Enhancing the Resilience of a Semiconductor Supply Network via Modeling and Simulation of Business Continuity Strategies for Alternative Sites

A Case Study of Building a Resilient Supply Network at Infineon

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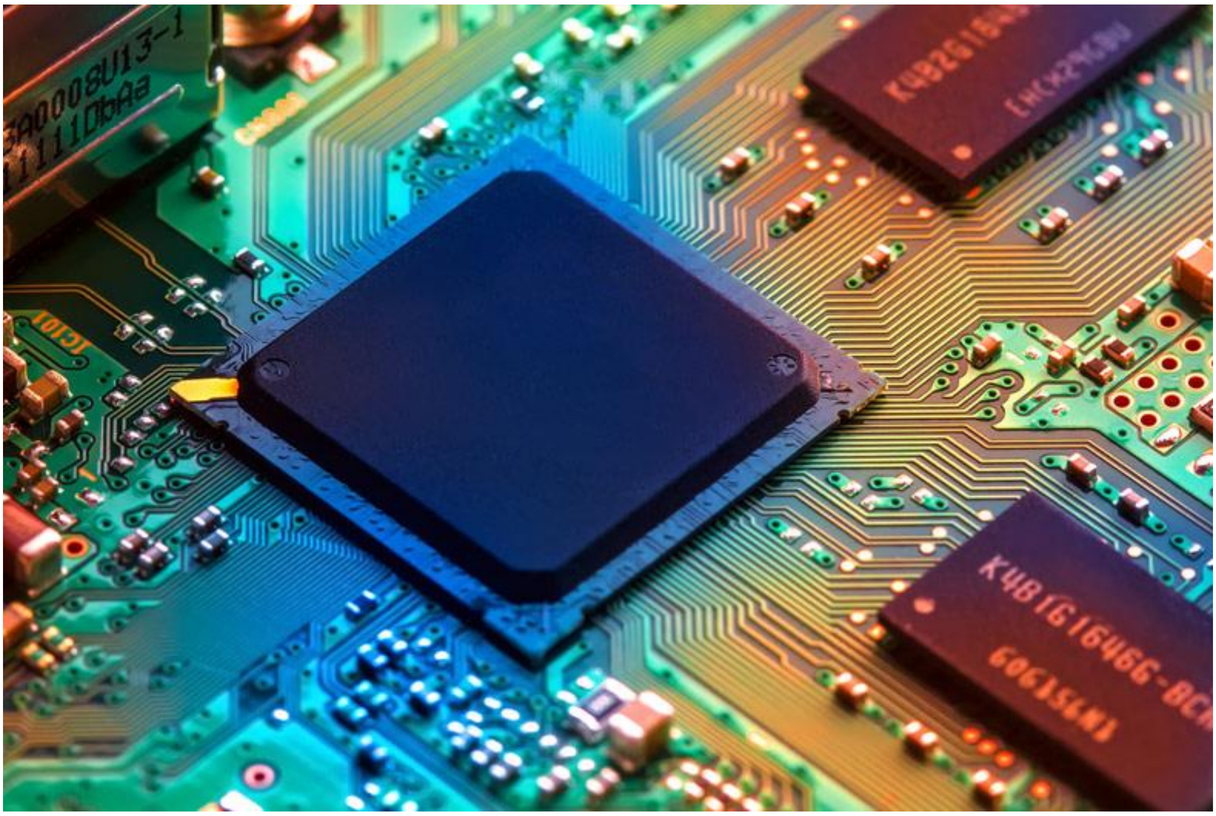

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PREFACE

This report is my master thesis for the Engineering and Policy Analysis program at the faculty of Technology, Policy and Management of TU Delft. This thesis project was carried out at the department of supply chain innovations at Infineon Technologies AG in Munich under the supervision of the TU Delft thesis committee. I am very thankful for the opportunity to investigate supply chain resilience in a practical setting via applying my simulation knowledge.

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GLOSSARY

ATV	Automotive Electronics Division
BC	Business Continuity
BCP	Business Continuity Planning
BCM	Business Continuity Management
BCSAS	Business Continuity Strategies for Alternative Sites
BE	Backend
BO	Backorder
CoC	Customer of Customer
CSC	Corporate Supply Chain
CT	Cycle Time
DB	Die Bank
DC	Distribution Centre
DES	Discrete Event Simulation
DS	Disruption Scenario
DTI	Dissatisfaction Tolerance Index
FE	Frontend
IFX/Infineon	Infineon Technologies AG
KPI	Key Performance Indicator
PG	Process Group
WIP	Work In Progress
WSPW	Wafer Stars Per Week
PMM	Power Management and Multimarket
SC	Supply Chain
SCM	Supply Chain Management
SCRM	Supply Chain Risk Management
SD	System Dynamics
SL	Sales Loss

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EXECUTIVE SUMMARY

Background Information

The world is exposed to all sorts of vulnerabilities and uncertainties. Over the last decade, many unpredictable catastrophes have been witnessed such as earthquakes, terrorist attack, computer virus attack, etc. When disasters occur, many supply chains have the tendency to break down, which takes a long time to restore (Tang, 2006). A vast amount of economic losses from supply chain (SC) disruptions follow. Under this context, supply chain resilience is at the heart of current SC management thinking (Melnyk, Closs, Griffis, Zobel, & Macdonald, 2014). SC resilience emphasizes the adaptive capability to absorb the impacts from disruptions, respond to and recover from them (Madni & Jackson, 2009; Ponomarov & Holcomb, 2009). Having resilient SCs is of vital importance for the semiconductor industry, which is challenged by extended SCs with long lead time, short product lifecycles and rapid changes in technologies.

As a result, business continuity management (BCM) is introduced, aiming to manage business under adverse conditions by the introduction of appropriate strategies (Business Continuity Institute, 2017). This research studies the Business Continuity Strategies for Alternative Sites (BCSAS). Those strategies enable fast recovery by transferring production for certain products from a primary site to an alternative site after a disaster. The alternative production rate and initial time may differ, depending on the type of alternative site.

This project entails the development of a simulation-based framework to evaluate different BCSAS in the context of the semiconductor industry for enhancing SC resilience. A case study is conducted with a leading semiconductor manufacturer, i.e. Infineon Technologies AG (IFX). This research supports the strategy preparation at IFX to determine the allocation of alternative sites.

The decision-making must meet the needs of the business and also gain the support of different parties involved, e.g. top management, operation department, factory, customers, etc. Stakeholders are often in conflict with one another in terms of their values, goals and perceptions. For instance, the management value business continuity while the factory might want more simplicity in work. Therefore, the determination and implementation of BCSAS involve multiple organizational processes.

Research Purpose

Diverse frontend sites manufacture different products due to different requirements for equipment, technologies, etc. There are four different types of alternative sites, i.e. cold site, warm site, hot site and mirror site. They are normal operating sites but they have different levels of preparedness for producing specific products (as shown in Table i). The mirror site is applicable for single product only whereas the other options are for process groups (PGs), which is an aggregation of products sharing similar toolsets and technologies. A specific site could be a cold site for process group A but a warm site for process group B. Thus the type of alternative site is PG-specific. As can be seen from the Table i, from cold site to mirror site, the time to respond after disruption gets faster because the flexibility in production increases from better conditions (equipped with tools, technologies, etc.). Due to the limited qualitative understanding, many customers tend to require a mirror site for their products. However, because of the capacity limit in a factory, not all products could have such a high level of the alternative site. Additionally, the investment upfront to establish them is another factor to take into account. The overall impacts and their trade-offs are difficult to assess.

Table i. Different Types of Alternative Sites (BCSAS)

Class	Strategy	Readiness				Responding time
		Working cleanroom	Equipped with tools	Technology qualified	Product qualified	
I.	Cold site	X				Slow
II.	Warm site	X	X			Medium
III.	Hot site	X	X	X		Fast
IV.	Mirror site	X	X	X	X	Very fast

The BCSAS incorporate two commonly-discussed principles for building SC resilience: flexibility and redundancy. Their contributions are debated and their relation is less-examined. By assessing diverse impacts of BCSAS, this research studies if it is worthwhile to persistently increase flexibility and how those two principles are interrelated to enhance SC resilience. Hence, the main research question proposed is:

What are the impacts of Business Continuity Strategies for Alternative Sites (BCSAS) on supply chain resilience and financial performance in specific disruption scenarios in the context of semiconductor manufacturers supply chains?

Research Approach

Considering the research question, a simulation-based framework is developed to evaluate the BCSAS. Two most popular simulation approaches are systems dynamics (SD) and discrete event simulation (DES) (Tako & Robinson, 2012). Nevertheless, catastrophes are seen as discrete events in this research, opposite to smooth and steady changes in SD. Since DES is proved to be valuable in studying complex system and evaluating policies in different scenarios with stochastic characteristics (Wu & Blackhurst, 2009), it is selected as the main research method.

As it is difficult to enumerate every possible disruption scenario and some of them may have similar effects, a selection of them is made based on a top-down (experts' discussion) and bottom-up (literature review) approach. Four disruptions scenarios, i.e. long-term cyber-attack (DS1), infrastructure destruction (DS2), strikes (DS3) and industrial accident (DS4), with different disruption lengths and depths are defined to study a broad range of situations.

One product (P1) and three PGs (P2, P3 and P4) are examined as a sample. The KPIs are selected from operational and financial perspectives. The fill rate changes and its recovery time are the key operational measurements of SC resilience while the financial performance includes the investment cost and total disruption cost (IFX cost, customer loss and Customer of Customer loss). The IFX cost, entailing backorder cost and sales loss, is the focal point, indicating IFX's potential economic loss under specific disruption scenarios. The comparison of investment cost and the IFX disruption cost determines the overall financial performance.

The simulation-based framework comprises three key processes. Firstly, the demand and supply management module leads the fulfillment of customer demand and tracks the accumulation of backorders. This regulates the production. Secondly, the production disruption exerts the impact of a specific scenario and the ramp-up process models the corresponding restoration phase, which is further validated by the experts. Lastly, the WIP is processed separately after a disruption with the identification of scrapping situations.

Overview of Findings

The disruption scenarios and specific PGs are found to have influences on recovery time and disruption costs, which will amplify or reduce the impacts of BCSAS. The main findings of their impacts based on the selected PGs and scenarios are summarized in the Table ii. As expected, the mirror site has the fastest recovery with outstanding achievements in DS1. But since it is for only product level, the financial performance is not comparable with PGs, which is beyond the research scope. A hot site seems to be a good alternative for mirror site, showing robust and excellent overall performance. It also demonstrates exceptional advantages in DS1. Unexpectedly, a warm site also has satisfying performance generally, except for DS3. Additionally, a warm site illustrates similarly positive performance as a hot site in DS2 and DS4 for P3 with short backorder rejection time and cycle time. Further beyond the anticipation, the cold site also demonstrates some achievements, especially in term of shortening the recovery time under DS2. Nevertheless, it is not cost-effective to cope with DS3, which is in line with the expert understanding. These benefits are amplified considering the total disruption costs in the SC.

Table ii. Overall Performance of BCSAS

Alternative site	**Overall Performance Compared with Base Scenario**		**Remarks on Specific Disruption Scenario**			
	Operational	Financial	DS1. Long-term Cyber-attack	DS2. Infrastructure Destruction	DS3. Strikes	DS4. Industrial Accident
Mirror Site	★★★★★	Not applicable (for Product only)	Outstanding			
Hot Site	★★★★	★★★★	Outstanding			
Warm Site	★★★	★★★		Similar performance to hot site for P3	Not cost-effective	Similar performance to hot site for P3
Cold Site	★★	★★		Outstanding at reducing the recovery time	Not cost-effective	

Conclusions and Recommendations

Diverse BCSAS have been modeled and evaluated to enhance the SC resilience in the semiconductor industry in this research. The research has shown the value of ‘flexibility’ and its connection with ‘redundancy’. Increasing flexibility improves SC resilience in a non-proportional manner and when the increase of flexibility is not cost-efficient, redundancy is recognized. Hence, the perception of redundancy comes from overrated flexibility.

When a mirror site is difficult to apply, the case study revealed that other BCSAS still demonstrate significant benefits at enhancing SC resilience cost-efficiently. A hot site is recommended to prepare for a variety of disruptions due to its robust performance, especially when IFX needs to take care of a considerable amount of economic loss at customer end. The warm site and cold site are not recommended for IFX to prepare for disruptions with short-term restoration. However, a cold site seems to be suitable to handle disruptions with long-term restoration for PGs with a strategic position and low sales price or quantity. Furthermore, a warm site might be sufficient for products that have a small number of backorders under the disruptions with long/medium-term restoration, according to the simulation results.

The outcomes provide the decision-makers with technical solutions to allocate different types of alternative sites in preparation for unanticipated disruptions. Before implementation, the multiple actor perspectives should also be addressed. Being aware of different perceptions and resources of various stakeholders involved is important to gain their support for initiating the changes. It is of crucial importance to emphasize how the BCSAS can fulfill the stakeholders’ interests and goals when communicating the business continuity plan. The multiple organizational processes are recognized in the project.

1. INTRODUCTION

Nowadays, due to the ongoing trend of globalization, the Supply Chain (SC) networks grow more complex and complicated than ever before. Companies around the world face various challenges in managing their SCs. Among those difficulties, disruption in an uncertain environment of SCs becomes one of the biggest concerns for corporates to operate successfully. Facing fiercer competition with lengthy SCs, long cycle times and short product lifecycles (Mayer, 2014), the semiconductor industry needs to build a more resilient supply network to cope with disruptive incidents (e.g. fire, earthquake).

This thesis project examines one semiconductor company as a case study to evaluate Business Continuity Strategies for Alternative Sites (BCSAS) via modeling and simulation in order to build such a resilient network with a satisfying financial performance. Essentially, BCSAS enable the production transfer for certain products from a primary site to an alternative site following a disaster. There are four types of alternative sites (strategies): mirror site, hot site, warm site and cold site. The distinction between them is the alternative production rate and initiating time, which will be briefly illustrated in this chapter. The BCSAS are very important for rapid disaster recovery and are often inquired by customers as part of the risk management procedures. When a major event happens, recovering is a struggling process, hence the alternative site providing additional capacity can help relieve the disrupted site of the burden.

Decision-making in this background involves multiple organizational processes and interests. For instance, the BCSAS meet the needs of business continuity by enhancing the SC resilience. However, it might also increase the complexity in the factory production and supply chain planning. As a result, the collaborative efforts from multiple internal and external stakeholders are required to implement a particular strategy. The multiple organizations are not explicitly modeled in the simulation, but the simulation outcomes can be used as technical support to demonstrate the benefits to other internal parties and ease the discussion with customers.

Different catastrophe scenarios disturbing the production at a manufacturing site are defined to test the trade-off and robustness of those strategies on different products. In this chapter, the background of supply chain disruptions and resilience in the semiconductor industry is briefly illustrated, followed by a short description of the case study company (Infineon). In addition, the research objectives, scope and research questions are defined, giving social and scientific relevance. Finally, the research methodology and outline of the thesis are presented.

1.1 Supply Chain Disruptions and Resilience in Semiconductor Industry

A supply chain is a network consisting of organizations, resources and activities involved in the whole process, from supplying the raw materials to the delivery of products to end customers (Lotfi, Mukhtar, Sahran, & Zadeh, 2013). A disruptive incident could happen in any of those activities. Numerous events occur each day in the world that could cause SC disruptions, including both natural and man-made disasters such as an earthquake, equipment failures, labor disputes and political instability (Melnyk et al., 2014). The economic losses from SC disruptions had risen by 465% from 2009 to 2011, leading to a total cost of $350 billion (Langley, 2012). Therefore, the ability to absorb the impacts, adapt to and recover from SC disruptions in the shortest time possible are vital for organizations, which means having SC resilience (Madni & Jackson, 2009).

As part of the technology sector driving the world's economy, the semiconductor industry is believed to have an impact on 10% of the world's GDP and has reached global sales of US$335.2 billion in 2015 (Semiconductor Industry Association, 2016). This industry is also considered to be one of the most complex industries in terms of both copious manufacturing process steps and globally distributed supply chains (Sun & Rose, 2015). Its supply chain is challenged by steep product ramps and long production cycle times, which implies longer time to recover from SC disruptions. Hence, the SC resilience is of crucial importance in order to solidify a leading position in the semiconductor industry. The consequences of not having a resilient supply network could be catastrophic.

An example demonstrating the significant influence from SC disruption in this industry is Ericsson's crisis in 2000: a microchip supplier plant had a fire disaster and Ericsson's production line was brought to a standstill due to lack of backup sources, which was estimated to bring a loss of $400 million (Norrman & Jansson, 2004). A similar case happened to Infineon recently. In the beginning of February 2015, an Infineon manufacturing site in Malaysia caught fire. Unexpectedly, in the same month, another fire incident followed at an Infineon's supplier in Korea. The incidents led to a 30 million euro loss of turnover and approximately 50 products and 100 customers were affected (Weixlgartner, 2016).

After those incidents, the semiconductor industry put much more emphasis towards business continuity management in case of disruptions. Business Continuity (BC), which is often described as common sense, is about building and improving resilience in businesses. There are different BC strategies to improve the resilience, including: multi-sourcing, supplier selection, extra inventory, collaboration, information sharing, etc. They aim at preventing interruptions and re-establish full functions as quickly and smoothly as possible (Ichelson, 2016). Business Continuity Strategies for Alternative Sites (BCSAS) offer another effective mitigation option to facilitate the recovery. It is an integral part of BC planning of an organization.

1.2 Infineon Technologies as a case study company

The case study company Infineon Technologies AG (hereafter: Infineon or IFX) is a leading semiconductor manufacturer, which designs and develops a wide range of semiconductors and system solutions. It has obtained revenues of 6,473 million € in the fiscal year 2016 (Infineon Technologies AG, 2017). Infineon addresses some of the most critical challenges of society: efficient use of energy, environmentally-friendly mobility and security in a connected world. With more than 36,000 employees worldwide (as of September 2016), Infineon has 34 R&D locations and 19 manufacturing locations (Infineon Technologies AG, 2017). This project focuses on the disruptions occurring at those manufacturing sites, particularly at frontend production for wafer fabrication (more information can be found in Chapter 3).

Infineon's business market is divided into four different segments:

- Automotive electronics – ATV (41%)
- Industrial Power Control – IPC (17%)
- Power Management and Multimarket – PMM (31%)
- Chip Card and Security – CCS (11%)

Infineon places great emphasis on the competitiveness of their supply chains, as this is a critical success factor for a semiconductor company. The Corporate Supply Chain (CSC) department focuses on improving the effectiveness and efficiency of Infineon supply chains for achieving a seamless operation and delivery. The Business Continuity (BC) department collaborates with CSC for developing BC strategies in response to unanticipated disruptions. Given this background, the thesis project works closely with both CSC and BC department to evaluate various BCSAS in terms of their impacts on SC resilience and financial performance.

1.3 Research Definition

This research studies the supply chain performance of Infineon under different catastrophes scenarios. Diverse types of alternative sites are considered as important mitigation options to cope with major production disruptions. In particular, four different types of alternative sites are to be investigated as BC strategies (i.e. BCSAS), as shown in Table 1. From strategy I-cold site to strategy IV-mirror site, the time to recovery for some specific products is getting shorter, as the alternate facility would be equipped better and ready for producing those products. However, every customer wants to have an alternative site for their products at its highest level of readiness, i.e. a mirror site which is able to produce the particular product promptly by having a resembling manufacturing environment (similar equipment and technologies). In reality, the determination of the type of alternative site for products is mainly based on a qualitative approach and customer influences. Nevertheless, there exists a large amount of investment upfront to have a satisfying level of an alternative site for many products. Therefore, the overall impacts of different types of alternative sites and their trade-offs are difficult to assess. A simulation-based framework is needed to quantify and evaluate them.

Table 1. Business Continuity Strategies for Alternative Sites (Infineon Technologies AG, 2016)

Class	Strategy	Readiness				Recovery time
		Working cleanroom	Equipped with tools	Technology qualified	Product qualified	
I.	Cold site	X				Slow
II.	Warm site	X	X			Medium
III.	Hot site	X	X	X		Fast
IV.	Mirror site	X	X	X	X	Very fast

This brings us to re-examine the frequently-discussed topic of **‘flexibility vs. redundancy’** in building SC resilience. Many researchers have conducted their studies by making a trade-off between ‘flexibility’ strategy and ‘redundancy’ strategy in order to conclude which one outperforms the other. Using simulation, Carvalho et al. (2012b) demonstrated the positive mitigation effects from both strategies, but with different performance: flexibility results in lower total cost whereas redundancy has better lead time ratio. Zsidisin and Wagner (2010) discussed which strategy is more beneficial under which circumstance. It is argued by some other scholars that flexibility is a better option due to the lower cost and operational benefit (Sheffi, 2005; Sheffi & Rice Jr, 2005).

However, those two strategies do not always oppose each other. In this project, the flexibility and redundancy are closely related. A high-level alternative site could process certain products during its normal operation. It aims to provide extra capacity quickly through highly flexible production after an emergency. This is achieved by switching to producing other designated products which need similar toolset and technology. Hence, the BCSAS can be seen to belong to the principle of ‘flexibility’. Different types of alternative sites imply different degrees of flexibility. But we can also consider an alternative site ‘redundant’ since a double set of technology and/or equipment at the alternative site is demanded, which is expensive to set up and may not be fully used in daily operation (e.g. the site is equipped with higher technologies than the normal need). Hence, is it always good to increase flexibility? How do we perceive the relation between flexibility and redundancy for enhancing SC resilience in terms of having flexible production at an alternative site?

The connection between those two strategies, which is rather less examined in current literature, is essentially important for understanding their influence for strengthening SC resilience. Ratick et al. (2008) mentioned in their study that adding backup facilities (redundancy) can be cost-effective to enhance the resilience and also increases the flexibility. But their research focuses on mapping the backup facility location instead of investigating the relationship between those two strategies. This thesis attempts to bridge this knowledge gap by probing the connection between flexibility and redundancy to SC resilience via modeling and evaluation of different BCSAS. The simulation-based framework measures the SC resilience, achieved from the flexible production, and financial performance in specific disruption scenarios in order to assess the interrelation between flexibility and redundancy with SC resilience.

1.3.1 Research Objectives, Scope and Research Questions

The main objective is to propose a simulation-based evaluation framework for BCSAS as a strategy-preparation tool to support decision-making in order to build a resilient semiconductor supply network cost-efficiently, since both disruption and investment costs would be taken into consideration. By using simulation, major disruptions at frontends will be modeled, and the consequences without alternative sites (i.e. only original site recovery) will be compared with the situations where different alternative sites are applied. The impacts of various BCSAS on supply chain resilience and financial performances can be quantified and assessed. Eventually, those BCSAS can be tested under different disruption scenarios for various products to investigate their robustness or suitable conditions. This will shed light on the perception of the relation between flexibility and redundancy for enhancing SC resilience.

Implementing the BCSAS cannot be achieved by one department and it needs the consensus from multiple stakeholders. The impacts of BCSAS may be perceived differently by diverse parties. The visual and tangible simulation outcomes can also help to persuade other stakeholders about the benefit of a certain strategy in order to gain their understanding and support.

The scope of the research limits the disruption scenarios under testing to catastrophes at frontend production, as the BCSAS were designed to focus on highly severe production disruptions (e.g. equipment damages) in the frontend site itself. Hence, the supplier side is also deliberately selected to be excluded from the research framework. Additionally, the associated risk probabilities are not considered when defining those catastrophe scenarios, since the research intends to explore the extreme condition rather than building an extended risk profile. This research does not attempt to prevent disruption from happening nor supports real-time decision-making. Instead, it aims to help the semiconductor manufacturers with decision-making ahead of time in order to have a better understanding of the impacts of alternative sites to prepare for disruptions. The scope of research will be further elaborated in section 3.5 after giving more contextual information in the following chapters.

Based on the research problem description and research objectives illustrated above, the main research question is proposed:

What are the impacts of Business Continuity Strategies for Alternative Sites (BCSAS) on supply chain resilience and financial performance in specific disruption scenarios in the context of semiconductor manufacturers supply chains?

To answer the main research question, the following sub-questions are formulated:

1. How is supply chain resilience apprehended and assessed in the context of the semiconductor industry? (Contextual question)

2. What are the main components that the simulation-based evaluation framework of BCSAS should constitute for enhancing supply chain resilience in semiconductor manufacturers?

3. What are the impacts of different BCSAS regarding SC resilience in specific disruption scenarios?

4. What are the impacts of different BCSAS regarding financial in specific disruption scenarios?

5. Which BCSAS show the best overall performance under which disruption scenarios and how does it imply the relation between flexibility and redundancy for enhancing SC resilience?

6. How can the final outcome be applied in semiconductor manufacturers in order to support the policy preparation to achieve a resilient supply network?

1.3.2 Social and Scientific Relevance

Social Relevance

Some semiconductor manufacturers have been struggling to focus on maintaining inventory performance in order to deal with SC risks, causing a 34% increase in days of inventory over the period between 2000 and 2012 (Mayer, 2014). Alternative sites are believed to be another mitigation option for enhancing supply chain resilience. The BCSAS can facilitate the recovery through flexible production after disruptions. Nevertheless, it involves considerate investment to set up. There are trade-offs between BCSAS in terms of recovery time, investment cost and associated financial losses under various disruption scenarios. Therefore, a simulation-based framework is proposed to quantify and evaluate those impacts to enhance SC resilience cost-efficiently. This could indirectly help reduce the *waste* in a variety of forms: excessive inventory, manufacturing and supplying redundant machines and unnecessary production environment configuration.

Furthermore, the simulation-based evaluation framework is a generic model setup, taking into account specific traits of semiconductor industry (e.g. long cycle time and short product lifecycle), as it is unique compared with many widely-studied industries. Lastly, the framework is a beginning step, which can be extended to perform more detailed and systematical analysis and can be applied to other companies within this industry after some adjustment.

Scientific Relevance

From a scientific viewpoint, this research also contributes to the academic community. Firstly, it examines the principles of ‘flexibility’ and ‘redundancy’ from a new perspective: instead of comparing and contrasting, this research explores their connection and influence to enhance SC resilience. By investigating the impacts of different BCSAS, we will gain a better insight of the value of flexibility and its interrelation with redundancy to strengthen resilience.

Furthermore, the supplier system is most often emphasized in current literature about SC resilience in order to reduce the probabilities and/or impacts of disruptions, e.g. multiple sourcing and supplier selection (Baker, 2007; Levary, 2007; Lodree Jr & Taskin, 2008; Svensson, 2003; Zsidisin, Panelli, & Upton, 2000). The production capacity restores instantly after the disruption in present simulation work (Carvalho et al., 2012b; Güller, Koc, Henke, Noche, & Hingst, 2015; Schmitt & Singh, 2012). In this project, the recovery ramp up is examined to shed light on the less-examined restoring process when the manufacturing process is disturbed by non-supplier issues. This can be a start for other scholars to perform more detailed research.

Additionally, the quantitative research so far is either based on linearity assumption, poor at handling complexity, or too detailed with intensive data analysis, which is challenging to replicate. With this background, a more generic simulation-based evaluation framework is needed. This research will utilize the dynamic strength of DES to complement static analysis and provide rational perspectives for a decision-making problem. Lastly, the decision-making under uncertainties is also taken into consideration by defining various disruption scenarios with probabilistic-distributed lengths.

1.3.3 Research Methodology

In this research, interviewing is one of the research methods. There are two main reasons for conducting interviews. Firstly, certain input data needs to be collected using experts' knowledge and estimates, such as the tool purchasing time of a BC strategy. Secondly, the results of the simulation also need to be interpreted and validated with the help of the experts' opinions. The interviews are conducted with respective colleagues from the Corporate Supply Chain department, Business Continuity department and three Supply Chain Planners in corresponding divisions at Infineon.

Discrete Event Simulation (DES) is the core method of this research, even though System Dynamics (SD) is also a commonly used quantitative method for modeling to support decision making in supply chains (Jahangirian, Eldabi, Naseer, Stergioulas, & Young, 2010). It is noticeable from literature study that SD is more frequently used to reduce the bullwhip effect than DES (Tako & Robinson, 2012), yet seldom applied in studying supply chain disruptions and resilience. This may be closely related to the inherent characteristics of those modeling approaches. SD models systems where state changes occur *continuously* over time, represented by stocks and flows (Brailsford & Hilton, 2001). SD models are based on differential equations; hence the state changes are smooth and steady, with approximately small steps of equal length (Tako & Robinson, 2012). Instead, DES models systems where state changes occur at *discrete points* of time, represented by queues and activities (Brailsford & Hilton, 2001). The DES models are stochastic in nature, often with probability distribution to create randomness (Jeon & Kim, 2016). Catastrophes are usually discrete events that suddenly happen to cause a significant loss in production and revenues, opposite to smooth and steady change; thus SD is also considered unsuitable for this SC disruptions and resilience project.

There are mainly three reasons for applying DES. Firstly, the manufacturing system and disruptions are not deterministic, consisting of different state changes in a discrete manner, which aligns with the DES methodology. Secondly, it is flexible for complex supply networks and enables 'what-if' analysis without interrupting real systems. Therefore, we could examine those BCSAS without having a pilot study and testing the results under a real disruption, which would be very costly. Furthermore, it is possible to compress time and simulate real-world influences, which is important for simulating such major disruptions and checking the system response over a long period (Stefanovic, Stefanovic, & Radenkovic, 2009).

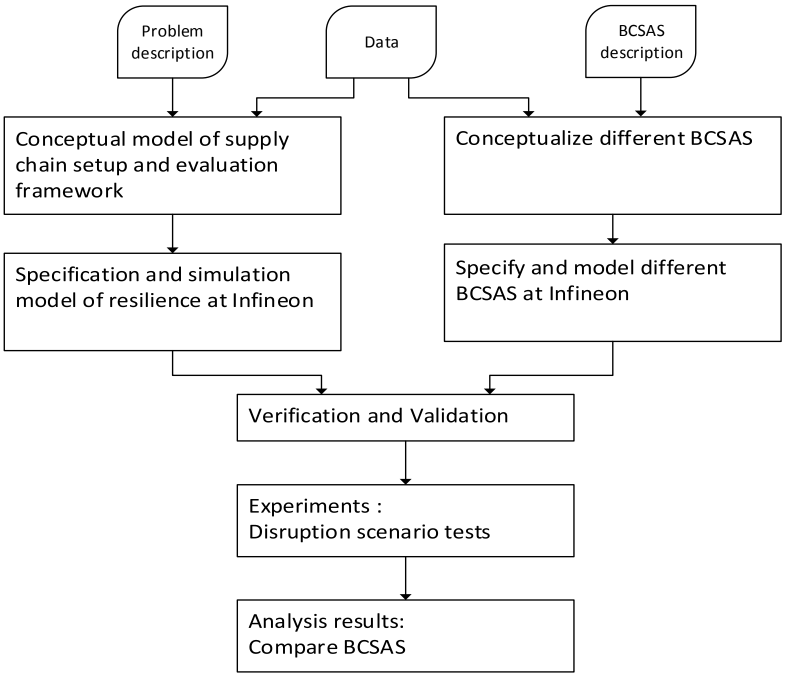


Figure 1. Steps Conducted in this Discrete Event Simulation (DES) Project

The software used to develop the simulation model in this project is called AnyLogic. It is the only simulation tool that supports all the most common simulation methods in place today: System Dynamics, Discrete Event and Agent Based modeling (more details could be found in AnyLogic website). The steps taken in this DES project (Figure 1) follow the methodology introduced in the book " Simio and Simulation: Modeling, Analysis, Application" by Kelton et al. (2014). Firstly, a conceptual model depicting a relevant supply chain setup for the semiconductor industry is developed based on the problem description and related data. In addition, the framework will be designed to illustrate the input, output and logic of the simulation model. Afterward, a discrete system model based on that as well as the specification in the context of Infineon will be developed, followed by verification and validation. The experiments are conducted for analyzing the results. After simulating the current situation, the next step will be testing the impacts of different BCSAS under different disruption scenarios for various products, which also share similar paths as mentioned above. Finally, those BCSAS are compared based on their effects on selected KPIs and their trade-offs will be discussed.

1.4 Structure of the Thesis

The master's thesis consists of nine chapters including this one. The second chapter presents the literature review about SC resilience on its perception, principles, assessment and improvement. Additionally, the decision making under risk and uncertainties are discussed, and major simulation work will be presented. In Chapter 3, specific characteristics about the semiconductor industry and its supply chain management are illustrated. The business continuity planning at Infineon will be demonstrated as an example of this industry. Chapter 4 defines the disruption scenarios and elaborates more on the business continuity strategies for alternative sites. Chapter 5 illustrates the conceptualization and development of the simulation-based framework for enhancing the SC resilience, including elements like KPIs, input data, key processes and assumptions. Based on this, chapter 6 demonstrates the design of experiments to evaluate those strategies. In the following chapter, the simulation outcomes of the current situation and investigated BC alternatives are analyzed. The impacts of those BCSAS under different disruption scenarios for different products will be studied via comparing the results between ‘as-is’ and ‘to-be’ DES models. In chapter 8, discussion about issues beyond the proposed simulation framework such as multiple actor perspectives and socioeconomic resilience are presented. The last chapter draws the conclusions, recommendations and further research based on the previous analysis.

2. LITERATURE REVIEW ON SUPPLY CHAIN RESILIENCE AND SIMULATION

Supply Chain Management (SCM) originates from an outlook by two consultants: Oliver and Webber, for defining strategic logistics management in 1982. The topics in SCM have attracted increasing interest since then and the research area has been enlarged to more than just logistic management. Currently, SCM is commonly believed to "*encompass the planning and management of all activities involved in sourcing, procurement, conversion, and logistics management (CSCMP, 2017).* In other words, SCM is managing the supplier system, internal logistics system and customer system as shown in Figure 2. In this project, the simulation framework aims to study the disruption in the production and the impacts on the internal logistic system as well as the customer system. Hence, the supplier system is excluded from this project scope. Nevertheless, in order to give readers an overview of supply chain resilience, the literature review presents a holistic perspective about resilience on the whole SC system.

