The workforce needs to have safe roadways to commute to a facility and a reliable communication system. It is crucial to include a comprehensive analysis of the interconnectivity of all supporting infrastructure components when completing a performance assessment and making recovery decisions in supply chain design.

3.3.2 Methods and Software

A Bayesian network is an effective way to determine the conditional probability of a specific infrastructure type given the information about the state of another infrastructure. This prior information is usually built on observation, expert opinion, engineering judgment, or a physical model (Bensi 2010). A model based on statistical analysis using a Bayesian network can always be updated once a new observation is obtained.

BN is built based on the "Bayes" theorem (Bensi 2010). The Bayes rule is used to describe how the probability of an event changes based on prior knowledge gained about the occurrence of an event. Equation 3.6 describes the formula of the Bayes rule and some primary terminology to help to understand the rule.

$$P(A|B) = \frac{P(A \cap B)}{P(B)} = \frac{P(B|A)}{P(B)} * P(A) \tag{3.6}$$

where,

$P(A|B)$: The conditional probability of event A given that event B has occurred

$P(A \cap B)$: The joint probability of events A and B

$P(A)$: The marginal probability of event A

$P(B|A)$: The likelihood of the observed event B

$P(B)$: The marginal probability of event B

Typically, the prior information about event A represents a belief about the probability of the prior probability. A similar term is used for the calculated probability (the posterior probability). It represents a belief about the probability after considering the observation. Obtaining an observation about event B narrows the sample space of the possible observation. Therefore, a normalizing factor calculated based on the Theorem of Total Probability appears in the denominator of equation 3.6.

A Bayesian network captures the dependency among variables by using probability dependencies (Kabir et al. 2015). It is a probabilistic graphical modeling method to represent knowledge of uncertainty. It combines graph theory, probability theory, and conditional probability. It consists of nodes to represent the random variables in a system and line and arrows connect the nodes in order to describe the probabilistic dependency that connects the random variables. Identifying the nodes and links in the BN must be carefully performed to avoid any misleading and unnecessary complications to the model (Bensi 2010). A BN works as an analytical tool to compute the probability of the variable of interest -- based on the condition of a previously observed variable (Ojha et al. 2018). The state of the variable of interest depends on the state of the previously observed variable.

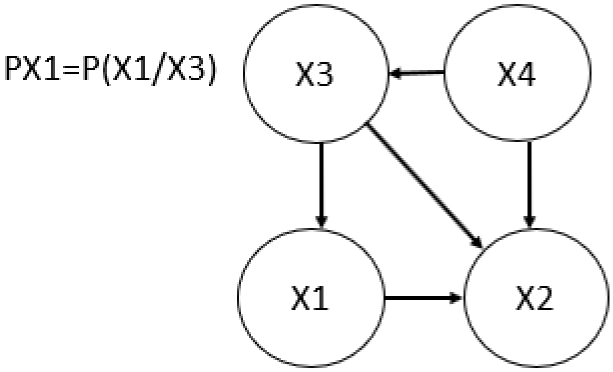


Figure 3.6 A Bayesian network

In the graphical representation of a BN, there are three kinds of nodes:

- Child nodes: the nodes with edges directed into them (X1, X2, X3),
- Parent nodes: nodes from which the arrows direct out of them (X1, X3, X4), and
- Root nodes: the nodes without arrows directed into them (X4).

For a system A that consists of multiple random variables x_1, x_2,x3, ….., x_n , the probability of the system is defined in this work a Bayesian network has been used to find the reliability of a specific infrastructure and its impact on the supply chain performance based on a prior probability of other infrastructure. Because the network of the infrastructure that supports the supply chain is small, an Excel sheet has been used to calculate the probability of each node based on the state of its parent nodes. More details will be explained in Chapter 4.

$$P(A) = P(x_1, x_2, x_3, \dots, x_n) \tag{3.7}$$

$$P(A) = P(x_1|parent(x_1)) * P(x_2|parent(x_2)) * \ldots * P(x_n|parent(x_n)) \tag{3.8}$$

$$P(\mathrm{A}) = \prod_{i=1}^{n} (x_n|parent(x_n)) \tag{3.9}$$

To describe the relationship between a child node and all the possible parent nodes a Conditional Probability Table (CPT) is constructed for each of the child node. The CPT shows the probability of a node to be in a state, given the knowledge about the state of the parents.

In this work a Bayesian network has been used to find the reliability of a specific infrastructure and its impact on supply chain performance based on a prior probability of other infrastructure. As the network of the infrastructure that supports the supply chain is small, an Excel sheet has been used to calculate the probability of each node based on the state of its parent nodes. More details will be explained in Chapter 4.

3.3.3 Bayesian Network Limitations

A Bayesian network is an effective tool to capture the dependency between the different parts, but it is highly dependent on the assumptions that we make about the parent nodes of certain infrastructure. Assumptions have been made based on literature and some research related to our interest.

Bayesian networks rely on conditional independence. As the number of parent nodes increases, the conditional probability table can become overly complicated. To avoid such a problem in this study, some deliberate assumptions have been made about connections between different kinds of infrastructure. Those assumptions make some of the prior knowledge about nodes biased. However, this is acceptable for the purpose of achieving the goal of this study.

3.4 Study Approach

Once the supply chain components and the reliability of infrastructure are defined and the risk included in the supply chain has been identified, the analysis of the supply chain performance can be started. A discrete event simulation model can be constructed using Extendsim to replicate a real-life system under normal conditions for different design strategies to understand the system as a whole and the role of infrastructure in the supply chain. Then disruption can be imposed as a different scenario to the system to examine the supply chain performance under disruption and measure its resilience and explore the available alternatives that can be applied in the supply chain to react to disruption.

3.4.1 Steady-State

The first part of the simulation is to build a model to simulate a real-life supply chain for facilities. This has been done after several trials to ensure that each component of the supply chain is working correctly to achieve the target goal of the outputs. The steady-state analysis shows how a facility runs under normal conditions and how the supply chain is influenced by the uncertainty of the reliability of infrastructure. The models under steady state serve as a reference for the validation of other scenarios. The number of outputs in each case study depends on time.

3.4.2 Imposed Disruption Scenarios

Disruption scenarios were imposed on the system by halting a facility from receiving raw materials. The disruption scenarios in both cases occur due to a total loss of supporting infrastructure of the logistics system that causes a total loss of a supplier due to a serious failure in a seaport or a roadway that will prevent the movement of ships and trucks. Further details will be provided under each case study.

3.4.3 Supply Chain Resilience Assessment

Supply chain is a relatively new term that arose in the 1980s to describe new management disciplines (Christopher and Peck 2004). A supply chain is a series of steps that are performed by collaboration among suppliers, manufacturers, and distributors until the goods finally reach customers. The main goal of a supply chain is to satisfy customers by ensuring the right quantity and proper quality at the right time and right location. Thus, it is very important that supply chains maintain resilience.

There is no definite answer to how we can determine supply chain resilience. Several aspects fall under supply chain resilience (Barroso et al. 2015): The size of the change that occurs to a system and still maintains the same control on the function of the system; the ability of the system to operate; and finally the ability of the supply chain to adapt to any change. Therefore, it is an essential step to define the system that we are interested in and to recognize the failure mode.

Risk of disruption can affect supply chain performance. This effect can be quantified through certain measures: profits, customer satisfaction, sales, and production level. Sheffi (2006) provides a graph for the disruption profile of the supply chain performance. The system goes through different stages. The performance declines during the disruption, but as responses and actions are executed, the system's performance will gradually increase.

Figure 3.7 shows that there are eight stages of responding to risk: initial preparation, the occurrence of disruption, first response, delayed impact, full impact, preparation for recovery, recovery, and long-time impact.

The disruption profile facilitates the visualization of the risk on the performance of the supply chain. It can be applied to assess the performance of the supply chain over time.

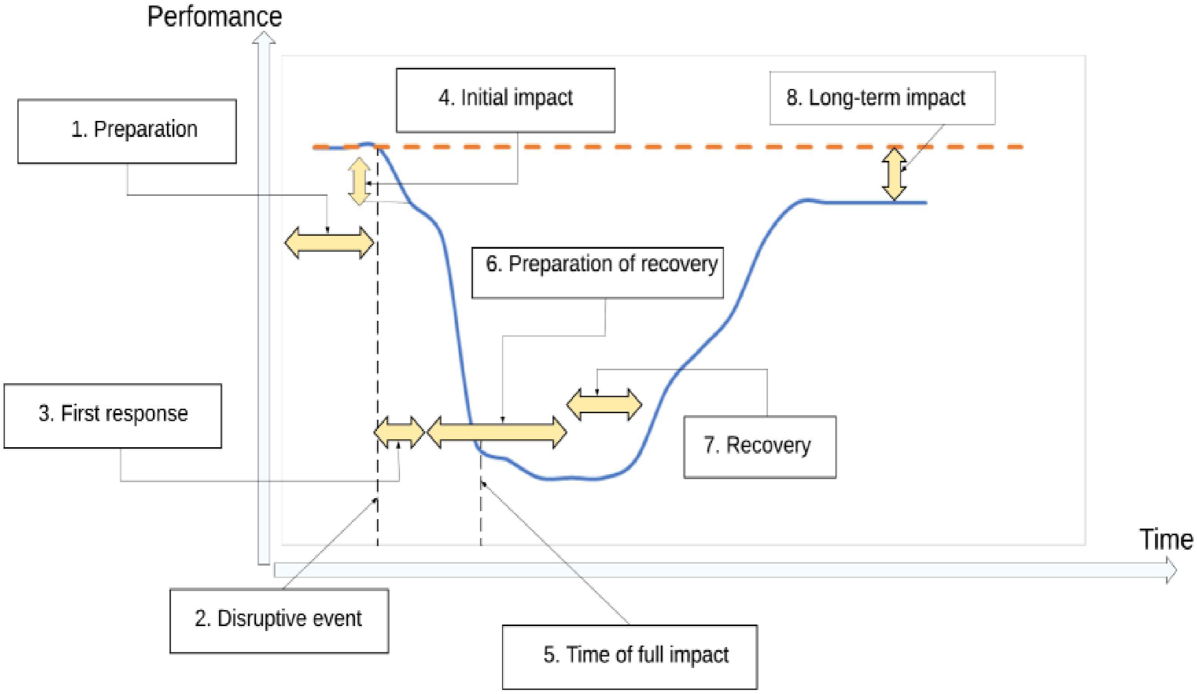


Figure 3.7 Disruption profile (Sheffi and Rice Jr 2005)

In this thesis, the supply chain performance under different scenarios is used as a resilience measure. The supply chain performance is defined through the fulfillment rate.

As the ultimate goal of the supply chain is to satisfy customers, we have chosen the number of outputs over a unit of time compared to the supply chain target over the same unit of time to track the propagation of any disruption through the movement of materials and information which will affect the number of outputs. This will also allow the comparison of the supply chain under different scenarios. The fulfillment rate is being used as a term to refer to the supply chain performance.

$$fulfillment_{\mathrm{t}} = \frac{number\ of\ output_{\mathrm{t}}}{target_{\mathrm{t}}} \tag{3.10}$$

Then, the supply chain resilience can be described through an index between 0 and 1(Schmitt and Singh 2012). The closer the index is to 1, the more resilient is the supply chain.

$$R_{\mathrm{i}} = \int_{t_\circ}^{t_1} \frac{(p - p_{\mathrm{t}})dt}{p_{\mathrm{i}}(t_1 \ - t_\circ)} = 1 - \frac{\sum_{t_\circ}^{t_1}(p - p_{\mathrm{t}})}{p_{\mathrm{i}}(t_1 \ - t_\circ)} \tag{3.11}$$

$$R_{\mathrm{i}} = 1 - \frac{\sum_{t_\circ}^{t_1}(1 - p_{\mathrm{t}}/p)}{p_{\mathrm{i}}(t_1 \ - t_\circ)}$$

where,

R_{i}: Resilience index of the supply chain at time i

p: Performance of a company when it is not affected by a disruption

p_{t}: Performance of a company at time t

t_1: is the upper limit of the time period that is used to calculate the resilience

$t_\circ$: is the lower limit of the time period that is used to calculate the resilience

3.4.4 Identification and Assessment of Mitigation Strategies

There are several ways to respond to risk. These ways include risk acceptance, avoidance, transfer, and mitigation (Ayyub 2014). The resilience of the supply chain depends on responding to the disruption by being prepared for it.

A resilient supply chain is capable of responding to risk. This can be done through the design of a supply chain or some strategies that can mitigate the risk impact or even remove it.

The models in this research were built to test resilience through specific design plan and other mitigation plans.

- Design plans
    - Redundancy: the supply chain has more than one supplier. Each supplier relies on a different transportation system.
- Mitigation plans
    - Conservation: to maintain the same level of production without substituting for the loss during a disruption.
    - Input reallocation: to replace the proportion of inputs to a critical output. (e.g., assign all the raw materials for a high-demand product).
    - Output substitution: to change the distribution of the products (e.g., provide all the outputs of a specific market).
    - Share resources: to collaborate with other supply chains and try to get raw materials during the disruption period.

Once all the methodology steps have been completed, the case study models can be developed. Both cases are being assumed to be located in the same area. The reliability of the types of infrastructure supporting the supply chains will be the same. Figure 3.8

provides a summary of the steps that will be followed in Chapter 3 to develop the DES model.

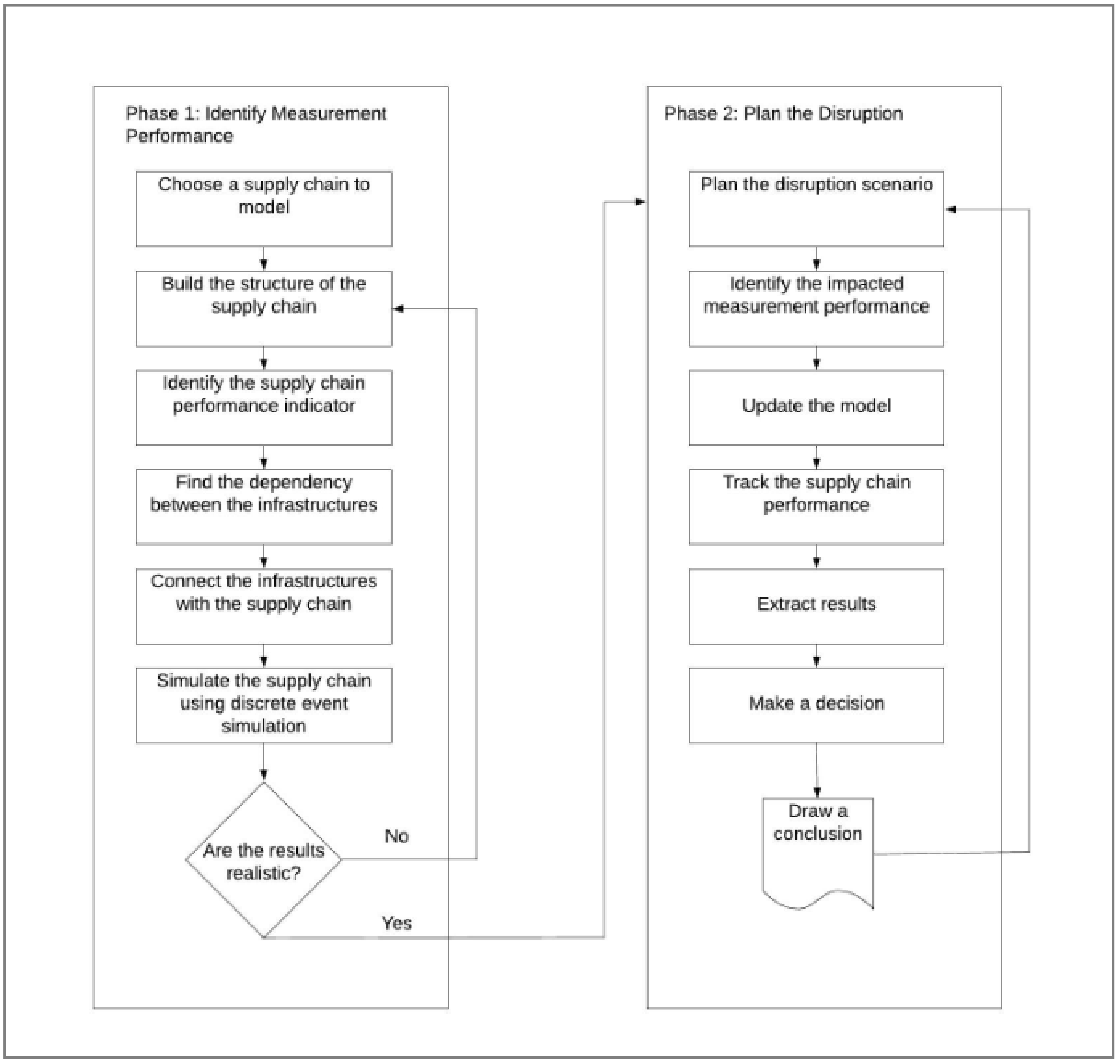


Figure 3.8 DES model development steps

Chapter 4: Case Studies

Assembly facilities of two different manufacturing sectors are considered and modeled in this chapter for the purpose of examining their respective supply chains and underlying physical infrastructure. DES model has been developed for each case. Both cases are assumed to be located in the same geographical area. The first supply chain is a food processing manufacturer. The second case study is a medical device assembly company.

