University of Strathclyde

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Probabilistic Analysis of Supply Chains Resilience based on their Characteristics Using Dynamic Bayesian Networks

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2016

A thesis presented in fulfilment of the requirements for the degree of Doctor of Philosophy

Declaration of Author's Rights

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed:
Date:

Acknowledgement

I would like to express my great thanks to my supervisors Dr Robert van der Meer and Professor Lesley Walls, whose selfless time and care kept me going all the time. This is for their tremendous academic support. Dr Robert van der Meer parenting supervision style is something I will not forget. I would like to express my great thank to Dr Farhad Shafti for his amazing support after my viva to let the corrections done. I would like also to extend thanks to Professor John Quigley and Dr Kevin Quigley for giving me the access to my first case study and funding my journey to Canada.

My sincere thanks also have to go to all staff in the department of management science for their endless support. I am also so grateful to all the supply chain managers and practitioners that gave me access to their companies’ confidential data. I am not able to mention their names individually due to confidentially issues.

A special mention goes to my beloved dad, brothers and sisters for almost unbelievable support. I could not forget that to mention also my biggest lost, my mum (1959-2011). Her support and caring about me is not something can be expressed by few words.

Last but not the least, I would like to express my great thank to my wife, son (Omar), and newcomer Mona (01/03/2016) for bearing with me during my PhD journey as well as for the joy they give me. I am not sure how I would have survived without them being in my life. They are the most important people in my world.

Abstract

There is an increasing interest in the resilience of supply chains given the growing awareness of their vulnerabilities to natural and man-made hazards. Contemporary academic literature considers, for example, so-called resilience enablers and strategies, such as improving the nature of collaboration and flexibility within the supply chain. Efforts to analyse resilience tend to view the supply chain as a complex system. The present research adopts a distinctive approach to the analysis of supply resilience by building formal models from the perspective of the responsible manager. Dynamic Bayesian Networks (DBNs) are selected as the modelling method since they are capable of representing the temporal evolution of uncertainties affecting supply. They also support probabilistic analysis to estimate the impact of potentially hazardous events through time. In this way, the recovery rate of the supply chain under mitigation action scenarios and an understanding of resilience can be obtained.

The research is grounded in multiple case studies of manufacturing and retail supply chains, involving focal companies in the UK, Canada and Malaysia, respectively. Each case involves building models to estimate the resilience of the supply chain given uncertainties about, for example, business continuity, lumpy spare parts demand and operations of critical infrastructure. DBNs have been developed by using relevant data from historical empirical records and subjective judgement. Through the modelling practice, It has been found that some SC characteristics (i.e. level of integration, structure, SC operating system) play a vital role in shaping and quantifying DBNs and reduce their elicitation burden. Similarly, It has been found that the static and dynamic discretization methods of continuous variables affect the DBNs building process.

I also studied the effect of level of integration, visibility, structure and SC operating system on the resilience level of SCs through the analysis of DBNs outputs. I found that the influence of the integration intensity on supply chain resilience can be revealed through understanding the dependency level of the focal firm on SC members resources. I have also noticed the relationship between the span of integration and the level of visibility to SC members. This visibility affects the capability of SC managers in the focal firm to identify the SC hazards and their consequences and, therefore, improve the

planning for adverse events. I also explained how some decision rules related to SC operating system such as the inventory strategy could influence the intermediate ability of SC to react to adverse events. By interpreting my case data in the light of the existing academic literature, I can formulate some specific propositions.

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Glossary of Key Terms

SC:

SC is used to highlight interactions between organisations and processes that lead to produce and deliver the customer requirements at the right time and acceptable cost. SC includes the supply zone, focal firms assets zone (production facilities, warehouses), transportation zone and demand zone.

SC member:

It refers to the part of SC that can contribute to the SC ability to fulfil its requirements.

SC structure:

It describes the topological structure of SC that show the material flow between SC tiers.

Complementary SC members:

They are SC members that all of them are essential to fulfilling the need of focal firm. They can be complementary in terms of the material or in terms of the capacity.

SC operating system:

It outlines the triggers of processes in the SC (information role) and the decision rules (e.g. the inventory rules, the reordering rules) to fulfil the customers’ demand.

SC integration:

It describes the intensity of relationships between the SC members and the span of these relationships across the supply chain.

The intensity of integration (integration level):

It defines the formalisation rules that control the relationship between the SC members (Market relationship, collaboration, joint venture, full integration).

The span of integration:

It describes the extent of the integration across the SC from the focal firm perspective. It can be basic (two members), extended (set of SC members) or ultimate (full) SC structure.

Resilience enablers:

They refer to the set of strategies that SC employs to improve the reaction and recovery of SC to adverse consequences of events.