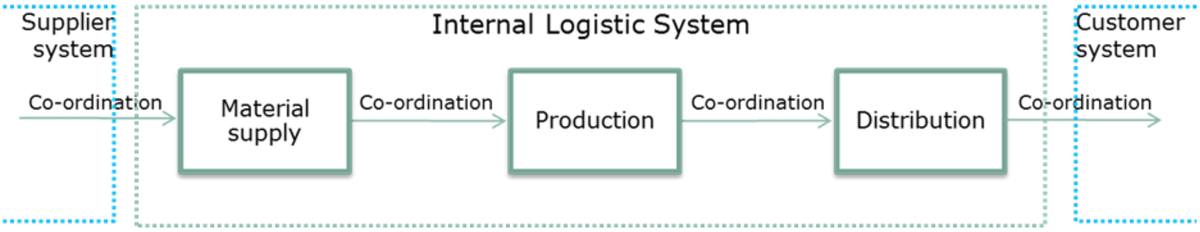


Figure 2. Supply Chain System, adapted from CSCMP (2017)

Every activity in a SC is exposed to a certain risk in today's turbulent environment, which may lead to an unexpected disruption. Therefore, SC managers have to think beyond 'business as usual' in order to strive for creating and sustaining competitive advantages through SCM (Christopher & Peck, 2004; Christopher & Towill, 2002). They need to think how to cultivate resilience to cope with SC risks and disruptions (Fiksel, Croxton, & Pettit, 2015). Resilience is at the heart of current SCM thinking (Melnyk et al., 2014). Especially in the semiconductor industry, where the demand is highly volatile and cycle time is long, having BC planning to enable a resilient supply network is of vital importance for companies to keep their market share. However, the term of SC resilience is still relatively new compared to other related topics e.g. supply chain risk management. Yet, its theory and practice have been developed rapidly through the past fifteen years.

This chapter is first introduced with the risk, uncertainty and vulnerability as cornerstones for the evolution of SC resilience. Secondly, different definitions of SC resilience will be introduced and one commonly-used definition from Ponomarov and Holcomb (2009) is adopted given the scope of this project. Furthermore, four principles are elaborated on to gain a better understanding. The main principles are based on the work of Christopher and Peck (2004), and more literature is reviewed to support the inclusion of sub-factors such as redundancy vs. flexibility. Following this, the SC resilience assessment and business continuity strategies are illustrated, as those land as a stepping stone for the thesis work. Lastly, the simulation approach and some existing models to investigate SC resilience are also discussed as a benchmark for this project.

2.1 Risk, Uncertainty, Vulnerability and Resilience

Supply chain risk management (SCRM) is often mentioned in other literature as an overarching background theme. SCRM is defined by Juttner et al. (2003) as: *"the identification of potential sources of risk and implementation of appropriate strategies through a coordinated approach amongst supply chain members, to reduce supply chain vulnerability."* SC resilience deals with a variety of risks using different strategies throughout the whole risk management process. Hence, SC resilience is a core element of it. Furthermore, according to Fiksel et al. (2015), the traditional SCRM depends on statistical information that may not exist and relies heavily on risk identification, where each risk is treated independently and their interactions are often ignored. These factors cause the ineffectiveness of traditional SCRM, which SC resilience could complement from a more dynamic perspective and prepare companies for unpredictable risks.

2.1.1 Decision-Making under Risks and Uncertainty

The concepts related to risks, vulnerability and resilience in supply chains become more important in the research from recent years. A risk is an uncertain, future event, that, if it occurs has a negative or positive impact on project promises (Project Management Institute, 2013). If a risk is positive, it can be perceived as opportunities, whereas if it is negative, it is deemed as a threat. In this report the term 'risks' refer to the negative risks. A risk has a probability between 0 and 1. Based on this background and the available information, three categories of decision-making are classified (Rosenhead, Elton, & Gupta, 1972): decision making under certainty, under risk, and under uncertainty. Decision making under *certainty* indicates all parameters are deterministic and known. The relation between input and output is unambiguous. However, this is very difficult to achieve in reality due to the limit of time, resources, etc.

Decision making under *risk* counts on the probability distributions, which governs the relation between the input and output. Identifying and assessing risks in order to plan and implement responses are the crucial activities in this type of decision-making. Decision making under *uncertainty* is the act of choosing between two or more courses of action when the outcomes of them are uncertain (Schultz, Mitchell, Harper, & Bridges, 2010). Under uncertainty, decision making is carried out but lacking the information about the parameters changes (Heckmann, Comes, & Nickel, 2015). Therefore, a probability can be assigned to a risk event and the likelihood of a future outcome is predictable in risk but not in uncertainty (Mentis, 2015). Uncertainty is uncontrollable, whereas risks, being unavoidable, can be managed from knowing the probability distribution of the uncontrollable random events and reducing their impacts (Wang, 2002). Hence, decision making under uncertainty is more challenging. In such situations, decision makers tend to base their decisions on their attitudes towards the unknown, e.g. positive, pessimistic and least regret (Eiser & van der Pligt, 1988).

Many scholars adopted this categorization and refer the supply risk to both decision making under risk and under uncertainty due to a mixed extent of information availability. Converting an uncertainty problem into a risk problem is not impossible, e.g. by the subjective estimation of probabilities based on experience, etc. Nevertheless, some aspects of the future are completely unknowable or unpredictable, and using subjective probabilities are not suitable to illustrate this volitional uncertainty (Schultz et al., 2010). To insert probabilities in such situations may make the decision makers more comfortable but does not necessarily assist in problem-solving (Rosenhead et al., 1972). Typical approaches to cope with uncertainty in decision-making include but are not limit to: 1) sensitivity analysis to determine the greatest sources of uncertainty 2) scenario analysis to demonstrate the overall uncertainty e.g. by creating the best and worst case 3) probabilistic analysis to assess the likelihood of potential outcomes 4) select the best strategy based on the expected value principle (Miller & Park, 2002).

Decision making in this project is mostly under uncertainty due to the lack of sufficient information. The scenario analysis is employed in this simulation project. The probability of each scenario is unknown and undefined, and a subjectively estimated probability distribution is used to describe the characteristic of the scenario. Different scenarios construct a picture of various risky situations in order to gauge the level of overall uncertainty. The details are depicted in Chapter 4.

2.2.2 Response Planning in Risk Management

Risks can be described using three elements: causes, risk event, and consequences, as shown in Figure 3. Causes are definite facts that exist in the environment giving rise to uncertainty and vulnerability. A risk event includes a set of uncertain events or circumstances affecting the objectives. The consequences would be the unplanned variations from objectives after the risk event occurs (Hillson, 2000).

Figure 3. Risk Description and Response using a Bow Tie Method, adapted from Hillson (2014) (Hillson)

A traditional operational risk management process includes six main steps: 1) identify hazards/causes 2) assess risks 3) analyze controls 4) determine controls 5) implement controls 6) supervise and review (Manuele, 2005). This project attempts to use a simulation framework to analyze and help determine controls (step 3 and 4) without extensive risk identification (step 1 and 2), therefore providing a strategy preparation tool for enhancing resilience. The first two steps aim at assessing the probability of occurrence and size of the impact. Based on the assessment, the response planning is carried out. A bow tie model Figure 3 shows three types of reaction to risk (Hillson, 2014):

a) Remove the causes, which will eliminate uncertainty completely. For example, building the project on an inland location with limited water sources to avoid the possibility of having a flood.
b) Insert barriers in between the causes and the risk event, which means to reduce the probability of a risk event occurring. This can be done to make the design more resistant to floods in the situation mentioned above.
c) Insert barriers in between the risk event and the consequences, indicating to minimizing the impacts after the risk event happens. A quick recovery from the flood belongs to this type of blocker.

The first two options are prevention while the last form is mitigation. In the context of SC management, the first two forms are associated with SC robustness, since they tackle risks from the frontend of the bow tie, aiming at maintaining a good performance level via preventive controls. The BCSAS can neither remove the causes nor reduce the probability of risk events happening. The goal of those strategies is to build a buffer between the risk event and the consequences so that the negative business consequences (financial loss, dropping customer satisfaction rate, etc.) can be eased. In this report, the SC resilience is seen from the recovery preparedness of BCSAS, i.e. quick restoration capability at the backend of the bow tie after a disruption event. The simulation is used to provide a visual and quantitative demonstration of the reduced impacts from the BCSAS. The traditional risk assessment is not good at dealing with uncertainty. The concept of resilience is believed to bridge the gap and supplement the conventional risk management programs (Pettit, Fiksel, & Croxton, 2010).

2.2.3 Vulnerability and Resilience in Relation to Risks

Vulnerability indicates the degree of fragility of a system, expressing its propensity to suffer damage (Douglas, 2007). Hence, vulnerability shows if a system is ready for unanticipated hazards, internally or externally. The causes in the environment together with the system design determine the system vulnerability. Vulnerability can be seen as the base scenario for risk analysis. Risk management is used in order to reduce vulnerability and/or increase resilience as an alternative (Elleuch, Dafaoui, Elmhamedi, & Chabchoub, 2016). Supply chain vulnerability specifies the propensity of undergoing adverse supply chain consequences (Svensson, 2002). Its sources and drivers come from four levels: i) stream/product or process; ii) asset and infrastructure dependencies; iii) organizations and inter-organizational networks; and iv) social and natural environment (Peck, 2005). A resilient network has more to do than the design and management of supply chain robustness. The networks and environment as the iii) and iv) mentioned above, which are external factors, also contribute to the vulnerability, hence mitigation is as vital as prevention for disruptions (Peck, 2005).

2.2.4 Expected Value

For risk assessment, expected value is often mentioned as a measurement. Generally, expected value represents the average outcome of numerous repeated circumstances (Nicholas & Steyn, 2008). Mathematically, it is the weighted average of the possible outcomes (see formula 1):

$$Expected\ Value = \sum(Outcomes \times Likelyhood)\ \ (1)$$

The expected value could present the decision makers the mean of the outcome in the probability sense for the sake of comparison among different alternatives. For example, insurance companies often use expected values to design different financial compensations packages for risk taking. However, this also brings the so-called "flaw of averages", i.e. *plans based on average assumptions are wrong on average* (Savage, 2012). When an average is used to represent an uncertain number, the results may be distorted as the impact of inevitable variations is overlooked (Savage, 2002). For this reason, we undermine the risks under uncertainty (Savage, 2012). The flaw of averages can be seen everywhere in engineering, finance, business, etc.

A real-life case occurred in Orange County, California in 1994. The Officials had built the county's financial portfolio based on a range of expected future behavior of interest rates explicitly considering the uncertainties. They drew the conclusion that the expected value is very positive and there was only a 5% chance of losing $1 billion. Therefore, they decided on full investment given the expected value, which hid the enormous risk. This extremely unlikely event happened and forced the Orange County into bankruptcy (Savage, 2002).

The risks with low probability and huge impact are called black swan risks (Taleb, 2008). The expected value in this situation misleads the assessment of the potential threat. The inputs are subject to increasing uncertainty in the world, which implies the expected value is mathematically correct but does not necessarily give the expected payoff in reality. The risk event either happens or not at all. Responding to blacks swans can be difficult to defend as the resources are spent on risks that did not occur or prevented, but no one will ever know. The average output in this simulation has some distinctions with the expected value portrayed here, which is further discussed in Chapter 8.

2.2.5 Justification of the Simulation Method with Regard to Risk Management

The method of DES has many benefits and it is closely related to risk assessing and control analysis in the procedure of risk management. Firstly, scenario analysis, as a frequently-used risk approach, can shed light on the overall uncertainty via studying the best and worst cases (Miller & Park, 2002). DES provides the possibility to test diverse scenarios without influencing the real-world SCs. Secondly, the DES enables measuring and quantifying the risks in terms of costs, manufacturing performance, etc. (Landtsheer et al., 2016), which facilitates the establishment of adequate strategies for risk mitigation. Lastly, the DES is helpful to evaluate certain impacts of BCSAS and compare them on a common base to support the decision making under risk and uncertainty.

2.2 Definitions of Supply Chain Resilience

SC resilience is becoming increasingly important in the business world for three main reasons. Firstly, SCs are more critical to the success of business today whereas they are also exposed to more disruptions than ever (Vassiliadis & Goldbach, n.d.) Hence, building resilience in SCs is ultimately improving the ability to recover from a disruption so that the performance could be quickly reinstated. Secondly, the traditional risk assessment such as risk register is not good at handling the rising uncertainties and vulnerabilities. A more resilient approach is needed to ensure the SC can respond as fast as possible facing an unexpected disruptive event (Pettit et al., 2010). Lastly, the customers nowadays are more concerned about the risk management and BC planning of their partners. Building SC resilience enhances the customer satisfaction and addresses the long-term value for multiple stakeholders through the lens of their propositions (Avery & Bergsteiner, 2011).

Even though many scholars and managers started to emphasize the importance of SC resilience, the exact notion of it is not well-defined. Some researchers address SC resilience as proactive efforts to protect against disruptions whereas others perceive it more as reactive capacity after disruptions (Kamalahmadi & Parast, 2016).

Melnyk et al. (2014) stated that two critical components are included in SC resilience, i.e. 1) resistance capacity: the ability of a system to minimize the impact of a disruption by evading the hazard entirely or reacting early; 2) recovery capacity: the ability of a system to return to a steady state of operational capacity after a disruption. The resistance capacity is often associated with robustness, which indicates the ability to absorb a disturbance while maintaining the original state (Zsidisin & Ritchie, 2009). Some scholars hold a similar belief that resilience is formed by these two dimensions: robustness, which is proactive perspective, and agility, which is reactive perspective. However, the concept of SC resilience in this thesis emphasizes more on *adaptive capacity*, which is more reflected from flexibility and agility. Flexibility is planned adaption to both expected or unexpected external circumstances (Güller et al., 2015) while agility is an unplanned adaptation to unforeseeable changes (Goranson, 1999). Those two terms will be discussed further later. It is also important to recognize the differences between adaptation and adaptive capacity. According to Chakravarthy (1982), adaptation concerns a state whereas adaptive capability incorporates the permanent ability to seek and seize new opportunities.

In fact, the concept of resilience is multidimensional and multidisciplinary (Ponomarov & Holcomb, 2009). Ponomarov and Holcomb (2009) had looked at it from ecological, social, psychological and economic perspectives. They proposed a definition of SC resilience through viewing and integrating multidisciplinary perspectives, which is commonly-cited and also adopted as the main understanding of SC resilience in this thesis.

Supply chain resilience is “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.” (Ponomarov & Holcomb, 2009).

This definition is comprehensive and focuses on the adaptive capability instead of the resistance capacity (robustness). As mentioned before, this project attempts to evaluate the impacts of BCSAS after a disruption happens in order to enable a cost-efficient level of flexible production for catastrophe preparation. Therefore, the scope is about the adaptive capability for recovering instead of resistance. Given this, the definition from Ponomarov and Holcomb is more suitable to express the resilience discussed in the project.

2.3 Supply Chain Resilience Principles

Christopher and Peck (2004) defined four principles that underpin resilience in SCs: 1) supply chain (re)engineering, 2) supply chain corporation, 3) agility, 4) creating an SCRM culture. Those four principles are regarded as four pillars for SC resilience (Wilding, 2013) and also serve as stepping stones for other work in the field of SC resilience (Briano, Caballini, Giribone, & Revetria, 2010; Christopher, Mena, Khan, & Yurt, 2011; Mandal, 2012). Figure 4 shows those principles and their relationships among each other. In the following part, more literature is reviewed to elaborate this framework.

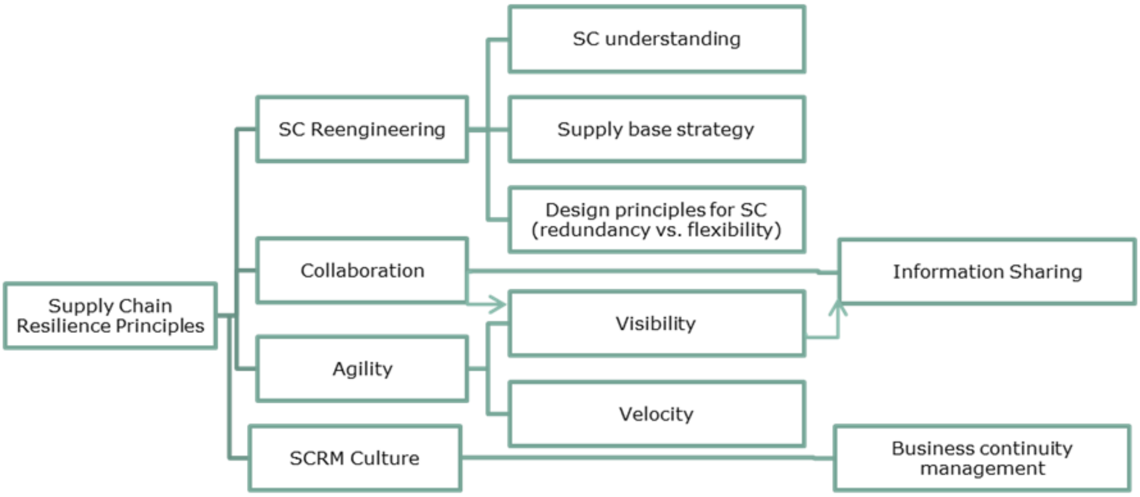


Figure 4. Supply Chain Resilience Principles, adapted from Christopher and Peck (2004)

2.3.1 Supply Chain (re)Engineering

Christopher and Peck (2004) emphasized that resilience should be designed in, hence traditional SCs need to be re-engineered to incorporate resilience. Three crucial recommendations for the re-engineering are provided: i) SC understanding, ii) supply base strategy, iii) design principles for SC resilience.

For SC understanding, the identification of ‘pinch points’ and ‘critical paths’ are addressed in order have a better comprehension of the network that connects customers and suppliers. ‘Pinch points’ are the bottlenecks in the supply chain, e.g. the frontend production for the semiconductor industry. A ‘critical path’ usually has the characteristics of long lead time, single source, and high level of identifiable risks (Christopher & Peck, 2004).

The discussion of supply base strategy highlights the issue of single sourcing and the need for selecting suppliers based on their risk awareness. Multi-sourcing and supplier selection process have been investigated by several scholars (Baker, 2007; Levary, 2007; Lodree Jr & Taskin, 2008; Svensson, 2003; Zsidisin et al., 2000). It is of crucial importance to select the right suppliers not only for supplying materials but also to improve information sharing and collaboration to achieve better performance (Barroso, Machado, & Machado, 2011). Multiple sourcing seems to be more reliable since it keeps several options open. However, (Zsidisin & Ritchie, 2009) found that multiple sourcing does not result automatically in lower supply risks.

However, most strategies under scrutiny by researchers are mostly supply-side mitigation policies (Barroso et al., 2011; Güller et al., 2015; Kamalahmadi & Parast, 2016) and decisions on inventory placement such as where inventory is held and how much is held (Lodree Jr & Taskin, 2008; Schmitt & Singh, 2012; Sheffi, 2005; Sheffi & Rice Jr, 2005; Wilding, 2013). Manufacturing network for the supply chain resilience is rarely touched upon in the present literature. The business continuity planning about production transfer to achieve a resilient internal supply network is an area yet to be explored.

In fact, those mitigation strategies mentioned above are about the trade-off of “redundancy vs. flexibility”, which are two frequently discussed design principles for SC resilience. Redundancy means reserving some resources in case of a disruption whereas flexibility implies being susceptible of modification or adaptation. The most commonly-used approaches of redundancy are excessive stocks and multiple suppliers. Having flexible transportation, flexible labor arrangement, flexible production and flexible supply base are examples of flexibility to improve resilience (Crum, Christopher, & Holweg, 2011; Pettit et al., 2010; Tang, 2006).

Both redundancy and flexibility can be effective to absorb the negative impacts from SC disturbances; while flexibility has a lower total cost, adding redundancy gives a better lead time ratio (Carvalho et al., 2012b). The mitigation effects of both strategies are confirmed by Zsidisin and Wagner (2010). Their survey results showed that redundancy and flexibility policies are suitable in different circumstances. Flexibility is more beneficial if risks originated from extended supply chains, whereas creating redundancy becomes more helpful when risk sources are outside the control of SC participants so that they can insulate themselves from the disruption waves.

Flexibility builds SC resilience by improving rapid adaptability during turbulence (Crum et al., 2011). Extreme Value theory is recently used to assess the value of flexibility under threatens of disruptions (Biçer, 2015). From the viewpoint of Sheffi and Rice Jr (2005), it is more important to make SCs flexible than adding redundancy which increases cost and is not useful for daily operation. The flexibility can be achieved considering the essential elements of SCs: correct alignment of the supplier relationship, standard conversion process, various distribution channels for customers, control systems with strong information gathering capability and risk-awareness corporate culture (Sheffi & Rice Jr, 2005).

On the other hand, redundant capacity is shown to be necessary along the critical path to moderate vulnerability and enhance resilience (Christopher & Rutherford, 2004). Even though there exists additional cost associated with redundancy, adding emergency backup facilities can be cost-effective to enhance the resilience, especially in long-term disruption scenarios. Furthermore, it actually increases the flexibility from turning the existing manufacturing sites to serve as backup facilities (Ratick et al., 2008). Johnson et al. (2013) also confirm this finding in their study that redundancy facilitates flexibility through the adaptable deployment of resources.

The BCSAS under investigation in this thesis are actually a combination of redundancy and flexibility policies, and their tradeoffs will be explored via simulation to shed more light on this issue. The alternative sites belong to the concept of *redundancy*, but there are different types of alternative sites, including various levels of transfers, e.g. tools and technology transfer. This allows a *flexible* structure of the manufacturing network to enhance resilience.

2.3.2 Supply Chain Collaboration

The underlying principle for SC collaboration is to reduce uncertainty and manage risks by exchanging information (Christopher & Peck, 2004). Pettit et al. (2010) identified collaboration, “the ability to work effectively with other entities for mutual benefit”, as one of capability factors to balance the inherent vulnerabilities in supply chains. Wieland and Wallenburg (2013) conducted an empirical study to explore the influence of three types of relational competencies (communication, cooperation, and integration) on SC resilience. The outcome showed that communicative and cooperative relationships have a positive effect on resilience, while integration only plays a limited role in enhancing resilience.

The supplier/customer involvement and collaboration are emphasized in a variety of literature (Fiksel et al., 2015). However, the collaboration within the organization is not mentioned that frequently in the current literature study, yet it is of crucial importance. The supply chain collaboration also contributes to building visibility along the SC, and are interrelated with or sometimes discussed under the category of agility. There is no clear boundary to draw. Most of the firms today still under-invest in collaboration either internally or externally in practice (Christopher et al., 2011; Wilding, 2013). Information sharing in collaboration can be considered a driver for collaboration (Christopher & Peck, 2004), or even a separate driver for resilience (Datta, Christopher, & Allen, 2007; Soni, Jain, & Kumar, 2014)

2.3.3 Agility

Building on the previous definition, agility is the ability to rapidly respond to change by adapting its initial stable configuration (Wieland & Wallenburg, 2013). Hence, agility is connected with the responsiveness of supply chains in case of disruptions. It is ranked the highest among 14 enablers of supply chain resilience by Soni et al. (2014). Christopher and Peck (2004) stated that agility incorporates many dimensions and two key ingredients are '*visibility*' and '*velocity*'.

Visibility is the ability to see from one end of the pipeline to the other (Christopher & Peck, 2004). It is defined as the "knowledge of the status of operating assets and the environment" by Pettit et al. (2010). Visibility indicates a clear picture of the inventories, demand and supply conditions, as well as the production schedule, etc. It can be distorted by intervening inventories upstream and downstream of the focal firm and by the presence of the bullwhip effect (Christopher & Peck, 2004). However, these two topics are widely studied and beyond this thesis scope.

Visibility can be achieved significantly via collaborative planning with customers and/or suppliers. As a matter of fact, it is often challenged within the internal organizational structure of the focal firm (Christopher & Peck, 2004). The research results from Blackhurst et al. (2011) demonstrated that the need for increased visibility in the supply chain has been discussed by all studied firms. Six firms highlighted the importance to monitor their supply chains in real-time in order to make strategic decisions to prevent forthcoming disruptions. This project does not intend to assist real-time decision making, but in a way to help prepare for the future disturbance. Visibility is considered as an input instead of a parameter here.

The concept of speed is built in agility, hence *velocity*, which incorporates speed and consequently time, is introduced as a vital building block of resilience (Scholten, Sharkey Scott, & Fynes, 2014). There are two main types of interpretation of supply chain velocity. Increased velocity in a fixed distance means reduced time. Thus, one is referred to the 'end-to-end' pipeline time, i.e. the time it takes from the upstream supply to the downstream delivery (Christopher & Peck, 2004). The other interpretation is in the background of a risk event, i.e. recovery speed, which is a key measurement of resilience. In this case, velocity is closely related to flexibility and adaptability, thus some authors consider it in the *flexibility* category (Fiksel, 2007; Soni & Jain, 2011).

It is also important to distinguish the velocity of recovery and the speed of risks, as the latter might have an impact on the former. Manuj and Mentzer (2008) categorized three different forms of the speed of risks: the rate at which the event leading to loss happens, the rate at which losses happen, and how quickly the risk event is discovered. In this project, the rate at which the event leading to losses is modelled as different scenarios to test the effects of BCSAS; the rate at which losses happen is identified from the client profiles using modelling approach from Montreuil et al. (2013), which will be further elaborated in chapter 5; the rate of a risk event being discovered is very difficult to quantify and validate, hence it is deemed as a parameter in the simulation.

Christopher and Peck (2004) suggested three basic foundations to improve velocity: 1) streamlined processes, e.g. parallel work and e-based rather than in series and paper-based, 2) reduction in inbound lead times, 3) reducing non-value adding time. However, some other findings (Carvalho et al., 2012b; Carvalho, Azevedo, & Cruz-Machado, 2012a) illustrated that redundancy (non-value adding) increases the velocity by reducing the lead times. The report's author inclines to believe that this is not contradictory to the viewpoint of Christopher and Peck. In the production scenarios, when catastrophes are not present, building inventories will require extra production capacity that could otherwise be used to increase the velocity as well as the mix of products to make the SC agile. However, in the case of a catastrophe, the agile SC may not be that 'agile' to provide sufficient production rates to compensate the required delivery speed; the excessive inventory becomes one of the effective approaches to ensure the velocity in the short term. Nevertheless, the inventory would run out one day and the adaptability to restore plays a significant role. Therefore, in the opinion of this thesis author, agility is a relative term depending on the flexible capacity, length and depth of a disruption.

2.3.4 Supply Chain Risk Management Culture

To create a risk management culture within business today is a requirement for operating successfully and this culture should extend to "supply chain continuity management" (Christopher & Peck, 2004). The internal supply chain risk management culture has an impact on resilience (Wilding, 2013). It creates a situational awareness and initiatives at various levels. In the case of a disruption, actions can be taken immediately at every level of the organization (Sheffi & Rice Jr, 2005).

Parallel to risk management is the issue to deal with the consequences of an accident and minimize the business impacts, which is normally known as business continuity management (BCM), aiming to get interrupted businesses started (Norrman & Jansson, 2004). Its primary objective is to allow the Top Management of an organization to continue to manage their business under adverse conditions, by the introduction of appropriate resilience strategies, recovery objectives, business continuity and crisis management plans (Weixlgartner, 2016). In many ways, BCM and risk management are overlapping (Norrman & Jansson, 2004). Developing action plans to minimize the impacts and recover from a catastrophic event is of crucial importance to BCM.

2.4 Assessing Supply Chain Disruption and Resilience

The question on how to assess the supply chain resilience has received little attention in research (Barroso, Machado, Carvalho, & Cruz Machado, 2015; Carpenter, Walker, Anderies, & Abel, 2001). Some features of *system resilience* are specified by Carpenter et al. (2001): a) the ability of a system to stay in the "domain of attraction", b) the ability of a system to self-organize, c) the adaptive capacity. However, their research is limited to the sociological system. In order to assess the resilience in a system, it should be specified which disturbances are of interest (resilience to what) and what system state is being considered (resilience of what) (Carpenter et al., 2001).

This section illustrates that the design characteristics of the supply chain have an impact on the types and severity of disruptions it exposes, while the specification of those disturbances under investigation will be elaborated in Section 4.2 (resilience to what). After disruptions, the typical time series for the system state of the supply chain is also depicted in this section (resilience of what).

2.4.1 Severity of Supply Chain Disruptions with Design Characteristics

The severity of a supply chain disruption can be defined as "the number of entities (or nodes) within a supply network whose ability to ship and/or receive goods and materials (i.e., outbound and inbound flow) has been hampered by an unplanned, unanticipated event (Craighead, Blackhurst, Rungtusanatham, & Handfield, 2007)." The SC disruptions are inevitable over the course of time and the SC risks are inherent. However, some factors (policies and practices) that will make a SC disruption more severe can be avoided whereas the others dampening the severity could be implemented. Craighead et al. (2007) conducted an empirical study about the impacts of SC structure on the severity of SC disruptions.

Their research result is summarized in Figure 5. Essentially, the supply chain *density* (geographical spacing of nodes within a supply chain) and *complexity* (total number of nodes and materials flows within a supply chain) will be more likely to increase the severity of a SC disruption. Additionally, an unplanned disruptive event occurring at a *critical node* is likely to be more severe than the same disruption affecting less critical nodes of the SC (Craighead et al., 2007). The criticality of a node is context-specific and relative to other nodes within a given supply chain. Falasca et al. (2008) used those three determinants identified by Craighead et al. (2007) as their inputs for a simulation-based decision framework, and examined their relationships to the occurrence and impacts of disruptions. They argue that simulation is a useful tool to test SC responses to different strategies for improving resilience. However, it should be addressed that even though the three design characteristics are important for enhancing resilience, most of the SC structure in this project is fixed. The research emphasis of BCSAS is placed on the supply chain mitigation capacities, particularly in recovery, as shown in the lower box of Figure 5. The mitigation capabilities could help reduce the severity and hence improve the resilience.

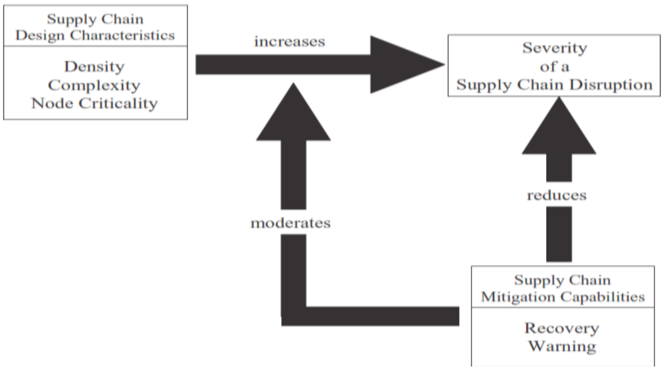


Figure 5. Factors Impacting Severity of Supply Chain Disruptions (Craighead et al., 2007)

2.4.2 Resilience Triangle

Tierney and Bruneau (2007) outlined a ‘resilience triangle’ graph (Figure 6) from disaster research to demonstrate the system loss of functionality (e.g. sales, production levels, fill rate) from disruption and the pattern of restoration and recovery over time. Thus, the performance evolution of a SC along the time can be used to analyze supply chain resilience. After a hazard event occurs, the performance decreases, but it will gradually be restored as actions are taken to recover. The depth of the triangle represents the disruption severity and the length of the triangle indicates the impacted duration, i.e. damping time. Hence, the smaller the triangle is, the more resilient the supply chain is (Barroso et al., 2011).

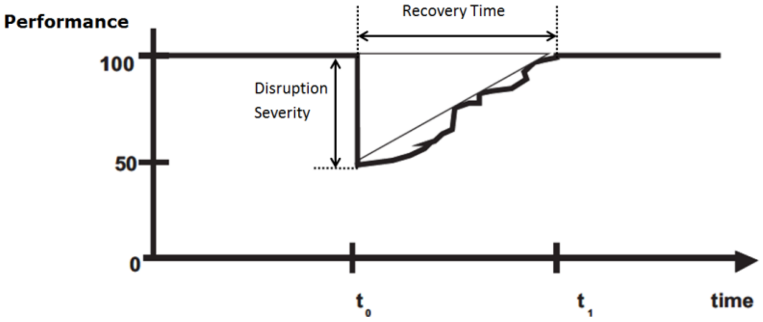


Figure 6. Resilience Triangle, adapted from Tierney and Bruneau (2007)

Extending from the ‘resilience triangle’, (Melnyk et al., 2014) illustrated a more detailed time series signature to depict supply chain resilience in four stages Figure 7. The vertical axis shows the system response, i.e. relative impact of a disruptive event measured in terms of euros, fill rate, etc. The four stages are: i) the *avoidance* phase indicates how long it takes for the firm’s performance to be impacted; ii) the *containment* phase is the time interval when the impacts deploy in the SC, which could also be instant such as an earthquake; iii) the *stabilization* stage shows that the system is trapped in the negative effects before it starts to recover; iv) the *return* stage illustrates the gradual recovery from disturbance until the system response level restores to the original or a different but stable level. Once recovered, the firm identifies and reflects the lessons learned, and prepares for future risks, forming a resilience cycle (Melnyk et al., 2014). This resilience cycle (avoidance ➝ containment ➝

stabilization ➝ return ➝ avoidance) corresponds with the 'resilience triangle' above but in a more systematic perspective.

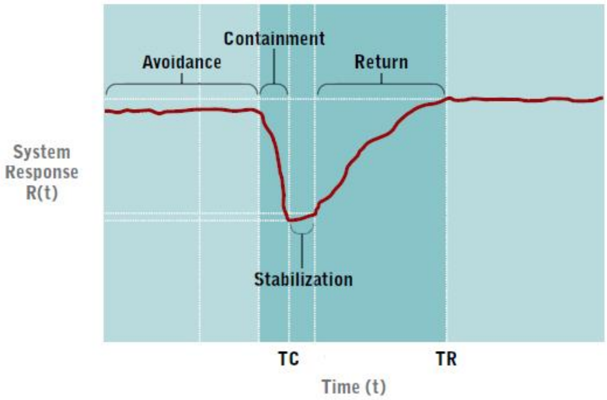


Figure 7. Time Series Display of Supply Chain Resilience Factors (Melnyk et al., 2014)

However, the phases of avoidance and containment are more related to the capacity of resistance, typically about the SC design characteristics. As mentioned in section 2.2, this project focuses on the adaptive capacity, especially the recovery capacity (along the phases of stabilization and return). Hence, the resilience assessed in this project will be measured in term of the time from TC-TR.

2.4.3 Zone of Resilience

In addition to the concept of 'resilience triangle' for measuring the SC resilience, there is another approach defining a zone of resilience. Pettit et al. (2010) proposed such a conceptual framework of SC resilience (shown in Figure 8), which is closely related to vulnerability and capability. Force of changes creates vulnerability while management control contributes to capacity. Supply chain resilience increases, as capabilities increase and vulnerabilities decrease. However, there may be unbalanced resilience. In the upper left corner of Figure 8, when high capabilities are deployed for coping with low vulnerabilities, there is eroded profitability, meaning there is too much redundancy taking away profits. On the opposite side of the graph, when high vulnerabilities and low capabilities co-exist, the SC is exposed to excessive risks. The balanced area in the middle, when capabilities match the vulnerabilities, is the 'zone of resilience' for improved performance (Pettit et al., 2010).