The purpose of the simulation is to build an appropriate model in order to analyze the supply chain and make future decisions to increase the supply chain resilience. Campuzano and Mula (2011) provide a list as a guideline for simulation models; these include:

- Not constructing a complex model, but a simple one that works.
- Trying to understand the problem to find the right technique.
- A model cannot be better than its inputs.
- Models cannot replace decision-makers; they are a tool to be used in order to understand.

4.1 Model Characteristics and Assumptions

The accuracy of simulation results is highly dependent on the system inputs. In this thesis, the input data are divided into two groups. The first group includes all the variables that are altered by the user to construct a specific setting. These variables include the number of raw materials that will change throughout the model to produce the outputs, the execution time for tasks and the number of workers, and finally the routing of raw materials and outputs. The second group is the disruption scenarios inputs. They are data imposed on the model only to test the system response. It is being done by stopping the generation of raw materials for a period of time. Figure 4.1 shows the characteristics and the assumptions required to construct the DES model.

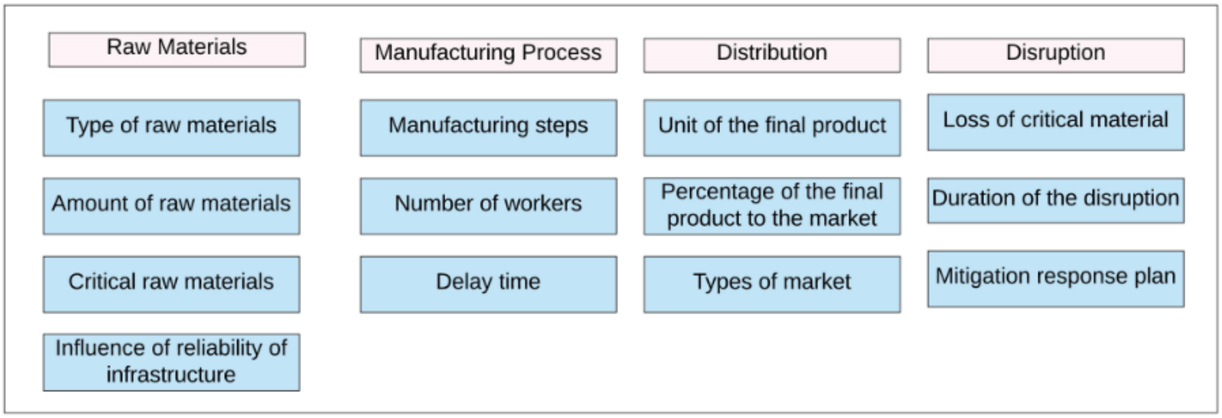


Figure 4.1 The characteristics and the assumptions that are required to construct the DES model

ExtendSim is a unit-less software which can work with undefined time. Thus, it is important to decide about the time unit once we start to build the model, and we should maintain the unit throughout the model to get the correct relationship. ExtendSim gives the flexibility to change the unit of time inside the activity block to be more realistic. Each of the case studies has a different time unit based on the manufacturing sector and the time between received raw materials.

4.1.1 Raw Materials

Most supply chains require different kinds of intermediate input materials to produce their final products. Critical raw materials are identified in the model. The critical materials include the effect of the reliability of infrastructure. As a result, critical materials ultimately control the model. This will be explained in detail for each case study.

The number of raw materials in each case study is modeled as a random variable based on a uniform distribution with a minimum value equal to the amount of provided raw materials by infrastructure n at time i and a maximum value equal to the amount of required raw materials by the facility at time i as was explained in equation 3.3 and equation 3.4 and as illustrated in Figure 4.2. In each case study, a table has been constructed for the critical raw materials that can be provided to the facility through each infrastructure system.

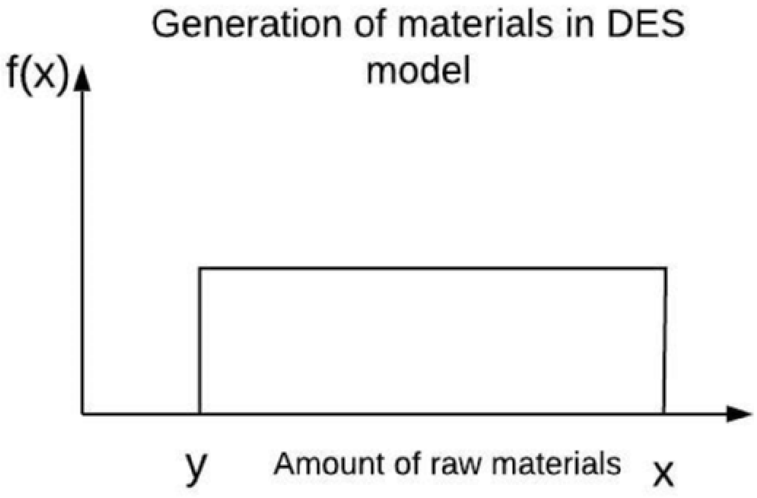


Figure 4.2 Raw materials in the DES model

4.1.2 Reliability of Infrastructure

The reliability of infrastructure that supports the supply chain is calculated based on the probability of failure of infrastructure. The included components of infrastructure in both study cases are roadways, electrical power, water and wastewater, workforce, and communication.

The purpose of constructing a BN is to define the reliability of all the types of infrastructure supporting the supply chain. Since BN relies on probability theory, the nodes that represent the infrastructure components will have a probabilistic nature. The impact of the reliability of infrastructure in the discrete event simulation will be captured by multiplying the reliability of infrastructure by the amount of the required critical material by the facility. The different types of infrastructure will be modeled as nodes and arrowed lines, as described in the following three steps.

1. Identifying the parent nodes and the child nodes in the network based on the definitions of each kind of node was explained in section 3.3.2. Figure 4.3 illustrates the different types of infrastructure that support the supply chain in the two case studies. Assumptions have been made about how each infrastructure component is connected to others in the network.
2. Calculating the reliability of the parent nodes: The reliability of the infrastructure can be calculated based on the calculation of the failure probability of the infrastructure. In the discrete event model of each case study, the parent nodes are roadways, electrical power, and communication. The failure probability of communication depends also on electrical power.

The workforce assumed to be controlled by the infrastructure. Pandemics are disregarded in this model (Telford and Kimberly 2020). The two facilities are assumed to be in an area where they experience blockage of the main highway roads around 15 days during the year and an electrical power outage of 7 days during the year due to disruption by natural hazards. Poisson distribution is being used to represent the occurrence of infrastructure disruption over time. The failure of each infrastructure disruption has a different rate as mentioned in Section 3.1.3.1.

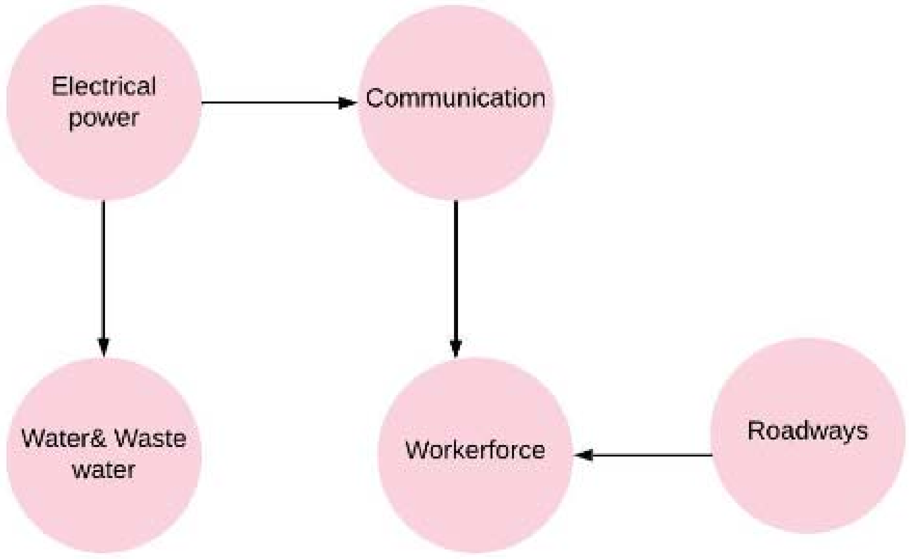


Figure 4.3 Bayesian Network of infrastructure in the DES model

$$\lambda_{roadways} = \frac{7}{365} = 0.01917 = 0.02 \tag{4.1}$$

where,

$\lambda_{roadways}$ is the rate of failure of roadways.

$$Reliability\ of\ roadways = 1 - 0.02 = 0.98 \tag{4.2}$$

$$\lambda_{electricity} = \frac{14}{365} = 0.04109 = 0.04 \tag{4.3}$$

where,

$\lambda_{electricity}$ is the rate of failure of roadways.

$$Reliability\ of\ roadways = 1 - 0.04 = 0.96 \tag{4.4}$$

3. Construct the conditional probability table (CPT). Once the reliabilities associated with the roadways and electrical power systems is calculated, the CPT of the reliability of a child node can be constructed. The reliability of each child node depends on the state of the parent node whether it is reliable or not (failure). Table 4.1 shows the variable names for each infrastructure.

We are going to refer to the reliability of infrastructure by the probability of the letters which appear in Table 4.1 and to the probability of failure using the same letters but with a dash on the top of the letter (e.g., $\boldsymbol{R}$ if the roadways are available , and $\bar{R}$ if the roadways are unavailable). Figure 4.4 shows how the state of the parent node affects the reliability of a child node.

The reliability and the failure probability of the parent node illustrated in Table 4.2-4.5 were calculated based on equation 4.2.

Table 4.1 Infrastructure variable names

R	**Roadways**
E	Electrical power
W	Water & wastewater
C	Communication
F	Workforce

The accuracy of BN analysis is highly dependent on the understanding of the relationship among the nodes. The relationship between every two components of infrastructure is being interpreted through probability. The following three tables show the probability of the infrastructure being reliable with the prior information about the state of the parent infrastructure given. All the values shown in the next three tables are based on the assumptions for the simulation.

Table 4.2 Reliability of the parent nodes of the BN of infrastructure

Infrastructure	**Reliability**
Electrical power	0.96
Roadways	0.98

Table 4.3 Reliability of communication based on the state of electrical power

State of electrical power	**Reliability of communication P(C)**	
Available, $\boldsymbol{E}$	$P\ (C\|E)$	0.92
Unavailable, $\boldsymbol{\bar{E}}$	$P\ (C\|\ \bar{E})$	0.85

Table 4.4 Reliability of water & wastewater based on the state of electrical power

State of electrical power	**Reliability of water and wastewater P(W)**	
Available, $\boldsymbol{E}$	$P\ (W \mid E)$	0.95
Unavailable, $\overline{\boldsymbol{E}}$	$P\ (W \mid \bar{E})$	0.8

Table 4.5 Reliability of workforce based on the state of roadways and communication

State of roadways	**State of communication**	**Reliability of workforce P(F)**	
Available, $\boldsymbol{R}$	Available, C	$P\ (F \mid R \cap C)$	0.95
Available, $\boldsymbol{R}$	Unavailable, $\bar{C}$	$P\ (F \mid R \cap \bar{C})$	0.7
Unavailable, $\overline{\boldsymbol{R}}$	Available, C	$P\ (F \mid \bar{R} \cap C)$	0.85
Unavailable, $\overline{\boldsymbol{R}}$	Unavailable, $\bar{C}$	$P\ (F \mid \bar{R} \cap \bar{C})$	0.25

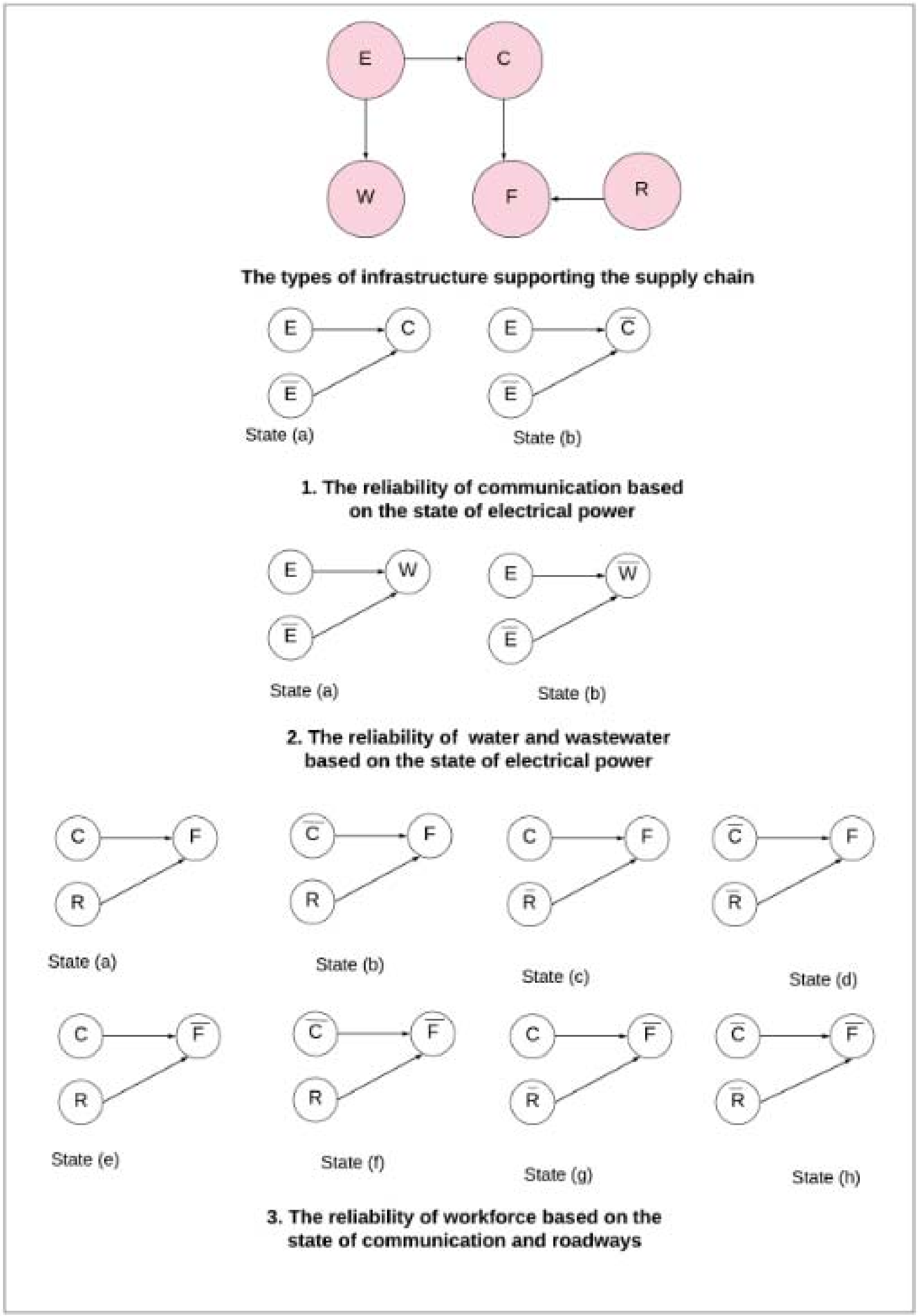


Figure 4.4 Parent nodes and child nodes of the BN of infrastructure in the DES model