Mitigation actions:

They denote the actions that SC management employs to reduce the vulnerabilities of SC.

Robust SC:

It refers to the ability of SC to maintain the same state as the base state once the adverse event has occurred.

Visibility:

It describes the ability to gain information about the SC structure, SC members' processes and hazards that might impact them.

Flexibility:

The ability to a quick reaction to 'consequences of adverse events by creating external resources that lead to maintaining the SC ability to fulfil its requirements.

Redundancy:

It describes the level of resources that the focal firm has to provide an internal ability to react to SC hazards.

Base SC behaviour:

It is a metaphor to refer to the captured steady state behaviour of SC in fulfilling its requirements within a described time interval.

SC system:

It is a set of variables that aid to capture the base behaviour of SC.

SC uncertainty:

It describes the lack of knowledge about and the random behaviour of SC processes.

Resilience:

It describes the ability of SC to absorb the shock of adverse events and the time for recovery to the base behaviour before the hazard occurrence.

Resilience analysis:

It is the process of figuring out the current ability of SC to react and recover to particular adverse events consequences. It also considers the evaluation of the resilience enablers' effect on the ability of SC to react and recover.

Time interval:

It refers to the discretized time unit to capture the SC behaviour in fulfilling its requirements.

The ability to absorb the shock:

It shows the deviation of SC behaviour from its base behaviour once the adverse event has occurred.

Time to recovery:

It shows how many time intervals the SC takes to recover to its base behaviour.

SC hazard:

It refers to the danger that potentially can cause harm consequences/effects. For example, flood.

SC vulnerability:

Intrinsic properties of SC can result in a susceptibility to a hazard. For example, a critical supplier is in the flood-prone location

Risk:

It is the likelihood that a hazard will initiate an event that causes its adverse consequences.

The economic loss:

It shows in units the difference between the demand fulfilment before and after the adverse event occurrence.

Total economic loss:

It describes how many units of demand that SC is unable to fulfil during the time from adverse event occurrence until the full recovery.

Uncertain recovery functions of SC member:

They are nonparametric functions that show implicitly how an affected SC member recovers to its base behaviour during the time with taking into account the uncertainty around this recovery.

Deterministic recovery functions:

They describe how a supply chain member recovers to its base behaviour based on assumptions about the type of recovery (exponential, linear and inverted exponential) and the planned time horizon to recovery.

Remaining inventory and capacity distribution:

It shows the uncertain distribution of demand fulfilment and the remaining inventory at the end of a time interval.

DBN:

Dynamic Bayesian network is a graphical representation of probabilistic dependencies between a set of variables through the time. It assists in reasoning under uncertainty by taking into account two types of causalities. These are the causality within a time interval and cross time intervals.

Discretization:

It refers to the process of partitioning continuous variables to discretized categories to reduce the calculation burden in DBNs. In Static Discretization; the discretized categories remain the same through the calculation. In Dynamic Discretization, the discretized categories change to reflect how the evidence is updating the distribution.

Business continuity of supplier:

It describes the probability distribution of a supplier to remain in the market.

Net worth changing rate:

It shows how the net worth of the supplier changes from a year to another.

Pipe coating process:

It describes a particular production process that pipes have to go through to meet the project requirements.

Note to the reader:

1- “We” "our" and "us" only have been used in some instances to highlight what can be a shared experience between the reader and author.
2- The quality of some figures is related to the necessary of using different software, which produce different graphical qualities.

1 Introduction

1.1 Supply Chain, Supply Network, Supply Chain Network

Beginning in the 1960s and 1970s organisations started to consider themselves as linked functions whose aim was to meet customer requirements (Womack, Jones, 1996). The management of materials within the boundaries of an organisation was initially the main focus of supply chain management (Christopher, 1992; Jones, Clark, 1990; Womack, Jones, 1996). The material management is also called ‘materials logistics management’ or ‘materials management’, and which refers to the internal integration within an organisation. In this integration or management, the functions that are involved in the material flow were grouped together. Thus, the materials management structure integrated the procurement, operations and distribution functions, with the purpose of improving the customer service while lowering the operating costs (Fredendall, Hill, 2001).