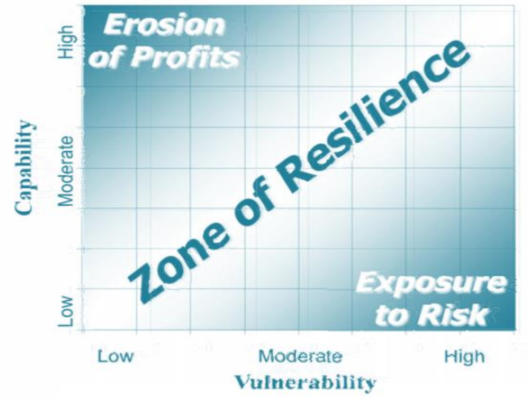


Figure 8. Zone of Resilience (Pettit et al., 2010)

In this project, the vulnerability factors such as supplier disruption, external pressures and turbulence are treated as the environment where the SC is located without further varying. However, the diverse disruption scenarios defined in chapter 4 could be an indication of vulnerability consequences. Additionally, the types of different BCSAS imply different levels of capability to recover. Hence, the simulation framework proposed in this project intends to identify the 'zone of resilience' for semiconductor manufacturing using the illustration of 'resilience triangle' and financial performance comparison.

2.5 Business Continuity Strategies to Enhance Supply Chain Resilience

Now we have a better understanding towards supply chain resilience, its principles and assessment, we will present a summary of business continuity strategies to enhance it in this section. Several BC strategies have been classified by many researchers. Some emphasize mitigation strategies on concrete actions whereas others tend to suggest management strategies pinpointing the awareness. Since the supply disruptions from upstream in the chain are more critical (Roberta Pereira, Christopher, & Lago Da Silva, 2014), most of the literature discusses sourcing strategies or other strategies regarding the upstream. In Table 2 the main BC strategies in the current literature are outlined.

Table 2. Summary of BC Strategies for Enhancing SC Resilience, adapted from Melnyk et al. (2014)

#	BC Strategy	Explanation
1	Add (backup) capacity	Add excessive/backup capacity to allow flexibility in producing a variety of products, which could help lower inventory, meet fluctuating demand and deal with disruptions
2	Add inventory	Create excessive/safety stock, which is a very common approach for companies to satisfy customer demand in the short term; the inventory could also be strategically allocated in different locations with supply chain partners.
3	Resilient supply base	This strategy includes a variety of mitigation policies from the supplier side. 1) multiple sourcing 2) flexible supply base 3) careful supplier selection 4) relation and collaboration with suppliers 5) redundant suppliers
4	Increase operational flexibility	Changing flows or product specifications in response to disruptions, such as alternative transport routes
5	Increase responsiveness	Immediately take actions to respond to disruptions, devoting all possible resources for restoring; increase the responsiveness to suppliers/ backup source/customers
6	Increase information sharing	Increase the quantity, quality, and speed of information throughout both internal and external supply chain, e.g. improving information technology and communication systems
7	Security	Improve the security in the system to prevent disruptions from theft, intentional damage, cyber attack, counterfeiting, e.g. firewalls, strengthened physical system
8	Preparedness	Designing contingency/business continuity plans to respond to different disruption scenarios. Make sure different groups understand what their specific responsibility is and what they are supposed to react to.

It can be seen from the Table 2 that those BC strategies are closely related to the main principles of supply chain resilience. Furthermore, they reflect on many capability factors for ensuring resilience proposed by Pettit et al. (2010), which are flexibility, capacity, efficiency, visibility, adaptability, anticipation, recovery, collaboration, organization and security. As mentioned before, the scope of this project is limited to an internal logistic-customer system, focusing on frontend production disruption. Hence, the safety stock, external supply base, responsiveness, information sharing and security will be considered as the environment where the business simulation is running but not variables to test in this research. The main strategy under scrutiny is #1-adding (backup) capacity in alternative sites after disruption (different speed for the capacity building for different BCSAS) to enable flexible and resilient production. This also reflects the preparedness strategy listed in the table above.

Some research has been carried out previously to study the effects of backup capacity. Adding emergency backup facilities can be cost-effective to enhance the resilience, especially in long-term disruption scenarios. Furthermore, it actually increases the flexibility by turning the existing manufacturing sites to serve as backup facilities (Ratick et al., 2008). Schmitt and Singh (2012) found out from a simulation that the responding speed of a backup source is more critical than its capacity and the impacts on customers will last significantly longer than the disruption duration.

2.6 Simulation for Analyzing Supply Chain Resilience

Apart from a vast number of qualitative research (empirical study, interviews etc.) on SC resilience in its principles, framework and relations, there also exists some quantitative research, especially in SC design and strategies testing. Many studies used DES to tackle SC problems from operational, tactical and strategic levels; nevertheless, the number of research where DES was applied to investigate SC resilience is still limited. Three main papers are found to depict the current situation of using DES to study SC resilience.

Firstly, Schmitt and Singh (2012) performed a quantitative analysis of disruption risk in a multi-echelon supply chain. They used DES to analyze the inventory placement and backup methodologies on reducing the impacts of SC risks. They modeled the risks from supply disruption and demand uncertainty and compared their influences. Some important conclusions from the study include 1) excess inventory to protect from demand fluctuation also have unforeseen benefits for responding to disruptions 2) the benefit of buffers have a non-linear impact on the resilience 3) minimizing the duration disruptions over time is more important 4) backorder cost plays a significant role in risk discussions. This paper studied several important aspects (e.g. inventory, disruption duration etc.), which this thesis work also addresses. The results of this project could also be cross-checked with the paper.

Secondly, Güller et al. (2015) carried out a DES-based analysis of supply chain resilience focusing on comparing the effects of JIT-concept, excess inventory, multiple sourcing, and flexible supply contracts. Deploying flexible supply contracts performs better in terms of a quick recovery of service level under all studied scenarios (volatile demand, production disruption with diminishing capacity at a supplier and supplier failures). However, this research is oriented towards supply side and the manufacturing side is not addressed.

Thirdly, Carvalho et al. (2012b) redesigned supply chain for resilience using DES. Their case study is for a three-echelon automotive supply chain. Two widely-used strategies, *flexibility* (restructuring existing transport) *and redundancy* (additional stock)*,* were considered when there are interruptions of material flows. The simulation results showed that both strategies are effective to mitigate turbulence adverse impacts. The flexibility strategy performs better in lead time ratio and reducing total cost compared with redundancy policy. The limitation of the research is that it looked into the material supplying issue, emphasizing the flexibility on transport. However, it cannot be universally applied across different sectors, as the automotive industry has distinctive processes and specificities. In the semiconductor industry, the transport is already very flexible and rapid, leaving less room for optimization.

However, the simulation models described above all emphasize the supplier system. The production capacity at the disrupted site restored instantly after disruptions and/or the backup capacity was built in immediately without ramping up (Carvalho et al., 2012b; Güller et al., 2015; Schmitt & Singh, 2012). In this project, the recovery process is examined to shed light on the ramp up when the manufacturing is disturbed by non-supplier issues.

Furthermore, there are also many studies looking into supply network modeling and simulation methodology to have a generic setup for supply network analysis, planning and risk management. Stefanovic et al. (2009) presented a “Supply network modeling and simulation methodology” for modeling structure and dynamics of complex supply networks based on process approach. Also, “Discrete-event simulation for semiconductor wafer fabrication facilities: a tutorial” (Fowler, Mönch, & Ponsignon, 2015) focused on the methodological and practical issues in simulation for the semiconductor industry from four levels (tool, manufacturing, internal supply chain and end-to-end supply). They also described and discussed the main steps and pitfalls of a simulation study in this domain.

2.7 Conclusion on Literature Review

Resilience is at the heart of current SCM thinking (Melnyk et al., 2014). It is closely related to risk management, which aims to reduce vulnerability and/or increase resilience as an alternative (Elleuch et al., 2016). Decision-making under risk counts on the probability distributions wheareas decision-making under uncertainty lack sufficient information about the parameters and outcomes changes (Heckmann et al., 2015). Uncertainty is uncontrollable but risk is manageable. A bow tie method illustrates three types of risk responses: 1) remove the causes, 2) insert barriers in between the causes and the risk event, and 3) insert barriers in between the risk event and the consequences (Hillson, 2014). The resilience approach taken in this project belongs to the third option. The concept of resilience emphasizes the ‘adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them’ (Ponomarov & Holcomb, 2009), hence it is believed to bridge the gap and supplement the conventional risk management programs (Pettit et al., 2010). This project focuses on the adaptive capability for recovering instead of resistance.

Furthermore, the main principles of supply chain resilience are introduced. Firstly, supply chain (re)engineering is addressed. It highlights decisions on inventory placement and the supply-side mitigation strategies. Abundant research has been conducted on the issues of single sourcing, multi-sourcing, supplier selection, etc. Zsidisin and Ritchie (2009) found out that multiple sourcing does not result automatically in lower supply risks. Redundancy and flexibility are often discussed as the design principles for SC resilience. Both of them are effective to absorb the negative impacts from SC disturbances while redundancy has a higher total cost (Carvalho et al., 2012b) and is more beneficial when risk sources are outside the control of SC participants. On the other hand, Ratick et al. (2008) argue that adding backup facilities can be cost-effective to enhance the resilience, especially in long-term disruption scenarios, whose concept is similar to the alternative sites in this report.

Secondly, supply chain collaboration is stressed as most of the firms today still under-invest in it either internally or externally in practice (Christopher et al., 2011; Wilding, 2013). Thirdly, agility as the ability to rapidly respond to change by adapting its initial stable configuration (Wieland & Wallenburg, 2013), incorporates two vital concepts: ‘visibility’ and ‘velocity’ (Christopher & Peck, 2004). The first one underlines the importance of information sharing to reduce the bullwhip effects whereas the latter could be interpreted as shorter ‘end-to-end’ pipeline time and/or quicker recovery speed, which is a key measurement of SC resilience. There are three foundations to improve velocity: streamlined processes, reduction in inbound lead times and reducing non-value adding time (Christopher & Peck, 2004). However, sometimes redundancy (non-value adding) could increase the velocity by reducing the lead time in the short term (Carvalho et al., 2012a; Carvalho et al., 2012b). Lastly, SCRM Culture is a crucial principle in supply chain resilience. There is an emphasis on business continuity management, which aims to minimize the business impacts under adverse conditions.

The assessment of SC resilience and an overview of BC strategies to enhance it are introduced. The severity of SC disruptions is impacted by SC design characteristics and SC mitigation capabilities. High density and complexity of SCs with critical nodes disrupted increases the severity whereas strong warning and recovery capability reduce the severity (Craighead et al., 2007). The ‘resilience triangle’ demonstrating the system response from disruption and the recovery over time is a common way to assess and analyze the SC resilience (Tierney & Bruneau, 2007). The smaller the triangle is, the more resilient the supply chain is (Barroso et al., 2011). This ‘resilience triangle’ is later extended to a resilience cycle (avoidance → containment → stabilization → return → avoidance), showing a more systematic perspective (Melnyk et al., 2014). In addition to this, the ‘zone of resilience’ (when capabilities match the vulnerabilities) is defined considering the risk profile and profit (Pettit et al., 2010). The business continuity strategies can be summarized into 8 aspects: 1)

Add (backup) capacity, 2) Add inventory, 3) Resilient supply base, 4) Increase operational flexibility, 5) Increase responsiveness, 6) Increase information sharing, 7) Security and 8) Preparedness.

Last but not least, some scholars have used simulation to investigate SC resilience and three main papers are found to depict the current situation (Carvalho et al., 2012b; Güller et al., 2015; Schmitt & Singh, 2012). They are very good demonstrations of how simulation can be useful to study such a complex issue. However, the simulation models described above all emphasized the supplier system. Furthermore, there are also many studies looking into supply network modeling and simulation methodology.

3. SUPPLY CHAIN MANAGEMENT IN THE SEMICONDUCTOR INDUSTRY

Semiconductors, also known as chips or microchips, are very critical in a vast number of products in our life, from mobile phones to cars and other electronic appliances. The semiconductor industry is believed to be one of the most complex and dynamic industries in the world (Sun & Rose, 2015). The industry develops rapidly in line with Moore's Law, i.e. *the number of transistors in a dense integrated circuit doubles approximately every two years* (Moore, 1998). This chapter will first emphasize the challenges in the semiconductor industry followed by an introduction to the internal supply chain. Particularly, the business continuity planning about manufacturing and supply chain at Infineon is demonstrated as a representation of this industry.

3.1 Challenges in the Semiconductor Industry

The semiconductor industry contributes to the increasing productivity, economic growth and innovations around the world. Up to 80% of innovation in the automotive industry is enabled by semiconductors, even more, when it comes to Hybrid and EV (Ehm, 2017). However, this industry, located in the early phase of the value chain, faces very fierce market competition and several industrial challenges:

- Highly volatile and dynamic demand: the semiconductor demands change fast, making it difficult to forecast. Furthermore, semiconductor manufacturers suffer from the bullwhip effect to a very large extent, as it is located upstream in the SC.
- Rapid technology changes: the semiconductor industry is one of most R&D intensive industries (McKinsey & Company, 2011), as the technologies develop at a very high pace, e.g. innovation in backend packaging. There exist rapid innovation cycles.
- Capital intensive: it is very expensive to purchase equipment, qualify technology and construct cleanrooms in wafer fabrications. The equipment to process wafer lots costs millions of dollars and a state-of-the-art frontend facility requires a large capital investment of three to four billion dollars (McKinsey & Company, 2011)
- Long lead time: the full cycle time from the frontend to backend till delivering to the customer could last several months. It takes up to 1000 process steps to turn a raw wafer to a finished chip, which is essential for achieving good quality (Ehm, 2017) Depending on the complexity of the chip structure and production-related delays (e.g. maintaining), the lead time is even longer.
- Short product life cycle: this challenge is associated with Moore's law that semiconductors are out of the market in a short time with decreasing value. The life cycle of semiconductor products lasts up to three years (Chou, Cheng, Yang, & Liang, 2007). This also indicates steep product ramp-ups for producing new products in order to meet changing specification and demands. This iteration accelerates at an increasingly fast pace.

Those challenges add onto each other, increasing the hardship in the semiconductor industry. The dynamic demand implies that the return on investment is more uncertain, nevertheless, the industry itself is capital intensive in nature, which makes the companies in this industry more fragile to disruptions. Furthermore, the contradiction between long lead times and short product life cycles requires highly efficient and agile manufacturing, which is difficult to achieve. In summary, the semiconductor industry faces rapid changes in technologies and demands, combined with long lead time and high investment costs, whereas the sales price of the final product decreases (Macher, Mowery, & Simcoe, 2010). The demand fluctuation due to product ramps up in the semiconductor industry is not considered, as this complicates the recovery ramp up after a disruption.

3.2 Internal Semiconductor Supply Chain with Global Manufacturing

To overcome the grand challenges in the semiconductor industry, it requires specific production structures with a globally distributed supply chain network (Sun & Rose, 2015). As shown in Figure 9, its internal logistic system with the manufacturing process can be divided into Frontend (FE), Die Bank (DB), Backend (BE) and Distribution Center (DC).

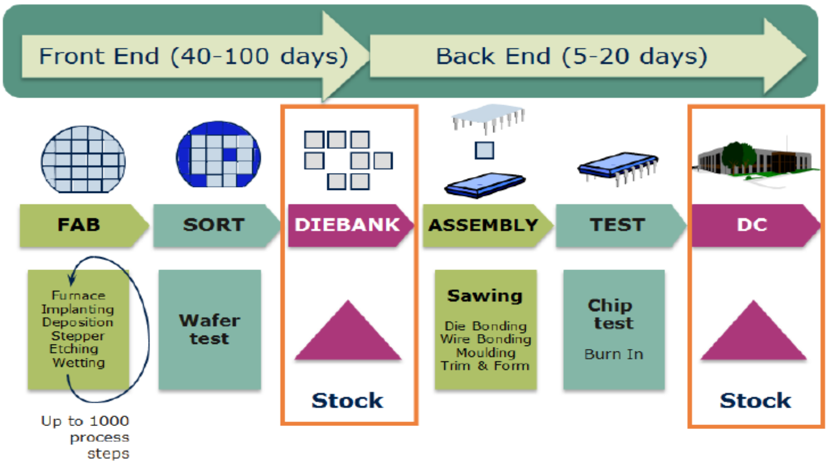


Figure 9. Semiconductor Production Processes, adapted from Ehm (2017)

In the FE, raw wafer lots are processed and different layers are applied on the raw material to obtain single dies on the wafer. The main elements included in the FE are fabrication (FAB) and wafer testing (SORT), which can take up to 12 weeks in total (Aelker, Bauernhansl, & Ehm, 2013). A very specific feature of semiconductor production in FE is the nonlinear process, meaning that a product re-enters a machine used before for several times during the manufacturing process. It is not unusual to have 35 revolving lithography steps in a FE fab to transfer the design via masks to the wafer. This nonlinear process makes the FE a typical bottleneck in the semiconductor manufacturing process (Ashayeri & Lemmens, 2007). Hence, it is more critical to focus on FE production and to have a resilient FE supply network. It is one important motivation for investigating FE disruption and recovery in this project. The DB, located in between FE and BE, serves as a disposition point where the finished dies from FE are stocked (Lee, 2001). The BE process is rather simpler compared with FE. The main tasks of BE are the assembly of dies into chips and final testing. Afterward, the finished products are stored in DC for final delivery. The BE cycle time is around 4 weeks but may vary depending on product structures.

In order to have a smooth production flow for such a vast number of wafers and chips, Infineon has a worldwide manufacturing network with 19 manufacturing locations spread across the globe (see Figure 10). The FEs are mainly located in Europe and America while the majority of BEs are in Asia. In addition to the in-house FEs and BEs, Infineon also has established strong partnerships with many silicon foundries and sub-cons. Under such a global supply network, it brings more challenges to coordinate the goods and information flow, but also offers possibilities to have backup capacity in an alternative site in case of catastrophes.

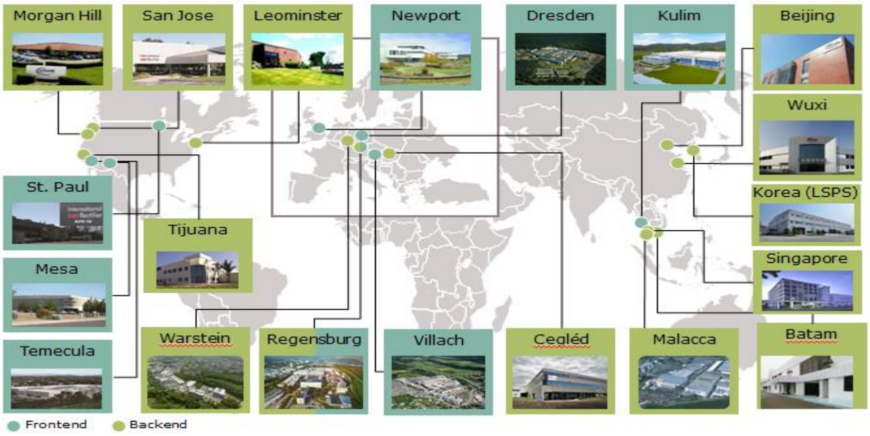


Figure 10. Global Manufacturing Network of Infineon (Infineon Technologies AG, 2017)

Infineon has more than 40000 sales products with distinguished design or customer specification and various technologies have to be in line with them. The entity relationship model shown in Figure 11 illustrates those connections. The column on the right side depicts product-related items while the column on the left refers to technologies. *Sales product*s represent sellable products, including more information on customer requirements about packaging and testing than basic types. A *basic type*, as the basic element of production, has its own technical characteristic properties as wafer diameter, chip geometry etc. This characteristic would require specific process technology, i.e. *process line*, which indicates all the process steps to be performed for manufacturing a basic type. A *process group* refers to an aggregation of similar process lines related to the same set of design rules in order to allow less detailed planning. For clarification, the products who share the same process group are hereby referred to as **PG** in this thesis and they are the focused entity level for modeling and further analysis.

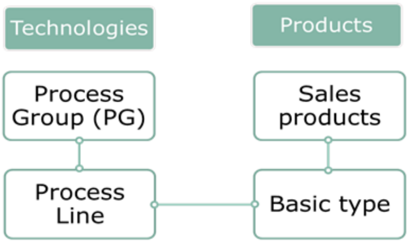


Figure 11. The entity relationship model at Infineon

3.3 Manufacturing and Supply Chain Continuity Planning at Infineon

Infineon has a tailored business continuity management system that ensures the availability of the supply chain and services in case of significant business disruptions and disasters. The business continuity management system identifies potential impacts that threaten Infineon and provides a framework for ensuring SC resilience in compliance with legal and regulatory requirements referring to ISO 22301:2012 (Weixlgartner, 2016). This section will elaborate more about the manufacturing and supply chain continuity planning at Infineon as part of their risk management.

3.3.1 Business Continuity Planning In Six Phases at Infineon

The Business Continuity Planning (BCP) aims to reduce impact and duration of disruptions. Six phases of BCP are shown in Figure 12. First, Infineon deploys *prevention* measures (e.g. via quality and security check) to prepare for unexpected disruptive events. In addition, Infineon has an *early warning* system that automatically detects critical external incidents and triggers early warning to potentially affected departments. When an incident happens, this early detection system will alert key functions to *respond* accordingly (Weixlgartner, 2016). The production decreases if impacted by the incident. Meanwhile, the activation of BC plans enables people with clear responsibilities to re-allocate resources and implement extra capacities, so that the production can *recover* as fast as possible. After the recovery phase, the manufacturing will be *restored* to the original level or even a higher performance. Afterward, Infineon reflects the *lessons learned*, and prepares for future risks. This BCP at Infineon corresponds with the resilience time series depicted in section 2.4.2 by Melnyk et al. (2014). As demonstrated in Figure 12, the reduced operational level is more limited (reduction of impact) and the time to recover to normal operation level is shorter (reduction of duration) with BCP than without BCP.

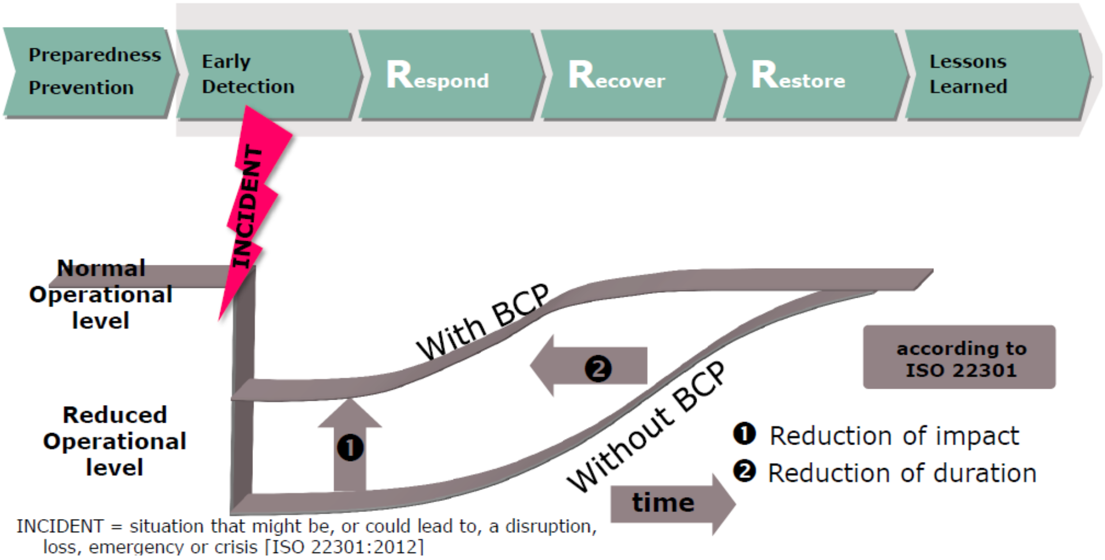


Figure 12. Business Continuity Planning In Six Phases at Infineon (Weixlgartner, 2016)

3.3.2 Business Continuity Strategies for Managing Supply Chain Disruptions

Many BC strategies are also planned at Infineon to mitigate the impact of unforeseen manufacturing interruptions and reduce the time needed to recover for the sake of SC continuity under adverse conditions.

Firstly, securing a supply of production materials are of crucial importance for manufacturing and supply chain continuity planning. A supplier evaluation system including supplier risk assessment is implemented at Infineon. This system assesses the overall performance for each supplier based on quality, logistics, financial analysis, etc. Furthermore, Infineon installed an intelligent inventory system to ensure the key chemicals for FE production are available for at least 6 months. The early warning system mentioned above also includes the supplier locations to evaluate the disruption impacts and send alerts (Weixlgartner, 2016). Nevertheless, the supplier side of risks and disruptions are out of the scope of this project.

Secondly, the logistic set up of Infineon has a standard transit flow based on harmonized processes and tools. There are also alternative emergency shipments to customers in case of any unforeseen crisis (Weixlgartner, 2016).

Thirdly, having extra stocks is often an easy approach that almost every manufacturing company does to deal with production interruptions. However, for the final products in semiconductor manufacturers, the issue of excessive stocks is more complicated. There exist unnecessary warehousing and stocking fees. More importantly, due to the long lead time and short product life cycle in the market of semiconductors, keeping a large number of inventories of certain finished products will expose Infineon to a severe risk of pricing depreciation, or even not being able to sell, as mentioned in section 3.1. Hence, having safety stock may be sufficient for short-term, minor interruptions in semiconductor manufacturers, but having excessive inventories is not an effective approach based on the special characteristics of this industry.

Lastly, there exists flexibility in production by qualifying high volume products at two or more sites (Weixlgartner, 2016). This brings in the possibility of producing one product at multiple sites, resulting in a certain level of elasticity in production capacity. Furthermore, there are versatile production corridors set for different processing priorities for wafer lots. A speed corridor implies the wafer lots there are given highest priorities, i.e. rocket and hot lots. Usually, the prior lots are selected based on the business impacts and non-stop operational flow (not allowed to stop at any operation technically such as pending setup). The wafer lots in speed corridor can, therefore, utilize extra capacity from other non-prior lots at the same FE. If possible, they could also be transferred to another site for production. Another option would be shifting the non-prior flexible products towards their alternative sites so that the prior lots can be processed at their mother site in order to optimize the overall supply.

However, only a few products are qualified in alternative sites because it is very expensive to set up needed tools and technologies for so many products at more than one site (redundancy). The impacts comparison among BCSAS in this thesis work is related to the last BC strategy “flexible production”: exploring the trade-off between flexibility and redundancy. The details and differences between each BC strategy for alternative sites are elaborated in the following chapter.

3.4 Project Scope

Since resilience in supply chains is a very wide topic, it would be difficult to take everything into consideration. In order to first map the simulation framework for enhancing SC resilience in the semiconductor industry, the research scope of this thesis work is rather limited to simplify and reduce reality as a starting point. In the previous sections, several simplifications have been pointed out to define the scope of this research and they are summarized as follows:

- This thesis work focuses on the FE disruption.
- This research considers only the internal logistic system and customer system, excluding the supplier system.
- This research considers neither the probabilities nor chain reaction of risks for defining the disruption scenarios.
- This research intends to study the impacts of business strategies of alternative sites, focusing on investigating the issue of redundancy vs. flexibility: adding (backup) capacity and increasing operational flexibility mentioned in section 2.5.
- The other aspects regarding resilience are considered as the background or the environment by default, such as good collaboration with customers and suppliers, efficient information sharing to ensure the visibility in the internal logistics system, etc.
- The preparedness and avoidance of the risks, including the design characteristics of the supply chain, are out of the research scope. Hence, the initial impact of disruption is given in all scenarios and the BCSAS are for reducing the full impacts after disruptions instead of reducing the probability of risks.
- The simulation framework is to provide a preparation tool for analyzing and selecting business continuity strategy in case of disruptions rather than for real-time decision making.
- The demand fluctuation due to product ramp ups in the semiconductor industry is not considered as this complicates the recovery ramp up after a disruption.
- The ordering behavior change after disruption is out of the scope of this project, meaning the demand remains the same after disruption, as in normal production.

3.5 Conclusion on SCM in the Semiconductor Industry

As one of the most complex and dynamic industries in the world, the semiconductor industry faces many challenges, mainly reflected from highly volatile demand, rapid technology changes, intensive capital, long lead time and short product life cycle. To overcome such grand challenges, specific production structures with a globally distributed supply chain network is needed. The internal logistics system consists of FE, DB, BE and DC. Being the bottleneck, the FE has the most complicated process and longest lead time in the SC, making it the critical node to a resilient supply network. The business continuity planning at Infineon unfolds in six phases, in line with the resilience time series depicted by Melnyk et al. (2014) in section 2.4.2. Infineon has developed several BC strategies to secure supply of production materials and standardize logistic set up. Having excessive stocks is not deemed effective based on the special characteristics of this industry. Furthermore, Infineon achieves flexibility in its production through creating speed corridors to prioritize processing certain products, which gives the possibility of alternative production. However, only limited number of products can have their alternative site activated due to the overall capacity limit in a fab. Therefore, this project intends to identify the impacts of different types of alternatives for different products. The design characteristics and communication in the SC to reduce risks as well as the demand fluctuations and customer behavior changes after disruption are not considered.

4. DISRUPTION SCENARIOS AND BUSINESS CONTINUITY STRATEGIES FOR ALTERNATIVE SITES

Disruptions in factories could happen in a variety of forms, stemming from a man-made incident to a natural disaster. Furthermore, one hazard event could have chain effects that lead to another disruption. It is not possible to list and investigate all situations, therefore as a starting point, four main disruption scenarios are defined for this research and presented in this chapter. Also, this chapter will further elaborate on diverse BCSAS.

4.1 Classification of Catastrophes in Literature

The disruptions under investigation are basically catastrophes, meaning it can bring disastrous business losses to the companies. Different types of catastrophes can occur with different consequences. Additionally, different catastrophes may have similar impacts (e.g. earthquake and large fire disaster). It is challenging to plan for each and every scenario. A classification of those disruption scenarios will help companies to design BC strategies for a set of similar situations. Harrington et al. (2010) categorized the sources of supply chain risk into three groups: supplier issues, supply chain collaboration issues and uncontrollable events with an emphasis on the supply risks. The risk sources could also be defined from the level of *network* (e.g. location, stakeholder) and *process* such as logistical operation (Heckmann et al., 2015).

The classifications listed above are quite general, encompassing more aspects than necessary for this project. Zsidisin and Ritchie (2009) treats supply chain disruptions as a type of risk source and gave examples of natural disasters, demand shifts, supplier problems, human behaviors, technology and regulatory issues. Expanding on this, the catastrophe classification framework developed by Stecke and Kumar (2009) is very thorough, viewing disruptions originating from a node, as in this project. Also, it fits manufacturing-oriented supply chain. Hence it is adopted as the literature foundation for summarizing the disruptions scenarios. This classification is outlined in Table 3.

Table 3. Classification of Catastrophes for Manufacturing-oriented SC, adapted from Stecke and Kumar (2009)

Classification of Catastrophes	Examples
Terrorist	
Attack on infrastructure	Power and communication services
Violence, mass killing	Bombing in public places
Bio/Chemical and nuclear terrorism	Sarin gas, anthrax
Hoax or propaganda intended to terrorize	Bombing
Sabotage of transportation media	Bombing airplane
Cyber terrorism	Computer viruses
War	Gulf War
Natural	
Infrastructure destruction	Earthquakes, hurricanes, floods
Transportation disruption	Erosion, dust storms
Health hazard	Epidemic, femine
Extreme weather	Cold wave, extreme temperature
Natural fires	Eruption, forest fires
Accident	
Industrial accidents	Gas leakage
Transport accidents	Airplane crash
Non-Terrorist	
Strikes	Workers strikes, political strikes
Environment	Changes in manufacturing technology

In the original classification framework, Stecke and Kumar (2009) also identified the severity and possibility of effects on various components in the supply chain (e.g. transportation, utilities) from diverse classes of catastrophes. Since this project focuses on the disruptions at frontend manufacturing, other affected components in the SC are not presented in the table above. The threat posed by a catastrophe depends on company-specific factors. Among them, the industry, geographic location and political environment are of most importance (Stecke & Kumar, 2009). Through discussing with the Business Continuity Department, four main disruption scenarios are developed, considering the specific characteristics of semiconductor production at the FE as well as the manufacturing network at Infineon. Their selection are described in details in the following section.

4.2 Selection of Disruption Scenarios

A top-down combined with bottom-up approach is used to define scenarios: experts' discussion with literature base. Four disruption scenarios are selected with different severity disruption length, and expected production recovery time. Uncertainty and correlated risks are also discussed.

4.2.1 The Approach Taken to Define Disruption Scenarios

Firstly, a meeting was held with the experts of BC department to analyze how the production was affected by a disruption. As shown in Figure 13, once an incident occurs that directly disturbed the production, the capacity would reduce significantly until reaching the system's climax. The *severity* can, therefore, be measured using the capacity loss. The more capacity loss there is after a triggering event, the severer a disaster is. It will take some time to put actions into place before starting to gradually restore capacity. The *disruption length* refers to the time it takes to respond before the production level could possibly increase. Following this, the production begins to ramp up and restore back to the original level. The ramp-up duration is seen as *production recovery time*. Disruption length and production recovery time depend on the specific incident and how fast the resources are allocated.

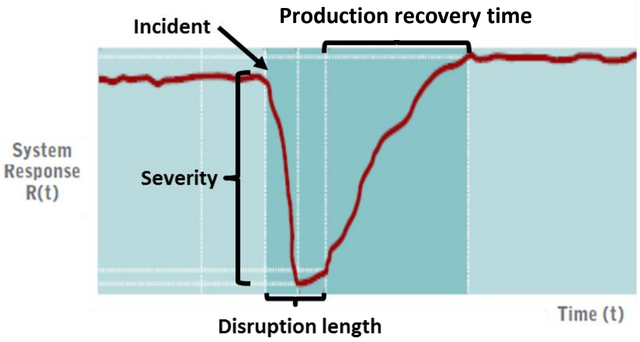


Figure 13. Disruption and Recovery Timeline

Secondly, in order to demonstrate the uncertainty in the future and test the robustness of the BCSAS, the system response curves ought to have different shapes (meaning different value combinations of the severity, disruption length and recovery time). A ‘disruption cube’ model is proposed to illustrate their combinations (shown in Figure 14). Three levels (low, medium, high) are set for each dimension, resulting in 27 possible scenarios. Every combination of those three dimensions marks a different ‘disruption zone’. As a starting point, we decided to further reduce the number of scenarios with certain ‘disruption zones’. The work of from Stecke and Kumar (2009) classified four main categories of catastrophes: Terrorist, Natural, Accident and Non-Terrorist as in Table 3, which offers the academic ground for the reduction.