Now the CPT can be created for each child node as explained in Figure 4.5 as indicated in the equations below:

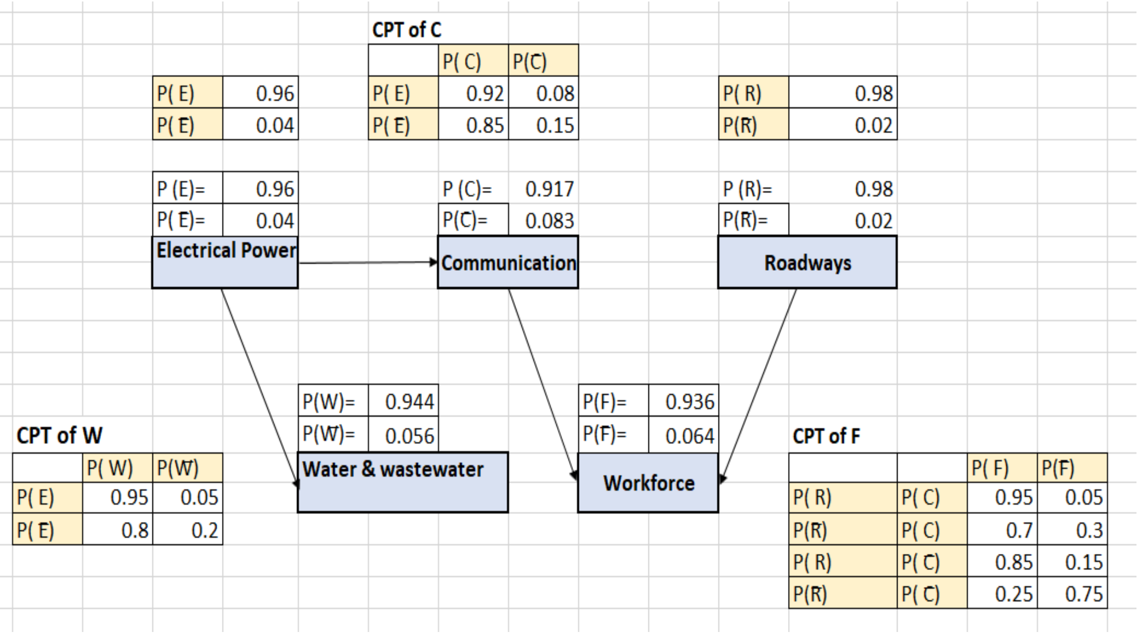
$$P(C) = P(C|E) * P(E) + \mathrm{P(C|/\bar{E}*P(\bar{E})} \tag{4.5}$$

$$P(W) = P(W|E) * P(E) + P(W|\bar{E}) * P(\bar{E}) \tag{4.6}$$

$$P(F) = P(F|(R \cap C)) + P(F|(\bar{R} \cap C)) + P(F|(R \cap \bar{C})) + P(F|(\bar{R} \cap \bar{C})) \tag{4.7}$$

$$P(F) = P(F \cap (R \cap C)) * P(R \cap C) + P\big(F \cap (\bar{R} \cap C)\big) * P(\bar{R} \cap C)$$

$$+P\big(F \cap (R \cap \bar{C})\big) * P(R \cap \bar{C}) + P\big(F \cap (\bar{R} \cap \bar{C})\big) * P(\bar{R} \cap \bar{C})$$



$P(E)$	0.96
$P(\bar{E})$	0.04

CPT of C

	$P(C)$	$P(\bar{C})$
$P(E)$	0.92	0.08
$P(\bar{E})$	0.85	0.15

$P(R)$	0.98
$P(\bar{R})$	0.02

$P(E)=$ 0.96
$P(\bar{E})=$ 0.04

$P(C)=$ 0.917
$P(\bar{C})=$ 0.083

$P(R)=$ 0.98
$P(\bar{R})=$ 0.02

$P(W)=$ 0.944
$P(\bar{W})=$ 0.056

$P(F)=$ 0.936
$P(\bar{F})=$ 0.064

CPT of W

	$P(W)$	$P(\bar{W})$
$P(E)$	0.95	0.05
$P(\bar{E})$	0.8	0.2

CPT of F

		$P(F)$	$P(\bar{F})$
$P(R)$	$P(C)$	0.95	0.05
$P(\bar{R})$	$P(C)$	0.7	0.3
$P(R)$	$P(\bar{C})$	0.85	0.15
$P(\bar{R})$	$P(\bar{C})$	0.25	0.75

Figure 4.5 Analysis of BN of the different types of infrastructure supporting the supply chain in the DES model

4.1.3 Manufacturing Process

The main goal of the supply chain is to turn raw materials into goods and/or services. This process includes multiple manufacturing steps that depend on the sector. In each supply chain case study, there are several tasks. Each task is modeled as an activity block with a specific number of workers referred to it as the activity block capacity and delay time to perform the task. Delay time can be a constant or random variable. Some of the tasks are performed by workers and others by machines, so the delay time is not constant and is susceptible to some change. To capture the uncertainty of the unknown delay, triangular distribution has been chosen to represent the delay time. It is defined by three values: the minimum value, the maximum value, and the most likely value as indicated in Figure 4.6.

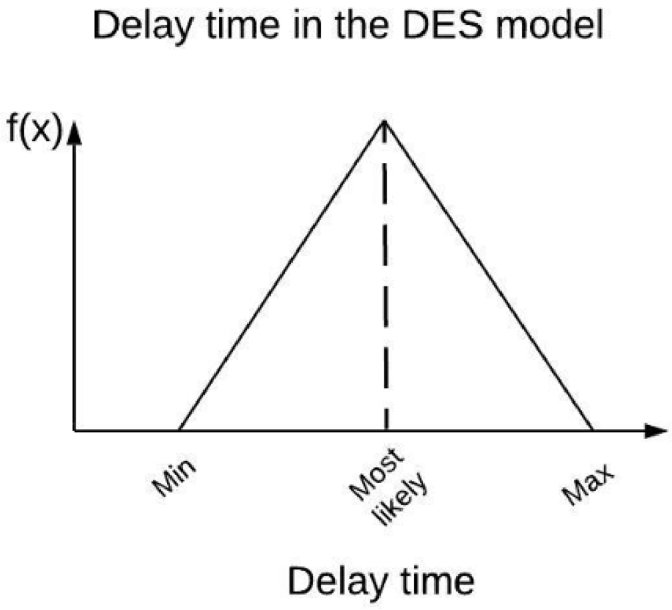


Figure 4.6 Delay time in the DES model

4.1.4 Disruption Scenarios

To expose the DES model to a disrupted scenario, we impose the disruption as a cut in the supply of critical raw materials due to a total loss of a seaport or a roadway. As a result, the facility will activate some contingency plans to deal with the disruption, for example, reliance on inventory or changes made in the kind and distribution of goods.

A comparison among the different scenarios can be done by identifying the supply chain performance, by measuring its ability to satisfy the facility target of production, and by finding the resilience index for each case to help make the right decision in order to strengthen the supply chain resilience to face any possible disruption and to recover its original performance in a short period of time.

4.2 Case Study 1: Food Processing

Company AB is an assembly distribution system. Figure 4.7 depicts the structure of the supply chain. It consists of one supplier, a manufacturing center that has multiple plants and multiple distribution destinations. This supply chain supports one product. The product is canned chicken sausage. The raw materials are delivered daily to the facility through one of the main highways that connect the suppliers with the manufacturing plants.

4.2.1 Model Construction

The simulation time-unit was set to hours indicating that a run over 648 hours is equal to 27 days. The output unit is the number of five O.Z cans produced. The facility runs two shifts. Each shift is 8 hours long.

4.2.1.1 Raw Materials

The generation of materials represents the daily amount of materials that can be provided by a supplier towards production of the final good. Raw materials are divided into two groups: the critical materials that will be controlled by the infrastructure reliability and the non-critical ones. For this case study, the frozen chicken is the critical material. The required raw materials are chicken, metal cans, spices, and other ingredients as illustrated in Table 4.6.

Table 4.6 Raw materials of the chicken manufacturing facility

Raw materials	**Variables**	**Amount**
Chicken	z	60000 lbs./day
Metal cans	$m1$	10560 lbs./day
Spices and others	$s1$	180000 cans/day

The amount of critical material is the minimum amount of the generated items served by each infrastructure based on uniform distribution. Each infrastructure will generate several items based on equation 3.3. Table 4.7 shows the number of materials provided by each type of infrastructure.

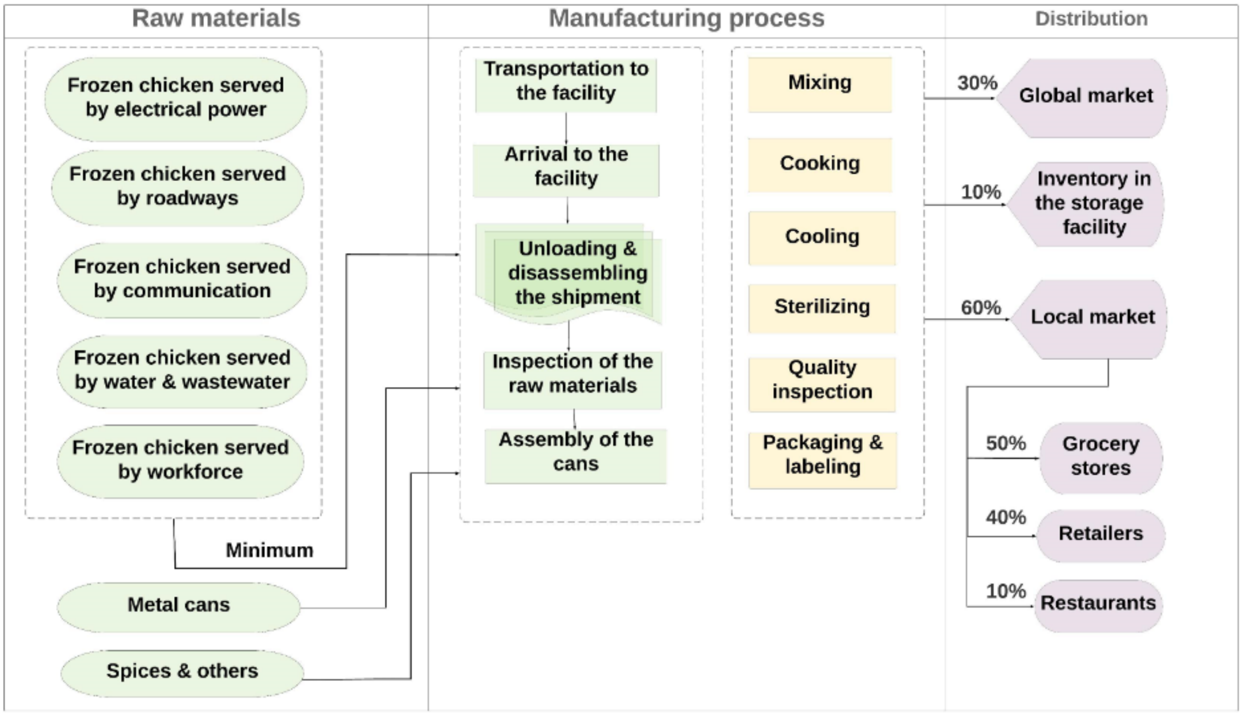


Figure 4.7 Structure of facility AB in DES model

Table 4.7 The number of materials provided by each infrastructure (z_n)

Infrastructure (z_n)	z	a	$x1$ **(lbs./day)**	y **(lbs./day)**
Roadway	z_1	0.98	60000	58800
Electrical power	z_2	0.96	60000	57600
Water & wastewater	z_3	0.944	60000	56640
Communication	z_4	0.9172	60000	54762
Workforce	z_5	0.9361	60000	56166

4. 2.1.2 Manufacturing Process

The chicken experiences multiple manufacturing steps until it becomes ready to be distributed to the market. The service time for each task is presented as triangular distribution. The tasks that are performed by workers are more susceptible to uncertainty than the automated ones. Then, when the materials arrive at the facility, they will be unloaded and inspected, as shown in Table 4.8. The table also shows the delay time of each task that is defined in each block of the activity block in the DES model, and the capacity of each block refers to the number of entities that the block can serve. Batch block is used to assemble the different materials to form one can of chicken sausage. Each one can of sausage consists of chicken, metal cans, spices, and other ingredients as indicated in equation 4.8. The number of produced cans relies on time. Each 1 lb. of chicken is enough to produce 3 cans.

$$c = \frac{1}{3}x_1 + \frac{1}{25}s_1 + m_1 \tag{4.8}$$

where,

c: 1 can of chicken sausage

x_1:1 lb. of chicken

s_1:1 lb. of spices and other ingredients

m_1: 1 metal can

The resulting function of produced cans at any time in days is $F(t)$.

$$\mathrm{F}(t) = 3\mathrm{tZ}. \tag{4.9}$$

where,

t: The time in days

Z: The minimum amount of received chicken based on the reliability of infrastructure.

Table 4.8 The delay time and the capacity of Activity block in DES model for case study 1

Task	Capacity	Min (hrs.)	Max (hrs.)	Most Likely (hrs.)
Transportation of chicken to the facility	1 shipment	1	1.5	1
Arrival of chicken to the facility/ unloading	1 shipment	2	2.5	2
Inspection of the chicken	1 shipment	1	1.5	1
Mixing	6000 cans	0. 67	0.7	0.67
Cooking	6000 cans	1.6	1.6	1.65
Cooling	6000 cans	0.67	0.7	0.67
Sterilizing	6000 cans	0.83	0.85	0.83
Inspection	100 cans	1.62	1.8	1.8
Packaging and labeling	100 cans	3.6	3.9	3.6

4.2.1.3 Distribution

To model the supply chain performance behavior under disruption, we will be focusing on the number of outputs that are allocated to each market. Transportation of the final product is disregarded in this project. The number of outputs helps to assess the supply chain's ability to satisfy customers in the local and global markets.

Outputs are listed by the number of cans and by categorizing the market for the final good into three groups: the local market, the global market, and inventory in the warehouses. The internal shares of the local market have been shown in detail because that will affect some of the strategies that the facility will be applying during a disruption.

Table 4.9 Total market distribution of the canned chicken sausage

Market	**Percentage**
Local market	60%
Inventory	10%

Table 4.10 Local market distribution of the canned chicken sausage

Destination	**Percentage**
Grocery	50%
Retailers	40%
Restaurants	10%

4.2.2 Scenarios and Response Plans

For this manufacturing supply chain, the simulation is being done for 648 hours (equivalent to 27 days), and the supply chain performance is being tracked every day because the materials arrive daily to the facility.

The manufacturing plant has only one local supplier for the chicken. The chicken is sent from the supplier to the facility through a highway. Three scenarios are being tested: the steady state, disrupted state, and finally the disrupted state while undergoing a response plan.