Supply Chain Management (SCM) has received the consideration of managers and researchers in the field of operations management from the early 1980s (Oliver, Webber, 1982). This attention has progressed by trying to integrate the upstream suppliers and downstream distribution centres to the material management (Christopher, 1992; Jones, Clark, 1990; Womack, Jones, 1996). SCM as a concept was initially conceived and developed within the automobile manufacturing industry (Vrijhoef, Koskela, 2000). According to Vrijhoef and Koskela (2000), the Just-In-Time (JIT)[1]delivery system, as part of the Toyota production system, was the first visible sign of employing SCM concept in practice (Vrijhoef, Koskela, 2000). Simchi-Levi *et al.* (2003, Page: 1) define Supply Chain Management (SCM) as “a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses and stores, so that merchandise is produced and distributed in the right quantities, to the right locations and at the right time, in order to minimize the system-wide costs while satisfying service level requirement”. Thus, the primary objective of SCM is to synchronise the flow of the material with the customer

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[1] JIT aims to reduce the cost burden related to high levels of stock and inventory within both internal and external Supply Chains. Implementing a Just in Time methodology, as the name suggests, ensures that materials are delivered at their point of use as and when required, not in any other quantity than that which is required, or at a time that suits the supplier rather than the recipient.

requirements and to be efficient and cost-effective across the entire system (Simchi-Levi *et al.*, 2003; Stevens, 1989).

In the last decade (starting from 2000) there has been a tendency to manage the supply chain as a network (Christopher, 2011; Kim *et al.*, 2011; Nagurney, Qiang, 2009; Slack, Lewis, 2002; Wilhelm, 2011). The supply chain in this school is seen as a network of suppliers, manufacturers, and customers and this vision have led to the term supply network (SN) being employed by, for example, Choi and Hong (2002) and Kim *et al.* (2011). The shifting from managing the supply chain to the supply network management can be attributed to three strategic factors. Firstly, the adoption of the supply network concept enhances the cooperative force between different members within the supply chain. This collaborative power helps to build a close relationship between suppliers, customers and other participants in the network. Furthermore, the cooperation between supply network members helps to reduce the supply base and optimises cost throughout the supply network tiers (Slack, Lewis, 2002). Secondly, the supply network perspective improves the competitive advantages of the business because supply network members are assumed to cooperate to achieve the network goals (Slack and Lewis 2002). Thirdly, Christophe (2011) states that one of the main advantages of looking at a supply chain as a network is moving from a push strategy to a pull strategy, by the sharing of information between participants in the supply network. In an ideal picture, the shared information and cooperation between the supply network members can assist to figure out the requirement of customers and react to this need more quickly, and so reduce the level of waste and inventory at each stage. However, the main functionality remains to fulfil the customer requirements. The literature on supply networks is inspired by generic network theory and complexity theory. Choi and Hong (2002); Kim *et al.* (2011) called the supply network a complex adaptive system, and employed social network measures to investigate this system. Kim *et al.* (2015) have applied graph theory to understand the resilience of supply networks. However, the view of the supply network as a generic network ignores several characteristics of the supply chain as it will be discussed in Chapter 3 and 8.

Bi and Lin (2009) state that the SN term implies that the primary concern is the supply side from firms’ perspective and so there is no consideration for the internal process and demand zone in the network. Bi and Lin (2009) suggest the use of the supply chain network (SCN) term because it incorporates the supply, the demand, and internal process zones which are the core supply chain management concerns. SCN finds its root in the early work of (Harland, 1996; Lambert, Cooper, 2000; Lambert *et al.*, 1998). Santoso *et al.* (2005) define the supply chain network as “a network of suppliers, manufacturing plants, warehouses, and distribution channels organised to acquire raw materials, convert these raw materials into finished products, and distribute these products to customers". Braziotis *et al.* (2013) believe SCN has been used as an intermediate term between the SC and supply network. Hearnshaw and Wilson (2013) have utilised the SCN as an alternate for SN. The main functionality of SCN remains to fulfil the customer demand. I will adopt the supply chain (SC) term to highlight that the focus in this research is the resilience of SC in meeting its target. The other reason for this adoption is to avoid confusion that the use of SN and SCN can create for practitioners involve in this research. The use of SC term does not mean to overlook the structural configuration. This research will examine the contribution of SC structure to understand SC resilience and the impact of the visibility to this structure.

1.2 SC Characteristics

The main functionality of the SC is to meet the customer demand. However, it has some characteristics that make it different from any other networks. The structural configuration (Kim *et al.*, 2015; Nair, Vidal, 2011; Soni *et al.*, 2014), the operating system (Spiegler *et al.*, 2012; Tang, 2006), and the level of integration (Jüttner *et al.*, 2003a; Świerczek, 2013) are some of SC characteristics that authors in the area of Supply Chain Risk Management mentioned their effects on understanding the SCs risk.