Based on their catastrophe classification, one single example under each main category is selected as our study disruption scenarios, which are marked bold in Table 3. They can be mapped in different ‘disruption zones’, indicating a variety of uncertainties. They are selected as a result of some well-known previous cases and the frequency reported in the media. In this instance, we referred to cyber terrorism as cyber-attack because the terrorism is generally for political purpose. The cyber-attack targeting industrial computer systems, such as Stuxnet, can pose a severe threat to daily operation.

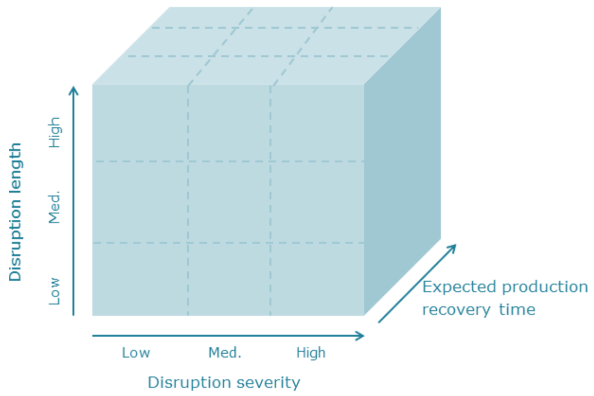


Figure 14. 'Disruption Cube'

However, it is difficult to quantify precisely the value in each dimension for a disruption scenario in reality. Therefore, in order to simplify this complexity, a distribution for the disruption length with an average severity level and a range of expected recovery time is set based on the estimation from experts and similar cases that happened previously in the semiconductor industry. The expected production recovery time is a general estimation (yet not related to the Infineon case). The numbers are more indicative to demonstrate a variety of scenarios of interest to study, rather than aiming to depict the reality accurately.

4.2.2 Defined Disruption Scenarios

Table 4 demonstrates a diverse range of catastrophes defined from short to long term disruptions with varied severities in line with the 'disruption cube'. Work In Progress (WIP), acting as a buffer, is also included when defining the disruption scenarios. A reduced number of scenarios is not extended or detailed enough for risk management, but it is still important for Infineon to decide which BC strategy enhances resilience with a good overall financial performance. As mentioned in section 3.4, the probabilities of those situations are not considered and only FE disruptions are treated in this project.

Table 4. Defined Disruption Scenario on Production

Disruption Scenario (DS)	Classification	Severity (% capa loss)	Disruption Length (week)	Exp. Production Recovery Time*	WIP Left	Example
1	Long-term cyber-attack	40	Uniform (24-26)	3 – 5 weeks	Y	Computer viruses, tools damaged, time for buying new tools
2	Infrastructure destruction	100	Uniform (1-3)	10 – 12 months	N	Earthquakes, hurricanes, floods, fires
3	Strikes	90	Uniform (2-4)	2 – 4 weeks	Y	Workers strikes, political strikes
4	Industrial accident	75	Uniform (9-12)	1–2 months	Y	Gas leakage, polluted water

**The data is collected via estimation from interviews and previous cases in history, not related to the IFX case*

It can be seen from Table 4 that Disruption Scenario 1 (DS1) has the longest length because it is very time-consuming to purchase machines for semiconductor manufacturers once the industrial control system is damaged by the cyber attack. The recovery time includes the testing and ramp-up, which is rather short. DS2 and DS3 have a short disruption length with high severity due to its inherent attributes. However, the capacity loss in DS2 mainly comes from the damages of machines and cleanrooms, whereas the production undergoes the turbulence in DS3 due to the unattended labor force. This means that the recovery of DS2 takes much longer than scenario DS3 considering the long repairing and purchasing time. DS4 demonstrates a severe disruption with medium-term restoration.

Additionally, the wafer lots can not stay in the diffusion furnaces or steppers for several weeks, as the quality will be compromised. Therefore, scrap across the fab tends to be significant after disruptions (Hillis, Chance, & Robinson, 2017). Under DS2, all of the WIP are assumed to be scrapped as a result of cleanroom destruction. In the rest of the scenarios, there are still WIP left but only a few due to the scrapping.

4.2.3 Uncertainty and Correlated Risks

As mentioned in Chapter 2, uncertainty deals with the future and exists when a decision maker cannot enumerate all possible outcomes and/or cannot assign probabilities (Thomas & Maurice, 2008), whereas risk, caused a triggering event, is a particular type of uncertainty that involves the real possibility of loss (Boundless, n.d.). Therefore, the risks could often be quantified using the probability and anticipated loss. The 'objective' probabilities are often calculated by the following types of theories: classical probabilities, frequentist probabilities, propensities and logical probabilities, and the information of that probability theory can be found in the study of Aven and Reniers (2013). When 'subjective probabilities' are used, the uncertainty (degree of belief) is often associated and the decision making is influenced by uncertainty assessment and value judgment (Aven & Reniers, 2013; Eiser & van der Pligt, 1988).

In this study, sufficient information is lacking to make a thorough risk assessment. It is impossible to list all sorts of incidents and the probabilities are difficult to assign objectively within a short time. The accuracy is also a question. The risk causes and triggering events are uncertain, but the end results could be captured to some extents using the proposed 'disruption cube' shown in Figure 14. This transfers the decision-making problem from pure uncertainty to some levels of risks (an exhaustive list of outcomes). The disruption scenarios selected in the Chapter take a reduced number of 'disruption cube zones' to define the impacts of several catastrophes on production. Distributions or ranges are used to quantify their zones. A severe earthquake and flood are two distinctly different events in the cause, but their impacts on the production might be the same, implying they are located in a similar 'disruption area'. Hence, the disruption scenario of infrastructure destruction might be a good summary of this type of situation. Therefore, the defined disruption scenarios give some indications on the uncertainties without considering the probability of the occurrence.

The defined disruption scenario is modeled as a single event, and correlated risks are not explicitly considered. Correlated risk refers to the simultaneous occurrence of many losses from a single event (Kunreuther, 2008). For example, many catastrophes like an earthquake could cause highly correlated losses: damaged infrastructure, destroyed transportation, interrupted telecommunication, etc. The investigation on correlated risks could add more robustness in the simulation outcomes. In this case, the characteristics of a disruption scenario are defined as the final impact on the production itself regardless of the detailed cause-effect relationship. The other factors exposed to the correlated losses are not explicitly modeled, mainly because the mathematics for correlated risks is less tractable (Wang, 1998). This adds the difficulty to quantify the uncertainty. Furthermore, the correlated risks might complicate the computation of recovery pattern, which was already challenging to capture.

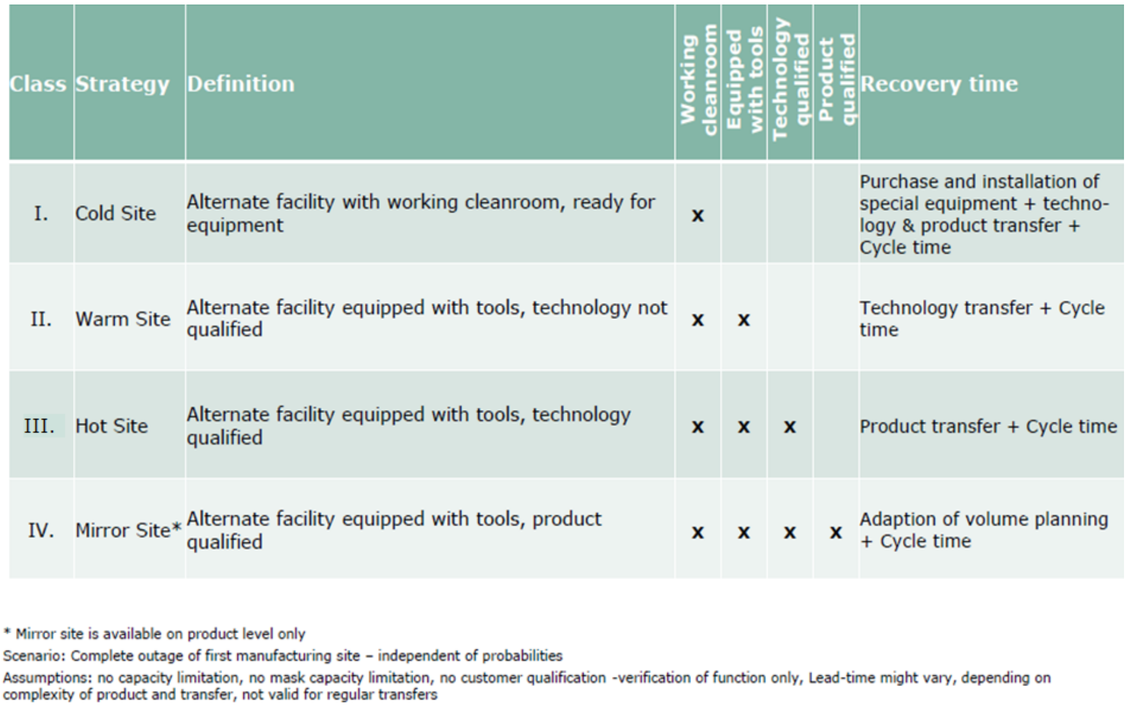
4.3 Business Continuity Strategies for Alternative Sites

After defining the disruption scenarios for research, there is a need to further illustrate on the coping strategies, i.e. BCSAS. Typically, there are four different BCSAS, meaning implementing four different types of alternative sites, namely: mirror site, hot site, warm site and cold site. The cost and effort to implement them differ, as seen in Table 5. This concept of alternative sites is usually applied in the area of disaster recovery for organizations to backup computer systems and/or data centers (Haag, Cummings, & McCubbrey, 2002), which places emphasis on data recovery instead of physical production capacity restoring, as discussed here.

In the context of the semiconductor industry, one process group (PG) usually has a primary production site, and a specific PG will have a corresponding alternative site selected. This alternative site can be one of the four types mentioned above based on the available tools and qualified technology. Hence, the alternative site is actually a normal operating site in itself, but processes different PGs than the specific one produced at its original primary site. It should also be addressed that the capacity mentioned in each BC strategy refers to *the capacity for a specific PG, not for the whole fab*. Thus the capacity is dynamic because of the production corridor mentioned in section 3.4.

Implementing BCSAS involves multiple organizational processes. The BC department is responsible for planning, but the divisions and factories are the operational bodies in charge of installing tools, qualifying technologies, etc. The complexity that the BCSAS add to the daily operation may conflict their interests. In order to gain support, the benefits of the strategies should be convincing. Furthermore, the customers also need to be onboard. Tangible simulation results may smooth the discussion with them.

Table 5. Business Continuity Strategies for Alternative Sites (BCSAS) (Infineon Technologies AG, 2016)



Class	Strategy	Definition	Working cleanroom	Equipped with tools	Technology qualified	Product qualified	Recovery time
I.	Cold Site	Alternate facility with working cleanroom, ready for equipment	x				Purchase and installation of special equipment + technology & product transfer + Cycle time
II.	Warm Site	Alternate facility equipped with tools, technology not qualified	x	x			Technology transfer + Cycle time
III.	Hot Site	Alternate facility equipped with tools, technology qualified	x	x	x		Product transfer + Cycle time
IV.	Mirror Site*	Alternate facility equipped with tools, product qualified	x	x	x	x	Adaption of volume planning + Cycle time

* Mirror site is available on product level only

Scenario: Complete outage of first manufacturing site – independent of probabilities

Assumptions: no capacity limitation, no mask capacity limitation, no customer qualification -verification of function only, Lead-time might vary, depending on complexity of product and transfer, not valid for regular transfers

A cold site is an alternative fab with working cleanroom. In order to be able to produce specific process groups, it is required to purchase special tools, transfer technology and/or product. Essentially, all the frontend sites in semiconductor manufacturers are at least cold sites since they all have cleanrooms. The start-up cost is zero but the additional cost of having the operation up running for new PGs is huge due to expensive machines and technology qualification. Furthermore, it takes a considerate amount of time to set up the production line for new PGs because of the long interval of purchasing and qualifying in the semiconductor industry.

A warm site is in between a cold site and a hot site. It is equipped with specific tools for the PG, yet lacks a particular qualified technology. Thus, the time to start production after a disruptive event will be delayed due to the time it requires to transfer technology and/or product, but still faster than a cold site. Qualifying technology also requires some additional cost.

A hot site is an alternative fab with tools ready and technology qualified for a specific PG, meaning it has a very similar environment to the original site. Following a disruption at the original site, a hot site allows the semiconductor manufacturers to transfer the wafers or start production from scratch rapidly. High volume for technology is required to become a hot site.

A mirror site, as a special case, applies only on product level (not for PG). It is a duplicate of the original site with everything prepared including a double mask set for each product update. However, this level of redundancy comes with a high cost as well. It demands a high volume of product for the sake of process stability. When a disruption occurs, the production can be initiated immediately after adaptation of volume planning.

There are some important assumptions for the alternative sites as follows:

1) Not all affected PGs would activate their alternative sites. However, for the selected PGs there always exists available capacity at the alternative site once it is capable of starting production.
2) The product qualifying for hot/warm/cold site is not considered in this study. In the case of a major disruption, the customers tend to take the responsibility of product qualifying. This means that the product qualification does not need to be included in the responding time of the semiconductor manufacturer. As this may vary depending on the situation and the customer specification, it is deliberately selected to be left out.
3) There exists a ramp up of production at the alternative site when the frontend is capable of starting production. Afterward, the lead time of wafer out is cycle time, which is influenced by the complexity of the PG.
4) The investigation is carried out on *Technology* level, not *Product* level; hence the product priority inside the PG is not considered.
5) Only one alternative site of a PG is studied. The type of this alternative site depends on the PG and the specific site selected by the experts.

4.4 Conclusion

Disruption scenarios are defined as man-made incidents or natural disasters that create substantial business losses with different consequences. These disruptions can be categorized in terrorist, natural, accident and non-terrorist catastrophes with many examples under each category. A ‘disruption cube’ is proposed to capture the final impacts of disasters, which transfers the decision-making problem from pure uncertainty to some levels of risks (an exhaustive list of outcomes). As a first step, a reduced number of combinations are selected based on the academic categorization. In this thesis, four disruptions scenarios defined have been defined (i.e. long-term cyber-attack, infrastructure destruction, strikes and industrial accident), to examine short and long-term effects and a varied severity level without considering the probabilities. Correlated risks are not explicitly considered given the low traceability and high complexity. Finally, four alternative sites are investigated (mirror, hot, warm and cold site) with the main major differences at responding time (due to different equipping levels) and investment. They are the focused Business Continuity Strategies to develop a resilient supply network.

5. A DISCRETE EVENT SIMULATION FRAMEWORK FOR ENHANCING THE RESILIENCE OF SUPPLY CHAINS

This chapter presents the design of a simulation-based framework for evaluating the impacts of business continuity strategies on resilience and finance for semiconductor manufacturers. This framework starts with a conceptualized model describing the supply chain setup in the semiconductor industry and the important entity relationships. Following this, the selected key performance indicators (KPIs) to evaluate different strategies are introduced. Section 5.3 describes the input data preparation. Section 5.4 demonstrates the key process implementation in the model. Furthermore, model boundaries and assumptions are illustrated in Section 5.5.

5.1 Model Conceptualization

The conceptualization step of the model develops a "vocabulary with which we can describe the problem domain". It does not contain an exact description of the problem, but indicates the variables to describe the situation (Verbraeck & Heijnen, 2016). In order to complete this step, it is needed to identify the semiconductor supply network setup, the entities and relations associated.

Operational Process Diagram

The supply chain setup shown in the operational process diagram (Figure 15) consists of frontend (FE), die bank (DB), backend (BE) and distribution centers (DC) until customers, which matches with the real-world logistic system depicted in Figure 9 on an abstract level. The complicated manufacturing and testing processes are out of the modeling scope and replaced with an average cycle time. As only one alternative site is considered in the framework, this setup offers a generic model setting.

A specific PG is produced at its primary site FE1 and transferred to the corresponding DB1 in normal production. The BE and DC are modeled as one aggregated object respectively, since detailing them does not impact the simulation outcomes. After a disruption (scenario) hits the FE1, the processing of the PG will be affected based on the defined scenario. Afterward, the production will undergo a ramp-up to restore. If a BCSAS is activated, the alternative production site FE2 will start to produce and deliver the products to customers following the internal logistic chain. The PG can be changed in the model, and the corresponding FE1 and FE2 will also change accordingly. Therefore, we can investigate a variety of PGs to cross check if the same type of alternative site has similar impacts on different PGs.

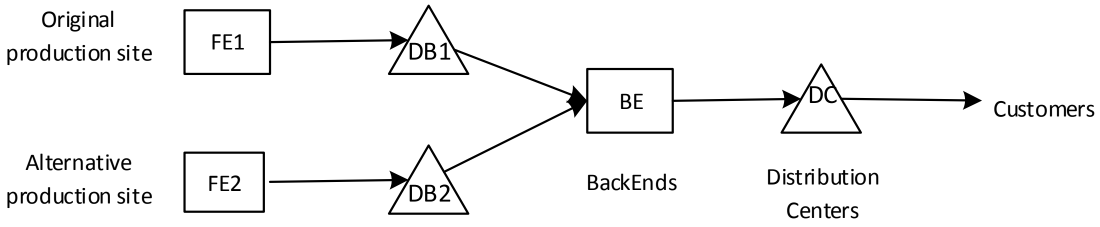


Figure 15. Supply Chain Setup in Model

Entity Relationship Diagram

In order to avoid ambiguous communication, the object-oriented description creates a definition framework, with a “vocabulary” that can be used to describe the system (Verbraeck & Heijnen, 2016). Different entities and their attributes were selected to depict the system as shown in the entity relationship diagram (Figure 16). The main entities chosen were: Order, Process Group (PG), Frontend (FE), Disruption and Business Continuity Strategy. Each entity and its own specific attributes are later used for the final simulation model. As mentioned before, the PG refers to the products belonging to the same technology process group in order to distinguish it from sales products.

An order has its property of ID, meaning every order is distinct and traceable. An order specifies the PG, its quantity and the date of confirming. For simplification, the wafer-start date is assumed to be the same date as the order confirming date. The expected delivery date is equal to the wafer-start date plus the respective cycle time for that PG. An order status could be either “fulfilled” or “unfulfilled”. The backorder rejection time is assigned depending on the process group.

At the center, the PG is connected with every other entity. Different disruption scenarios affect its scrapping status. One specific PG is produced in a corresponding primary FE. Different PGs might have different business continuity strategies available to them. The PG’s sales price, penalty factor and impact factor are used to calculate the IFX disruption cost whereas the other factors about customer and Customer of Customer (CoC) are used to assess the customer end loss. They are discussed in more details in the next section.

A frontend can be a primary site and/or an alternative, which is determined given a specific PG, so is the current alternative level. The production input includes average cycle time (CT), scrapping situation (whether to scrap WIP completely based on the disruption scenario) and production rate, usually measured using Wafer Start Per Week (WSPW). A disruption scenario is modeled to occur on different primary FEs affecting the specific PG produced there. The defined characteristics in Chapter 4 such as severity, disruption length and WIP situations are used to classify different types of scenarios about their impacts on production.

Different business continuity strategies can apply to diverse PG on its designated alternative site (FE2 in Figure 15). An expected alternative level is defined in the experiment. If it is higher than the current alternative level (e.g. a hot site is being tested while the alternative site is a warm site presently), the investment for upgrading will also be taken into consideration when comparing the final financial results. The main differences among strategies are the responding time to be able to provide extra capacity on the alternative site. This will be further explained in section 5.4.2.

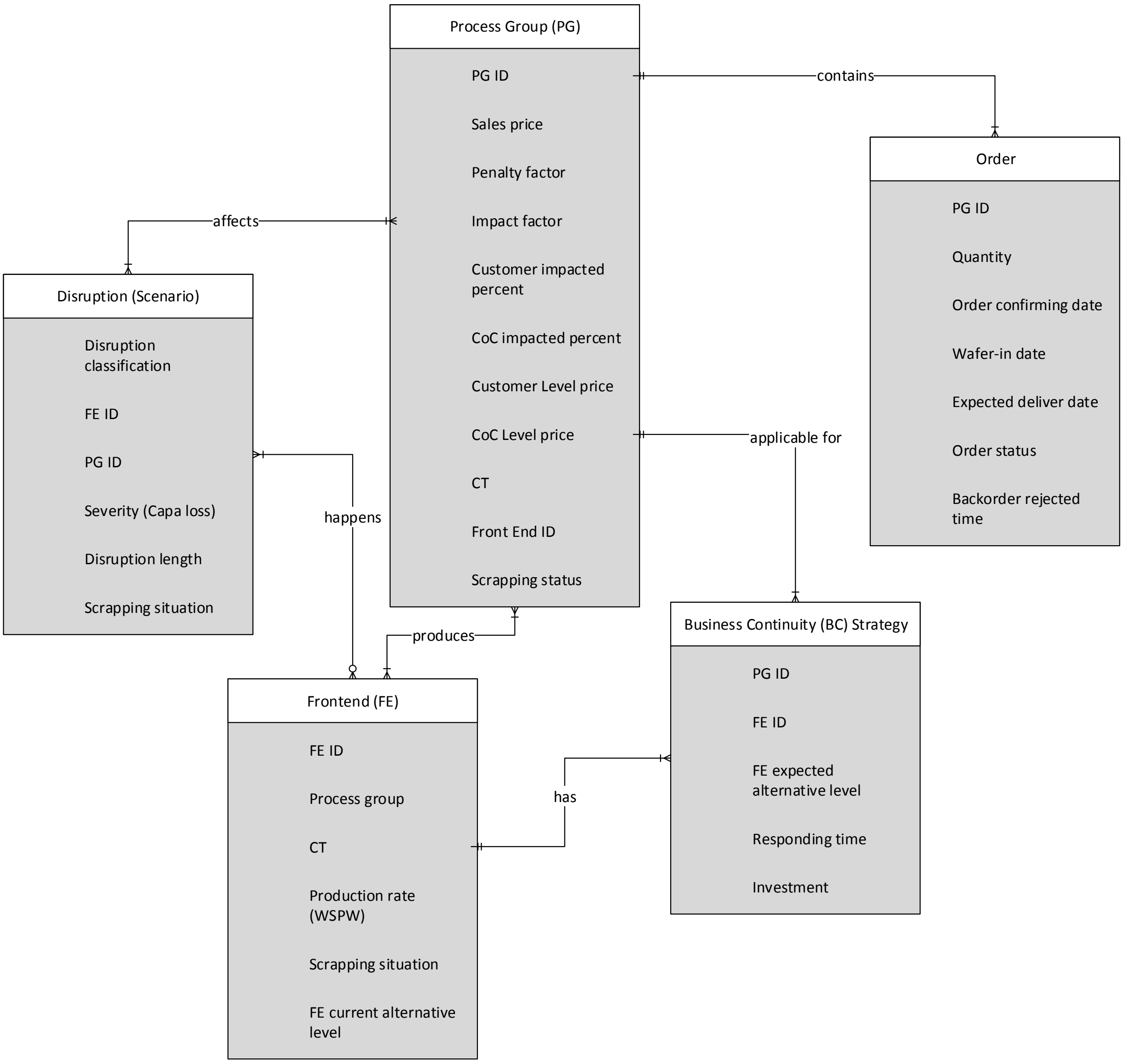


Figure 16. Entity Relationship Diagram of Key Objects in Model

5.2 Key Performance Indicators to Evaluate Business Continuity Strategies

Key Performance Indicators (KPIs) are vital to evaluate different business continuity strategies on how they perform in order to make conclusions. A set of KPIs is selected (shown in Table 6) to capture the performance of BCSAS operationally and financially for answering the research questions. The initial selection of those KPIs is based on current simulation literature about supply chain resilience. Furthermore, the experts from both CSC and BC department agreed with the chosen KPIs. The KPIs in red are the focus of the simulation results as they are dynamic, and they give the most crucial information on the resilience and financial performance.

Table 6. Selected KPIs for Evaluation

	KPI	Definition	Remark
Operational Performance	**Fill Rate**	All orders can be fulfilled by on-hand inventory	Equal to α service level
	Recovery time	The time it takes after the disruptive incident to reach to a stable fill rate	Can be seen from the fill rate graph
Financial Performance	Investment Cost	The cost to invest in Business Continuity strategy (e.g. technology transfer) for alternative site upgrading	A deterministic value, estimated by experts
	Total Disruption Cost	**IFX Cost**, including backorder cost and sales loss	
		Customer End Loss, including Customer loss and Customer of Customer (CoC) loss	Special conditions (explained below)

From an operational viewpoint, the fill rate and its recovery time are commonly selected KPIs to measure the SC resilience as mentioned in section 2.4. With a pre-defined disruption depth and length, a smaller triangle means shorter recovery time and a more resilient system. The fill rate defined here is equal to α service level. *It measures the probability that all customer orders arriving within a given time interval will be completely delivered from stock on hand* (Tempelmeier, 2011):

$$\mathit{Fill\ rate} \ = \{\mathit{Total\ Supply\ at\ DC} \,/\, \mathit{Total\ Demand}^{1}\}\ \mathit{every\ week}\ (2)$$

The financial performance consists of two parts: Investment Cost and Total Disruption Cost. The investment cost is a deterministic value estimated by the experts about a specific BC strategy on a specific PG. In the total disruption cost calculation, the customer end loss, including customer as well as Customer of Customer (CoC) is taken into consideration when it is not *force majeure* or IFX cannot fulfill its recovery plan.

Force majeure is a common clause in contracts that essentially frees both parties from liability to certain duration when an event happens outside the control of the parties, such as hurricane, strikes and earthquake (Schaffer, 2012). This means within the duration of force majeure, IFX does not need to be responsible for the losses of the customer end. However, if it is not *force majeure*, or IFX does not fulfill the recovery plan, it has the liability to compensate the customers' business loss, which can be much more costly than the internal cost. It should be addressed that the focus of the financial KPIs is the IFX cost, as most of the defined catastrophe scenarios are typical force majeure events. Despite this, the customer end loss demonstrates a larger consequence on the whole supply chain, and it has a vital impact on the IFX business when not in *force majeure* or not being able to execute the recovery plan.

The calculation of total disruption cost can be seen in Table 7. A backorder is "an order that cannot be currently filled but is requested nonetheless for when the item becomes available

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[1] Total Demand includes the customer demand due at current week and the accumulated backorders

again” (Wiktionary, n.d.). If the customers will not wait for the replenishment, the demand becomes a lost sale. Two factors are introduced to calculate the related backorder cost and sales loss as the total internal cost of IFX. The penalty factor is the punishment for having backorders while the impact factor implies the punishment for the sales loss and future business due to loss of good will from the disappointed customers. The values of two factors are input variables decided by the IFX management board based on the business impacts (see Appendix A1).

Table 7. Calculation of Financial KPIs

KPI		Calculation	Remark
IFX Cost	IFX backorder (BO) cost	BO quantity * sales price * penalty factor	
	IFX sales loss (SL)	SL quantity * sales price * impact factor	
Customer End Loss	Customer loss	X% * BO quantity * sales price * customers lever	week -1
	Customer of Customer (CoC) loss	X% * Y% * BO quantity * sales price * CoC lever	week- 2

The business loss of customers and CoC can be seen as a consequence of the backorders from IFX. Because IFX has delayed delivery, the lines downstream are affected. However, due to the fact that not all customers of IFX might be affected or that they have stocks/second suppliers, only X% have a line down. Going further down the supply chain, we say that Y% of the CoC are affected, meaning that from IFX’s perspective X%*Y% of the CoC’s lines are disrupted. Hence, the X and Y represent the PG attributes of impacted percent at customer and CoC sides as shown in Figure 16. The customer lever and CoC lever for all PGs are selected to be 5 and 20 respectively by the experts, according to the hierarchy of business impacts, shown in Figure 17. Due to the confidentiality, the results of financial KPIs will be presented in a normalized manner in chapter 7.

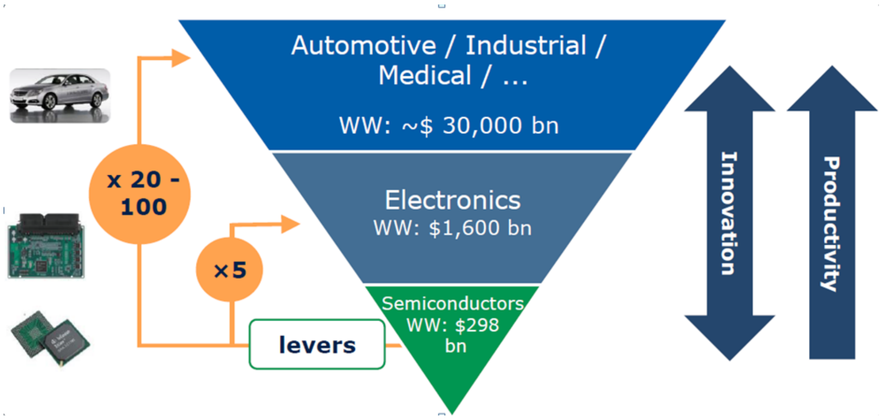


Figure 17. Hierarchy of Business Impacts in Semiconductor industry (Ehm, 2017)

5.3 Input Data Preparation

The business continuity planning model contains a wide range of input data which needs to be identified and processed before further experiments could be conducted. In order to have a diversity of products/PGs and types of alternative sites, one product and three process groups are selected from the BC department for the case study, denoted P1, P2, P3 and P4. For the convenience of reference, they will all be referred to as PG, even though it could be only one type of product in this PG for P1. Furthermore, P1 and P2 are from PMM division whereas P3 and P4 belong to ATV products.

5.3.1 Order-related

For each PG, the data about its monthly sales quantity and sales price for the past five years were obtained via the internal portal. The sales information is treated as the input for the customer demand in the simulation framework. The historical sales quantity for each PG was plotted in Microsoft Excel using a box plot in order to remove the outliers. Only two outliers were founded due to the steep product ramp up in the semiconductor industry.

The sales data of most PGs shows an obviously growing trend over the five years. After discussing with the experts, some early data points were removed because their values are far from the current market (frequent product ramp ups in the semiconductor industry). As mentioned in section 3.4, the demand fluctuation due to product ramp ups is not considered as this complicates the recovery ramp-up after a disruption. Hence, the mean of the remaining data points is taken as the deterministic value for the order quantity to remove this effect. The orders do not specify the customers, as they are aggregated. As the simulation model uses a *week* as the time unit, the sales quantity is converted to weekly quantity with a downward scaling to accommodate the computation capacity of AnyLogic.

An ‘order’ will be injected to the model with the information of PG ID, the quantity and sales price at the beginning of every week T_0 (seen as order confirming date as well as wafer-start date). The expected delivery date will be $T_0 + CT_{FE} + CT_{BE}$.

Backorder Rejection Time

When a backorder stays for some time, the clients may lose patience and cancel the order, leading to a lost sale. The client satisfaction versus order delivery time modeling in the research of Montreuil et al. (2013) has laid a scientific grounding for determining the rejection time given a dissatisfaction tolerance index (DTI) and a satisfaction curve. Figure 18 shows how the rejection time is obtained in three examples of satisfaction curves (impatient client, neutral client and very patient client).

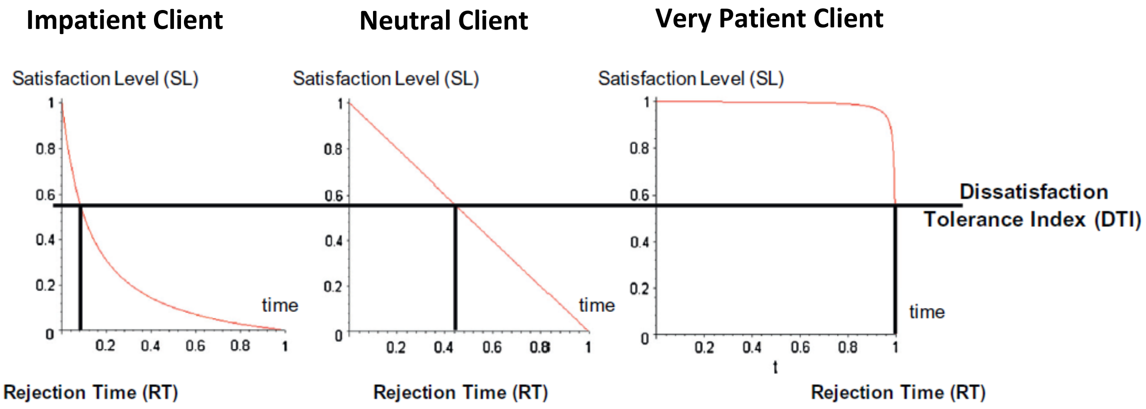


Figure 18. Determining the Rejection Time Given a DTI and a Satisfaction Curve, Illustrated with Three Types of Clients

In summary, a client has the maximum satisfaction level when the delivery is on time and the satisfaction level decreases as the delivery time diverges from the expected value. The satisfaction level drops rapidly for an inpatient client once the delivery time is delayed. The neutral client has a linear declining satisfaction curve along with the delivery time. The very patient clients stay at a high satisfaction level until the delivery time extends excessively and then the satisfaction level reduces drastically (Montreuil et al., 2013).

In this simulation framework, the clients' profiles are determined based on the product classification and expert interviews. The selected products are mainly classified as 'Designed_In' (P1, P2, P4) and 'Multisource' (P3). Designed_In products are developed together with the customers and IFX is probably the single product supplier for the customers. On the contrary, there are usually competitors available for supplying multisource products. Hence, clients purchasing Designed_In products could be categorized as the *very patient* type while the clients buying Multisource products might belong to the *neutral* type. The exact satisfaction level curve and DTI (shown in Figure 19) are determined together with the interviewed experts based on their experience. The rejection time is identified from the graph below: 26 weeks for very patient clients (Designed_In products) and 4 weeks for neutral clients (Multiple-source products). This rejection time is often unknown or case-specific in the real world, but using this method to model the rejection time gives a reasonable indication of simplified reality. The detailed order-related information about the investigated PG can be found in Appendix A2.