- <u>Steady state</u>: the amount of frozen chicken is influenced by the reliability of infrastructure under normal conditions.

$$54762 \leq z \leq 60{,}000 \text{ (critical material)} \tag{4.10}$$

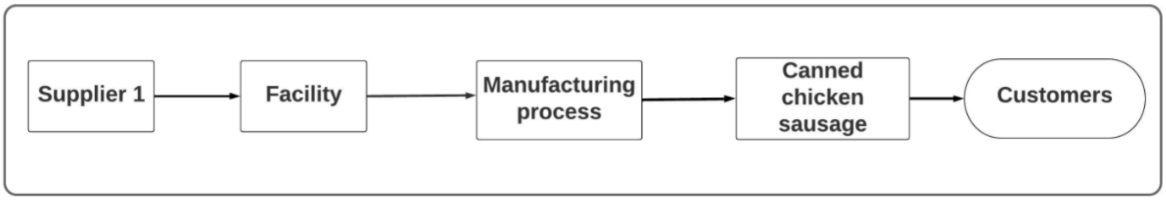


Figure 4.8 Facility AB under normal state

- <u>Disrupted state</u>: affected by a transportation disruption of seven days, which causes an interruption in the flow of critical materials from the supplier to the facility for seven days.

$$z = 0 \text{ (critical material)} \tag{4.11}$$

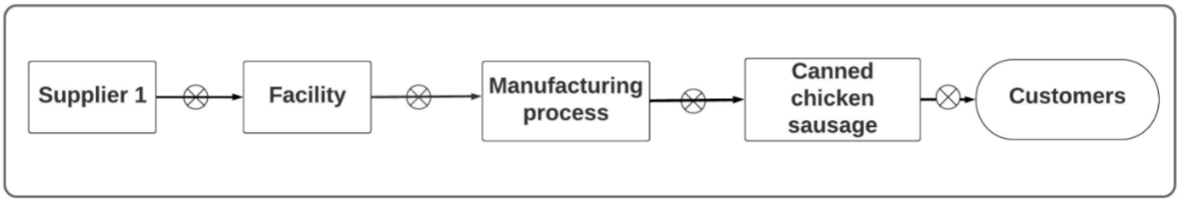


Figure 4.9 Facility AB under disrupted state

- Response plans for the disrupted state (shared resources).

  The facility can adapt to the disruption by keeping the same target of cans and getting the critical materials from another supplier by agreeing to useless amount of raw materials. The supply chain will be willing to share the resources of a new supplier with other supply chains ahead of time by paying a premium for the new supplier (van Donk and van der Vaart 2005). This agreement provides the facility with certain amount of materials during the loss of its main supplier. In this case study, the assumption is that the facility runs during the disrupted days by relying on a local resource that can provide the facility 50-70% of their regular requirement of the critical materials for eight days.

$$30000 \leq z \leq 42000 \text{ (critical material)} \tag{4.12}$$

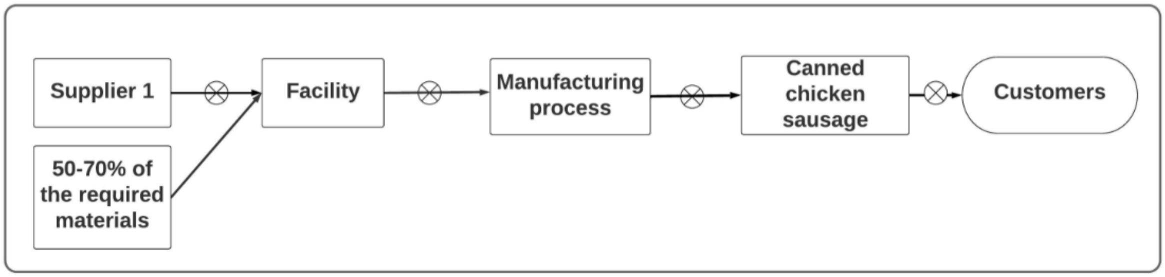


Figure 4.10 Facility AB under a disrupted state with the mitigation plan

4.2.3 Results and Analysis

4.2.3.1 Steady State

The objective of this work is to quantify the resilience of the supply chain to risk due to the reliability of infrastructure and a total failure of the infrastructure responsible for logistics (seaport/roadway). The resilience index is calculated for the steady state and disrupted state before taking any response action and after taking a response. It is calculated for a time window between 1 and 27 days.

The condition of the steady state was tested by running the model for 27 days to achieve the daily target of facility AB of the canned chicken sausage. We calculate the performance of the facility by dividing the number of outputs over the daily target of the facility. The fulfillment rate of the steady state shows the impact of the reliability of infrastructure. During the steady state, the facility is provided with raw materials from the supplier.

Figure 4.11 shows the amount of the critical materials provided by the supplier based on the reliability of infrastructure under a steady state. Here we can notice that the amount of critical materials is not a constant value. This result aligns well with the assumption that materials will follow a uniform distribution with specific minimum and maximum values. The figures also show the influence of the loss of suppliers due to the disruption of the roadways when the facility will not receive any materials during the seven days. And finally, it shows the impact of adapting the facility to share resource plans where the amount of the chicken has increased from zero to almost 50% of the original one.

4.2.3.2 Disrupted State

Once we were certain that the model was operating well under the normal state, we ran the model for 27 days and imposed a disruption scenario to the facility by losing all the critical materials provided by the supplier due to a natural hazard that caused seven days of a block to the main highway that is used to transport the critical materials to the seaport. This disruption prevented the facility from receiving the materials from supplier 1 as shown in Figure 4.11. They provided zero materials. As a result, the fulfillment rate dropped to zero.

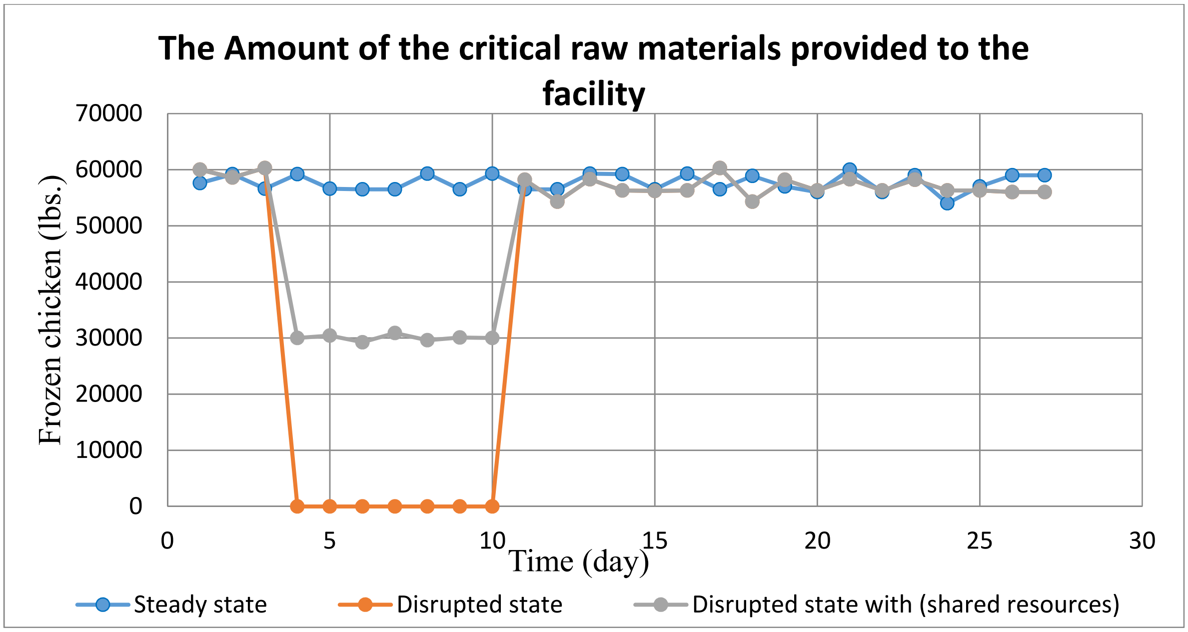


Figure 4.11 The amount of chicken provided to the facility

4.2.3.3 Disruption and Mitigation Response

The production of the canned chicken sausage is being tracked over time to capture the impact of the disruption and test the different mitigation responses. The steady state is being used as a reference to validate the other scenarios. For the disrupted state, we included the calculation when no backup plan is applied. We evaluate the impact of shared resources with other supply chains. Sharing resources is a mitigation plan used in this model. We assume this facility is of medium size and has medium capabilities. Therefore, it will rely on a local supplier to gain 50-70% of its original needs. In this case, the facility will receive a different amount of materials based on the amount that the temporary resource can provide.

The performance of the facility under the different scenarios and response plans for each of the specific destinations is illustrated in the following figures based on equation

3.9, by dividing the number of outputs over the daily target of the company. The performance of the facility varies under the steady state due to the reliability of the different types of infrastructure supporting the supply chain. Table 4.11 shows a sample of the fulfillment rate of the facility for the output distribution under the different scenarios.