SC structure refers to the topological structure of SC, that shows the material flow between SC tiers (Cigolini *et al.*, 2014; Persson, Olhager, 2002). However, some authors believe that the SC structure can also be associated with the business relationships between different SC members (Hearnshaw, Wilson, 2013). In this research, I focus only on the SC structure that shows the actual material flow as the aim of this research is to analyse the resilience of SC in meeting the demand of customers. Therefore, when SC structure is mentioned in this work, I mean the structure that visualises the material flow between SC members. Three key dimensions have been employed to describe SC structure. These are the horizontal structure (number of channels), vertical structure (number of stages), and the spatial dimension (Lambert *et al.*, 1998; Randall, Ulrich, 2001; Samaddar *et al.*, 2006). The horizontal structure shows the number of nodes at the same tier, the dependency between them, and with the next tier (Choi, Hong, 2002; Kim *et al.*, 2011; Samaddar *et al.*, 2006). The vertical structure (Second dimension of SC structure) is concerned about the number of tiers in the SC (Samaddar *et al.*, 2006). The traceability of more SC tiers can lead to a better view of the material flow. However, the level of visibility to the information about the input and output of SC members is a factor to be considered as it has been mentioned in Chapter 2. The ability to realise the vertical structure of the SC for many stages (tiers) is subject to a disagreement in the literature. Recall Choi and Hong (2002) and Bi and Lin (2009). In Choi and Hong (2002), the data collection process required three years for mapping the SN structures, with an undeniable power of the case study partner over their suppliers. That is why Bi and Lin (2009) describe the work to analyse SC structure as not practically applicable due to difficulties in capturing data across many tiers.

The spatial complexity refers to the location of a member (node) and the distance between nodes in SC (Choi and Hong 2002). Every member in SC has its location, which can be in the upstream close to the initial source of supply or near to the end user. According to Samaddar *et al.* (2006), the location of the member in SC affects its experience from the changes in the behaviour of some members, such as the fluctuation of customers' demand and, the interaction with other members of SC. In addition to the location of the node within SC, Bi and Lin (2009); Simchi-Levi *et al.* (2014) point out the importance of considering the geographical location of a node. Bi and Lin (2009) argue that each node in SC can be called a geographical node. A geographical node represents the site where a supplier, a factory, a warehouse, a distribution centre, or a store is located. Simchi-Levi (2010) and Simchi-Levi *et al.* (2014) state that the geographical location of a node gives an indication about 'risk events' that can hit that a node. However, the recognition of a node location within the SC and its geographical location is clearly related to the realisation of the vertical and horizontal dimension of SC. The structural configuration has considered analysing SC resilience (Kim *et al.*, 2015; Nair, Vidal, 2011; Soni *et al.*, 2014). However, the latter studies are limited to identifying the critical nodes and connections in the network that can be lost, and that lead to a network disruption. They do not offer a perspective about how this structure can be seen from a SC management level to analyse the SC resilience. Such analysis also ignores the uncertainty of decision makers about the SC processes and flow.

SC integration portrays the level of alignment and coordination between SC members. It includes primarily the use of shared information system between SC members such as suppliers, manufacturers, transportations and other supporting services involved in fulfilling the demand. While Flynn *et al.* (2010) argue that the impact of integration on SC performance is still in its infancy, Świerczek (2013) state that from SC risk perspective, two dimensions of SC integration can drive to snowball consequences of an adverse event. The first dimension is the intensity of integration. It means how strong the relationships between two members of SC are. It can be at any level from non-integrated (market relationships) to fully integrated relationship. The second dimension is the span of integration. It refers to the structural boundary of the integration. It can be basic (two members), extended (set of SC members) or ultimate (full) SC structure. Świerczek (2014) finds that while the risk propagation in the SC can be amplified by the more intense integration between the SC members, it can have a less effect when the span of integration is longer due to the ability of the structure to absorb this disruption. It confirms partially the observations of (Jüttner *et al.*, 2003a; Peck, 2005) that the integrated part of the SC structure can either absorb or amplify the impact of adverse events. Jüttner, Peck *et al.* (2003), Peck (2005) and Świerczek (2014) focus on the relationships between the propagation of consequences and the level of integration from a high level of view where there is no consideration how and why the integrated SC part can absorb or amplify the disruption.

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The SC operating system shows triggers of the processes in the supply chain (Tang 2006). It can be principally a push, pull or a push-pull system from the focal firm perspective (Russell, Taylor, 2010). Ben Naylor *et al.* (1999) illustrate the decoupling points between the push and pull system based on the operations strategies, as can be seen in Figure 1-1. However, the decoupling points and operations strategies are affected by how firms see themselves within SC. For example, if the retailer tends to have a market relationship with its suppliers, they can decide to either have a pull supply cycle (e.g. by not having inventory) or they can have push supply cycle types where they store finished goods. Tang (2006) in his discussion of product management mentions that the operating systems indicate the level of stock that a SC member carries and the role information play in triggering the SC processes. However, the influence of decisions rules (e.g. inventory level) related to the operating system on the propagation of adverse events consequences has not been studied from an analytical point of view.