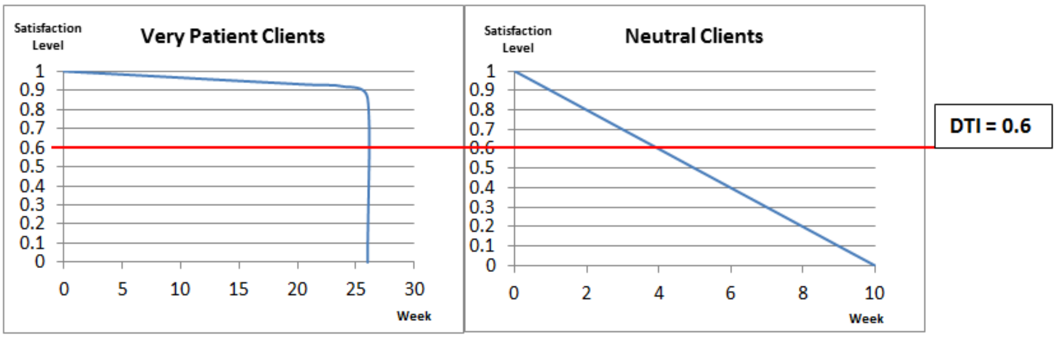


Figure 19. Rejection Time Determination in This Project

5.3.2 Production-related

The production rate is often measured using Wafer Starts Per Week (WSPW). One wafer could produce different sizes and quantities of products depending on the product specification. In order to avoid the unnecessary unit conversations, *one unit of product* is taken as the production and supply unit. When modeling normal production, the WSPW is assumed to be equal to weekly customer demand in product unit. This is to depict an ideal situation where the fill rate is always 1 before disruption, as the fill rate fluctuation beforehand is not of concern for the research.

After the products enter the primary site FE1, they have a cycle time (CT) in FE and BE. This CT varies in reality. For the sake of simplicity, the average CT in FE for PG is calculated based on the historical data of past three years (see Appendix A3). The CT in BE is assumed to be 4 weeks for all PGs.

When a disruption hits, the original site has a production restoring ramp-up. However, it is very difficult to collect this information since it is scenario-specific. Even though the previous incidents could give indications, the exact recovery pattern is not documented. Section 5.4 will elaborate how the simulation framework tackles this issue.

5.3.3 BCSAS-related

In order to evaluate different BCSAS, it is important to gather the information about their responding time (e.g. time to transfer technology) and the corresponding investment to have a higher level of the alternative site than the current type. Table 8 summarizes the data items needed for modeling various BCSAS. The completely filled table contains confidential information and is attached in Appendix A4. The time and investment are estimated by experts. Each PG has its customized setting. The "X" marks the cells where the information is not needed. The time to purchase tools and qualify technology follows a triangular distribution while the time to transfer products follows a uniform distribution. The response time for one type of alternative site in the model does not mean adding the time needed altogether since some of the actions can be done in parallel. As an example, a hot site could transfer products and adjust the volume planning in the same time, so the response time will be the one that is longer, i.e. time to transfer products. The investment to transfer products and adjust volume planning is neglected as this is not a separate cost for a specific strategy.

Table 8. Input Data of BCSAS about Responding Time and Investment

	P1	P2	P3	P4
Primary Site (FE1)				
Alternative Site (FE2)				
Current Type of alternative site	Mirror	Hot	Warm	Cold
Time to purchase tools	X	X	X	
Time to qualify technology	X	X		
Time to transfer products	X			
Time to adjust volume planning				
Investment in transfer tools				
Investment to qualify technology				
Production rate				

A front-end fab roughly manufactures 70 to 200 process groups. Hence, there is usually enough production capacity for one or a few process groups as an alternative site. The main question for alternative sites will be how fast they can produce after being well-equipped and how much they can produce compared to the primary site. This information about production rate is gathered via interviews and will be elaborated on in Section 5.4.

5.4 Key Process Implementation in Model

The key processes in the simulation framework include 1) demand and supply management, 2) production disruption and ramp-up, 3) WIP processing during the disruption. This section will elaborate on how they are implemented in the model. The other basic processes follow the logic of conceptual model. The simulation implementation is modularized into different windows and the details can be found in Appendix B.

5.4.1 Demand and supply management

In the simulation mode, apart from the material flow of entity *Product (PG level)*, there is a separate information flow of entity *Order* to record the customer demand and control the production (shown in Figure 20). Every week, an order is generated with the information of the wafer-start date and the due date to control the WSPW at FE1. After the PG has been processed along the supply chain, the DC delivers the demanded PG and quantities to customers, if possible. An event is triggered weekly to compare the inventory in DC with the expected demand due to deliver. If the stock satisfies the demand, the order is fulfilled. Otherwise, the DC will supply all on-hand inventories and accumulate backorders. Next week, the new total demand for DC consists of the customer demand due at that week and the accumulated backorders, as shown in the formula below:

$$DemandDC(current - week) \ = \ OrderIn.get(due - current - week).Qty \ + \ BODC(accumulated)$$

In the meantime, the entity *order* will stay in the system ("OrderIn") until the backorder is fulfilled or it becomes a lost sale after the rejection time. The cost of sales loss, backorders and the resulting customer loss and CoC loss are calculated according to Table 7. The DB also has variables to record the demand at the point and the on-hand inventory, and the supply is determined based on similar logic illustrated above. Hence, the supply network can be seen as a pull system.

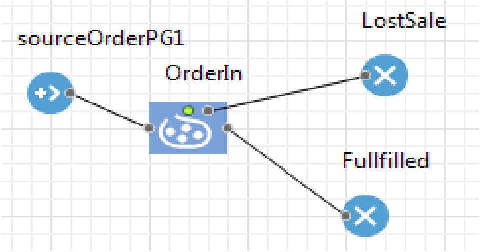


Figure 20. Order Flow in Model

5.4.2 Production disruption and ramp-up

The production algorithms play an important part in the simulation framework because the different results of the KPIs are caused by the production changes introduced by the disruptions and business continuity strategies.

5.4.2.1 Production at original site

The algorithms to determine production rate at the original site over time is illustrated in Table 9. The time horizon can be divided into three parts: before, during and after a disruption. Before disruption, the WSPW equals to customer demand, maintaining a fill rate of 100%. During the disruption length, the WSPW is reduced according to the defined capacity loss, equal to the remaining capacity multiplied by customer demand. The WIP is processed separately and will be discussed in the following section. After the disruption length, the original site starts to ramp up from the previous production rate.

Table 9. Algorithm Design about Production at Original Site

Timeline	WSPW at the disrupted site	Explanation
A. Before disruption	= customer demand	Normal production, fill rate = 1
B. During disruption	= remaining capacity * customer demand	Denoted as PRTemp
C. After disruption	Phase I, recovery ramp up: **= PRTemp + rampUpSlope *i * DemandFE**; i++;	1. rampUpSlope: from estimation 2. The quantity is never lower than the previous level
	Phase II, reach ramp up cap: = (1 + 20%) * customer demand	Assumption: The maximum recovery capacity is 20% more than normal production rate
	Phase III, stabilizing/adjusting after the backorder for FE diminishes: = DemandFE	**The time horizon under investigation lasts until the backorder for FE diminishes**, leading to a satisfying fill rate after CT

An important concept is introduced here, i.e. DemandFE. This variable is the "bucket" to store the total quantity of wafer lots required to produce at the FEs. It resembles the variable storing total demand at DC but has more things to take into consideration. The formula for calculating this DemandFE is as below:

$$DemandFE = Customer\ Demand\ due\ at\ current\ week + backorder\ for\ FE + Scrapped - SalesLoss;$$

$$Backorder\ for\ FE = DemandFE - ProduceFE$$

The customer demand due at current week is the base as in normal production. Due to disruption, the required quantity that FE cannot supply is accumulated as backorder for FE, adding to the DemandFE. Furthermore, there might be scrapping in disruption, meaning some products inside FE could not be delivered to DB, so this quantity needs to be reproduced. Lastly, if an order became a lost sale, the associated quantity should be deduced from the demandFE to avoid over production. In reality, the supply chain planners would devote every resource to recover and it is out of the scope to replicate the supply chain planner behaviors. Thus in this simulation framework, we take a rational perspective and consider the influencing factors when planning the recovery. The influencing factors were not explicit in current literature or industry practice.

The *rampUpSlope* is a variable to ensure the production has an increasing WSPW based on the DemandFE. A protection algorithm is also implemented to avoid WSPW drop during the recovery ramp up. The maximum recovery capacity (i.e. ramp up cap) is set to be 20% more than normal production rate for each PG, since the fab is operating approximately at its maximum capacity but may still have some flexibility (speed corridor) for one or few PGs. The production rate will stay at the cap for backorder compensation before it stabilizes at its original level. It should emphasize that the time horizon under investigation is until the FE backorder diminishes, as it would have enough capacity to restore by then and what happens afterward is out of the research scope. A corresponding production rate curve using the algorithm is demonstrated in Figure 21.

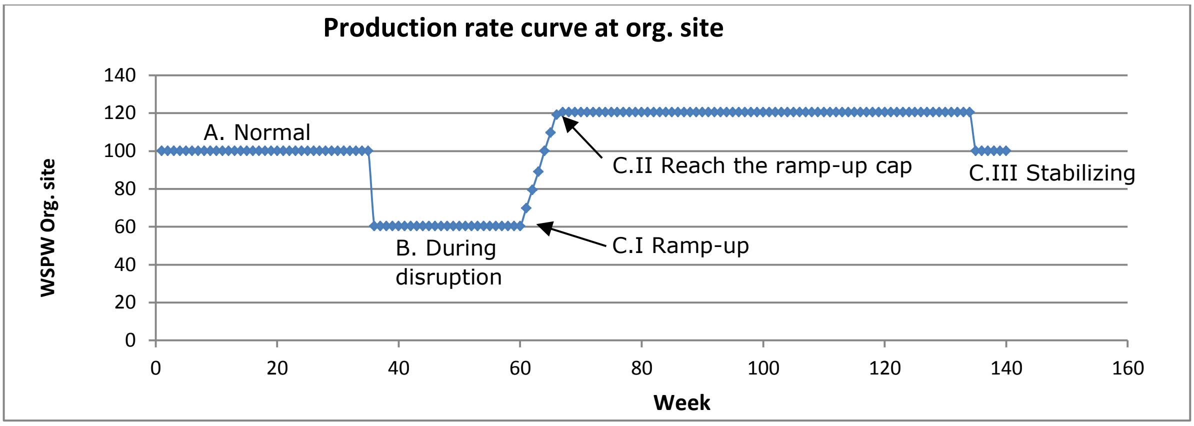


Figure 21. Production Rate at Original Site As An Example

5.4.2.2 Production at alternative site

After the disruption incident, the ramp up at the alternative site shares the very similar algorithm as a disrupted site with four major differences:

1) The alternative site starts to produce after the responding time instead of the disruption length.

2) The maximum production rate is set to be 70% of the normal WSPW for the mirror/hot/warm sites since the affected PG has to share similar tools with other PGs there. The cold site capacity can reach to 100% if needed due to the purchasing and installation of new equipment.

3) In the simulation, the alternative site no longer produces once the FE backorder diminishes (a steep drop in production rate curve), as what happens after (e.g. produce other PGs or expand sales) is out of the research scope.

4) Different BCSAS are modeled differently in terms of the responding time (e.g. a hot site responds faster than a warm site), but the shape of their ramp-ups afterward is similar, as can be seen from the demo graph in Figure 22. According to the interview result, the ramp-up duration at the alternative site is usually 2-3 months depending on the PG.

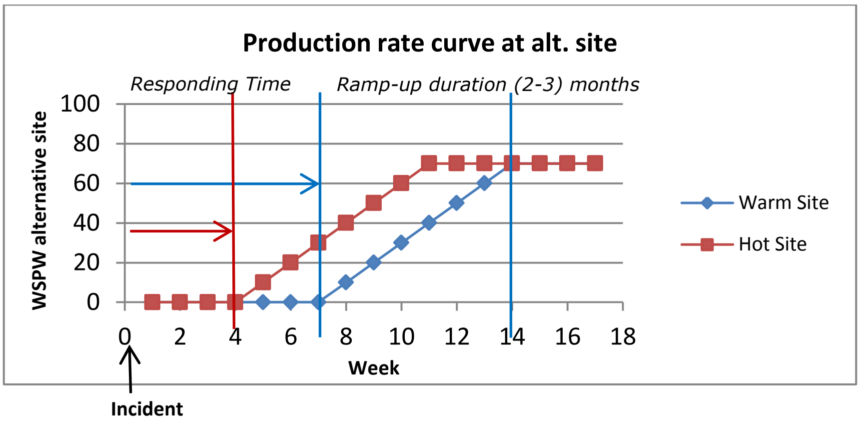
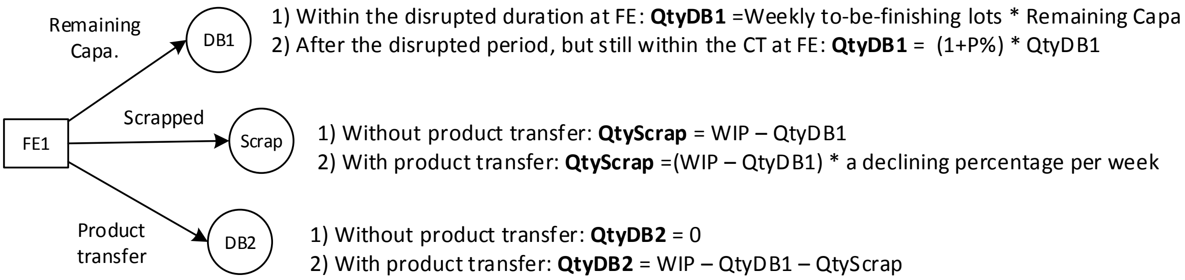


Figure 22. Production Rate at Alternative Site as An Example

5.4.3 WIP processing during disruption

When a disruption hits, WIP is processed separately and it has three directions: move to DB1, scrapped or move to DB2 (when there is product transfer), as shown in Figure 23. The wafer lots cannot stay in the diffusion furnaces or steppers for a long time (e.g. several weeks) because the quality will be compromised. Therefore, scrapping across the fab is mostly likely to be significant (Hillis et al., 2017). Since the FE is modeled as a "Delay" with a fixed CT in AnyLogic, the lots come out at weekly intervals. Most of the wafer lots are modeled to be scrapped in the first weeks since the number of scrapped lots may be identified early on. Scrapping a large number of wafer lots in early phase has two benefits: 1). avoids a huge peak at restoring production due to the algorithm and time delay of rejected backorders. 2). demonstrates the ramp up of dealing with WIP as well.



1) Within the disrupted duration at FE: **QtyDB1** =Weekly to-be-finishing lots * Remaining Capa
2) After the disrupted period, but still within the CT at FE: **QtyDB1** = (1+P%) * QtyDB1

1) Without product transfer: **QtyScrap** = WIP – QtyDB1
2) With product transfer: **QtyScrap** =(WIP – QtyDB1) * a declining percentage per week

1) Without product transfer: **QtyDB2** = 0
2) With product transfer: **QtyDB2** = WIP – QtyDB1 – QtyScrap

Figure 23. WIP Paths During Disruption

Where there is no product transfer, the remaining capacity at FE1 could process a portion of WIP and move them to DB1 whereas the rest of WIP would be scrapped. The scrapped quantity can be reduced with product transfer. Furthermore, if the disruption length is shorter than the CT of a PG, then there will be a ramp-up of WIP moving to DB1 after the disruption period in the model.

5.5 Model Assumptions

The model assumptions also cover the spectrum of the modeling boundaries. Some of them have already been mentioned before and are emphasized here. They can be divided into three parts: assumptions about the production process, about associated cost and generic model setup.

Production Process

1. There are two-week demand-equivalent stocks at DB and DC respectively, about the average stock level in reality. The production recovery process will also include the stock building.
2. In normal production, the production rate always meets the customer demand which is a deterministic value from the sales historical average.
3. The FE CT is deterministic in the model for each PG using an average value from historical data without consideration of load, utilization or facility changes.
4. WIP is processed separately within the CT.
5. The recovery cap is set to be 120% of the normal production rate at the original site and 70% at an alternative site, excluding cold site, which can reach to 100%.
6. In the simulation, the time horizon under investigation lasts until the backorder for FE diminishes. The alternative site no longer produces once the FE backorder diminishes and the original site produces according to demand because what happens after (e.g. produce other process groups or expand sales) is out of the research scope.
7. The production ramp up is based on a rational perspective without consideration of replicating the behaviors of supply chain planners.

Associated Cost

1. It takes one more week until the customer and two more weeks until the CoC are affected with a line down, meaning the economic loss at customer end are delayed for 1-2 weeks.
2. The impacted percent at customer and CoC (X% and Y%) are both set to be 20%, based on a previous case.
3. Inventory holding cost (e.g. warehousing) is intentionally neglected. This is because compared with other costs and the risks to lose sales, it is negligible.
4. The investment to transfer products and adjust volume planning is neglected.
5. The maintenance cost of the warm or hot site is not considered in investment.
6. The total cost does not include WIP holding cost, since the satisfaction of customer demand (with profit margin) is considered as the benchmark instead of the raw cost.

Generic model setup

1. The current simulation model tests only for one PG per scenario.
2. The disruption and production events are modeled as weekly events instead of detailing to days.
3. An order is PG specific with customers being aggregated and it is injected to the model weekly.
4. The safety stocks are built in the beginning of the model and the products are transferred from DB and DC when demand requires.
5. The connection time between FE-DB-BE-DC-Customer is set to 0 meaning the transit time is neglected. The transit time from one downstream site to an upstream site along the supply chain (1-3 days) is almost negligible compared to the long cycle time (3-6 months) in semiconductor production.
6. The supply of raw materials is always sufficient to guarantee the calculated WSPW can be supplied.
7. The unit of WSPW is product-equivalent.

5.6 Conclusion on Framework Development

This chapter mainly introduces the development and design of the simulation-based framework for evaluating the BCSAS to enhance the resilience in four phases shown in Figure 24. The conceptualization firstly demonstrates the semiconductor supply chain setup from frontend, backend, DC to Customers with stocking points at DB and DC. The key entities considered are: Order, Process Group (PG), Frontend (FE), Disruption and Business Continuity Strategy. The PG is in the center of the entity relationship diagram, as their distinctive properties in business impacts, type of current alternative site and applicable business continuity strategies have a large influence on the system performance. The main operational KPIs are fill rate and its recovery time while the key financial KPI is IFX cost, which consists of backorder cost and sales loss. The long-term business impacts are considered in calculating the financial KPIs. Furthermore, the customer and CoC loss will also be examined under certain conditions to illustrate the large consequences on the whole SC.

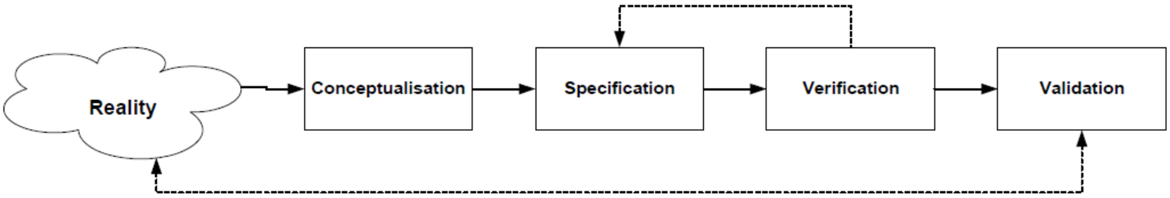


Figure 24. Schema of the Simulation-based Framework Development (Verbraeck & Heijnen, 2016)

The specification includes three elements: input data preparation, key process implementation and model assumptions. The mean of selected historical sales data for each PG is taken as customer demand in order. The variable “backorder rejection time” illustrates the time it takes for customers to cancel their backorders in the model, which is determined given a dissatisfaction tolerance index (DTI) and a satisfaction curve (Montreuil et al., 2013). The satisfaction curves versus order delivery time are based on the categories of the clients of PGs (neutral or very patient clients). The information about time to respond (e.g. to transfer products and technology) for each BCSAS and the corresponding investment to upgrade an alternative site is gathered.

The key process in the model consists of three parts: I) demand and supply management, II) production disruption and ramp up, and III) WIP process during the disruption. The supply network can be seen as a pull system, where the order with customer demand is injected in the model to control production. If supply is not sufficient after disruption, the backorder will be accumulated until it becomes fulfilled or a lost sale. Part II includes algorithms for calculating the production rate (WSPW) at the disrupted site and the alternative site. A disruption makes the original FE lose the defined capacity. After this length, it will have a restoring ramp-up until it reaches the maximum capacity (120% than normal WSPW). When the backorder for FE diminishes, the original site will stabilize and produce according to demand. An important concept called “DemandFE”, storing the total quantity of wafer lots required to produce at the FEs, is introduced to be the base of the production ramp-up. The alternative site shares similar algorithm of ramp-up but responds after their required time instead of the disruption length. Additionally, the maximum recovery capacity differs. For part III), WIP is processed separately within three paths: move to DB1, scrapped or move to DB2 (when there is product transfer). The author also defines the model assumptions and boundaries, which are divided into three components: production process, associated cost and generic model setup.

6. DESIGN OF EXPERIMENTS TO EVALUATE BUSINESS CONTINUITY STRATEGIES

After the verification and initial validation of the model, the experiments for evaluating business continuity strategies on those PGs under different disruption scenarios are designed. This chapter consists of three sections: Section 6.1 describes the treatment of the experiments including the start-up time, run length and number of replications; Section 6.2 describes the factors and their combinations in the simulation experiments; Section 6.3 illustrates the expected simulation behaviors and outcomes from qualitative understanding.

6.1 Experimental Settings

When a simulation starts, the values of the variables have not yet been stabilized, which will not represent reality (Verbraeck & Heijnen, 2016). The system needs to be in a steady state before we activate a 'disruption' event. To begin with, the FE needs to build WIP and stocks in order to have product flow in the supply chain at a steady rate. Since the cycle time, production rate and customer demand are deterministic, we can calculate this start-up time to reach a normal production. As different products have different values, we take the longest one and slightly extend it for a stabilized performance. The start-up time is set to be 35 weeks before the disruptive event happens.

The run length is not constant for all scenarios. Every disruption is a one-time event for a run. When the system restores to the original level after the disruption, the experiment finishes with stable KPIs. In order to show the steady period afterward, the graphs in the results part will extend the time horizon a bit further.

The model is stochastic in nature as some parameters are with probability distributions. Therefore, replications are needed to present the variety of input variables with an acceptable level of randomness effects. One way to deal with the random variation is to perform a number of independent replications, and take the average of the measures of interest (Burghout, 2004). As a Rule of Thumb (Law & McComas, 1991), at least 3 to 5 replications are recommended.

The experiments are conducted in the *parameter variation* environment in Anylogic. Two environment parameters need to be set there to define the number of replications: 1) *iteration* for the parameter variation with the same seed, 2) *replication* for generating different seeds. Therefore, the total number of (replication) runs in model = *iteration* * *replication*. This is actually the common interpretation of the number of replication in literature.

Currently, the experiment sets 10 *iterations* and 5 *replications*, resulting in a total number of 50 runs for each experiment. A *Student-t* test is performed to compare one set of average values of KPIs obtained from current setting to an experiment where the number of *iteration* and *replication* is 30 and 10, respectively. The null hypothesis is accepted. Hence, there is not a significant difference on simulation results if the number of runs is increased.

Additionally, a 95% confidence interval for KPIs is achieved using the present experimental setting.

6.2 Design of Experiment Description

In order to have a better understanding of the impacts of different BCSAS on supply chain resilience, as well as financial performance, an extensive number of experiments are needed. The Design of Experiment is shown in Table 10 with three main factors: process group, disruption scenario and business continuity strategies including the base scenario (self-recovery at the disrupted site) as well as BCSAS (cold / warm/ hot/ mirror sites). This design is to demonstrate if the BCSAS are robust under different disruption scenarios for various PGs. In addition, we can identify which BCSAS will perform the best in a specific scenario. The cells marked with "X" in the table represent the experiments to conduct.

Table 10. Design of Experiments

Process Group	Disruption Scenario	Base Scenario	Mirror Site BCSAS-IV	Hot Site BCSAS-III	Warm Site BCSAS-II	Cold Site BCSAS-I
P1 (Product)	DS1 DS2 DS3 DS4	X X X X	X X X X			
P2	DS1 DS2 DS3 DS4	X X X X		X X X X		
P3	DS1 DS2 DS3 DS4	X X X X		X X X X	X X X X	
P4	DS1 DS2 DS3 DS4	X X X X		X X X X	X X X X	X X X X

The Design of experiments (DoE) is a systematic method to engineering problem-solving that determines the relationship between affecting factors and the outputs, which is often carried out under the constraint of engineering runs, time, and money (British Standards Institution, 2015).

DoE often includes controllable and uncontrollable input factors, responses and hypothesis testing. Their connections can be illustrated in Figure 25. The controllable input factors are the parameter that can be modified in the experiments, e.g. the three main factors mentioned in Table 10. The uncontrollable input factors are unchangeable factors such as the uniform preventive controls in this case, which are not modeled. Nevertheless, they have influences on the system, which need to be recognized in reality. The responses are the output measures, which are the KPIs listed in section 5.2 in this project. The hypotheses are given in the following section as the expected simulation behaviors and outcomes.

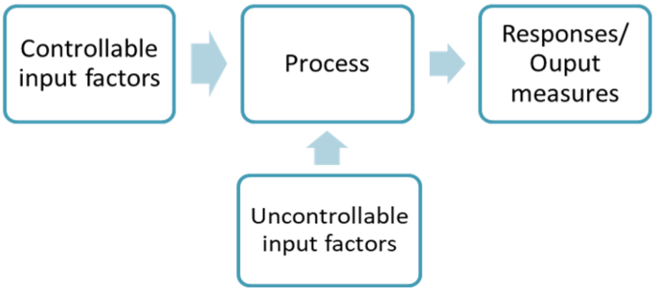


Figure 25. Factors and Responses in DoE

To summarize, four defined disruption scenarios will be activated for each PG independently in the experiments. The disrupted site recovery on its own is considered as base scenario. Then, different BCSAS are implemented as testing scenarios. The KPIs are compared within the same row because the same PG and disruption scenario offers the common base. Hence, the different strategies are compared with base scenario (result-as-is) as well as with each other (result-to-be). Therefore, the DoE in Table 10 enables us to compare alternatives and to identify significant input factors. Additionally, testing under different disruption scenarios can improve the robustness (e.g. fitness for use under varying conditions) and balance the trade-off when there are multiple KPIs requiring optimization financially and operationally (Anderson & Whitcomb, 2000).

It can be seen from the table that some cells are not tested. Firstly, P2, P3 and P4 do not have a mirror site. This is because of the technical limitation: mirror site is only applicable for *Product* level but they belong to *Process Group* level. Additionally, the experiment does not test downgrading the current type of an alternative site since the investment has been made already. For example, P3 does not have "cold site" in its experiment, because its current alternative site is already a warm site. The current type of the alternative site for P4 is a cold site, hence there are possibilities to upgrade it to a warm or hot site. Therefore, the experiments test the performance of activating the current BCSAS as well as upgrading in the case of a disruption. In total, there are 44 experiments to be performed.

6.3 Hypothetical Simulation Behaviors and Outcomes

After a disruption occurs in the simulation, the production is expected to be affected directly. However, due to the buffering effects of the stocks, the fill rate curve is expected to stay stable for a particular duration of time before it falls. When the disruption length finishes, the production at original site starts to recover, but the increase of fill rate is foreseen to be delayed due to the cycle time in production, which might result in a similar curve as Figure 7. As the production continues to build up, the fill rate grows at an accelerating pace. The disruption costs start rising from the point where fill rate is not 1 and continue rising until the fill rate is fully recovered. If an alternative site is activated, its production undergoes a ramp-up after the demanded responding time.

The expected outcomes can be divided into two parts: base scenario itself and comparison between the BCSAS and base scenario. In terms of the base scenario, we expect the recovery time of fill rate will be the longest in DS2, followed by DS1 or DS4, and the DS3 will restore the quickest. The anticipated financial losses remain in the same order. Regarding the comparison, the experts held the belief that the cold site and warm site would not curtail the fill rate recovery time and financial losses significantly in any disruption compared with the base scenario. From the expectation of the experts, the additional capacity provided at the cold and warm site is too late to be useful for disaster recovery but might contribute to stock building. However, the hot site and mirror are believed to reduce the negative impacts.

6.4 Conclusion

The model experiment setting includes a start-up time of 35 weeks, a flexible run length until the system is restored and 50 replications. The Design of Experiment (DoE) is used to for scenario analysis, which includes controllable and uncontrollable input factors, responses and hypothesis testing. BCSAS are tested under four different disruption scenarios on four PGs, and their performances are compared with base scenarios (self-recovery at the disrupted site) as well as between each other. In total, 44 experiments are to be carried out to examine the impacts, robustness and/or conditions for various BCSAS. The hypothetical simulation results based on the qualitative understanding is described. Essentially, the cold and warm sites are not expected to have positive impacts on fast recovery. The generated results and analysis are presented in the next chapter.

7. ANALYSIS AND RESULTS

The disruption scenarios and BCSAS described in Chapter 4 are implemented in the simulation framework illustrated in Chapter 5. Furthermore, the experiment is designed in Chapter 6. This results in different values on the KPIs for various scenarios. The results are analyzed in this chapter in five parts. First, the outcome of base scenario will be presented to show that the diverse disruption scenarios have different degrees of impacts. Then the performance of each BCSAS on resilience and finance compared with base scenario will be assessed, followed by a cross comparison between them. This is to identify which strategy performs the best under which condition and test the robustness of a strategy. The detailed results can be found in Appendix C. Following that, the generated simulation results are further compared with the hypotheses and the associated uncertainties are illustrated. Verification and validation are described in the end of this chapter.

7.1 Results of Base Scenario

Different disruption conditions have diverse effects on the fill rate recovery and IFX cost, which are the most important KPIs in this research. Furthermore, their impacts might also be amplified or reduced for various PGs based on the product characterization. The start-up time is not shown in the following figures. The IFX cost is normalized due to confidentiality. The maximum cost is normalized to be 10000 whereas the lowest value is 0. The impacts of the normalized values are identified and indicated in Table 11 after the discussion with the experts in the BC department.

Table 11. Impacts Indication of the Normalized Monetary Value

Metric	Description	IFX cost range in the report
Low	Insignificant cost for one PG	Under 8
Medium	The impact is limited and the loss is often bearable	[8, 80)
High	The amount is significant but fixable with current resources	[80, 160)
Critical	Serious impacts, struggling to fix	[160, 320)
Extreme	Catastrophe loss which poses severe threats to business	Over 320

Figure 26 shows the average fill rate changes for four PGs in the four disruption scenarios defined. In general, the fill rate curve of P1, P2 and P4 share resembling trends in all disruption situations. However, P1 and P4 have similar recovery time while P2 often restores quicker than them. The reason is that P2 has a shorter cycle time, which means the products can be delivered earlier, resulting in a faster restoration. Furthermore, the fill rate of P3 seems to have the fastest return in every disruption scenario (DS) with differentiating growth curves than others. This is mainly because P3 has a much shorter backorder rejection time, which decreases the total demand in fill rate calculation and the production burden.

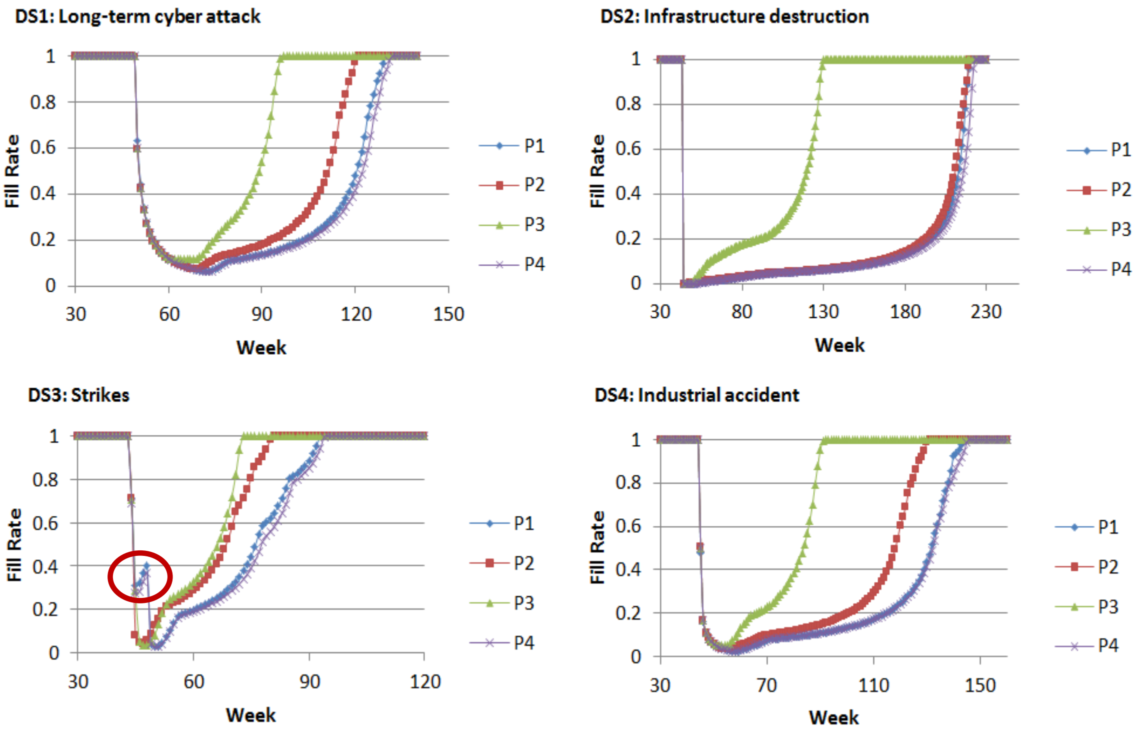


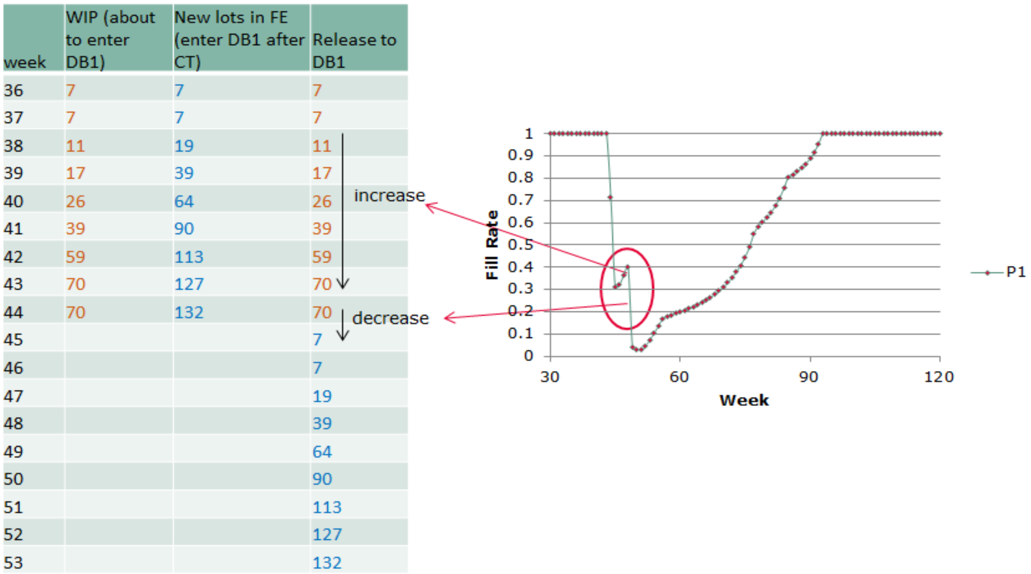
Figure 26. Average Fill Rate Changes for PGs under Diverse Disruption Scenarios

In DS1 (long-term cyber-attack), the fill rate declines more smoothly and its lowest level is higher compared with other disruption scenarios. DS1 has a medium capacity loss whereas the rest has high severity; hence the remaining capacity in DS1 plus the safety stocks help to deal with the disturbance longer. As a result of backorder rejection time difference, the fill rate of P3 maintains at its bottom for about 2 months while the others continue to decrease until the turning point. DS2 (infrastructure destruction) has the largest consequence as expected: the fill rate stays low (below 20%) for a very long time (about 3 years) before it shows a significant upward trend. However, the impact is reduced extensively for P3 due to the backorder elimination.