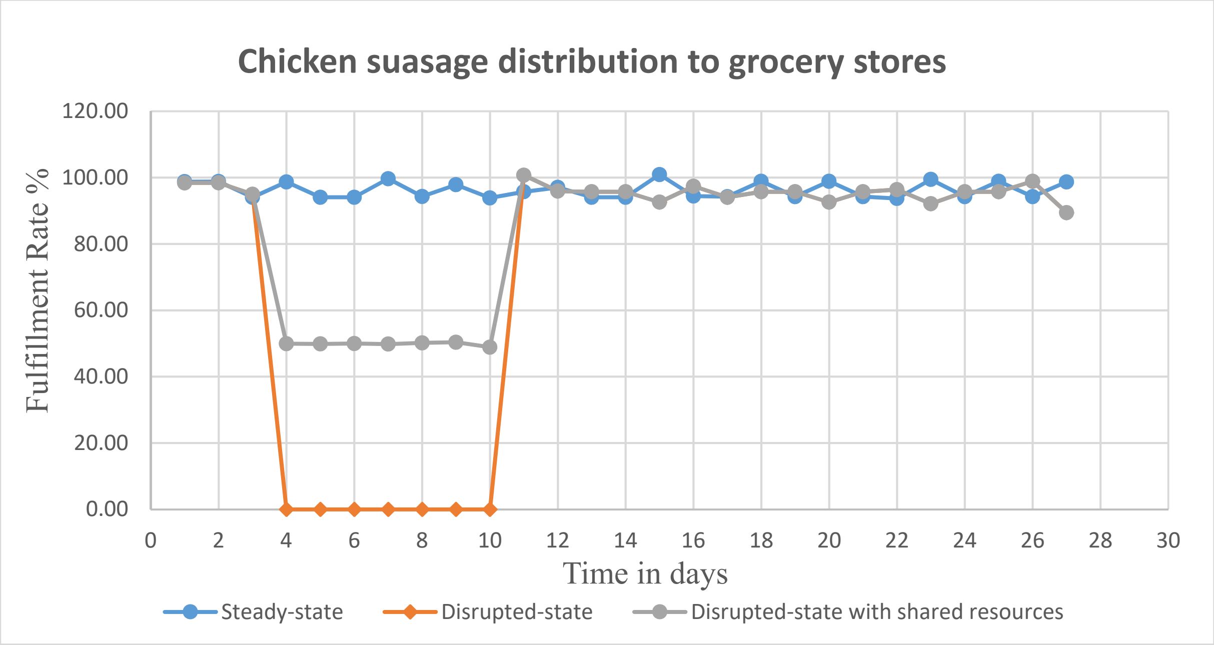


Figure 4.12 Fulfillment rate of chicken sausage distribution to grocery stores

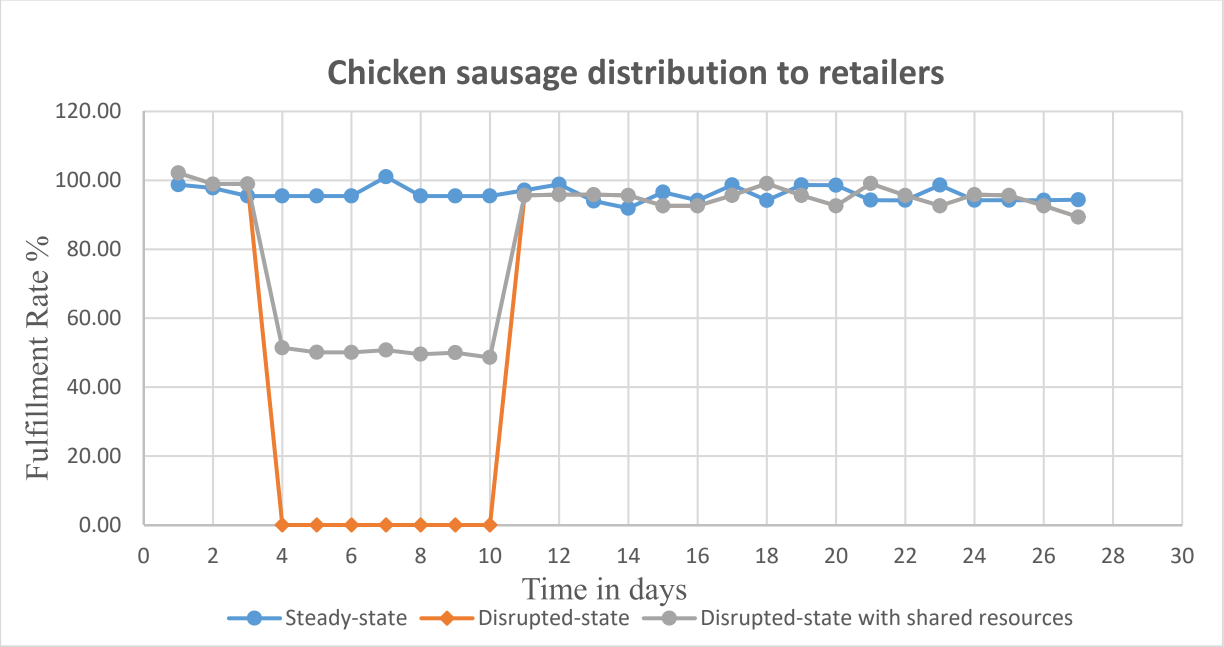


Figure 4.13 Fulfillment rate of the chicken sausage distribution to retailers

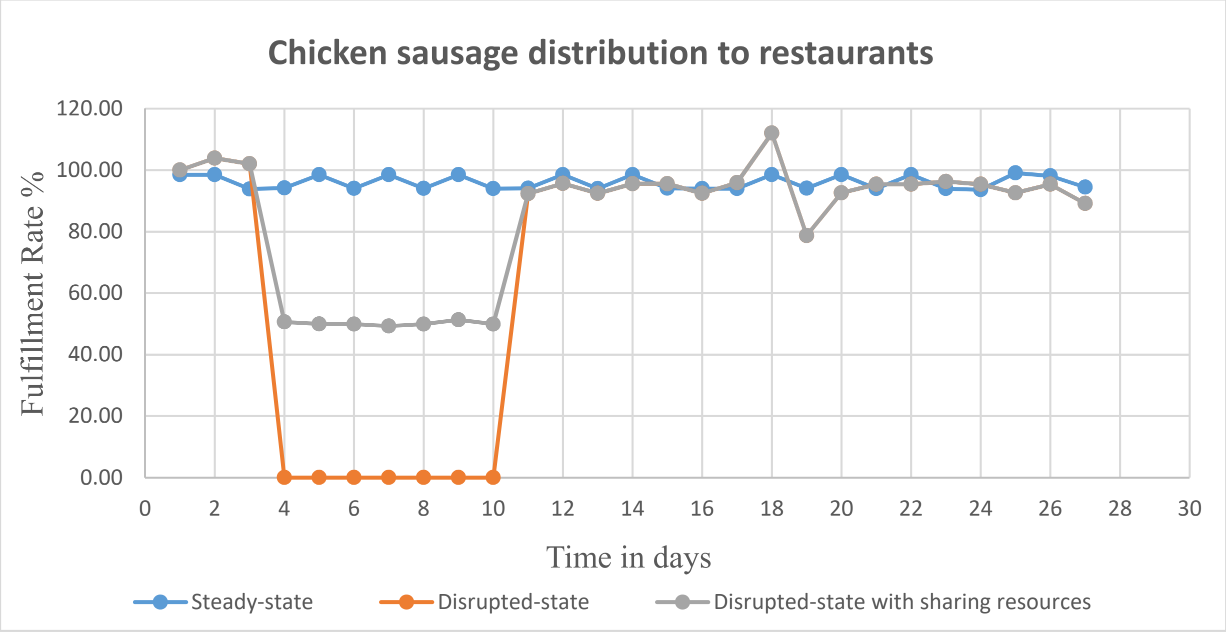


Figure 4.14 Fulfillment rate of the chicken sausage distribution to restaurants

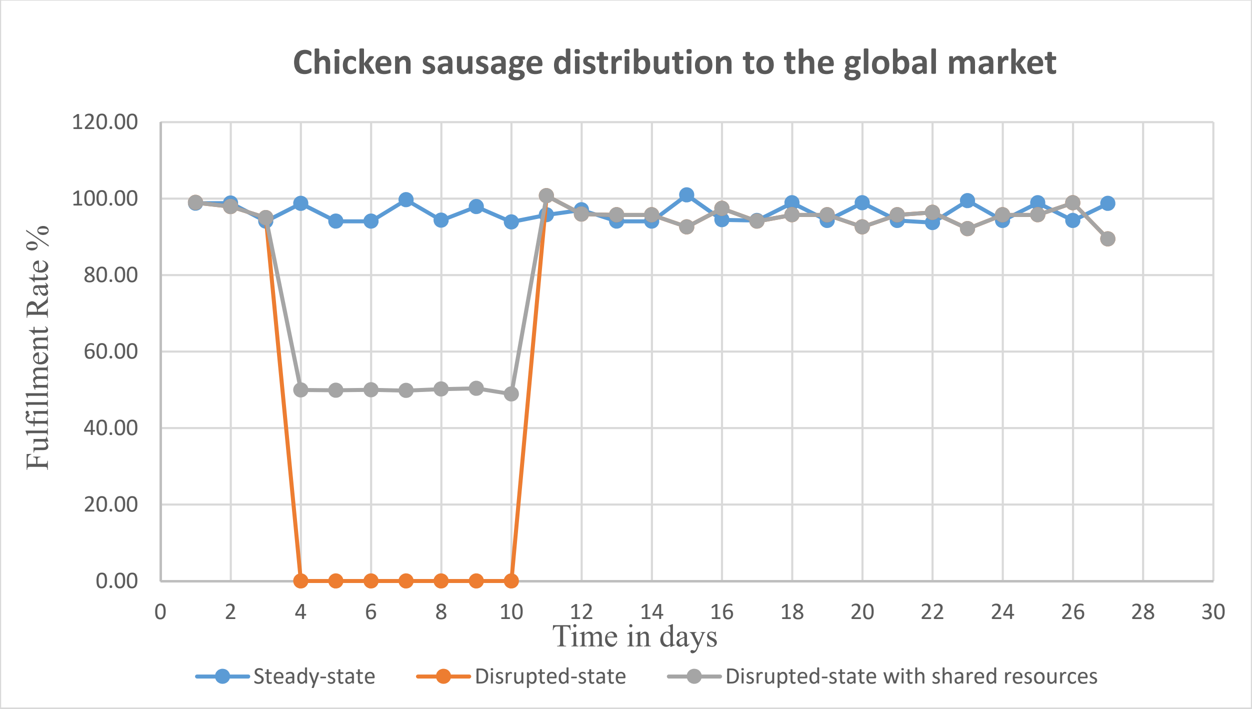


Figure 4.15 Fulfillment rate of the chicken sausage distribution to the global market

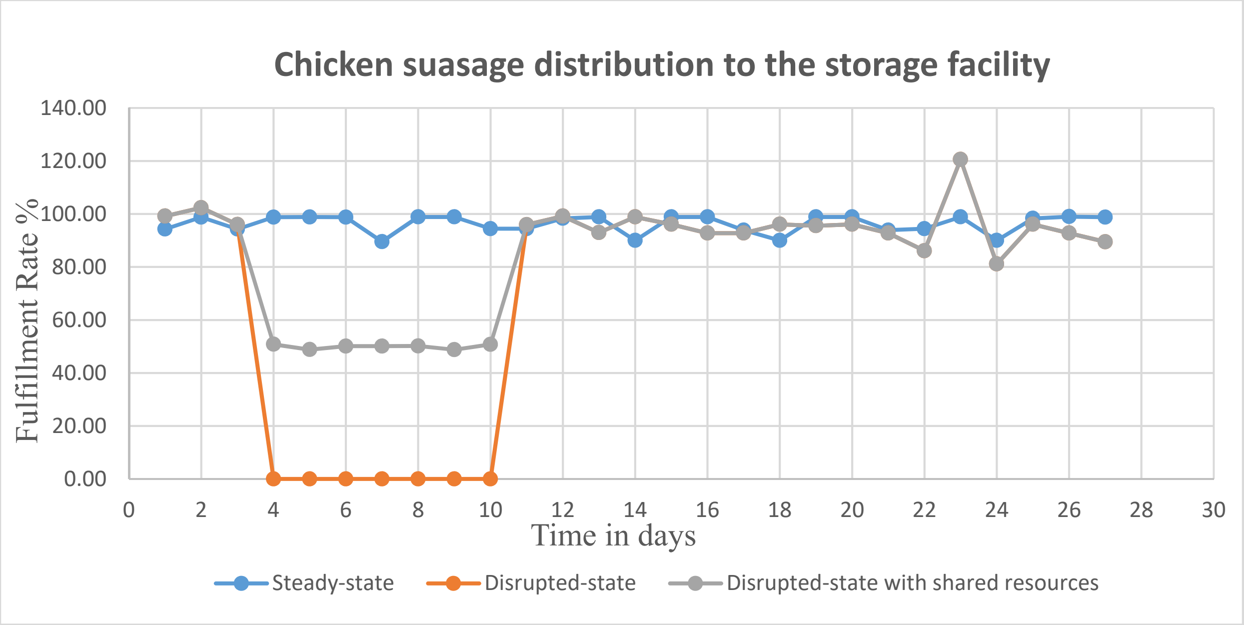


Figure 4.16 Fulfillment rate of the chicken sausage distribution to the storage facility

4.2.3.4 Resilience Index

The resilience index of a supply chain AB is calculated based on the concept of the resilience profile presented in Chapter 3. The resilience index depends on the performance of the supply chain under different scenarios. In the steady-state assumption, the supplier can deliver the materials between day 1 and day 27. The amount of materials received by facility AB varies from one day to another due to the reliability of the infrastructure; therefore, the fulfillment rate is still high between 95-100% as illustrated in Figures 4.12 to 4.16. The resilience index is calculated for the time window between day 1 and 27 based on equation 3.10 as shown in Table 4.12. When the disruption occurs and the fulfillment rate reaches zero, this indicates that the facility is not capable of withstanding the negative impact of the loss of the supplier. Consequently, the resilience index becomes 0.65.

Table 4.11 Fulfillment rate of chicken sausage distribution to grocery stores

Fulfillment Rate %			
Day	Steady state	Disrupted state	Disrupted state (shared resources)
1	99	98	98
2	99	98	98
3	94	95	95
4	99	0	50
5	94	0	50
6	94	0	50
7	100	0	50

8	94	0	50
9	98	0	50
10	94	0	49
11	96	0	50
12	97	101	101
13	94	96	96
14	94	96	96
15	101	96	96
16	94	93	93
17	94	97	97
18	99	94	94
19	94	96	96
20	99	96	96
21	94	93	93
22	94	96	96
23	99	96	96
24	94	92	92
25	99	96	96
26	94	96	96
27	99	99	99

When the facility adopts a mitigation plan to respond, the resilience index increases, too. This strategy will increase the resilience of the supply chain and it will allow the facility to keep its production although not at the same level as the original one. Optimally, the facility will be able to satisfy its customers.

Table 4.1 Resilience index of facility AB

Scenario	**Resilience index**
Steady state	0.96
A disrupted state without a mitigation plan	0.65
A disrupted state with shared resources	0.82

4.3 Case Study 2: Medical Device Assembly

Company AC is another assembly distribution system for medical devices located in the same geographical area. The company's manufacturing system has two lines of production. The first is IV bags made from resin film and the associated plastic for tubing. The second production processes two types of medical kits. Figure 4.17 explains the structure of the supply chain. It consists of one supplier, a manufacturing center that has multiple plants, and multiple distribution destinations. The facility also has a warehouse to keep an inventory of the raw materials. Material is shipped to the facility every six days through a seaport.

4.3.1 Model Construction

The simulation time-unit was set to hours indicating that a run over 2016 hours, which is equal to 14 weeks. The output unit is the number of intravenous (IV) bags and medical kits. The facility runs one 12-hour shift.

4.3.1.1 Raw Materials

The generation of materials represents the number of raw materials that can be provided by a supplier every six days. Raw materials are divided as in the previous case study into two groups: the critical materials that will be controlled by infrastructure reliability and the non-critical ones. The resin film is the critical material in this case study; the other required raw material is plastic as illustrated in Table 4.13.

Table 4.13 Raw materials of the IV bags and medical kits

Raw materials	**Variables**	**Amount**
Resin film	x	40000 lbs./6days
Plastic	s	10000 lbs./6days

The amount of the critical material (i.e., resin film) is the minimum amount of the generated items served by each infrastructure. This has been modeled by using a uniform distribution. Each infrastructure will generate several items based on equation 3.3. Table 4.14 shows the number of materials provided by each type of infrastructure.

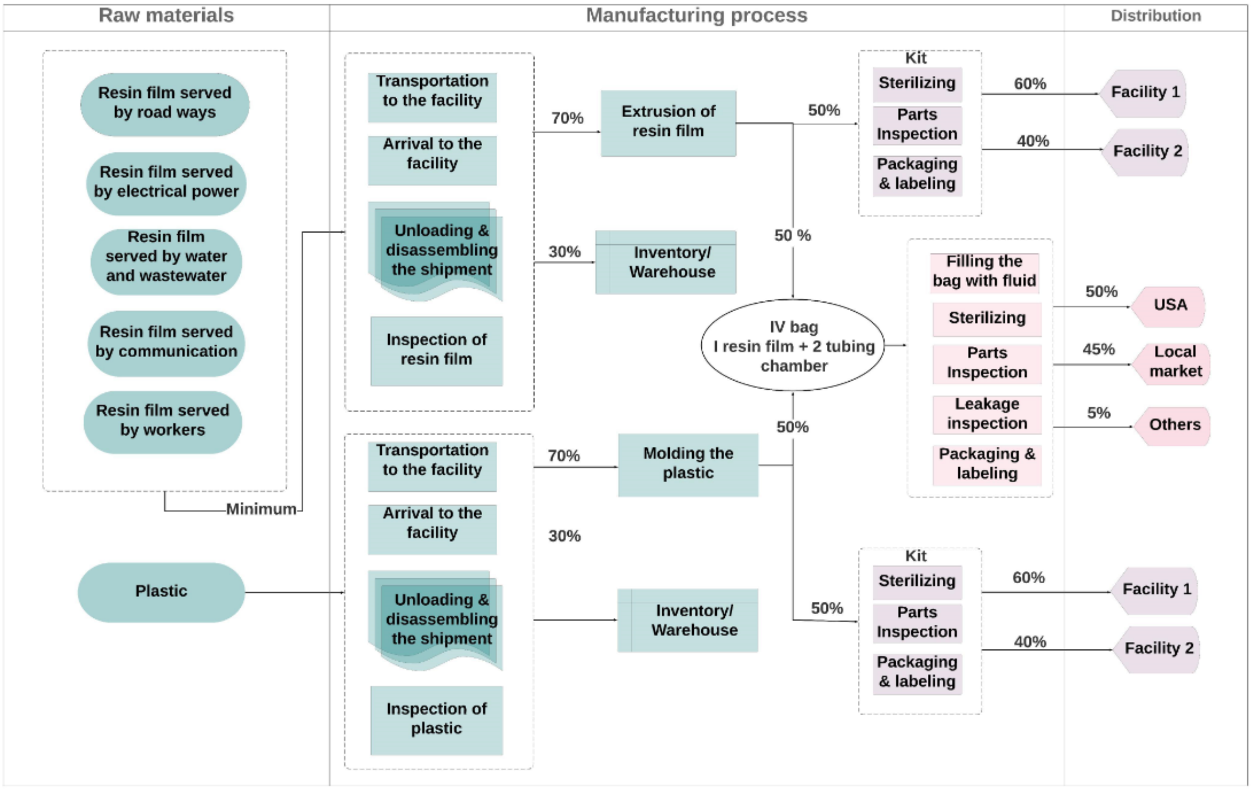


Figure 4.17 Structure of facility AC in DES model

Table 4.14 The number of materials provided by each infrastructure (z_n)

Infrastructure (z_n)	z	a	$x1$ **(lbs./day)**	y **(lbs./day)**
Roadway	z_1	0.98	40000	39200
Electrical power	z_2	0.96	40000	38400
Water & wastewater	z_3	0.944	40000	37760
Communication	z_4	0.9172	40000	36688
Workforce	z_5	0.9361	40000	37444

4. 3.1.2 Manufacturing Process

The resin film and the plastic need to be processed until they become IV bags and medical kits. The service time for each associated process task is modeled as triangular distribution. As mentioned in section 4.2, the tasks that are performed by workers are more susceptible to uncertainty than the automated ones. Table 4.15 shows all the manufacturing tasks that are required to produce the IV bags and the medical kits. The shipment that arrives at facility AC will be unloaded and inspected.

Table 4.15 shows the delay time of each task that is defined in each block of the activity block in the DES model and the capacity. Batch block is used to assemble the different materials to form one IV bag. Each IV bag consists of resin film and plastic as indicated in equation 4.13. The number of produced IV bags relies on time.

$$v = 1r + 2b \tag{4.13}$$

$$k1 = 1r \tag{4.14}$$

$$k2 = 2p \tag{4.15}$$

where,

v: 1 IV bag

r: 1 lb. of resin film

b: 1 tubing$=\frac{1}{8}p$

p: 1lb.of plastic= 8 tubings

$k1$: kits made of resin film

$k2$: kits made of plastic

The resulting function of produced IV bags and medical kits at any time in days is $F(t)$.

$$F(t) = 0.7Zt \tag{4.16}$$

where,

t: The time in weeks

z_i: The minimum amount of received resin film based on the reliability of infrastructure at time i

Table 4.15 The total delay time and the capacity of Activity block in DES model for case study 2

Task	Capacity	Min (hrs.)	Max (hrs.)	Most Likely (hrs.)
Transportation of the resin film	1 shipment	1	1.5	1
Arrival of raw materials to the	1 shipment	1	2.5	2
Inspection of raw materials	1 shipment	1	1.5	1
Assembly and filling with fluid	10 bags	14	14.5	14
Sterilizing	500 bags	7	7.5	7
Parts inspection	10 bags	23.8	28	28
Leakage inspection	6 bags	23.3	23.5	23.3
Packaging & labeling	10 bags	28	35	42

4.2.1.3 Distribution

The goal of the facility AC is to meet the target number of IV bags and medical kits allocated to each market. There are four relevant markets for this case study: the U.S. market, the local market, other countries or whether to other facilities of the parent company for further processing. Transportation of the final product is disregarded in this project. The number of outputs is essential to the assessment of the supply chain performance.

Outputs are listed by the number of IV bags and kits made of resin film and plastic and by categorizing the market of the IV bags into three groups: the local market, USA market, and other countries. In contrast, the medical kit bags are sent to two other facilities for further processing.

Table 4.16 Total market distribution of the IV bags

Market	Percentage
USA market	50%
Local market	45%
Other countries	5%

Table 4.17 Total market distribution of medical kits

Destination	Percentage
Facility 1	60%
Facility 2	40%

4.3.2 Scenarios and Response Plans

For this manufacturing supply chain, the simulation runs for 2020 hours, and the supply chain performance is tracked every 6 days because of the same amount of time that the facility receives the raw materials. We will discuss two design plans. The first one is the original assumption that the manufacturer has only one resin film supplier that sends the materials through a seaport. The second plan is to assume that the company relies on two suppliers. Three scenarios are being tested for the two plans: the steady state, the disrupted state, and finally the disrupted state while undergoing a response plan.