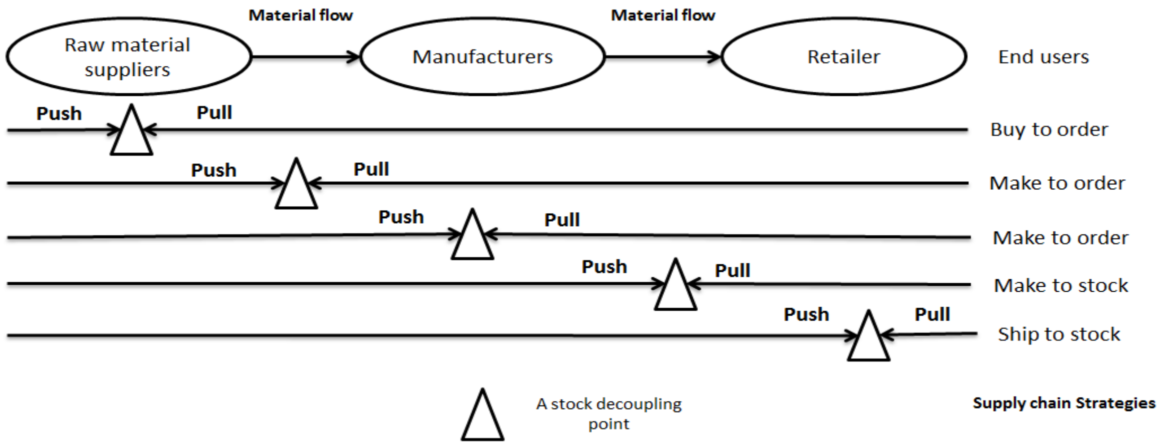


Figure 1-1: General Push-Pull description based on SC strategies adopted from (Ben Naylor *et al*., 1999) Page: 113

1.3 SC Resilience Analysis to Aid SC Management

Supply chains are increasingly vulnerable to various types of disruptions. Petit *et al.* (2010) state that SC vulnerabilities have amplified due to factors such as more specialised factories, more centralised distribution centres, greater outsourcing, reduced supplier base, more volatile demand, technological innovations, and globalised supply chains. The latter factors mean that decision makers face a greater level of the uncertainty about SC processes. Knemeyer *et al.* (2009); Norrman and Jansson (2004) see that many of the SC vulnerabilities can be attributed to the lack of slack in the SC, and proactive plans to deal with ‘risk events’ and their consequences. This has triggered questions about how SC risk should be managed, and which has extended the call to build more resilient and robust SCs, to yield an ability to manage SC ‘risk’.

The increased prominence of using robustness and resilience terminology in the SC management literature is associated with the expansion of adverse events that impact the local and global SCs such as the Japanese tsunami and Thailand floods, which are rare and highly uncertain. Wagner and Neshat (2010) show that the number of natural catastrophic events has increased steeply since 2000; hence, SCs have been increasingly exposed to external natural hazards. Some of these hazards are inevitable, especially the environmental and financial ones. For example, the April 2016 earthquake in Japan has seen Toyota lose 200 Million Dollars despite all the risk mitigation actions that Toyota had in place. So, there may be a realisation that the resilience can be one way of proactive management for SC risk (Pettit, 2008). However, there is still interrelated understanding between what can be risk mitigation actions and enablers to improve the resilience. The former, generally speaking, aim to reduce the chance of an event attached to a hazard. This eventually leads to an improvement in the resilience of the SC. In contrast, the latter seek to improve the supply chain reaction to the consequences of adverse events attached to hazard occurrence, where the chance of occurrence might not be reducible. Therefore, the majority of resilience enablers and capabilities, such as building flexibility and redundancy, are directed against such events. This does not necessarily mean that these adverse events are catastrophic events. They could be any unavoidable events or events with chances that cannot be reduced. On the other hand, some resilience enablers/capabilities can be still regarded as mitigation actions. For example, supply chain redesign to avoid hazard prone areas reduces the chance of events that are related to environmental hazards, although it steers eventually to a more resilient one. Therefore, there should be a clear differentiation between the latter two types of actions because they result in distinct consequences. In mitigation actions, the aim is to reduce the chance of adverse events to take place, whereas the resilience enablers and capabilities should proceed to a better resistance to, and recovery from, adverse consequences of events.

The above discussion shows that the first challenge in SC resilience is the ambiguity around the terminology. While the resilience emanates from being an important concept to manage the supply chain, it has obvious interconnections to other terms that have emerged with the development of SC risk management in general. The current standpoint of SC risk and resilience literature seems to overlook how these terms can be clearly defined, and interrelated to each other. This is in a way that can shape the quantitative analytical effort of the research, and guide a better support for SC management decision making under the uncertainty.