Compared with other scenarios, the fill rate has the shortest recovery time in DS3 (strike), since many WIP are kept as buffers and the capacity ramps up fast. It is noticed that there are two groups of trends in DS3: with a small peak during declining period (P1 and P4) or without (P2 and P3). This phenomenon will be explained in the following part. DS4 (industrial accident) also has the second largest influence on fill rate that it takes about 2 years for fill rate to reach to the original level with an exception of P3 (about one-year recovery).

The fill rate changes shown in Figure 26 correspond with the qualitative assessment from the experts. However, the simulation shows the unforeseen behavior of fill rate in DS3 (circled in red in Figure 26 and Figure 27), as it does not decrease until the lowest point, but instead, the fill rate has a slight increase before declining to the bottom. This can be explained by the unexpected buffering effects of WIP. In the case of quick production recovery or transferring products to an alternative site, new wafer lots released from FE to DB1 are fewer than the

WIP processed before, due to CT delay (see Figure 27). P1 and P4 has a long CT, hence their simulation results demonstrate this ‘WIP ramp-up’ effect strongly.



week	WIP (about to enter DB1)	New lots in FE (enter DB1 after CT)	Release to DB1
36	7	7	7
37	7	7	7
38	11	19	11
39	17	39	17
40	26	64	26
41	39	90	39
42	59	113	59
43	70	127	70
44	70	132	70
45			7
46			7
47			19
48			39
49			64
50			90
51			113
52			127
53			132

Figure 27. Explanation of Unforeseen Fill Rate Behaviors

From the financial perspective, the economic loss caused by those disruption scenarios shows similar S-shaped growth curves (Figure 28). For all PGs, the cost initially increases slowly and then rapidly. It undergoes a negative acceleration phase until it stabilizes. It is obvious from Figure 28 that P2 endures the largest financial loss for IFX compared with other PGs in the same scenario. The financial losses of P2 in every scenario are identified as *extreme*, based on Table 11. This can be explained by its large sales quantity and expensive sales price, which can be seen as an indication of high business impacts. On the contrary, P3 might have rather small business impacts, resulting in the lowest cost in each scenario (*low* or *medium* impact given the indication from Table 11).

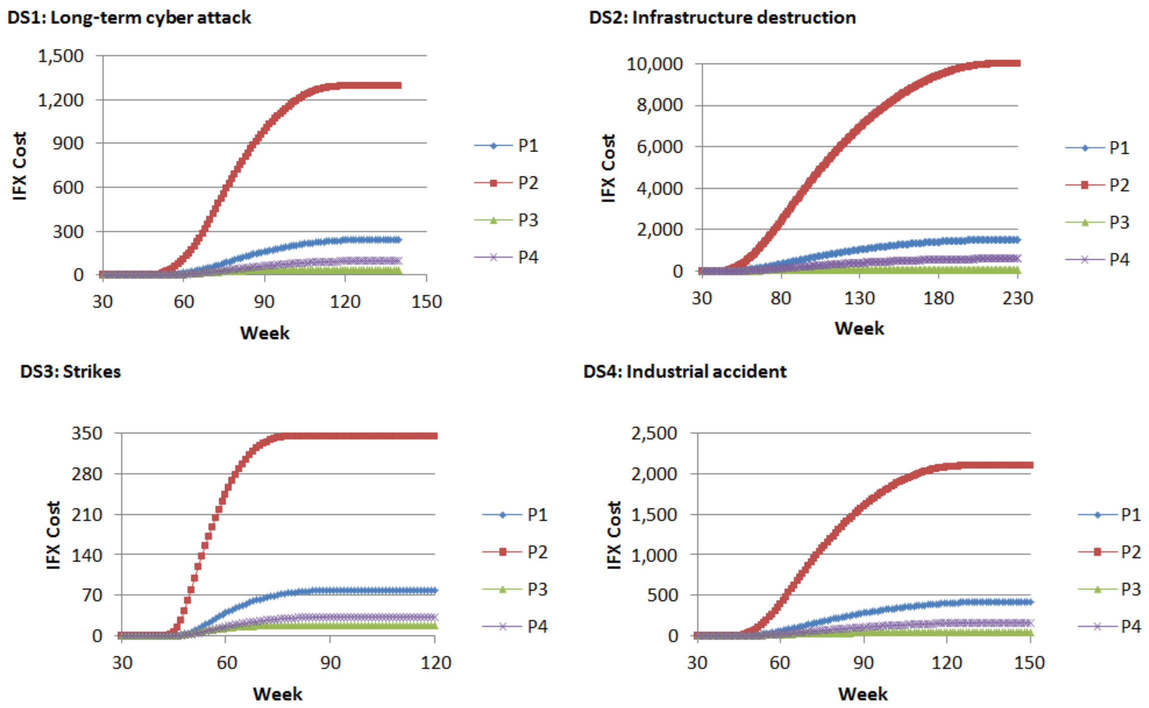


Figure 28. Average IFX Cost for PGs under Diverse Disruption Scenarios

In general, the IFX cost shown above depicts the backorder cost for P1, P2 and P4, since their production recovers much faster than their backorder rejection time, causing zero sales loss. However, the IFX cost under DS2 is drastically higher than other scenarios and leads to *extreme* financial consequence. It consists of both sales loss and backorder. The sales loss growth is demonstrated in Figure 29, which usually happens after the backorder rejection time with no sufficient capacity available. Due to a short backorder rejection time for P3, its IFX cost always constitutes both sales loss (similar to Figure 29) and backorder cost, which is the main part; thus, its IFX cost curve still follows the trend of backorder cost curve. Furthermore, the customer loss and CoC loss are proportional to backorders; therefore, they have similar growth curves as IFX cost, illustrated in Figure 28, with different values. The financial loss of DS3 is significantly smaller than other scenarios because of the nature of this type of disruption. The severity ranking of financial consequence is DS2>DS4>DS1>DS3, which corresponds with qualitative assessment as well.

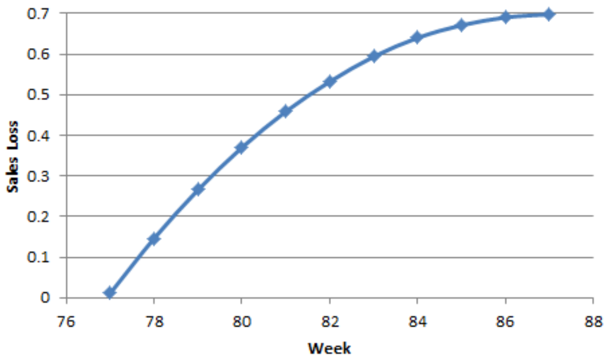


Figure 29. Sales Loss Growth Curve under DS2 (Infrastructure destruction) for P4

7.2 Impacts of BCSAS on Selected KPIs

Diverse BCSAS show different impacts on KPIs under the disruption scenarios. Overall, those business continuity strategies show positive influence by shortening fill rate recovery time and reducing disruption cost, including the customer loss and CoC loss. This section will elaborate on each BCSAS about their performance.

7.2.1 BCSAS I – Cold Site

P4 is the only PG that has a cold site as an alternative site now; therefore the results analyzed and presented in this section are all from P4. Figure 30 shows the KPIs comparison of base scenario and cold site in long-term cyber-attack disruption (DS1). It shows that a cold site can help facilitate the restoration of fill rate significantly, with a similar shape of fill rate growth curve as base scenario. Additionally, it could reduce the financial loss to a certain degree (from *high* to *medium,* as indicated in Table 11). Those two observations can be generalized in all disruption scenarios (excluding strikes), indicating a positive impact of cold site to prepare for catastrophes. The 95% confidence interval is used to calculate the lower limit (LL) and upper limit (UL) of the KPIs in the following figures. Since the interval range is quite narrow, the average value is believed to be representative.

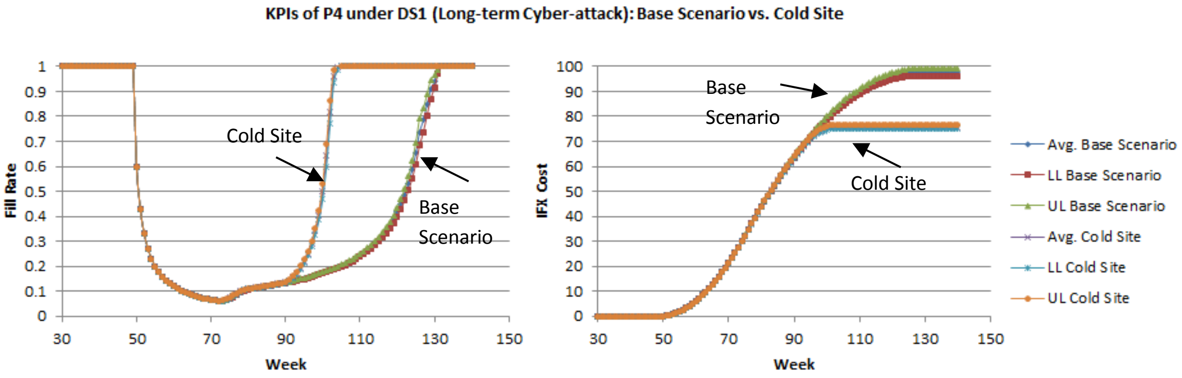


Figure 30. Comparison between Base Scenario and Cold Site (DS1, P4)

The cold site has an adequate performance among various disruption scenarios as demonstrated above, and in comparison, it has the exceptional achievement in DS2 (infrastructure destruction). It could be demonstrated by examining Figure 30 vs. Figure 31. It is clearly seen from Figure 31 that the cold site averagely *havened* the recovery time of fill rate and IFX cost (from *extreme* to *critical*) in DS2. This means for disruptions like earthquake, which has severe capacity loss with long- term production ramp up, a cold site is very useful to save the business loss even though it has large initial investment.

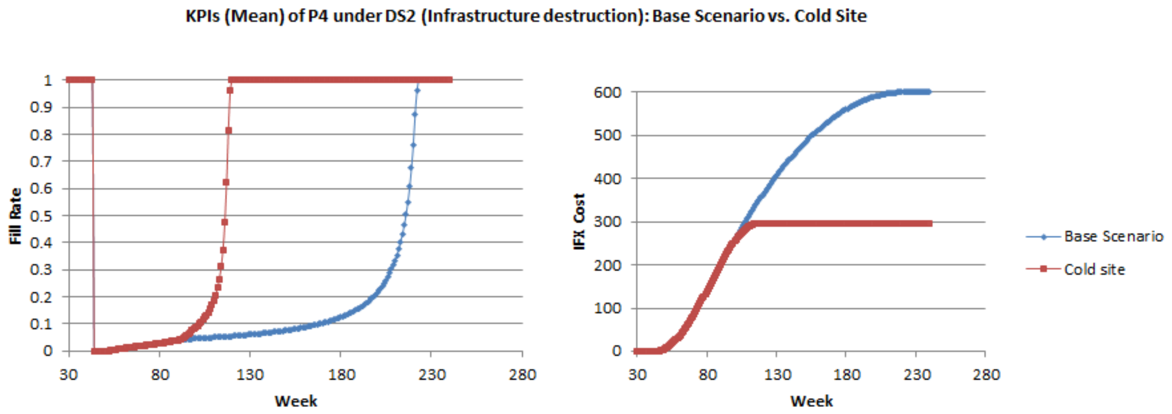


Figure 31. Comparison between Base Scenario and Cold Site (DS2, P4)

However, the cold site is not cost-effective in situations like strikes (DS3), where it is a short term disruption with *medium* financial loss. As illustrated in Figure 32, the black box implying the range of IFX cost under base scenario is almost overlapping with the red box displaying the range from cold site. Thus it can be said that the performance of cold site is almost similar to base scenario given the 95% confidence interval. Due to long responding time, the cold site is not able to help the original site when it already has a short recovery time in an event like DS3. Further considering the extra investment, a cold site is likely to increase the total cost. This conclusion is in line with the qualitative understanding from the experts.

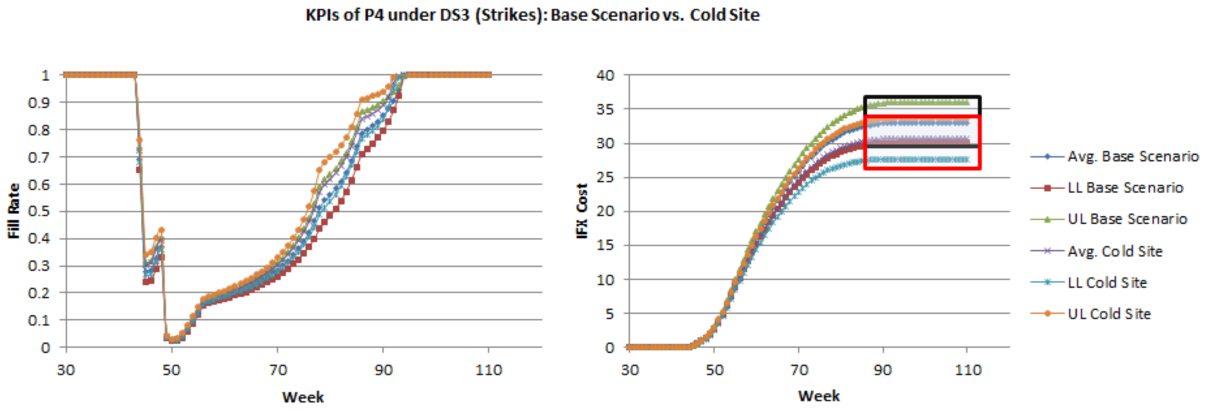


Figure 32. Comparison between Base Scenario and Cold Site (DS3, P4)

7.2.2 BCSAS II – Warm Site

The experiments about warm site have been carried out on P4 and P3. The impact of warm site on P3 is reduced, which will be presented and explained in section 7.3.5. However, the basic contribution of warm site on those PGs is similar. Hence, the results of P4 are used here for illustration. Generally speaking (excluding strikes), the warm site reduces the fill rate recovery time by more than 50% and cuts down the corresponding IFX cost to a degree between 35% and 65% roughly, as shown in DS1 (long-term cyber-attack) in Figure 33. In this case, the financial loss level decreases from *high* to *medium*. The narrow confidence interval indicates a good estimate.

Besides the relative value comparison with the base scenario, the absolute value of disruption cost is also important. For example, the warm site in DS1 and DS2 both have about 60% to 65% of cost reduction compared with the base scenario, but in absolute terms, the warm site reduces *63 monetary units (medium* impact*)* in DS1 whereas up to *352 monetary units (critical* impact*)* in DS2 averagely. This distinct gap is related to the nature and influence of the disruption itself, as mentioned in section 7.1.

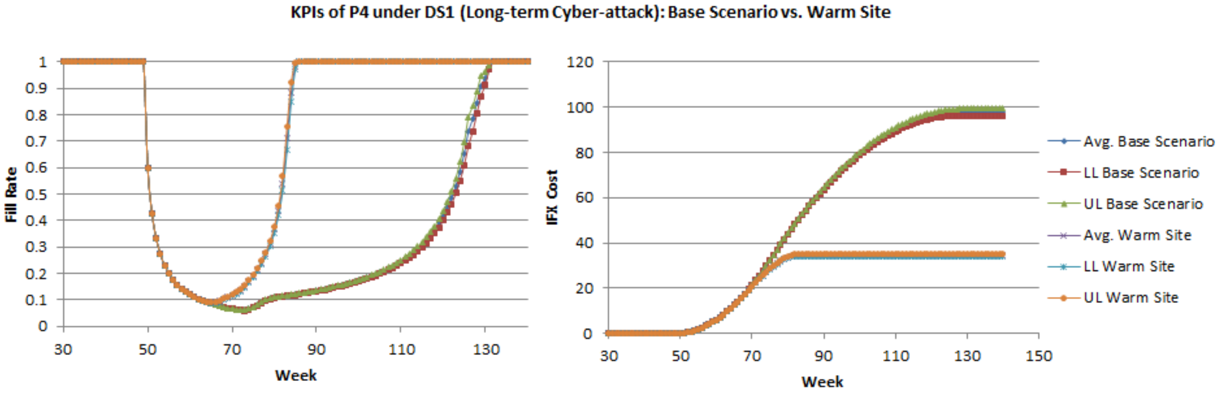


Figure 33. Comparison between Base Scenario and Warm Site (DS1, P4)

However, the warm site does not have desired financial performance for short-term disruptions with quick production ramp up such as strikes (DS3). Figure 34 shows the KPIs comparison of base scenario and warm site under DS3. Despite shortening the return time of fill rate to a large degree, the IFX cost resulted from the warm site is not drastically different than base scenario considering the possible data range (black box vs. red box). In addition, extra investment needs to be made to establish a warm site; hence the benefit may not be very appealing in this situation.

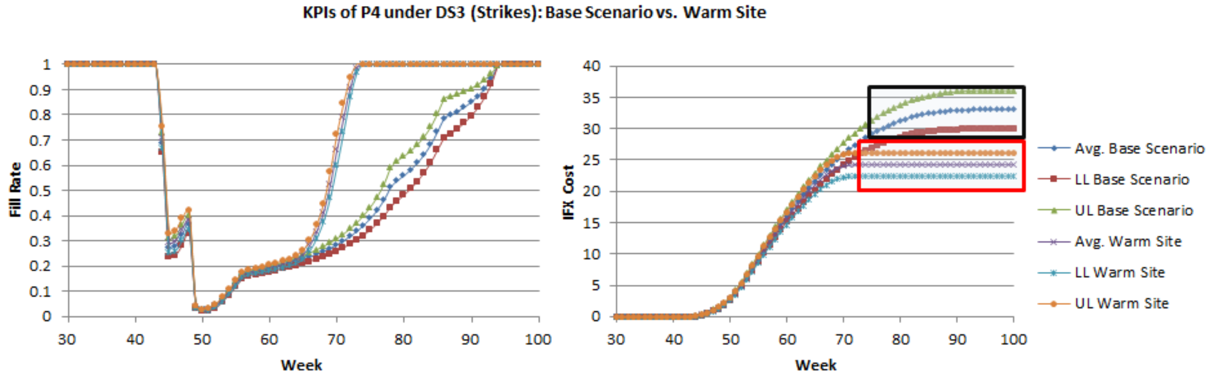


Figure 34. Comparison between Base Scenario and Warm Site (DS3, P4)

7.2.3 BCSAS III – Hot Site

Overall, the hot site has robust and excellent performance in all selected disruption scenarios. The resulted system response is similar for all PGs: hot site curtails the fill rate restoration time and financial loss to a massive extent compared with the base scenario as well as cold and warm sites. Nevertheless, this distinction is again diminished for P3. Unlike cold and warm site, a hot site also shows cost-effective behaviors for all tested PGs in medium capacity loss disruptions with quick ramp-up (e.g. strikes), as depicted in Figure 35.

The fill rate has a higher level before and after the turning point with a significant cut on recovery time. The IFX cost is also moderately lessened with consideration of the confidence interval.

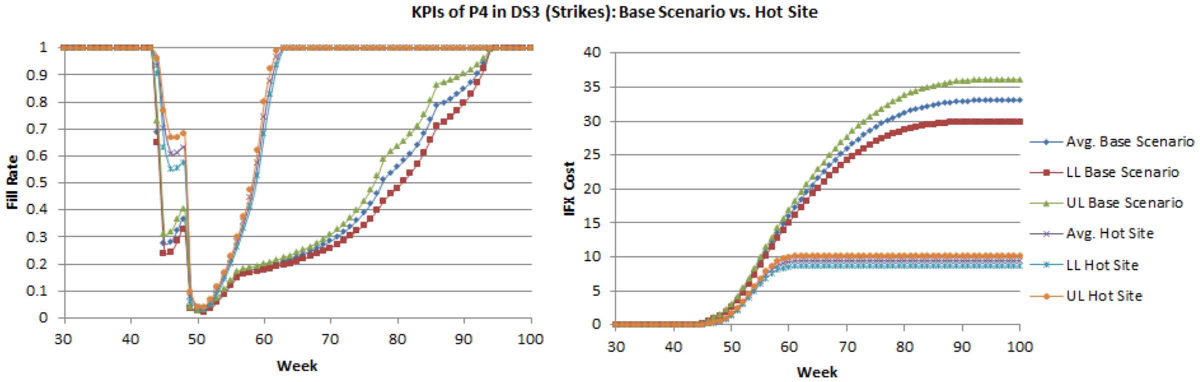


Figure 35. Comparison between Base Scenario and Hot Site (DS3, P4)

Moreover, the hot site displays outstanding performance in DS1 (long-term cyber-attack) when comparing the effects under every disruption scenario individually (neglecting the influence from the disruption itself). This can be demonstrated in Figure 36. The fill rate shows a different curve with a higher level of a turning point and shorter interval than base scenario. This leads to a small area of 'resilience triangle', which implies a resilient system according to (Barroso et al., 2011). In addition, the IFX cost is cut to only 2% than previously (reduced from *high* to *low*). This great financial advantage of the hot site is even amplified for P2 with large sales volume and high price.

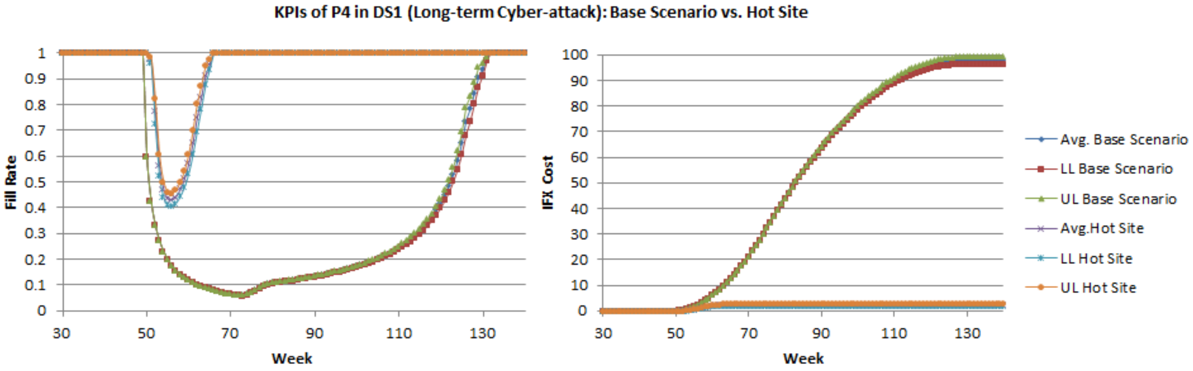


Figure 36. Comparison between Base Scenario and Hot Site (DS1, P4)

7.2.4 BCSAS IV – Mirror Site

As the mirror site in this research project is only applicable on P1 (product level), the experiments have only be conducted on P1 so as the conclusions drawn. The 'resilience triangle' of fill rate resulted from mirror site is remarkably smaller than the base scenario with compellingly shorter recovery time. The triangle is downsized both in terms of the depth and width. More importantly, the reduction of financial loss from having a mirror site is enormous. Those two benefits are shown in Figure 37 as an illustration, and the financial loss is reduced from *extreme* to *medium* in this case.

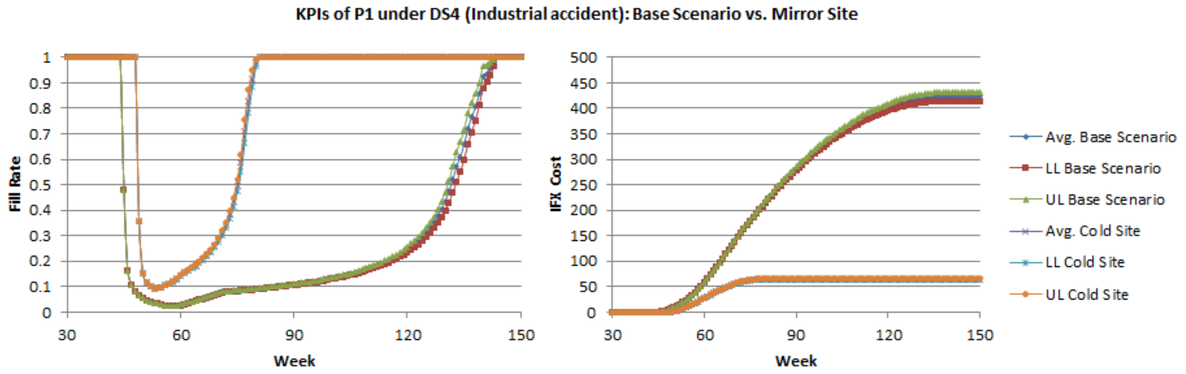


Figure 37. Comparison between Base Scenario and Hot Site (DS4, P1)

However, the common problem is that it requires a long time of operation at the mirror site, which might be difficult to achieve for a large number of products and contributes to the complexity of daily maintenance. Therefore, the mirror site is very expensive to set up with a variety of practical challenges. Furthermore, it may also influence the production curve at the original site. Those two issues will be discussed in the next chapter.

Still, the mirror site is within the scope of this study in order to demonstrate the substantial benefit it can bring and confirm the qualitative assessment. Particularly, under the disruption scenario with medium severity (e.g. long-term cyber-attack), the mirror site has the potential to completely compensate the capacity loss and keep the fill rate at 100%, which leads to zero financial loss.

7.3 Comparison between BCSAS

From the testing scenarios, the resulted trends of those KPIs for different PGs seem to be similar with few exceptions. The average values of outcomes for P4 with and without alternative sites are presented in this section for illustration, as they are representative and P4 has the most options of BCSAS for comparison. Furthermore, the mirror site is not included in the comparison, because its outcomes cannot be applied to process group level. Nevertheless, we identified large positive effects a mirror site could stimulate, as highlighted in section 7.2.

7.3.1 Disruption Scenario 1 – Long-term Cyber-attack

Compared with the base scenario, every BCSAS helps to lessen the impacts from DS1 (long-term cyber-attack), as can be seen from Figure 38. The fill rate restoration time and financial loss of IFX are reduced to different degrees depending on the types of alternative site. According to the results, the hot site shows the most benefit in terms of all the KPIs concerned. It has the highest fill rate during the whole time horizon (at least above 40%), with the shortest restoring time and least disruption cost for IFX. The average customer loss is cut from *130* unit to *3.2* unit whereas the CoC loss is reduced from *104* unit to *2.6* unit for P4, indicating significantly lesser financial losses (from to *high impact* to *low impact* based on Table 11 in this case).

The warm site has a lesser degree of an impact than the hot site but its reduction is still more than half of the base scenario. The performance of a cold site is worse than warm and hot site but better than base scenario. Further considering the investment needed to make in order to activate the alternative site, all BCSAS seem to be worthwhile with the hot site being the most profitable.

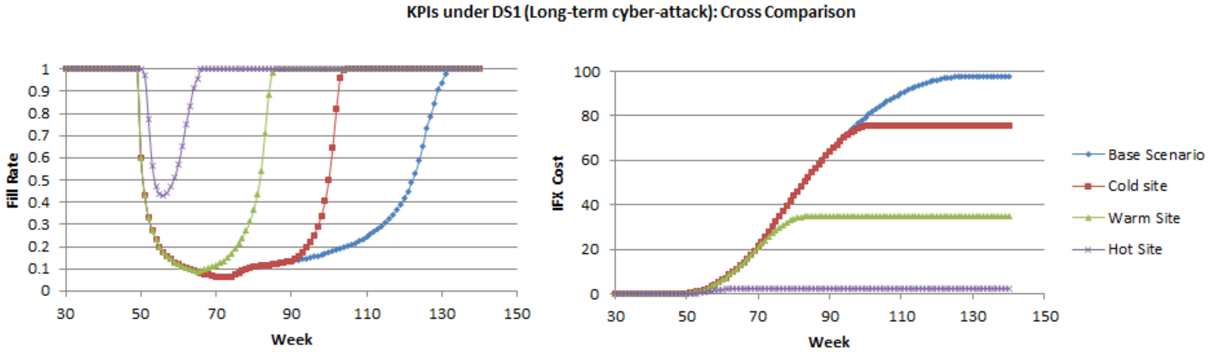


Figure 38. Cross-Comparison between BCSAS under DS1 (Long-term Cyber-attack)

7.3.2 Disruption Scenario 2 – Infrastructure Destruction

In DS2 (Infrastructure destruction), the benefits of BCSAS are *outstanding* compared with the base scenario, as in Figure 39. Because the nature of this type of disruption (long-term restoration) leads to extremely large costs, the advantages of alternative sites are amplified: the system recovery time is reduced from 4 to 2 years roughly for all BCSAS, and the corresponding IFX cost is reduced to at least half as well.

Unexpectedly, the cold site has the fastest return of fill rate. This is because the maximum production rate at cold site reaches to 100% due to the additional capacity from the installation of new equipment in cold site, while the others are assumed to reach to only 70%. Therefore, even cold site responds later than the warm and hot site, it has more operational capacity afterward for a long period, which leads to a faster recovery.

The financial loss level is reduced from *extreme* to *critical* with all the applicable alternative sites. However, the IFX disruption cost from the cold site is still the largest whereas the hot site has the best financial performance. It can be seen from Figure 39 that hot site starts to restore the earliest and the demanded quantity is considerable at the beginning. This accumulative effect in the early phase helps to compensate a late recovery. It also explains why the warm site leads to a higher cost than hot site even though there does not exhibit a significant difference in terms of their recovery time.

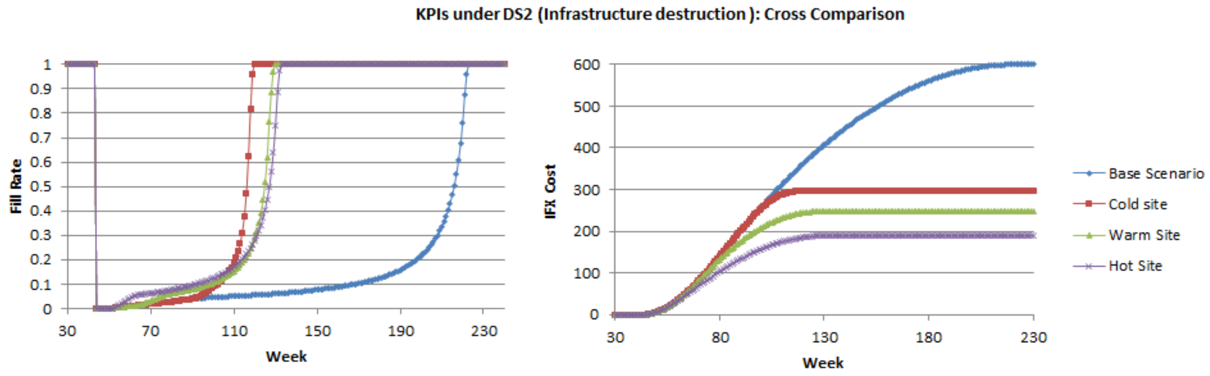


Figure 39. Cross-Comparison between BCSAS under DS2 (Infrastructure destruction)

7.3.3 Disruption Scenario 3 – Strikes

Figure 40 shows the average value of KPIs from various business continuity strategies under DS3 (strikes). The hot site and warm site can facilitate the resuming and curtail the disruption cost. The cold site has similar performance on fill rate recovery and IFX cost as base scenario given the confidence interval. However, the benefit of the warm site is also not desired considering the confidence interval as well as the investment cost to make it up running. The box circled in Figure 40 depicts the unprofitability mentioned above. In this type of disruption, only hot site shows a significant positive influence, which is aligned with the understanding of experts. It is worth mentioning that since the disruption scenario itself does not cause as large financial loss as other scenarios. The savings from having alternative sites are also limited (financial loss roughly remains at *medium* level).

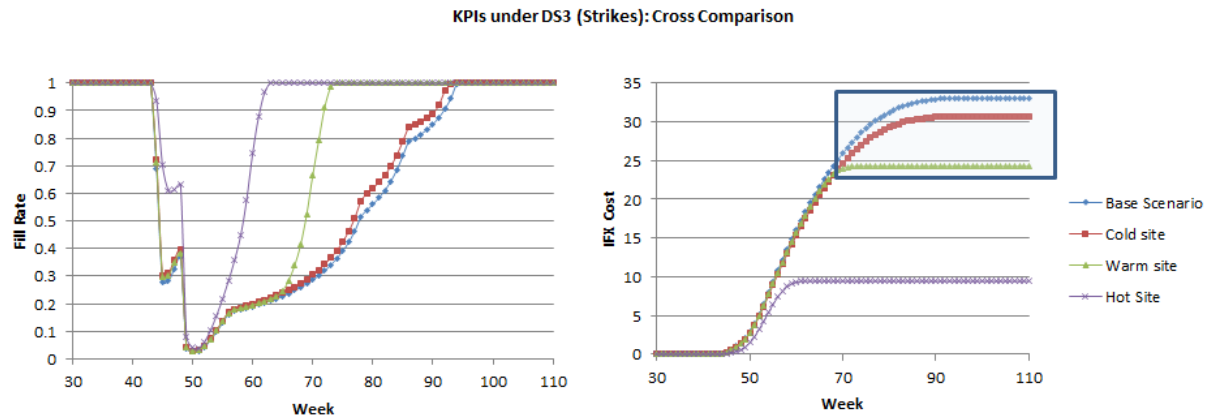


Figure 40. Cross-Comparison between BCSAS under DS3 (Strikes)

7.3.4 Disruption Scenario 4 – Industrial Accident

The BCSAS are useful under DS4 (industrial accident), as can be seen from the Figure 41. The hot site shows most significant benefits on the selected KPIs. It has the highest fill rate all the time, with the shortest restoring time and least disruption cost as in DS1. The cold site also demonstrates a good performance compared with base scenario.