4.3.2.1 Design Plan One

- Steady state: the amount of resin film is influenced by the reliability of infrastructure under normal conditions. The facility has one supplier that sends the materials through the seaport.

$$36688 \leq z_{\mathrm{i}} \leq 40{,}000 \text{ (critical material)} \tag{4.17}$$

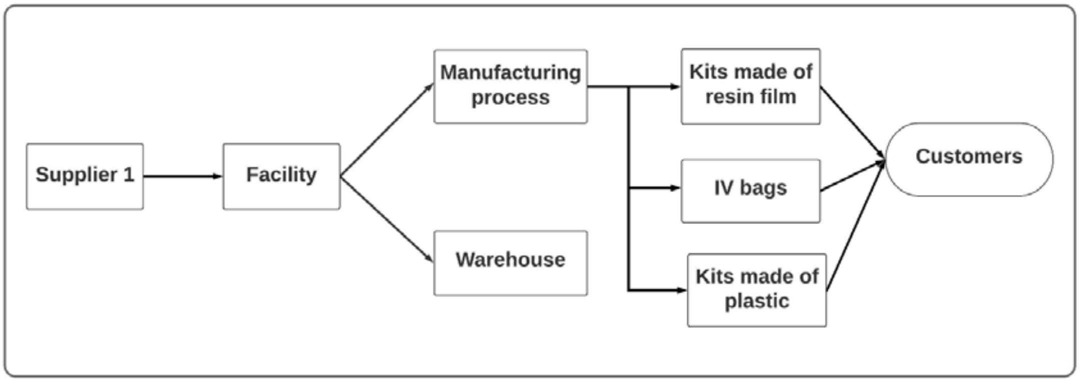


Figure 4.18 Facility AC with design plan one under normal state

- Disrupted state: affected by a transportation disruption for two weeks, which causes an interruption in the flow of the resin film from the supplier to the facility.

$$z = 0 \text{ (critical material)} \tag{4.18}$$

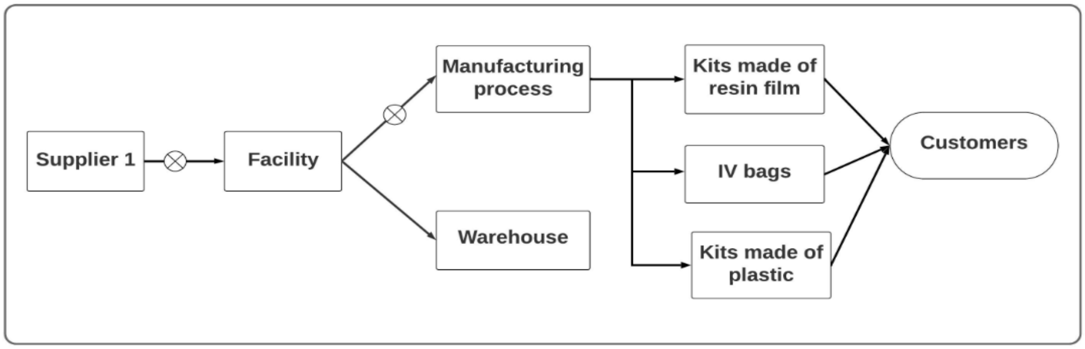


Figure 4.19 Facility AC with design plan one under disrupted state

- Response plans for the disrupted state (Using inventory)

  The facility can mitigate the disruption in getting critical materials by keeping the same weekly target of outputs and relying on the inventory of raw materials. In this case, the supply chain will be able to produce IV bags and medical kits. The stored amount of materials depends on how much and for how long the facility has been storing the materials when the disruption occurs. In this case study, an assumption has been made that when the run starts, the inventory in the warehouse is zero. The disruption occurs during the third week. The amount of raw materials is a function of time.

$$z_{\mathrm{i}} = \sum_{i=i}^{j} 0.3Z_{\mathrm{i}}(\text{critical material}) \qquad (4.19)$$

where,

j: number of the last week before the occurrence of the disruption

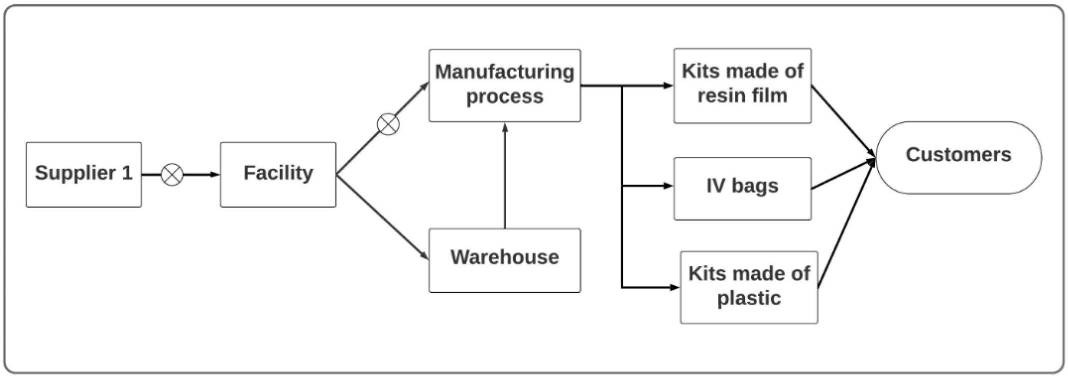


Figure 4.20 Facility AC with design plan one under a disrupted state with a mitigation plan of using the inventory

Another mitigation plan the facility can follow to mitigate the impact of the disruption is to do a reallocation of the raw materials obtained from the inventory during the disruption. The facility will produce just the IV bags from the resin film. More details will be discussed in the results.

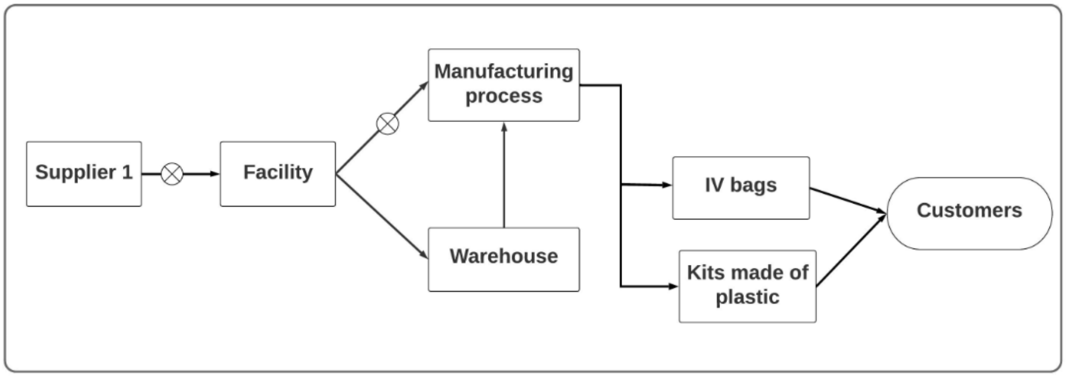


Figure4.21 Facility AC with design plan one under a disrupted state with a mitigation plan of reallocating the resin film

4.3.2.2 Design Plan Two

- Steady state: the amount of resin film is influenced by the reliability of infrastructure under normal conditions. The facility has two suppliers that send the materials through a seaport and roadway

$$z_{\mathrm{i}} = x_1 + x_2 \text{ (critical material)} \tag{4.20}$$

where,

$x1$: The amount of resin film provided by supplier 1 (70% of the required materials by the facility)

$x2$: The amount of resin film provided by supplier 2 (30% of the required materials by the facility)

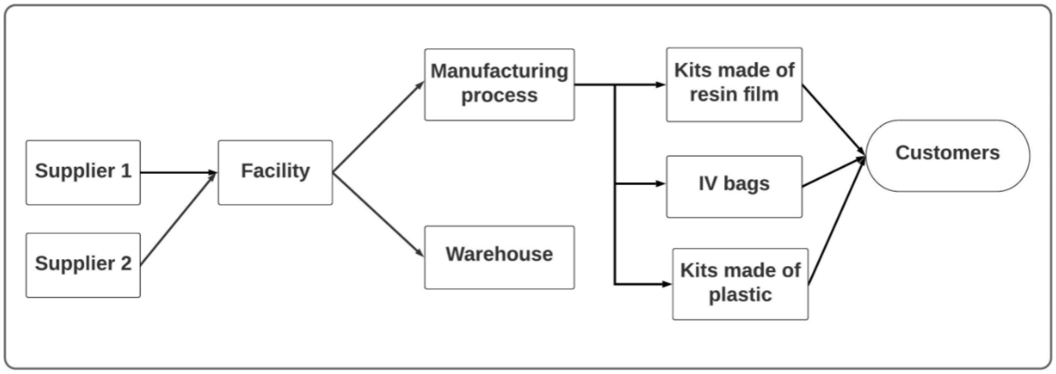


Figure 4.22 Facility AC with design plan one under normal state

- Disrupted state: affected by a transportation disruption for two weeks, which causes an interruption in the flow of the resin film from supplier 1 to the facility.

$$x1 = 0 \tag{4.21}$$

$$z_{\mathrm{i}} = x_2 \tag{4.22}$$

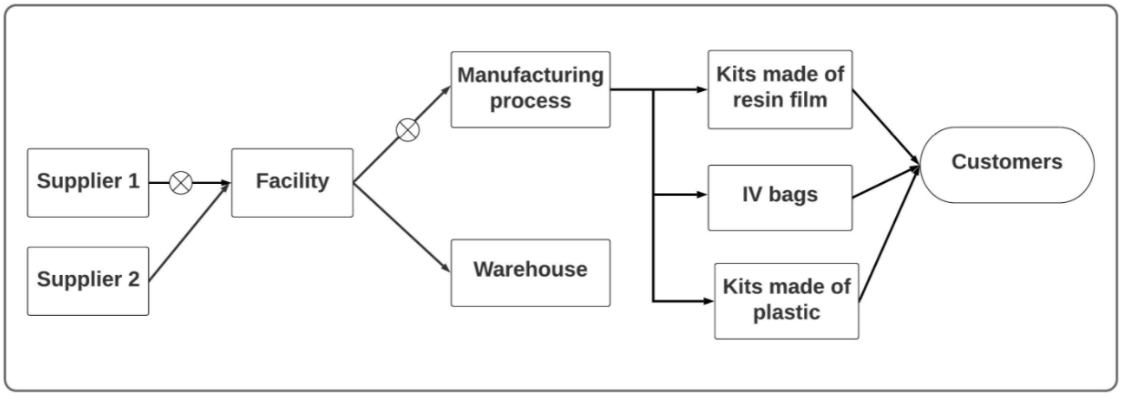


Figure 4.23 Facility AC with design plan two under a disrupted state with a mitigation plan of using the inventory

- Response plans for the disrupted state (using inventory)

  The facility is still receiving 30% of the amount of raw materials by relying on the inventory of raw materials. The amount of raw materials depends on the amount provided by supplier 2 and the stored amount of materials in this case study. An assumption has been made that when the run starts, the inventory in the warehouse is zero. The disruption occurs during the third week. The amount of raw materials is a function of time and the amount provided by supplier 2.

$$z_{\mathrm{i}} = x_2 + \sum_{i=i}^{j} 0.3Z_{\mathrm{i}}(\text{critical material}) \tag{4.23}$$

where,

j: number of the last week before the occurrence of the disruption

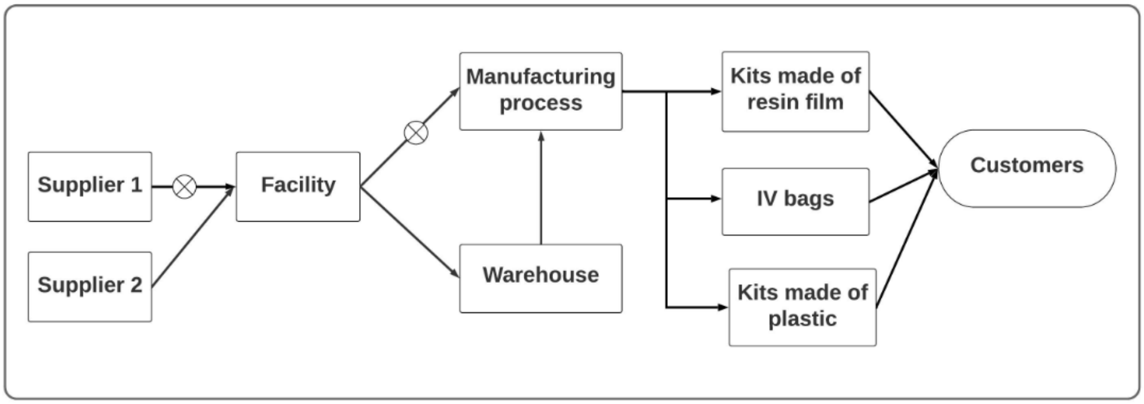


Figure 4.24 Facility AC with design plan two under a disrupted state with a mitigation plan of using the inventory

The second mitigation is the reallocation for the raw materials obtained from the inventory. The facility will produce just the IV bags from the resin film. The difference in this design plan from the previous one is that the facility is still receiving materials from supplier 2 and also all the materials will be allocated for the production of the IV bags.

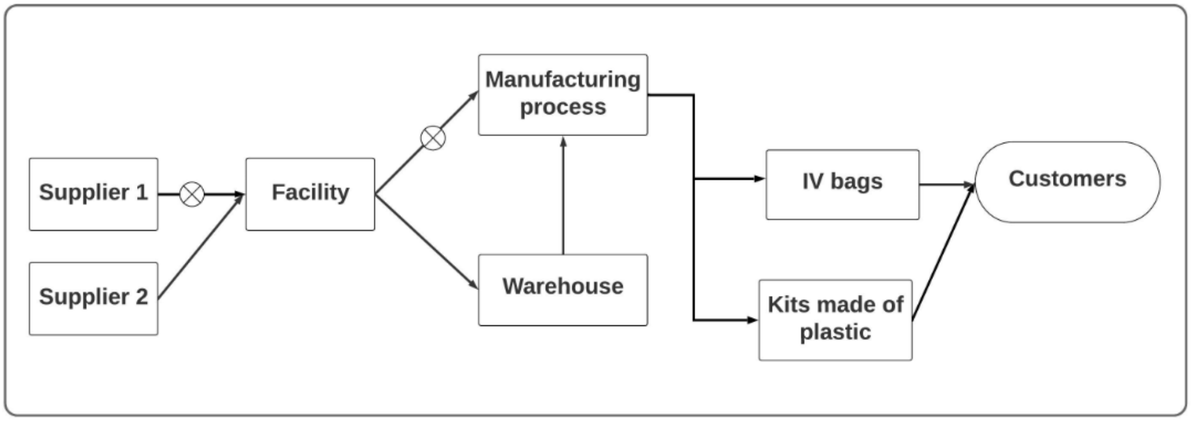


Figure4.25 Facility AC with design plan two under a disrupted state with a mitigation plan of reallocating the resin film

4.3.3 Results and Analysis

4.3.3.1 Steady State

To create the steady state condition for each design plans we ran the model for 14 weeks in order to match the weekly target of facility AC of the IV bags and the two kinds of kits. We tracked the performance of the facility by dividing the number of outputs over the weekly target of the facility. The fulfillment rate of the steady state of the two-design plan clearly shows the impact of the reliability of infrastructure. During the steady state, the facility is provided with resin film from the supplier. Figure 4.26 shows the amount of the provided resin film under normal state and disrupted state conditions. The amount of critical materials is not a constant value. This result meets the assumption that materials will follow a uniform distribution with specific minimum and maximum values.

4.3.3.2 Disrupted State

For this part of the research, we ran the model for 14 weeks and hit the facility with disruption due to a natural hazard that caused a two-week shutdown to the seaport. This disruption prevented the facility form receiving the resin film from supplier 1 in the two-design plan as shown in Figure 4.26 and Figure 4.27. When the facility has only one supplier, the materials delivered during the disruption is zero. As a result, the fulfillment rate reaches zero under design plan one whereas in the plan with two suppliers, the facility can keep a low level of production.