An additional trigger for SC resilience evolvement can be the stimulus of various literature streams on Supply Chain Risk Management. Resilience is a well-known concept in engineering, ecology, and other fields. Although it is defined a bit differently from one domain to other, it is still orbited around the ability of the system to resist and recover. Table 1-1 summarises how resilience has been defined in many fields including definitions from the SC literature. It can be noticed from the literature descriptions that the output of a resilient system does not have to be consistent, although the consistency of output can be an indicator that a system is resilient. The resilient system should not only have a level of resistance to adverse consequences of events but it also should have the ability to bounce back to its normal or better state. Thus, the resilience of SC is an indicator of the status of the SC through the time and not only at the point of adverse event occurrence. The resilience supposed to be understood differently way from the robustness which has been described by Christopher and Rutherford (2004) as the capability to maintain a stable output with a reasonable variation in the input.

A study conducted by the World Economic Forum and Accenture (2013) has reported that 80% of firms were concerned about their SCs resilience to disruption (Ambulkar *et al.*, 2015). The latter industry interest in SC resilience accompanied with scholars' attention to advance the literature of SC resilience to an occurrence of disruption (Kim *et al.*, 2015). However, despite this massive interest in SC resilience, there have been few attempts to highlight how this resilience can be measured and analysed. Appropriate measurements and analysis can aid supply chain management to employ proper resilience enablers and explore the impact of the current enablers in improving the resilience of the supply chain. Kim *et al.* (2015) state that in spite of the stated conventional value of redundancy as a resilience enabler, it has not improved the resilience of SC structures that have been considered by their research. This illuminates the importance of the resilience analysis as a prerequisite to understanding the influence of current resilience enablers, and the need for more resilience enablers. So, resilience analysis is about predicting the SC resilience level by taking into account the adverse events that SCs are countering and the resilience enabler that the SC has. Recently, Kamalahmadi and Parast (2016) state in their literature review of the work on supply chain resilience, that the research in SC resilience analysis is still sparse. Without understanding and measuring the resilience level of SC, it would be difficult to assess its reaction to, and recovery from a disruption. It would be hard also to assess the real value that a resilience enabler can add to improve the resilience of SC. Kamalahmadi and Parast (2016) argue for more research to advance the resilience analysis and measurement.

Table 1-1: Cross-Literature Resilience Definitions

Field	Reference	Definition
Ecology	(Folke *et al.*, 2002)	Ability to bounce back from a disruption while preserving diversity, integrity and ecological processes
Supply chain	Ponomarov and Holcomb , 2009 Page: 131)	"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"
Supply chain	(Sheffi, Rice, 2005)	Ability of supply chain to react to an unexpected disruption and bounce back to its normal operations
Supply chain	(Christopher and Peck, 2004)	Ability of the supply chain to coming back to its original state or move to a better state after being disturbed
Engineering (Networks resilience)	(Mohammad *et al.*, 2006; Najjar, Gaudiot, 1990)	A network ability to operate and maintain an acceptable level of service under the presence of adverse conditions and repaid recovery to its normal functionality.
Enterprise Resilience	Centre of resilience	"The capacity of a system to survive, adapt, and grow in the face of unforeseen changes, even catastrophic incidents."

Hosseini *et al.* (2016) point out in their review of resilience measures for various systems that the system distinctive characteristics play a great role in understanding its resilience level. The current few attempts to analyse the resilience of SC also seem to have little focus on the impact SC characteristics on its resilience and how these features can affect the resilience analysis process. This is apart from Kim *et al.* (2015) Nair, Vidal (2011) and Soni *et al.*(2014) who have focused only on the structure SC. This leads to another challenge about how the distinctive SC characteristics affect their resilience?

1.4 Research Aim and Objectives

In the previous section, it has been shown briefly that the SC resilience needs to be captured through time. However, there is ambiguity about the terminology to assist in understanding the resilience of SC, and few attempts to suggest ways of how SC resilience can be quantitatively analysed when considering the SC distinctive characteristics. Therefore, the aim of this research is to advance the quantitative analysis of SCs through using Dynamic Bayesian Networks (DBNs). DBNs are directed acyclic graphs for reasoning under uncertainty through time. A DBN is capable of using partial knowledge about one variable to update the uncertainty about other variables in the model. In principle, DBNs present a possible model class for analysing resilience because they can capture the dynamic uncertain behaviour of a supply chain due to the effects of potential adverse events. However, despite their potential theoretical appropriateness, there are many ambiguities around DBNs applications in practice. Therefore, there is a need to understand how standard modelling process can be adapted to employ them. Therefore, to achieve the research aim, the objectives are as follows:

1. To clarify the interrelations between terminologies that contribute to the SC quantitative resilience analysis,
2. To empirically explore the role that DBNs play in informing the quantitative SC resilience analysis to different problems,
3. To report the key lessons around the process to employ DBNs to understand and support decisions about SC resilience based on the SC characteristics,

These research objectives are first probed through the examination of the literature to form a theoretical basis about the SC resilience and DBNs. This theoretical basis is then further developed and informed by the output of my multiple case studies. The use of multiple case studies is related to the infancy of the research in SC resilience analysis and the critical realist view of the world.

1.5 Thesis Structure

Figure 1-2 shows the thesis structure. While the problem context has been addressed briefly in Chapter 1 with some characteristics of SCs that might impact SC resilience analysis, in Chapter 2 I will survey in detail the prevailing literature in SC resilience, paying particular attention to the ambiguity and interrelation between the terms that form this domain and the few analysis attempts. Then, I will develop a theoretical base about the interrelation between terminologies based on the cross-analysis with risk management literature. I will also introduce the theoretical pillars for SC resilience analysis. Then, I will illustrate several measures that can be used to represent the output of DBNs to understand the ability of SC to absorb the shock and recover its normal state.

In Chapters 3, I will explore how SC resilience has been modelled from a macro complex level that ignores its characteristics from a decision maker perspective. From that, I will investigate theoretically the role that DBNs can play to analyse SC resilience. DBNs primary constructs and a standard protocol to apply them will then be considered.

In Chapter 4, I will discuss the suitability of multiple case study methodology based on the current state of knowledge about SC resilience and Dynamic Bayesian Networks and the philosophical stance of the researcher. Then, data collection methods for this research will be explored in detail.

In Chapter 5, Chapter 6, Chapter 7, I will present within case analysis for four SCs in the UK, Malaysia, and Atlantic Canada respectively. In Chapter 5, I will investigate the use of DBNs to evaluate and examine the impact of suppliers' business continuity on the resilience of a tubes SC. I will introduce several factors related to facility locations and financial stability of suppliers for the sake of predicting their business continuity.

In chapter 6, I will employ DBNs to understand how the interdependent view of the supply, the inventory and the production can steer towards better management of the spare parts, and support decisions about their resilience, through After-Sales agreement.

In chapter 7, I will apply DBNs to check food SCs resilience in Atlantic Canada considering the presence of critical infrastructure and extreme weather conditions. Differently from the previous two cases, I will use a structure view of the performances of SC members to predict the resilience. In principle, it is similar to (Garvey *et al.,* 2015) theoretical work in BBN.

In Chapter 8, I will build a cross-case analysis based on four main streams. These are:

- The role of DBNs in informing the SC resilience analysis and support decision making based on SC characteristics
- The lessons learned from DBNs applications to analyse the resilience of SC,

- The impact of SC characteristics on their resilience as has shown by DBN output,
- The clarification of terms that can lead to a better analysis of SC resilience (post case studies).

I will draw my conclusions in Chapter 9. I will review what has been reached in respect of my research objectives. Then, I will highlight further work concerning the obtained propositions and the use of DBNs. Some areas of research that have implications for the current research and appeared to be useful for future applications of DBNs will be identified.