The warm site lessens disruption cost. Additionally, it has a similar achievement on fill rate recovery as the hot site, but the hot site curtails more cost due to the accumulative effect mentioned above. However, those positive impacts of the warm site were not expected from experts. Qualitatively speaking, the warm site starts to respond when the original site already has restored their production, which is believed to be too late for contributing. Nevertheless, the extra capacity from alternative site helps to compensate a large number of backorders in an early manner. It would take a significantly longer time for the additional production rate at the primary site to cover the backorders. This was overlooked from qualitative analysis.

A hot site is the best fit under DS4, but a warm site could also be a good option if it is difficult to establish a hot site when certain limitations are taken into consideration (discussed in chapter 8).

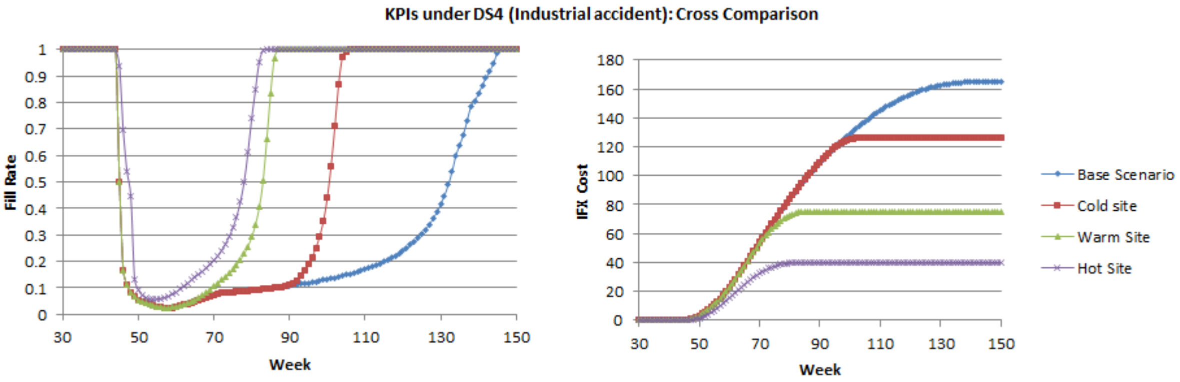


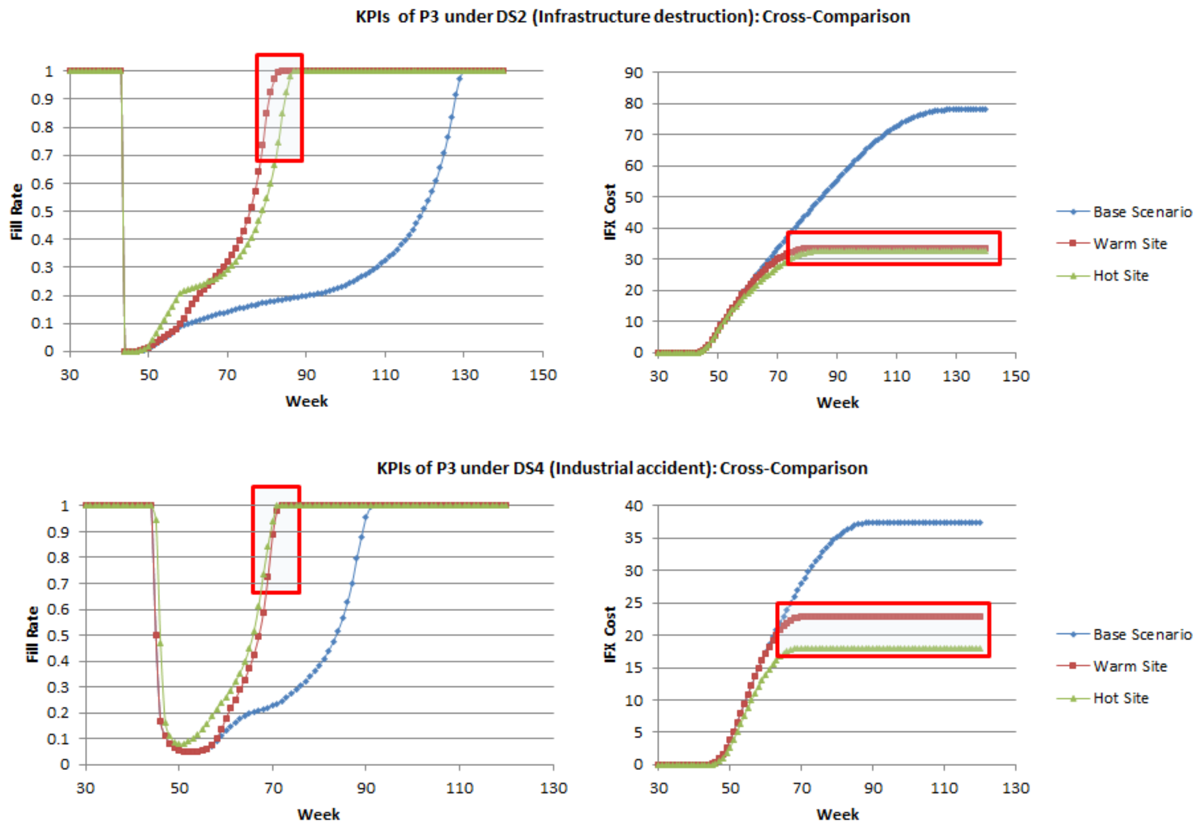
Figure 41. Cross-Comparison between BCSAS under DS4 (Industrial accident)

7.3.5 Exceptional Case

Even though the BCSAS have similar effects on other PGs as described on P4, there are exceptions due to the characteristics of process groups. They are summarized as below:

- The hot site shows a much more positive impact on P2 than other PGs due to the business impacts of P2 (e.g. reduce the financial loss from *critical* to *low* in DS1) Furthermore, these benefits are amplified considering the total disruption costs in supply chains (Customer loss and CoC loss).
- The benefits of the warm site and hot site are reduced for P3 compared with other PGs. This means the reduction of fill rate recovery time and disruption cost after running a warm site or hot site under the same disruption condition is not as large as other PGs. The base scenario of P3 already has comparatively lighter consequences than others because of its short backorder rejection time and cycle time, as well as low sales quantity and price. Therefore, on top of this, the warm site and hot site do not seem to be very powerful on P3.
- Due to a similar reason mentioned above, the warm site and hot site do not have a significant difference for P3 in terms of fill rate recovery and the IFX cost, as indicated by the red boxes displayed in Figure 42. Considering the extra investment to upgrade a warm site to a hot site, it might be more cost effective to maintain the warm site for PGs with attributes like P3 in preparation for mid/long-term severe capacity loss

situations. However, certain limitations of modeling need to be considered, as discussed in the next chapter.


KPIs of P3 under DS2 (Infrastructure destruction): Cross-Comparison

KPIs of P3 under DS4 (Industrial accident): Cross-Comparison

Figure 42. Cross-Comparison between BCSAS for P3

7.4 Discussion about Simulation Results

The general trend from the generated simulation results is in line with the expectation with some unanticipated findings on the system behaviors and the impacts of a certain strategy. Furthermore, the variability and/or uncertainty are recognized in the results.

7.4.1 Simulation Results vs. Expected Modeling Behaviors

The generated simulation results fulfill the expectation mainly in three aspects. Firstly, the anticipated consequences of those four disruption scenarios are shown and ranked similarly from the simulation. Secondly, the warm site and cold site as expected do not demonstrate the desired cost-efficiency at coping with disruptions with short-term restoration. Thirdly, the mirror site and hot site have exceptional benefits in terms of fast recovery. These sites usually have the 'most resilient' results, followed by a warm and cold site.

However, there are also a few unexpected behaviors. The two peaks in the fill rate growth curve caused by the buffering effects of WIP for P2 and P3 are not foreseen (mentioned in section 7.1). Additionally, the warm site demonstrates positive impacts at reducing fill rate recovery time and IFX cost in disruptions with medium/long-term restoration, as a large number of backorders are often overlooked. A cold site even has the quickest recovery on the fill rate because of the additional capacity supplied by new tools. Lastly, we did not recognize the influences of the product specifications. For example, the product classification and cycle time can have extensive impacts on the performance, as pointed out in the section 7.3.5.

7.4.2 Uncertainty in the Results

Even though the lower limit and upper limit illustrated in the figures in section 7.2 seem to be very close to the average in each situation, there still exists uncertainty or variability in the simulation results. As already seen from the previous results in section 7.2, the most significant scenario is the strikes. The box plot (Figure 43) shows the spread of IFX cost using various BCSAS to cope with strikes. No extreme value is observed (see Appendix D1). The median of the cold site and the hot site is similar to base scenario. However, they have a larger interquartile range, indicating a higher amount of variability. The hot site nevertheless has a distinct small range at a lower position. Therefore, the uncertainty in the results further convinces the decision makers that the cold site and warm site is not cost-effective.

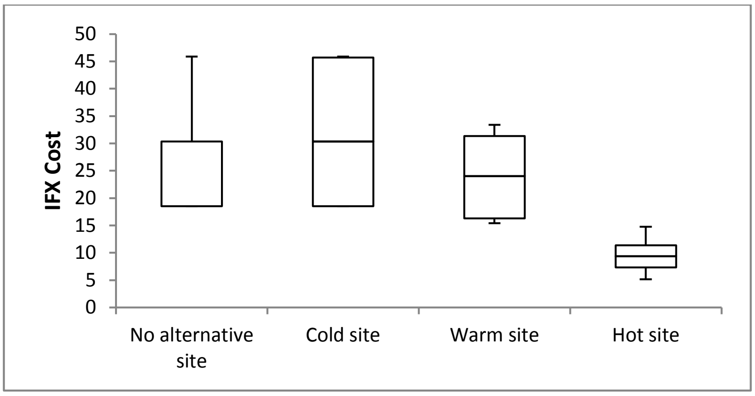


Figure 43. Box Plot of Avg. IFX Cost for each BCSAS in Strikes Scenario (P4)

In the other disruption scenarios, the uncertainty in the results has less influence, which can be demonstrated in Figure 44. From cold site to hot site, the boxes are positioned in a ladder shape in Figure 44, which indicates the distinct performances between each other even considering the volatility. The range of base scenario is typically the largest, given the uncertainty of recovery on its own. Different types of alternative sites have a narrow spread, exhibiting certain variability. Their interquartile ranges may seem to be smaller than Figure 43 due to the scale of the value. More information on results variability is in Appendix D.

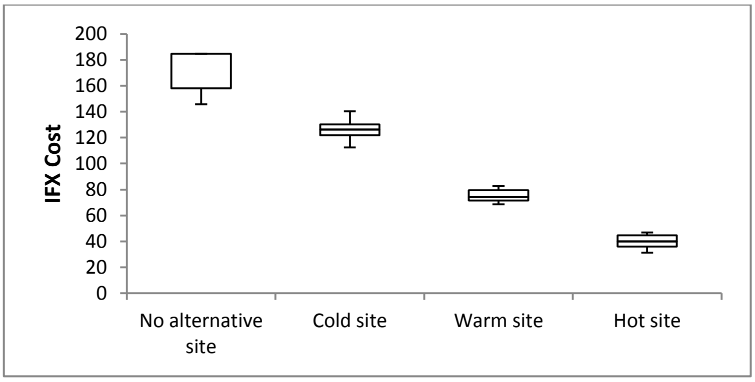


Figure 44. Box Plot of Avg. IFX Cost for each BCSAS in Industrial Accident Scenario (P4)

7.5 Verification and Validation

Verification and validation are carried out to examine the correctness of the model. Verification is used to check that the model is correctly coded, i.e. it is correctly translated from specification to simulation model. After verification, validation is employed to check that the model represents reality (Sargent, 2013).

7.5.1 Verification

Verification mainly checks the following three aspects (Verbraeck & Heijnen, 2016):

1) Have the input variables been correctly coded?
2) Is the model logic coded correctly?
3) Are the output variables calculated correctly?

The verification process in developing this simulation framework answers the three questions. Firstly, the input variables are checked to be correctly coded. For instance, the triangular distribution of tool purchasing and technology-transfer time generated from model fits the distribution of those input parameters in the specification. Secondly, the model logic is checked with unit testing and the help of "traceln" function in AnyLogic. The model was developed incrementally, meaning that each unit performs as designed before adding on more modules (Huizinga & Kolawa, 2007). The 'traceln' function allows tracking the logic of key decision points and processes. Thirdly, the output variables are calculated correctly, as the values for the output variables fit the data analysis results.

7.5.2 Validation

After verification, the model needs to be compared to reality to check if it is realistic enough. It is difficult for this project to conduct *replicate validation*, i.e. comparing the value of an output value in reality to the same output result calculated by the simulation model (Verbraeck & Heijnen, 2016). Because this project is explorative in nature; the disruption scenarios are defined based on literature and experts whereas the alternative sites have not been activated to deal with such catastrophes before. Therefore no real-world data exists to accurately measure the output variables identified in the simulation framework.

The validation techniques used in the project include internal validity, extreme conditions behavior test and face validation.

Internal Validity

Internal validity usually incorporates several replications (runs) of a stochastic model, which are made to determine the amount of variability in the model (Sargent, 2013). Fifty replications are performed for each combination of factors in DoE. It can be seen from the figures in section 7.2 that the amount of variability from the results (range between the lower limit and upper limit) is rather low. An example of all the possible outcomes in the 50 replications can be seen in Appendix E1. There is no output located extremely far away from the average, implying consistency in results.

Extreme Conditions Behavior Test

Extreme conditions behavior tests are carried out to check whether the model responds plausibly under extreme conditions and what the limits are for the model to be plausible (Sterman, 2000). To perform the extreme conditions behavior test, no disruption scenario is inserted (zero capacity loss) at first. From the simulation, the resulted production rate and fill rate remains stable with zero financial loss, as shown in Appendix E2, which is reasonable.

Additionally, the sales quantity in reality varies from thousands of chips per week to millions of chips per week for different products. Nevertheless, their frontend production rate could be similar due to the similar WSPW. As demonstrated in Figure 45, one wafer lot could produce a different number of chips: the products with high production volume tend to have smaller die size whereas the low volume products often have larger die size. When the quantity was set to an extremely large value in simulation, the model ran out of computation capacity. After adjusting the scaling of a model entity (e.g. it used to represent 10 chips but now switched to 100 chips), the model shows resembling recovery speed as the low-quantity products, which is close to reality due to their similar WSPW.

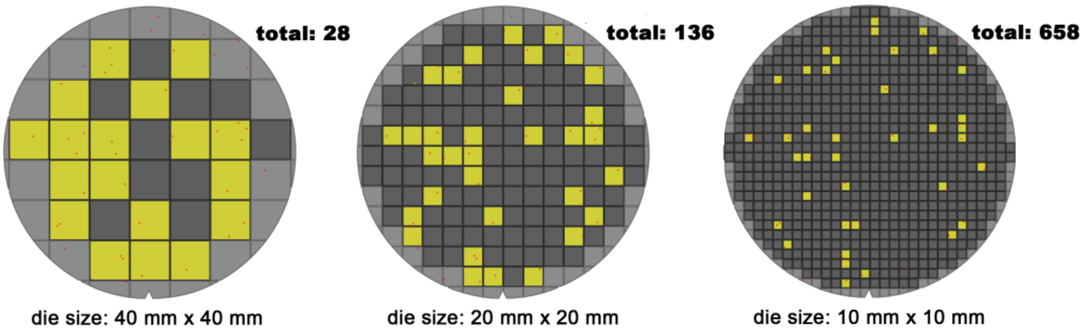


Figure 45. One Wafer Could Produce Different Number of Chips due to Different Die Sizes

Face Validity

The face validity often involves experts who have an in-depth knowledge of the system, criticizing the model's structure and its outputs (Sargent, 2013). The simulation model was built incrementally, meaning that testing is performed from a simple disruption scenario implemented on a single process group. The initial results were first face validated through the interviews with the business continuity experts. The preliminary model in the beginning phase was not realistic enough to capture the recovery time. After implementing a series of adjustments through iterations, the final model was presented to the division experts in order to ask whether the model behavior is reasonable.

In the discussion, three supply chain planners from ATV and PMM divisions were invited for the *face validity.* They have all been in the task force of former disruption management with extensive experience in planning production at FE. They would be the commanders once a disruptive incident happens.

Three interviews were conducted individually to avoid influences from each other. Firstly, the restoring curves of production rate at the disrupted site and the resulting fill rate are confirmed. For a short-term disruption, the production ramp-up can be considered almost linear for simplification. For long-term restoring, the experts agreed with the simulation-generated shape and gave further explanations (as shown in Figure 46). Usually, there will be some quick-wins first before encountering bottlenecks in production. Additionally, the extra capacity is assigned for recovering backorders. The fill rate curve showed a smooth drop near the end due to the buffering effects from stocks, whereas it had a slower recovery at the beginning because of the WIP building. Secondly, the production restoring ramp up time from simulation approximates to the expert estimation. It should address here that the characteristics of those curves may be amplified or reduced depending on the PG. Lastly, the assumptions about production ramp up at alternative sites are confirmed with the experts. For more information about validation interviews, please refer to Appendix E3 and E4.

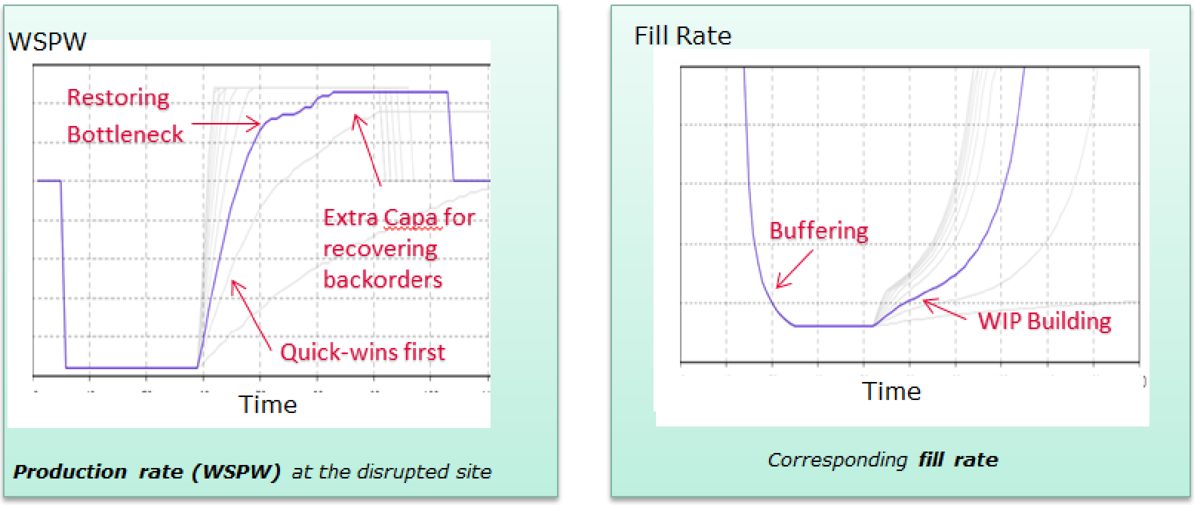


Figure 46. Expert Explanation from Face Validity

However, the production curve showed an immediate recovery at the disrupted site when there is a mirror or hot site for DS1 (Appendix F), which does not seem to occur in reality. This is because of the model boundary of time horizon, i.e. until the backorder for FE diminishes. The alternative site no longer produces once the FE backorder diminishes and the original site produces according to demand immediately.

7.6 Conclusions on Results Analysis

This chapter has presented the simulation results and analysis. Firstly, the disruption scenarios and specific PGs are identified to have different effects on recovery time and disruption costs, which will amplify or reduce the impacts of BCSAS. Then, the comparison between BCSAS and base scenario is carried out, followed by a cross-comparison between each strategy. In summary, the main findings are drawn as below:

- The mirror site clearly has the most benefit in all disruption scenarios, especially for long-term cyber-attack (DS1). But it is only for product level, difficult to apply and expensive to maintain.
- A hot site is a very good alternative for mirror site, showing robust and excellent performance at selected KPIs in all disruption scenarios. It demonstrates compelling advantages for disruption scenario with a medium capacity loss (DS1).
- The warm site has a good performance generally, excluding at strikes (DS3).
- The cold site shows the quickest recovery in long-term disruption scenario such as infrastructure destruction (DS2) while hot site still has better financial performance.
- For quick ramp-up disruption scenario (DS3), the hot site has the best performance whereas warm and cold sites do not show the desired cost-efficiency.
- For mid-term, severe capacity loss disruptions (DS4, industrial accident), the hot site and warm site have the similar achievement on fill rate recovery yet the hot site reduces cost more effectively.
- For P3 with short backorder rejection time and cycle time, the warm site has a similar effect as a hot site in DS2 and DS4.
- These benefits are amplified considering the total disruption costs in the supply chain (Customer loss and CoC loss).

Furthermore, the verification and a qualitative form of validation are conducted to ensure the framework is modeled correctly and represent reality. Internal validity, extreme conditions behavior tests and face validity demonstrate the consistency of results and the reasonable simulation behaviors.

However, the simulation results have certain limitations due to the model simplification and reduction. Therefore, issues that the simulation-based framework is not able to explicitly tackle should also be further discussed, as in the following chapter. This is important for determining the applicability of the framework and implementing the solutions in reality.

8. DISCUSSION AND REFLECTION

The previous chapters have focused on researching and analyzing in order to provide technical solutions to enhance supply chain resilience with good financial performance. The simulation has demonstrated its benefit at identifying the unexpected behaviors of fill rate, which was not foreseen from the qualitative analysis. Moreover, the backlogs tend to be overlooked by the experts when planning the business continuity strategies. The impacts of cold site or warm site are underestimated in this case. Hence, the simulation outcomes also help to improve the decision-making by detecting the blind spots.

But ultimately, the results should serve the purpose of supporting the implementation of actions. Advising strategically is the final output of this thesis work. This chapter will elaborate on the possible challenges to apply certain BCSAS from both the contextual and technical perspectives. Possible limitations resulting from the boundaries drawn in the project and model will be highlighted.

8.1 Segmentation of Business Impacts

Ensuring that the alternative site has sufficient capacity to produce the studied process groups is an important assumption in the simulation-based framework. This project explicitly put the PGs in priority for activating their BCSAS. When a catastrophe happens in reality, it is likely that many PGs are affected to a large extent and not all of them could have alternative capacity available to, which is not examined in this project yet. Therefore, the benefit evaluated above can only apply to the selected PGs, while the selection is most likely based on their business impacts.

This problem gets more complicated when segmenting the business impacts. Several PGs have high sales volume and price, which will cause massive economic losses for IFX directly once not being able to deliver. Some PGs may have larger profit margin than others, which could also be seen as an indication of high business impacts. Furthermore, certain PGs have a strategical position even with low sales quantity and price, because they are crucial to maintaining a trustworthy relationship with key customers. In terms of key corporate partners, various divisions (ATV, PMM, IPC and CCS) within IFX might have different identifications. The complexity of semiconductor industry in terms of product structure and multiple stakeholders made it difficult to do segmentation by determining an exact business impact for a specific PG.

Additionally, the customer loss and CoC loss calculated in this project serve as indicators for the total disruption cost in order to illustrate the cascading effect on the whole supply chain when semiconductor manufacturers experience catastrophes. In reality, the information about the influencing factors (e.g. X% and Y%) on customer and CoC is often difficult to gather. There will be a variation on the business impacts at the customer end depending on the product classification and customers, which will result in different values of total disruption cost. For certain customers, IFX is their single supplier for some products whereas other customers might have a secondary source. The uncertainty of business impacts at customer end contributes to bigger challenges for IFX. However, the accuracy of it is out of the research scope.

8.2 Change Management

From the simulation results, it seems upgrading a warm site to a hot site is the most cost-effective way in preparation for many sorts of possible disruption scenarios. However, it is not the norm in reality, which stimulates thinking: what are the reasons behind. First, there exist a vast number of products in the semiconductor world, leading to a tricky selection problem mentioned above. Besides, another matter of concern is about change management.

“One of the most baffling and recalcitrant of the problems which business executives face is employee resistance to change” (Lawrence, 1969). The inherent resistance to change in people’s mind shapes people’s attitudes as well. It requires the global operation division to first reckon the need proposed by BC department and then set up the change which finally takes place at the site. The engineers at the front end may tend to wonder that “if everything works fine now, why to bother to change?” Furthermore, running alternative production requires the consensus of customers to ensure they accept the quality of products manufactured at the alternative site. As it can be seen from above that many stakeholders are involved and the complexity of executing BCSAS may not be appealing to all of them, change management is therefore needed to reach a satisfying outcome for them.

Actor analysis, rooted in stakeholder analysis and described in the book “Policy Analysis of Multi Actor Systems” (Enserink, 2010), is a commonly-used method to support design activities and strategic advice in the corporate sector. It considers the *perceptions, values, and resources* of actors in order to understand the networks better. For example, having different missions, the involved parties at implementing BCSAS might have different perceptions towards the added value of enhancing the supply chain resilience via BCSAS, and they have their unique resources to utilize. The power-interest matrix in Figure 47 is drawn to visualize their interdependencies for change management. However, an extensive actor analysis is out of the research scope of this project.

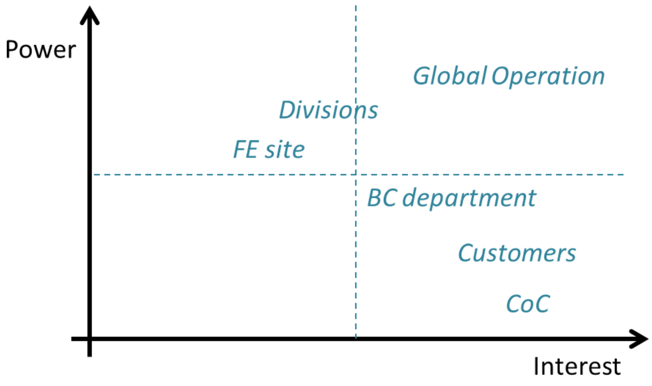


Figure 47. Power-Interest Matrix

8.3 The Limited Perspectives

8.3.1 Lack of an Explicit Multi-actor Focus

Given the lack of an explicit multi-actor focus in the simulation, the model has the limitation of strategically advising internal parties. The impacts were quantified through the lens of management, but not from the perspective of factory level. Hence, the complexity in operation is not reflected in the KPI calculation, which might change how the divisions and FE sites perceive the results. Additionally, the decision-making of multiple actors can have influences on each other. As an example, if the global operation and divisions are very supportive for the BCSAS, the FE sites may change their opposition, since there exists certain inexplicit hierarchy in the actors. The simulation does not take this into consideration, which in reality may result in different directions. However, the visual and tangible outcomes from the simulation are very effective at demonstrating the benefits and facilitating the communication with multiple stakeholders.

8.3.2 Interpretation of Expected Value in this Project

The average value of IFX cost calculated in this project is different than the commonly perceived 'expected value', which is often used to help the decision makers to maximize profits under risks. It is the weighted average of the possible outcomes. The IFX cost in the simulation is the estimated mean value of economic losses if a specifically-defined disruptive event happens. To compare the 'expected value' with the potential investment for analyzing the trade-off, it is often needed to multiply the resulting cost needs with probability. In this case, we lack the lens of the probability; hence the IFX cost is not technically an 'expected value'. However, when there exist large differences in magnitudes between the IFX cost and the investment, the financial performance could be evaluated and interpreted qualitatively based on the quantitative data.

However, the 'expected value' itself does not always present the truth. For instance, the likelihood of having a magnitude 7 earthquake is 1%, which will lead to a possible loss of 100 million, and the expected value would be 1 million. In reality, either an earthquake does not occur, or if it occurs, the company will lose 100 million. The 'expected value' has the flaw of averages, which often mislead the decision-making and underestimate the risks. This is also a reason why the 'expected value' is not used in the project.

8.3.3 Resilience Measurement and Deterministic Assumptions

The supply chain resilience examined in the project entails the concepts of the 'resilience triangle' and 'zone of resilience'. The resilience triangle can be easily observed from the fill rate curve while the zone of resilience is more difficult to evaluate. In this case, the author deems the investment to upgrade an alternative site to a higher level as the 'profitability erosion'. However, this may not be sufficient to assess profitability as there are other costs to be scrutinized (some are mentioned in 8.4). Furthermore, the change in fill rate is taken to measure the system response, but the lead time ratio, the revenue and the units lost can also be seen as good indicators.

Additionally, a deterministic value of cycle time and demand has been used in the project as the first step to study the dynamics of BCSAS towards building a resilient semiconductor network. However, readers should be aware that those two aspects often have fluctuations, which implies the outcomes from real practice will be more volatile and less robust.

8.4 Technical Barriers

Besides the untamed problems discussed in the sections above, technical barriers that are not incorporated in the simulation-based framework also exist. Firstly, the maintenance of warm, hot and mirror site is not modeled because this value is difficult to foresee. Secondly, it will also complicate the daily operation at the alternative site. The extra cost of those two parts is not recognized when evaluating the BCSAS in this project. In addition, it requires long operational time at a hot site or mirror site if the production ramp-up in the original site is slow (as in earthquake situation). Providing long-term service might be hard to achieve when the alternative site itself is operating almost at its maximum capacity.

There is also a shortcoming of the designed algorithm. The production at the disrupted and alternative site is not treated independently; instead, a number of products planned to process at those sites are based on a common *DemandFE*, influenced by both of them. This means the production at the alternative site will have a strong impact on the production restoring at the primary site. In reality, this happens as well since the backup provides comforting effects. However, the algorithm and modeling boundary exaggerate this issue, which can be demonstrated in Figure 48.

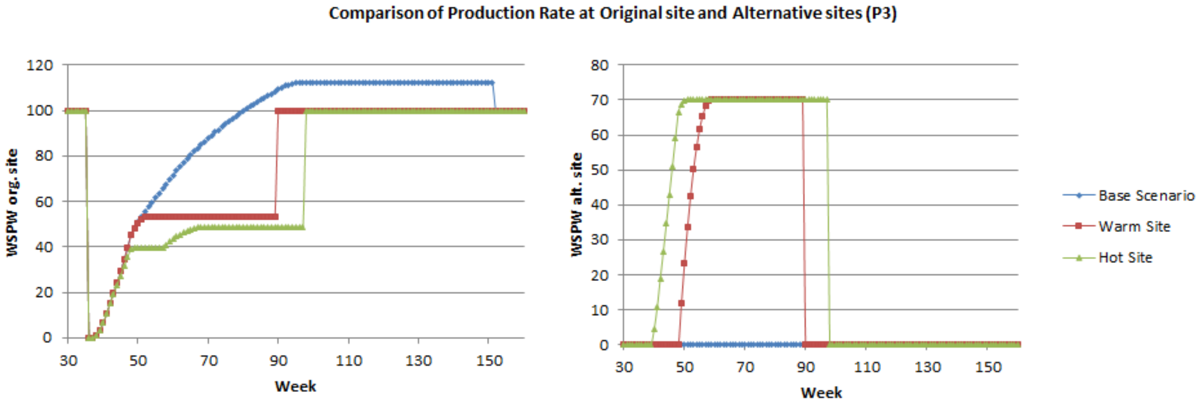


Figure 48. Production Rate Comparison Resulted From Different BCSAS (P3)

It is manifested in Figure 48 that WSPW at the original site has a smoother ramp-up curve in base scenario. When a warm site is activated supplying extra capacity, the production at the original site has experienced zero growth before shooting back to normal capacity. The zero growth stems from two reasons: 1) the algorithm calculates the WSPW based on a deterministic ramp-up slope multiplied by *DemandFE*, which is reducing when the alternative site is ramping up, and 2) the protection algorithm ensures the WSPW would not drop before recovering. Once all the backorders at FE have been compensated, the simulation automatically switches the alternative production off and enables the original site to produce in line with demand immediately, leading to a sharp increase. At that time, the capacity would be sufficient and what happens afterward is out of the research scope. This phenomenon is more obvious with the hot site, which explains why the hot site and warm site has similar performance for P3 in disruptions with long-term restoring. However, this is not the exact picture of the reality, therefore, it could be a future direction to polish the algorithm and extend the boundary.

8.5 Usage of the Model in Infineon and the Connection with Grand societal Challenges

The main purpose of the model was to identify the impacts of BCSAS. From this simulation, the benefits of BCSAS on some sample PGs under certain disruption scenarios are identified. This project demonstrates the unexpected benefits as a good starting point. Furthermore, the simulation model is able to provide tangible information for illustration purpose. Therefore, the model was simplified to be more user-friendly and interactive (users can modify the data) after this project. The updated model has been transferred to the BC department so that the BC experts could use it to visually demonstrate the KPIs changes with different BCSAS. It could help convince other internal stakeholders and ease the conversation with customers.

Beyond Infineon, the philosophy of alternative sites and the simulation approach to enhance SC resilience could be 'transplanted' for other grand societal challenges, e.g. socioeconomic resilience. The socioeconomic environment encompasses the local, national or even international setting that affects countries, communities, economies, and natural resource policies in the study area (Charnley, Jakes, & Schelhas, 2011). Disasters in such a large-scale environment have more critical consequences than the disasters at a company level, damaging economies and well-being of millions of people. The socioeconomic resilience is defined as the 'capacity to mitigate the impact of disaster-related asset losses on welfare' (Hallegatte, Bangalore, & Vogt-Schilb, 2016). Rapid recovery, as one of the vital elements in establishing socioeconomic resilience, relies on strength of the political system, financial availability, and technical resources.

The alternative sites studied in this project can be stretched to the general capability of using alternative resources, when the principal ones could not function sufficiently in the socio-economic environment (Cimellaro, 2016). For example, when the Emergency Operations Centre was destroyed in the World Trade Centre terrorist attack, there was no other facility that could replace it immediately or instantaneously, which made the recovery more challenging (Cimellaro, 2016). Hence, the development of an alternative path for critical facilities and infrastructures in society is of crucial importance. Based on the necessity and environment, the level of preparedness can be various, such as whether equipped with backup water and electricity sources, alternative transportation tools, information system servers, operationalists, etc. This could be a variant of the cold site, warm site, hot site, etc.

The simulation is further proved to be valuable at testing different plans for responding to disasters from this project. This can be extended to contingency plans in the urban resilience systems, e.g. hospitals, which are regarded as critical networks as part of the governmental services. Cimellaro (2016) illustrated a DES model that investigates the impact of emergency plan of a hospital, taking into account the hospital resources, the emergency rooms, the circulation patterns, etc. in his book *Urban Resilience for Emergency Response and Recovery*. The simulation results show the waiting time of patients is significantly shorter with an emergency plan. There are several other simulation models applied and mentioned in his book. Therefore, the potential of simulation in the field of socio economic recovery can be seen as promising.