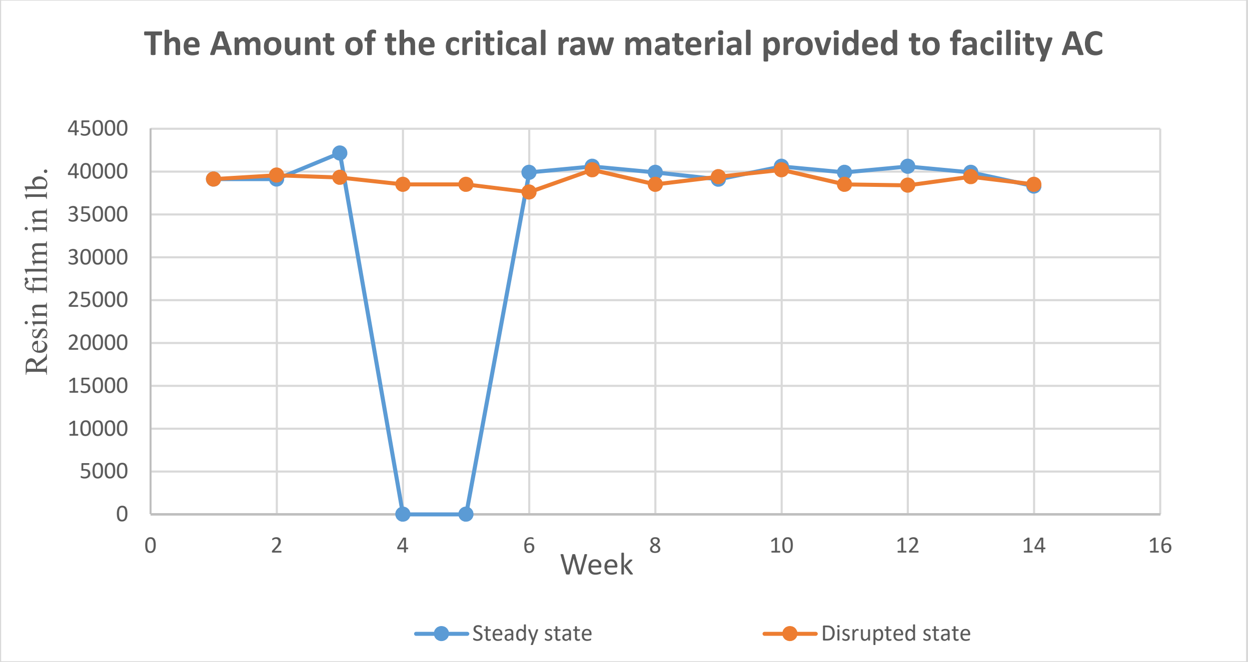


Figure4.26 The amount of resin provided to the facility for design plan one

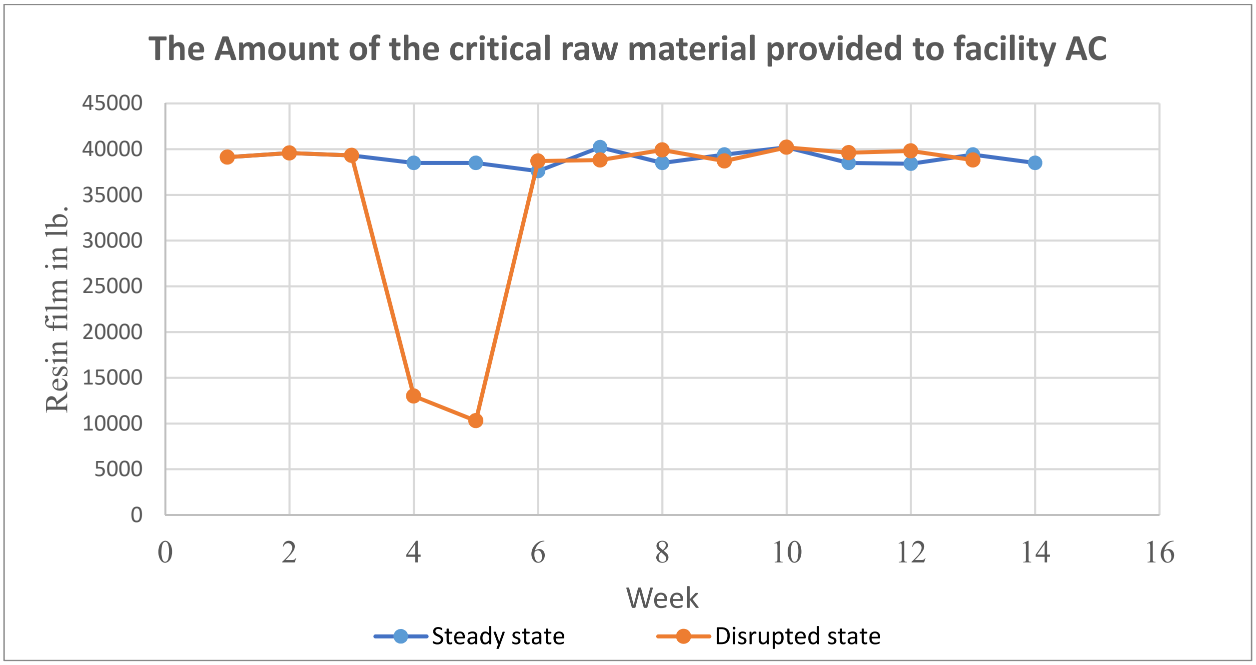


Figure 4.27 The amount of resin provided to the facility for design plan two

4.3.3.3 Disruption and Mitigation Response

We track the disruptions of specific products to observe their impact and test the different mitigation responses and the different design plans for the two-design plans. As a reference, we included the calculation when no backup plan is applied. First, we evaluated the impact of using the inventory to produce IV bags and medical kits. The facility uses 50% of its inventory the first week, assuming that it doesn’t know how long the disruption will stay and another 50% the second week. The difference between the two-design plans is that when the facility has two suppliers, the facility still has a partial amount of the materials (30%). Thus, the production will never reach zero. The second mitigation plan is the decision to relocate the raw materials by producing the product with high demand or priority. In this case, the facility keeps the production of the IV bags and halts the production of the medical kits made of the resin film. In this way, all the resin film in the inventory and the received materials in design plan two will be allocated to produce IV bags. The testing results of the two-design plans are graphically presented for the 14 weeks. Table 4.18 shows a sample of the fulfillment rate of the IV bags distributed to the USA.

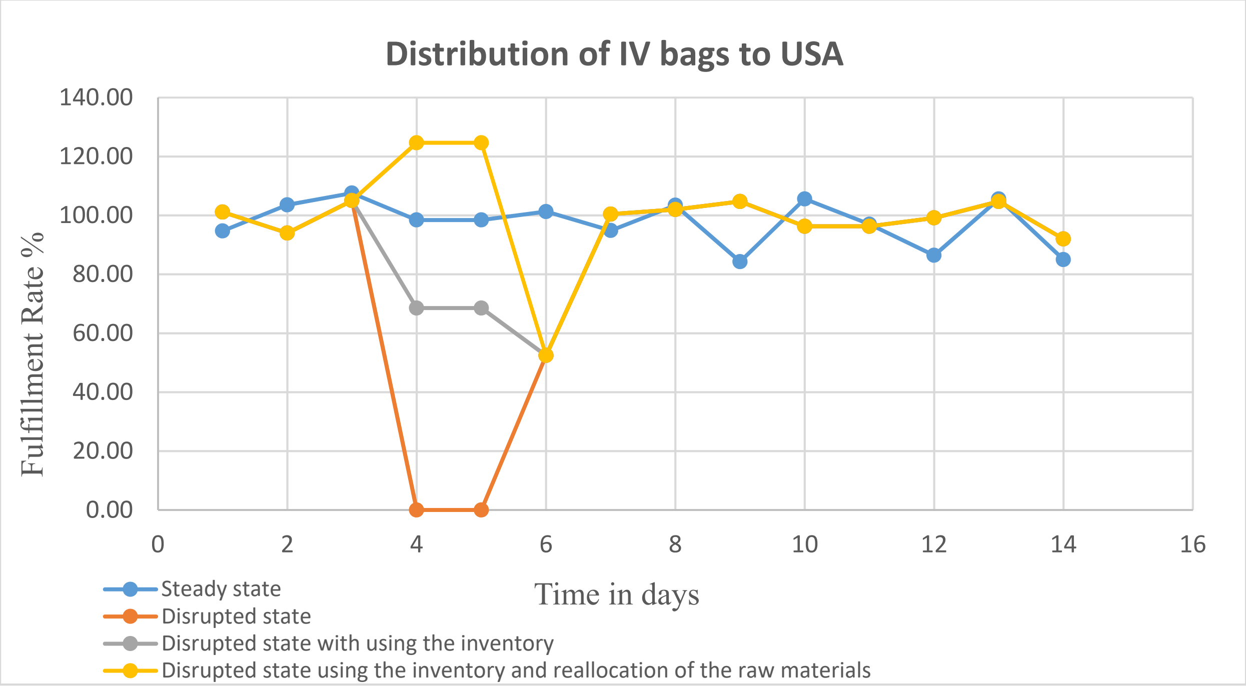


Figure 4.28 Fulfillment rate of IV bags distribution to the USA for design plan one

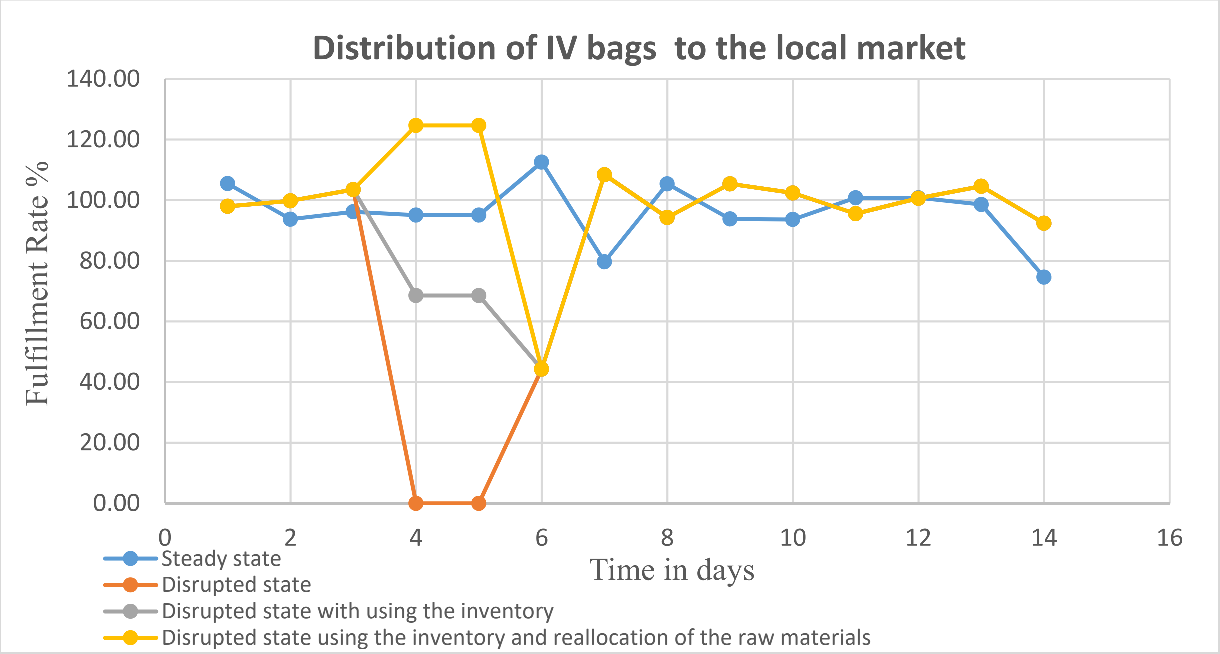


Figure 4.29 Fulfillment rate of IV bag distribution to the local market for design plan one

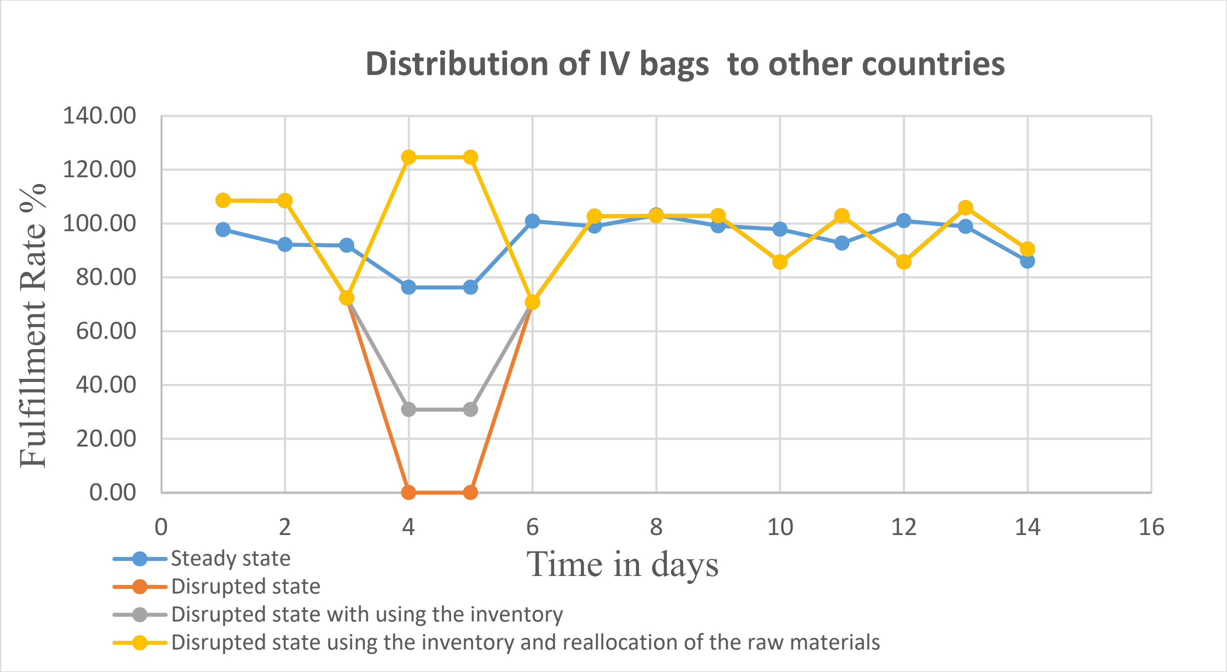


Figure 4.30 Fulfillment rate of IV bag distribution to other countries for design plan one

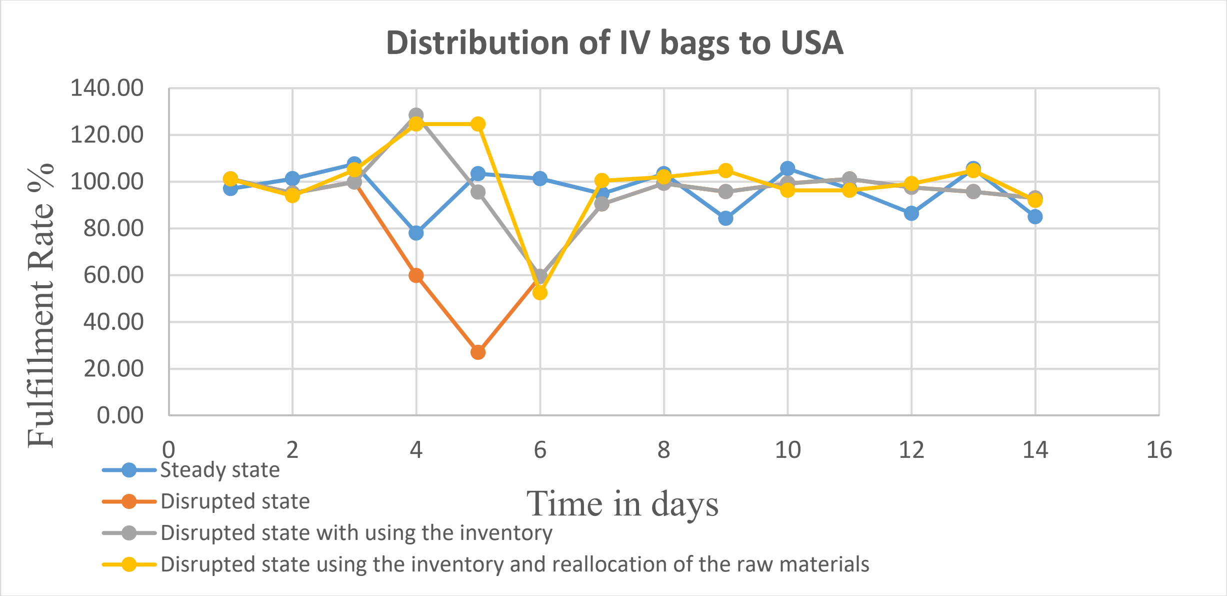


Figure 4.31 Fulfillment rate of IV bag distribution to the USA for design plan two