8.6 Conclusions for Discussion

This chapter mainly discusses and reflects upon the elements of the simulation framework from four aspects: segmentation of business impacts, change management, limited perspectives and technical barriers. Due to the capacity limit at FE, a selection of process groups or products seems inevitable in order to implement BCSAS, which is often based on business impacts. However, its segmentation is not easy because there are different criteria to determine the business impacts. The priorities from different divisions may also be different. Furthermore, the estimated influences at customer and CoC vary based on the customer profile.

Even though the technical solution could be obtained using the simulation, the change management is needed to cope with the resistance to change existing universally. Actor analysis is briefly introduced to gain a better understanding of the actors involved and their perceptions as well as resources. The simulation lacks an explicit multi-actor focus. However, the tangible benefits could facilitate communication. The model was simplified and transferred to BC department for demonstration purpose. Additionally, the philosophy of alternative sites and the simulation approach could be ‘transplanted’ to enhance socioeconomic resilience. The other limited perspective and technical barriers mainly reflect upon the limitations in the modeling scope and algorithm: 1) single measurement of the system response 2) deterministic cycle time and demand 3) maintenance and operational cost not considered 4) shortcoming of the designed algorithm for calculating the production rate.

9. CONCLUSION, RECOMMENDATION AND FUTURE DIRECTIONS

This thesis presented a simulation-based framework that models diverse business continuity strategies for alternative sites (BCSAS) and disruption scenarios, in order to evaluate their impacts on supply chain resilience and financial benefits for the semiconductor industry in case of disruptions. The decision making of BCSAS must gain the support by different parties involved, as the implementation is of interests to multiple stakeholders and comprises multiple organizational processes. Therefore, it is of crucial importance to demonstrate the benefits for ease of discussion with stakeholders. The simulation results convey the messages in a tangible way.

This chapter will draw the conclusions of this project. Section 9.1 presents the answers to the formulated sub-research questions proposed in Chapter 1, which leads to answering the main research question. Based on the findings, the recommendations for Infineon are given in section 9.2. Followed by that, the scientific and social contribution of this project is highlighted in section 9.3. This chapter ends with suggestions for future research.

9.1 Conclusions – Answering the Research Questions

Sub Question 1:

How is supply chain resilience apprehended and assessed in the context of semiconductor industry? (Contextual question)

Supply chain resilience is at the heart of current SCM thinking (Melnyk et al., 2014), especially for the semiconductor industry. It faces rapid changes in technologies and demands, combined with long lead time and high investment costs, whereas the sales price of the final product decreases (Macher et al., 2010). Due to those huge industrial challenges, an expected or unexpected major disruption will have catastrophic consequences on the business in this industry. Supply chain resilience gives the adaptive capability to respond to disruptions, and recover from them; hence it plays a crucial role for semiconductor manufacturers. The frontend production is the most expensive and vital part of the supply chain, which can be seen as a critical node exposed to vulnerability. The BCSAS provides extra capacity within the disruption duration, which demonstrates the 'redundancy' concept. However, different types of BCSAS indicate a certain degree of 'flexibility' in the preparation phase. A 'resilience triangle' (see Figure 6), which illustrates the system response (i.e. fill rate) from disruption and the pattern of restoration and recovery over time, is mainly used in this project to assess the resilience. The smaller the triangle is, the more resilient the supply chain is (Barroso et al., 2011). Additionally, the financial performance about the disruption cost and investment is examined in order to take the 'zone of resilience' into consideration.

Sub Question 2:

What are the main components that the simulation-based evaluation framework of BCSAS should constitute for enhancing supply chain resilience in semiconductor manufacturers?

The main components this simulation-based framework should constitute can be divided into two parts: entities for the supply chain setup (see Figure 15 and Figure 16) and key processes to depict the normal and disrupted systems (see section 5.4). The details can be found in chapter 5. In summary, the model needs two types of flows:

1) Product flow, which starts from FE production and goes to DB, BE, DC until the final delivery to customers. As the research is at aggregation level, the detailed operational process at each site can be simplified with a cycle time. The product has a set of attributes such as the process group (PG), sales price, cycle time, scrapping status and various influencing factors for the calculation of disruption cost.
2) Order/Demand flow, which generates the customer demand weekly and calculates the accumulated backorders. An order has information of PG, quantity, the confirming date, delivery date, etc.

The process of demand and supply management is needed to ensure the FE production is planned in line with demand, which is updated based on the DC supply and customer demand. A disruption is simulated to cut the FE production rate down by a defined percentage (severity) for a certain period (disruption length). The disrupted site should have the capability to ramp up and restore afterward. Business continuity strategies are activated by enabling the alternative site to provide extra capacity after their responding time, which is the distinction between different types of BCSAS. By implementing the entities and processes described above, the simulation framework could provide a rough picture for evaluation of BCSAS.

Sub Question 3:

What are the impacts of different BCSAS regarding supply chain resilience under specific disruption scenario?

The BCSAS have diverse impacts regarding supply chain resilience shown from the fill rate recovery, and even the same strategy has distinct performance under different disruption scenarios for different PGs. Due to this diversity, a qualitative manner based on quantitative data is used to evaluate the impacts.

A cold site facilitates the restoration of fill rate *significantly* in DS1 (long-term cyber-attack) and DS4 (industrial accident). Moreover, it demonstrates exceptional achievement in DS2 (infrastructure destruction), better than other mitigation options. However, it does not shorten the recovery time of fill rate in DS3 (strikes). Therefore, it can be said to increase the overall SC resilience to a certain degree. Compared with the base scenario (no alternative site), the warm site and hot site reduce the fill rate recovery time *to a massive extent* for all studied PGs under every disruption scenarios investigated, illustrating high resilience. Nevertheless, the hot site often shows faster fill rate restoration than the warm site, demonstrating its excellent performance at enhancing the SC resilience. The 'resilience triangle' of fill rate resulted from mirror site is *remarkably* smaller than the base scenario with *compellingly* shorter recovery time. The triangle is downsized both in terms of the depth and width. Those indicate an extremely high level of resilience.

Sub Question 4:

What are the impacts of different BCSAS regarding financial performance under specific disruption scenario?

The financial performance constitutes the investment cost and disruption cost. The investment is made up front, which aims to equip an alternative site better for a faster response after disruptions so as to reduce the resulted costs. However, if the investment is too large compared with the potential saving, the business continuity strategy may not be a cost-effective option. Since the mirror site is at product level whereas the others are process groups (consisting many products), the financial performance is not comparable. Additionally, the nature of disruption scenario affects the absolute value of disruption cost.

Based on the simulation results, all BCSAS seems to have *satisfyingly positive* financial performance with some *exceptions*. It is difficult to use the five categories indicated in Table 11 to conclude the financial impacts here, as it depends on the PG and the disruption scenario. Generally speaking, the hot site shows the best financial performance in terms the cost-efficiency and robustness. The financial saving is critical. Following this, a warm site is shown to be economical as well. However, their financial performance for P3 seems to be similarly good as an exception due to the characteristics of products. Furthermore, the warm site does not show the desired cost-efficiency under DS3 (strikes). The financial performance of the cold site is worsened under DS3, leading to unprofitability. However, a cold site still demonstrates significantly lower disruption cost compared with the base, especially under DS2 (infrastructure destruction). For P2, with a high sales quantity and price, the financial benefit is amplified from having any type of alternative sites. This amplification extends considering the total disruption cost in the supply chain, i.e. Customer loss and CoC loss.

Sub Question 5:

Which BCSAS show the best overall performance under which disruption scenarios and how does it imply the relation between flexibility and redundancy for enhancing SC resilience?

This sub-question is answered based on the simulation outcomes from the context of this project with the selected process groups/products. Mirror site seems to be the best option for a single product, yet the aggregative effects as a process group in terms of the operational difficulty are not investigated in this project. From the analysis, a hot site shows the best overall performance at enhancing resilience with an excellent financial performance under almost every disruption scenario, only with a slightly slower fill rate recovery than a cold site for DS2 (infrastructure destruction). However, for P3, a warm site seems to have the best overall performance under DS1 (long-term cyber-attack) and DS4 (industrial accident) considering the cost-efficiency.

Therefore, it is manifested that flexibility enhances SC resilience, but it does not indicate a proportional increase. In certain situations, when flexibility continues to increase, a limited improvement on resilience is accomplished with soaring cost, this could be perceived redundant. For instance, in this case of study, having a warm site is not redundant for P3 to prepare for DS1 and DS4, since it has a satisfying level of flexibility to achieve desired overall performance. But a hot site in this situation could be seen as redundancy due to the overrated flexibility. Essentially, the flexibility contributes to building SC resilience to a large degree, nevertheless, it is perceived to transit to redundancy in situations when the increase is not cost-efficient anymore.

Sub Question 6:

How can the final outcome be applied in semiconductor manufacturers in order to support the policy preparation to achieve a resilient supply network?

The final outcomes described above can be seen as technical support to assist the policy preparation or strategic decision-making about upgrading certain alternatives. Based on different products' attributes and disruption scenarios, the suitable strategy evaluated from simulation may be different. The business continuity department can demonstrate those results to persuade high-level management and customers that various types of alternative sites could have satisfying accomplishments. Additionally, the simulation-based framework can be extended to study a wide range of process groups/products in semiconductor manufacturers, which could provide customized solutions for specifically requested products or even a more overall picture to determine the types of alternative sites. However, the strategic decisions can be supported and improved only through a robust framework and involvement of stakeholders, which needs further enhancement beyond the project. The next section elaborates on the answers to this question.

9.2 Comparing the Results with Literature

The simulation results confirmed many findings in the literature review conducted in Chapter 2 about the relevant elements and their effects in SC resilience. The unforeseen aspect is that the SC resilience increases in a non-linear manner with flexibility, which turns to redundancy at a certain environment/level. This is further explained in Section 9.4. The confirmed findings are summarized as three main parts discussed in detail in this section.

Firstly, flexible production is expected to build resilience, as it enables contingent rerouting and contributes to agile responses after disruptions (Carvalho et al., 2012b; Datta et al., 2007; Manuj & Mentzer, 2008; Sheffi, 2005; Sheffi & Rice Jr, 2005; Tomlin, 2006). This can also be seen from the outcomes of different types of alternative sites. A mirror or hot site has high flexibility in their production and could often respond much faster than the warm and cold site after a disaster, which may save vast amount economic losses from the rapid recovery.

Secondly, the simulation also proves that buffers (e.g. inventory) have nonlinear benefits on the resilience of the system, but they are not an attractive strategy to cope with long-term disruptions (Blackhurst et al., 2011; Schmitt & Singh, 2012; Tomlin, 2006; Zsidisin & Ritchie, 2009). The buffering effects have been demonstrated from the delay of fill rate drop after the incident. The declining pattern of fill rate in each scenario depicts the nonlinear benefit, especially in strikes. However, the stocks may help ease the short-term recovery pressure but they are not effective for long-term disruptions e.g. infrastructure destruction.

Thirdly, the cost of loyalty and backordering play a critical role in risk discussion (Schmitt & Singh, 2012). This is shown from the distinct results of P3 compared with other PGs. On the one hand, backordering helps a company to secure its market when there is insufficient supply. On the other hand, it adds the complexity when recovering from a major disruption. Due to less quantity of backorders, the system takes a shorter time to catch up with the current demand as illustrated by the outcomes of P3. This is in line with the simulation study of Schmitt and Singh (2012).

9.3 Recommendation for Infineon

From the analysis above, the advantages and disadvantages evaluated from the simulation-based framework are clearer. Since the mirror site demonstrates such a high performance, it is recommended for IFX when the products have very high business impacts. However, the operational difficulty in the application should be further considered. The other BCSAS could also help to enhance the supply chain resilience to different degrees. The final performance of them is closely related to the specific disruption scenario and process group. Hence, the recommendation for implementing them should also take into consideration those two aspects. Every selected disruption scenario incorporates many possible triggering events with similar characteristics. For example, the impact of an earthquake may be similar to a terrorist bomb in terms of the severity resulted from infrastructure destruction. Therefore, the BCSAS can be applied to prepare for a wide range of major disruptions.

9.3.1 Rankings of BCSAS for Implementation

For Designed_In PGs (P2 and P4) with long backorder rejection time, the recommendation level for BCSAS under specific disruption is ranked in Table 12 according to the simulation results. The scores are from 1 (least favorable) to 5 (most favorable), with ‘X’ meaning ‘not recommended’. The interpretation of the numbers is qualitative rather than quantitative, e.g. a ‘3’ is significantly more recommended than a ‘1’ but not exactly three times. The hot site gets a ‘3’ under DS3 but a ‘5’ under DS2, because of the severer impacts under DS2.

Table 12. Recommendation Ranking of BCSAS for IFX

Disruption Scenario	Characteristics of Disruption Scenario	Hot Site	Warm Site	Cold Site
DS1. Long-term cyber-attack	Medium capacity loss, mid-term restoration	4.5	3	1
DS2. Infrastructure destruction	Severe capacity loss, long-term restoration	5	4.5	4
DS3. Strikes	Severe capacity loss, short-term restoration	3	X	X
DS4. Industrial accident	Severe-capacity loss, medium-term restoration	5	4	3

It can be seen from the table above that the warm site and cold site are not recommended for IFX to prepare for disruptions with short-term restoration. A hot site is often more recommended than others, especially when IFX needs to take care of a considerable amount of economic loss at the customer end (e.g. P2). However, IFX should be aware that the extra benefit for a specific PG from hot site compared with other alternates is the *most* in disruptions with medium capacity loss and medium-term restoration, whereas the *least* in severe disruptions with long-term restoration. A cold site is highly recommended to prepare for the latter disruption scenario for PGs with the strategic position but not large sales price or quantity. Similarly, IFX may not need to upgrade a warm site to a hot site for those PGs or for 'Multisource' PGs with short backorder rejection time (e.g. P3) when preparing for severe capacity loss disruptions with medium/long-term restoration, according to the simulation results on the selected PGs.

9.3.2 Tool for More Rational Decision-making and Better Communication

In reality, the determination of BCSAS is based on qualitative analysis and is influenced by the customers many times. The customer would always prefer to have a mirror site, not only because it seems to be the best but also the customers fail to see the large positive impacts from other types of alternatives. The most-pushing customers may end up having a mirror site for their products, leading to unbalanced resource allocation or non-rational decision making. It is difficult to apply mirror site for thousands of products to satisfy diverse customers, but it is feasible to implement hot site or warm site for a series of process groups which contains many products. Once the positive impacts can be identified, IFX has the opportunity to better design BCSAS based on different PGs and risk profiles so that an overall blueprint of the business continuity could be drawn. The simulation-based framework is the first step to unfold this process.

Furthermore, this project is also the first try within IFX to provide tangible information on this issue. The simulation offers quantitative analysis in a more recognized way with clear graphs and detailed figures. This visual presentation serves as a powerful communication tool for IFX to increase the awareness of the decision-makers and customers about the possible influences from diverse BCSAS. This generic model can also be used by the internal customers, allowing them to enter different inputs and compare the outcomes. This facilitates the understanding of the behavior and results of the model.

9.3.3 Before Implementation

However, the technical solutions from this project do not automatically guarantee a successful transit. Firstly, the simulation-based framework is not very dynamic yet considering the cycle time, demand, extra operational cost etc., hence IFX should pay attention to that limitation before implementing. Secondly, the influences between the primary site and alternative site are amplified in this project and it should be further examined. Once the framework is more robust, the actions to involve different stakeholders in an early manner need to be taken so that the priorities can be agreed upon and resistance to changes are mitigated.

9.4 Scientific and Societal Contribution

First of all, this project re-examines the principle of 'redundancy vs. flexibility' to enhance SC resilience through the perspective of interrelation. The benefit and trade-off of those two strategies are often discussed in the literature. Their positive mitigation effects have been discovered (Carvalho et al., 2012b; Zsidisin & Wagner, 2010). Some scholars tend to believe flexibility is a better option due to the lower cost, operational benefit and resource saving (Crum et al., 2011; Sheffi, 2005; Sheffi & Rice Jr, 2005). However, some others argue that redundancy is necessary along the critical path and it increases flexibility from the adaptable placement of resources (Johnson et al., 2013; Ratick et al., 2008). This research has illustrated the connection between those two strategies to SC resilience. Flexibility improves SC resilience yet not proportionally and when the increase of flexibility is not cost-efficient, redundancy is perceived. That is to say the suitable level of flexibility influences the perception of redundancy. When the flexibility is overrated, redundancy is recognized. Nevertheless, when satisfying cost-efficiency is reached, the flexibility can be perceived necessary rather than redundant.

Furthermore, present literature mostly emphasizes the disruptions and strategies at the supplier side, but this project has shed more light on the impacts of catastrophes directly at production (non-supplier issues). This simulation-based framework explicitly looked into the production restoration and provides more insights into such a less-examined aspect, which can be a start for other scholars to perform more detailed and systematical research.

Additionally, this project utilized the DES to provide quantitative assessment and rational perspectives for a decision-making problem often based on qualitative analysis. It demonstrates the value of DES in the field of SC disruption and resilience by evaluating different design alternatives via a case study.

Lastly, the simulation-based evaluation framework is a generic model setup, incorporating specific traits of the semiconductor industry, and it can be extended to other companies within this industry by changing certain input parameters. A suitable match offers cost-efficiency, which could indirectly help reduce the waste in a variety of forms such as excessive inventory and unnecessary production environment configuration.

9.5 Suggestions for Future Research

As described in section 3.5 and chapter 8, there are certain limitations and boundaries of this project, which can be extended from future research.

Systematical Analysis

A risk profile can be built to incorporate the likelihood or frequency of occurrence of those defined disruption scenarios. By doing so, the time horizon of investigation could be extended e.g. 50 years and a more broad picture of the disruption impacts can be estimated. This will help to reach comprehensive evaluation and comparison of the BCSAS in terms of the supply chain resilience and financial performance.

A variety of product or process groups can be studied to test the robustness and the cost-efficiency of the BCSAS based on different product characterization. This simulation-based framework examines four PGs, which can be representative for certain cases but still needs more evidence. Therefore, we can categorize various products by having similar main influencing factors such as backorder rejection time, cycle time, price and quantity. The impacts and benefits from business continuity strategies for alternative sites can be better understood from conducting a more systematical analysis.

Dynamics and Complexity

As mentioned in chapter 7, the algorithm to model the production ramp-up is still rather rough. It is needed to further study the dynamics of production ramp-up at a site after a major disruption and the influences from having extra capacity from alternative sites. Will this drag the recovery at the primary site? How big is the impact?

Furthermore, the dynamics of the real-world system originating from the demand volatility, cycle time fluctuations, as well as the customers' behaviors, could also be further investigated. How would those impact the simulation results and reality implementations?

Since this project only considers the disruption at frontend, it would be interesting to explore the impacts of disruptions that could occur at any node across the supply chain from suppliers to customers and the impacts of having the alternative back ends. This would help illustrate the complexity in practice.

Proactive Design

This simulation framework is to provide a preparation tool for analyzing and selecting business continuity strategy to enhance the resilience from recovery capability. It does not aim to reduce the likelihood of a disruptive incident (i.e. resistance capability). A possible question largely extending this research scope would be: how can we proactively design the supply chain in order to make it more resilient?

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APPENDICES

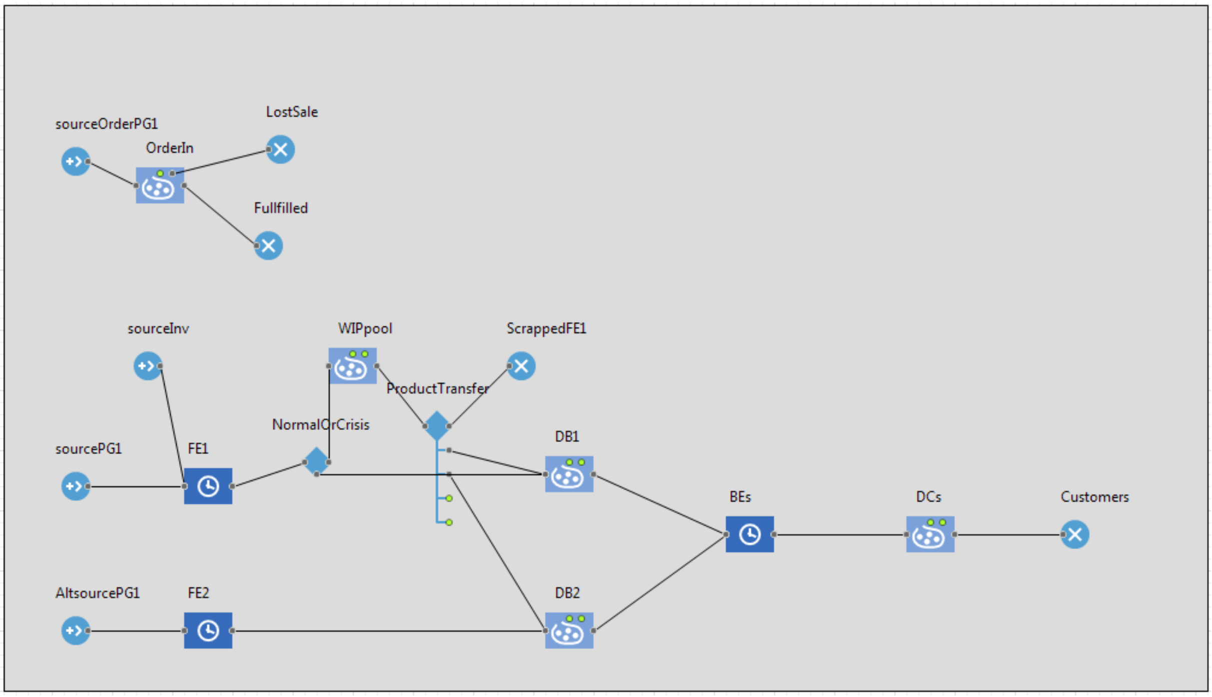
A. Input Data Preparation (Confidential)

Due to the confidentiality, the contents cannot be published.

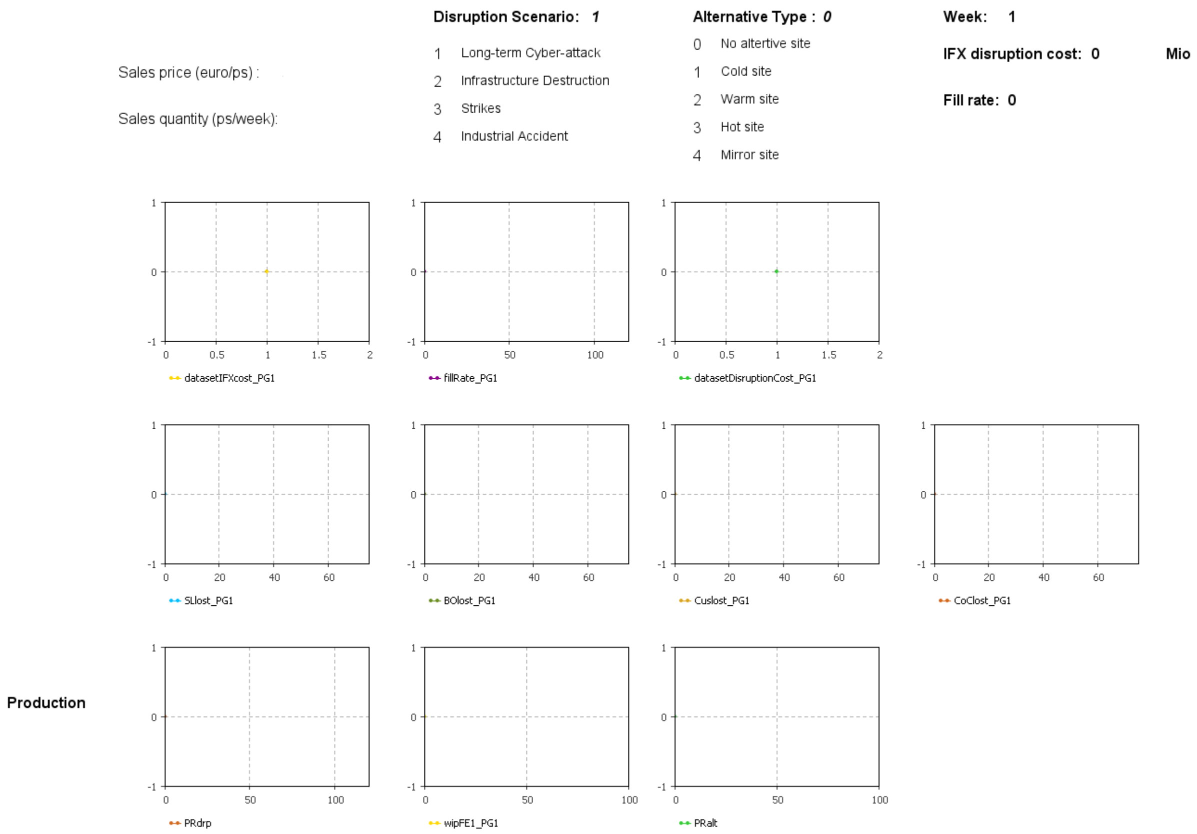
B. Model Implementation Details

This appendix illustrates different modules of the model and they are shown in different windows when the simulation is running. In total, there are six parts: logic, graphic KPIs, numerical input and output parameters and events. The events are defined using Java.

B1. Logic Window



B2. Window of Graphical KPIs:


Disruption Scenario: *1*

1 Long-term Cyber-attack
2 Infrastructure Destruction
3 Strikes
4 Industrial Accident

Alternative Type : *0*

0 No altertive site
1 Cold site
2 Warm site
3 Hot site
4 Mirror site

Week: **1**

IFX disruption cost: **0** **Mio**

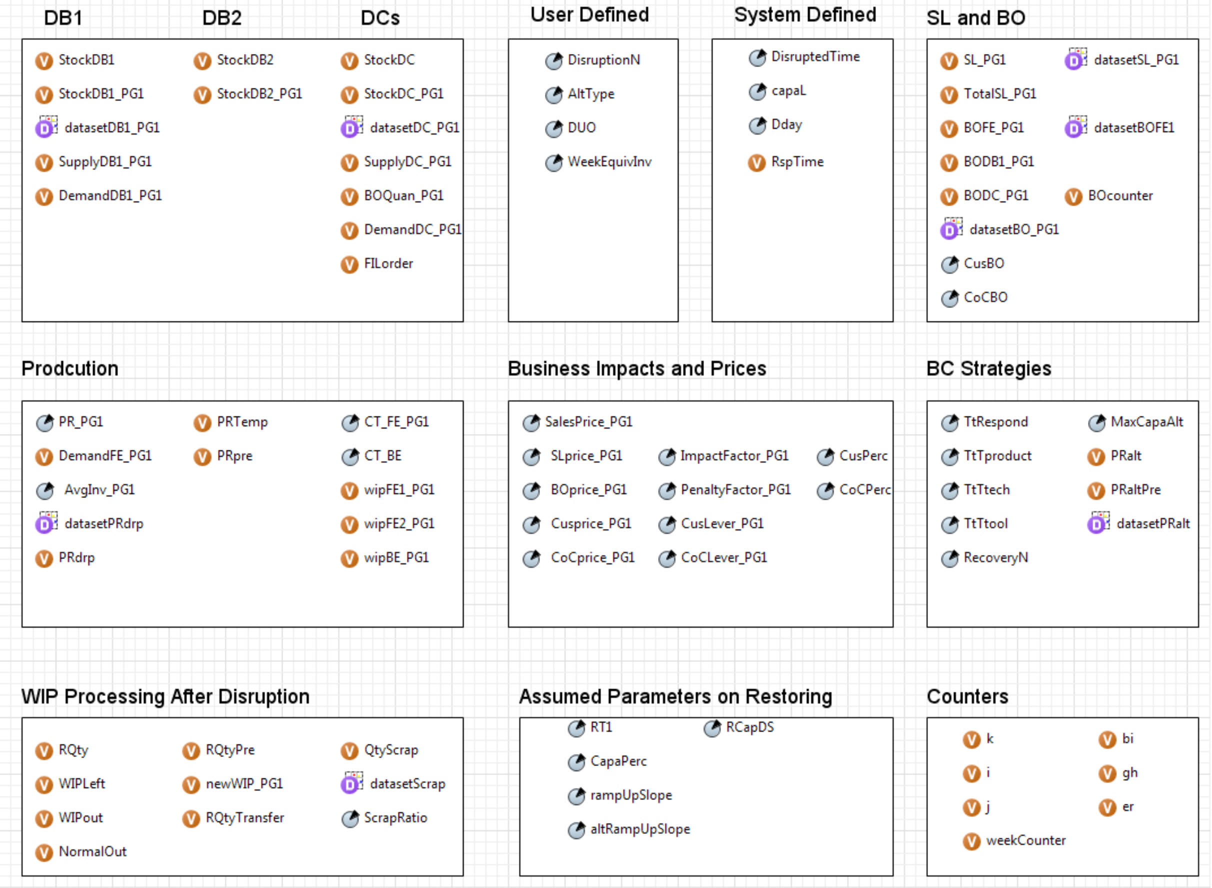
Fill rate: **0**

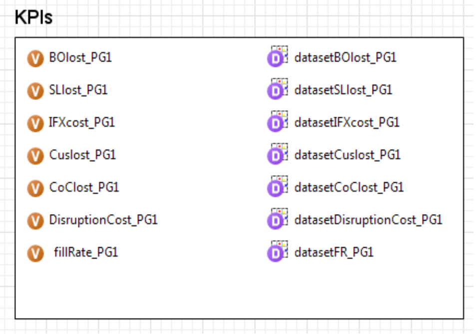
Sales price (euro/ps) :

Sales quantity (ps/week):

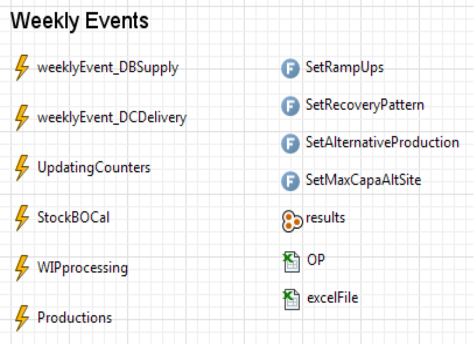
Production

B3. Window of Input and Output Parameters





B4. Events Window



B5. An Example for Defining Events using Java (Productions Event)

```
if (weekCounter<= WeekEquivInv*2) //by default, 2 weeks demand equiv. stock at DB
and DC, respectively
{
sourceInv.inject(AvgInv_PG1);
};

if (weekCounter <= Dday)
{
PRdrp = PR_PG1[weekCounter];
sourcePG1.inject(PRdrp);
}

else if (weekCounter > Dday && weekCounter <= (Dday + DisruptedTime))
{
PRdrp = (int) Math.round(PR_PG1[weekCounter]*capaL);
PRTemp = PRdrp;
sourcePG1.inject(PRdrp);
}


datasetScrap.add(weekCounter, QtyScrap);

DemandFE_PG1 = PR_PG1[weekCounter] + BOFE_PG1 + QtyScrap - SL_PG1;
//traceln(weekCounter+"DemandFE" + DemandFE_PG1);

if (weekCounter > Dday + DisruptedTime)
{
SetRecoveryPattern(RecoveryN);
}

datasetPRdrp.add(weekCounter, PRdrp);

RspTime = Math.round(TtRespond);

if (weekCounter > Dday+RspTime)
{
SetAlternativeProduction(AltType);
}

datasetPRalt.add(weekCounter, PRalt);

BOFE_PG1= DemandFE_PG1 - PRdrp - PRalt;

if (BOFE_PG1<0)
{
BOFE_PG1=0;
}

datasetBOFE1.add(weekCounter,BOFE_PG1);
QtyScrap = 0;
```

C. Simulation Output (Confidential)

Due to the confidentiality, the contents cannot be published.

D. Results Variability (Confidential)

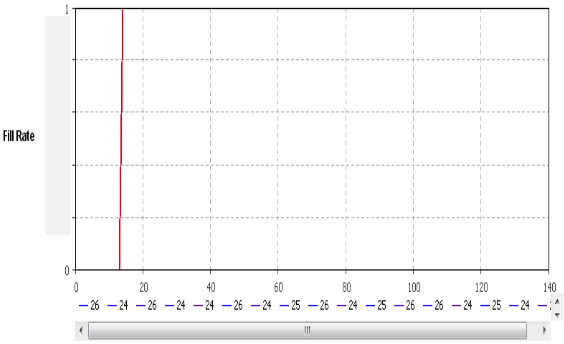
Due to the confidentiality, the contents cannot be published.

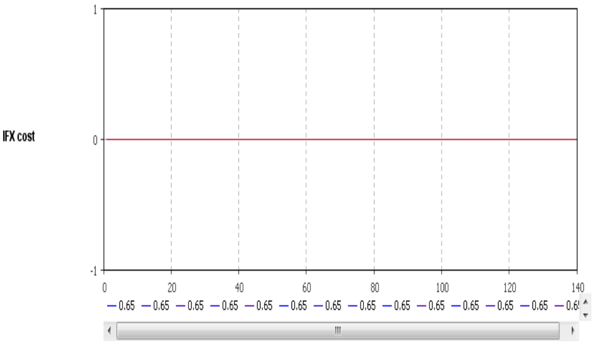
E. Validation Details (Confidential)

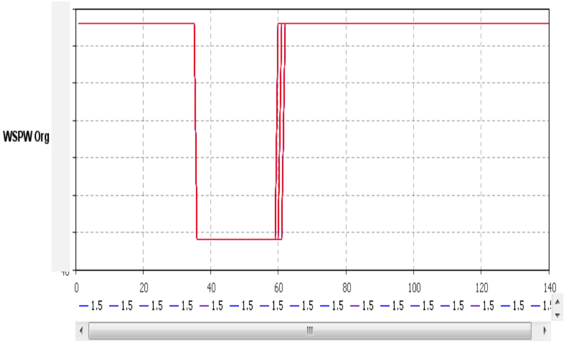
Due to the confidentiality, the contents cannot be published.

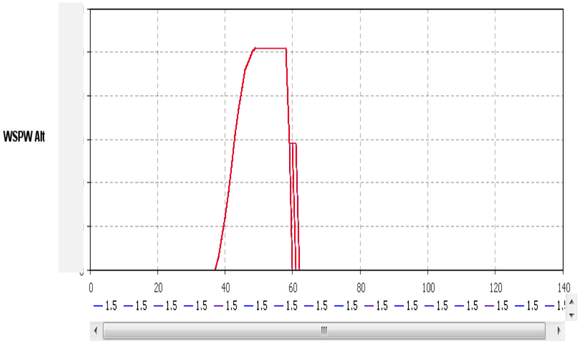
F. Instant Recovery of Production Rate at Disrupted Site

F1. Production and KPIs from mirror site under DS1 (Long-term Cyber-Attack), P1









F2. Production and KPIs from hot site under DS1 (Long-term Cyber-Attack), P2