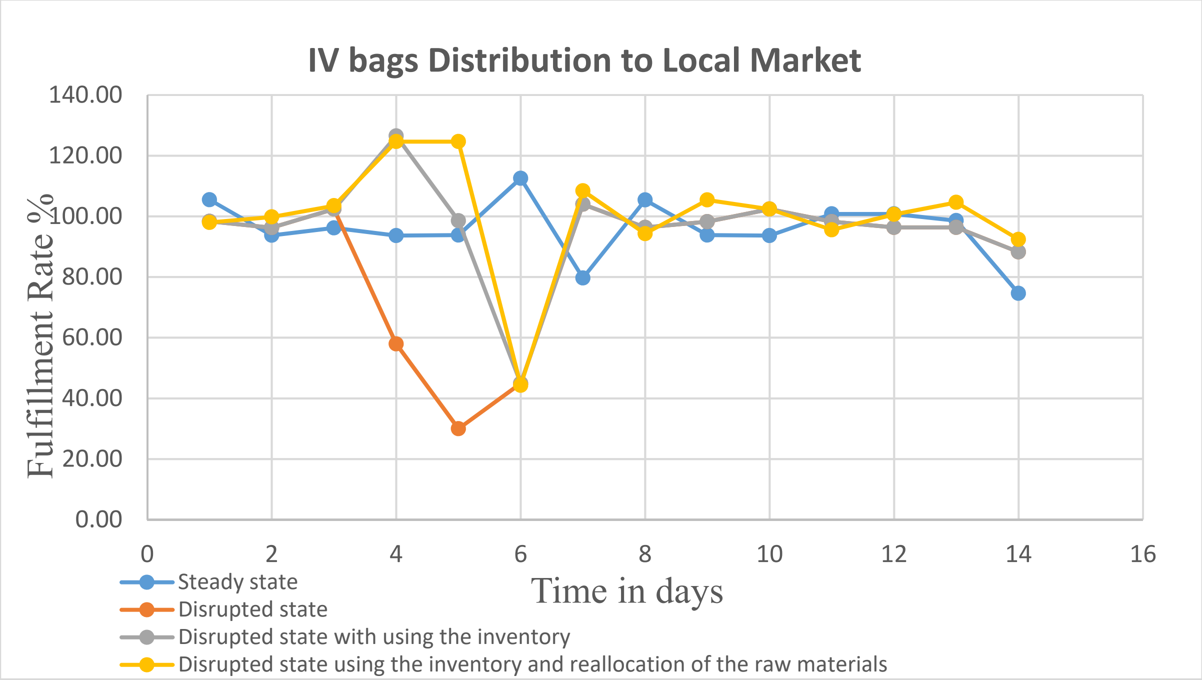


Figure 4.32 Fulfillment rate of IV bag distribution to the local market for design plan two

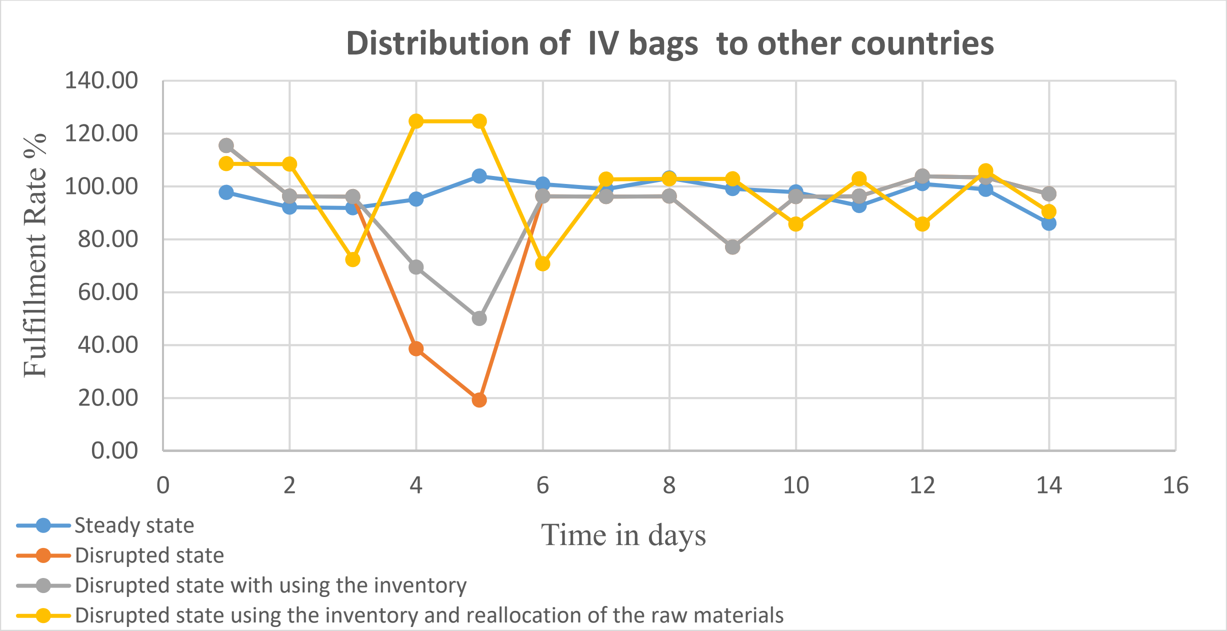


Figure 4.33 Fulfillment rate of IV bag distribution to other countries for design plan two

4.18 Fulfillment rate of IV bags distribution to the USA for design plan one

Fulfillment Rate %				
Day	Steady state	Disrupted state	Disrupted state using inventory	Disrupted state using inventory and reallocation of the raw materials
1	95	101	101	101
2	104	94	94	94
3	108	105	105	105
4	98	0	69	125
5	98	0	69	125
6	101	52	52	52
7	95	100	100	100
8	103	102	102	102
9	84	105	105	105
10	106	96	96	96
11	97	96	96	96
12	86	99	99	99
13	106	105	105	105
14	85	92	92	92

4.3.3.4 Resilience Index

The resilience index of a supply chain company is found based on the concept of the resilience profile presented in Chapter 3. The performance of the supply chain exceeds its maximum value by applying some of the mitigation plans. Since the resilience index is a value between 0 and 1, the maximum fulfillment rate that can be considered in the equation will be equal to or less than 100%. In the steady-state assumption, the supplier can deliver the materials between week 1 and week 14.

The resilience index for the two-design plans under the normal state is similar; the impact of the redundancy in having two suppliers appears under the disruption. The resilience index for the facility under the disruption is 0.79. It reached to 0.85 when the facility depended on two suppliers. The table shows the different resilient indices for the two-design plan under tracking the different mitigation plans. The resilience index for both designs when using the inventory and reallocation are the same due to the assumption that made earlier that resilience index is equal to or less than 100%. But the fulfillment rate for design two when the facility has two suppliers at different locations is higher than the first design plan where the facility has only one supplier.

Table 4.19 Resilience index of facility AB

Resilience index		
Scenarios	Design plan one	Design plan two
Steady state	0.95	0.95
A disrupted state without a mitigation plan	0.79	0.85
A disrupted state with using the inventory	0.90	0.93
A disrupted state with using the inventory and reallocation of the raw materials	0.95	0.95

4.4 Discussion and Assessment of the Proposed Methodology Results

The steady state in each model represents a baseline to judge the performance of each supply chain under disruption by applying the equations presented under each case study. The graphical presentation, the calculation of the fulfillment rate, and the resilience index under disruption compared to the steady state works as an effective indicator of the resilience of the supply chain. The discrete event model succeeds in presenting a clear picture of how a supply chain operates during a normal state.

4.4.1 Risk and Resilience in Steady State

One of the primary steps of the simulation process for the two case studies is to develop the risk in the supply chain for the steady state due to the variation in the reliability of the different types of infrastructure. For the first case study, Figure 4.11 shows how the arrival of the frozen chicken for 27 days is not constant. Everyday a different type of infrastructure controls the amount of the critical material provided to the facility. Thus, the number of the canned chicken sausage differs from one day to another. This is also true for the medical device assembly company. The amount of the critical material provided to the facility varies based on the reliability of the different types of infrastructure. The amount of resin film for a facility relying on one supplier is shown in Figure 4.26 and for a facility relying on two suppliers is shown in Figure 4.27.

Based on the fulfillment rate of the food processing facility over a time window of 1 day to 27 days, a resilience index of 0.95 is obtained. For the medical device assembly, considering the fulfillment rate over a time window of 1 week to 14 weeks, a resilience index of 0.96 is obtained for both design plans. For both, supply chain resilience depends on the reliability of the different types of infrastructure. Under the normal conditions of the steady state, the two facilities can increase their resilience by considering more reliable types of infrastructure. The risk that threatens the supply chain performance under normal conditions points out the importance of relying on more reliable types of infrastructure.

4.4.2 Risk and Resilience in Disrupted State

The second kind of risk that we dealt with in the simulation is due to the failure of infrastructure responsible for the transportation of the raw materials to the main facility. The simulation of the supply chain showed that the risk due to the failure of infrastructure depends on multiple factors: the number of suppliers; the reliability of the infrastructure critical to the logistics; the state of the system once the disruption occurs in terms of inventory; and other available mitigation plans. Time plays a significant role. The time of the occurrence of the disruption and its duration affected the supply chain's ability to respond to the negative effect of the disruption. The amount of stored materials in the inventory depended on the time of occurrence.

The food processing facility case shows how a small supply chain can be susceptible to a huge risk. The supply chain receives raw materials daily. The probability of the failure of the supply chain due to the failure of the infrastructure supporting the transportation of the material is huge. Once the failure of the main highway occurs, the facility is incapable of producing enough canned chicken sausage to meet their daily target. The fulfillment rate reached zero for 7 days. The resilience index dropped from

0.95 to 0.65 during the disruption, but if the facility applies a mitigation plan, such as sharing the resources of a local supplier who can provide the facility with 50-70% of the original required amount by the facility, the resilience index can reach to 0.82 over the same time window. The mitigation plan that was implemented was effective; it increased the resilience index to 0.82. However, it is still risky since the facility will not receive a definite amount of materials.

In the second case study, we notice the difference in the supply chain performance under disruption of the seaport for two different design plans. In the case when the supply chain loses its only supplier due to the failure of the seaport, the resilience index decreases from 0.95 to 0.79. When the facility has two suppliers, one provides the facility with 70% of the required amount of the critical material through a seaport and the other one provides 30% through roadways. The resilience index exceeds 0.79. It reaches to 0.85 as indicated in the table. This shows how redundancy is effective in facing the negative effect of disruption. It didn’t totally avoid it, but it decreased its influence.

The medical device assembly case study features a larger facility that is better equipped to face disruption. Two mitigation plans have been used. The first one is to use the raw materials stored in the inventory; that increased the resilience index to 0.9 in the case of one supplier and 0.93 in the facility with two suppliers. The other mitigation plan the facility can apply is to use the inventory as well as to reallocate some of the critical material to produce a specific product. In the medical device case, the decision was made to allocate all of the resin film to produce the IV bags, thereby resulting in the production of more IV bags and halting the production of kits made of resin film. In this case, the facility will be able to meet the required fulfillment rate and in the case of two suppliers, it exceeds 100% as shown in all the previous figures that show the fulfillment rate. As a result, the facility was able to return to its original performance. The fulfillment rate for the supply chain with two suppliers is higher, but for resilience calculation purposes, we assumed the maximum fulfillment rate is 100%. Therefore, we got the same resilience index for the two design plans. The fact that the facility is more prepared to survive the disruption by allocating inventory for the critical raw materials shows that this is a very successful strategy. Simulation was adequate tool to provide us with the output number and allow us to track that number under different scenarios.

Simulation captured the interaction between the different parts of the supply chain including the reliability of infrastructure and presented the influence of the reliability in a very effective way through the different amounts of materials served by each infrastructure.

Discrete event simulation is an effective manner by which to present the amplified risk movement starting from the supplier to the end of the supply chain by providing the number of outputs as the defined unit of time.

In summary, we can point out these important points about the two studies:

The implementation of different scenarios results in different resilience indices for each supply chain.

The Supply chain resilience index is high for the supply chain that is prepared for the disruption and where the supply chain is built to mitigate any possible risk before it occurs.

Acquiring an uncertain amount of material as a mitigation plan for the food processing case still carries some risk. However, it helped to increase the resilience index of the supply chain.

In the second case study, the design plan had redundancy by relying on two suppliers where each supplier uses a different type of infrastructure to transfer the materials. This allowed the facility to exceed the weekly target once the mitigation plan of using the inventory and reallocating the materials was applied.

Chapter 5: Conclusion

The primary contributions of this work are four-fold and described below.

1. Developing an appropriate model to represent the supply chain performance under various scenarios, and to show the flow of the risk among the supply chain components.

The Discrete event simulation that has been done in this thesis provides us with a realistic model to understand supply chain performance under uncertainty. It shows how risk starts at one component of the supply chain and transfers to other components. Discrete event simulation allows us to examine the supply chain performance under different scenarios and allows us to notice how the risk profile changes based on the design of the supply chain and the reaction plans that are taken. The fulfillment rate that has been used as a performance indicator provides information about the amplification of the disruption as it moves from the start point of the disruption until it reaches to the customers. Although the work can't provide an explicit solution, it can help to understand the behavior of the supply chain and the impact of uncertain risks that can occur at any time due to the failure of infrastructure.

2. Improving the understanding of the role of reliability of infrastructure on the supply chain performance under steady state and disrupted ones.

The reliability of infrastructure is a major factor in the resilience of the supply chain. It plays an essential role in the ability of a supply chain to fulfill its goal. The failure of infrastructure cannot be avoided, but we can prepare the supply chain to face risk and decrease its vulnerability to failure. The resilience of a supply chain is achieved by decreasing the probability of the occurrence of the disruption in the facility or by reducing its effects on supply chain performance. Thus, the company must prepare for specific risks. To increase supply chain resilience due to the failure of infrastructure critical for transportation, we should understand the high dependency among the other types of infrastructure. The Bayesian network was an effective method in representing that dependency. However, the results of Bayesian analysis are biased due to our assumption about the infrastructure responsible for the failure of other types. However, this is still acceptable in order to accommodate our interest in analyzing a specific role of infrastructure.

3. Providing a quantitative assessment of the resilience of supply chain.

A resilience index has been used throughout the simulation. The role of the resilience index is substantial in measuring the ability of the supply chain to handle any possible risk. The company's resilience index was identified in this research by measuring the supply chain's ability to meet its goal during a specific period. The fulfillment rate as an indicator over time is a measure of the supply chain's ability to meet its goal during a period of disruption and recovery. The resilience index helps the company to test multiple scenarios and make decisions about the right strategies that will increase the resilience of the supply chain.

4. Enhancing adaption of the supply chain to overcome the possible risk of disruption due to the failure of infrastructure.

Mitigation plans are important although their implementation is not always possible. The activation of the plans depends on the time of the occurrence, the duration, and the state of the system. Therefore, it is necessary to identify the risk that we are preparing for. In this research, we have been dealing with the reliability of different types of infrastructure and the total loss of the infrastructure critical to transportation. Simulation allows conducting a study on a possible scenario. This will enable any supply chain to identify any risks that might affect the supply chain and the probability of these risks to affect it. Once the source of risk is known, a specific mitigation plan can be applied.

And finally, the thesis is aligned with the general belief that a supply chain is as strong as its weakest component. Therefore, it is important to focus on increasing the resilience of that supply chain by making the components and the link to other components more robust by increasing redundancy in the supply chain and developing mitigation plans that can be applied once the disruption occurs. The supply chain should rely on more reliable infrastructure to decrease the influence of the disruption to maintain a continuous performance.

Future work can be done to analyze the supply chain under a total failure of other components of the supporting infrastructure and their impact on the supply chain.

The input data are logical, but for future work, it will be useful to enhance the data by including the transportation details (e.g. distance, time, and more details about the trucks or ships). It will also be helpful if this model can be applied to an existing case study to enhance the model and overcome some of the limitations.

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