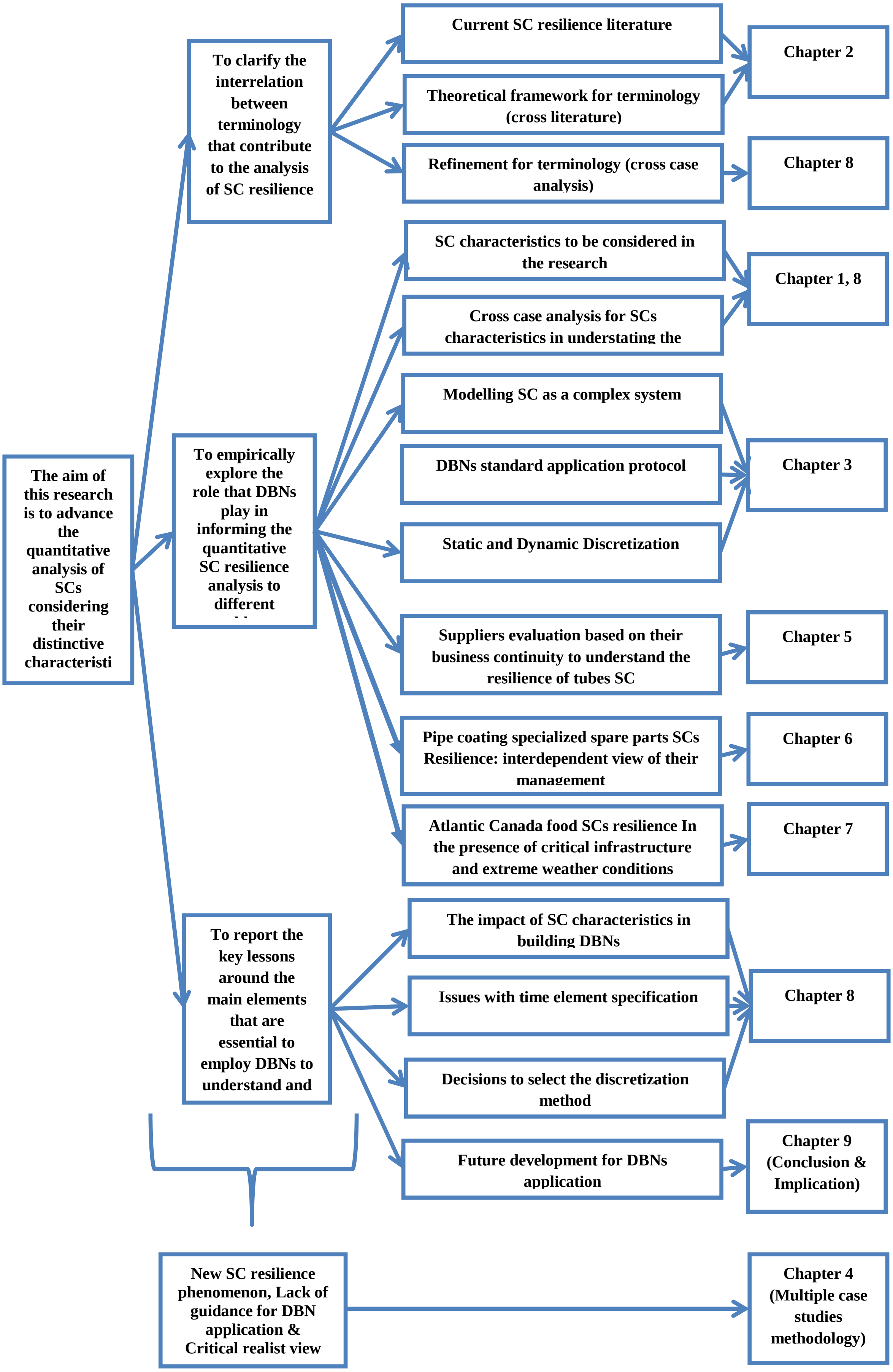


Figure 1-2: Thesis structure

2 Supply Chain Resilience Literature Review and Analysis

2.1 Introduction

In the preceding chapter, I outlined the motivation and the initial context of the research and gave an overview of some dilemmas in the current SC resilience literature. In this chapter, I will inquiry the research on supply chain resilience enablers and analysis. I will pay particular attention to ambiguity around the scope and definitions of SC resilience and its interrelated fields and the endeavours to apprehend how this resilience should be analysed. Then, I will propose constructs that aid SC risk and resilience analysis based on across literature study.

2.2 SC Resilience Literature

The SC resilience literature can be subdivided for this research purpose into two streams. These are

- SC resilience enablers where the emphasis is on tools to improve the resilience,
- SC resilience analysis where the concentration is to realise the current level of the resilience and the need for actions to enhance the resilience.

2.2.1 SC Resilience Enablers

The first widespread empirical study of SCs resilience enablers has undertaken by (Christopher, Peck, 2003). The study motivated by transportation disruptions due to fuel protests and an outbreak of Foot and Mouth Disease. Christopher and Peck (2003) have found little awareness about SC vulnerability and resilience. Christopher and Peck (2004) propose a conceptual framework arguing that SC resilience can be enhanced through some practices such as reengineering SC, having a high level of collaboration between SC members and a SC risk management culture. Christopher (2005) proposes that a resilient SC should be flexible and agile to recover quickly. In a parallel time frame, MIT researchers have conducted multiple case studies to analyse the effects of terrorism attacks on SCs resilience post 9/11. They identify the sources of SC disruptions and management responses to these disruptions. The importance of flexibility and redundancy is emphasised (Rice, Caniato, 2003; Sheffi, Rice, 2005).

(Pettit 2008, Pettit, Fiksel et al. 2010, Pettit, Croxton et al. 2013) recognise seven classes of vulnerabilities in SC: turbulence, deliberate threats, external pressures, resource limits, sensitivity, connectivity, and supplier/customer disruptions. To counter these vulnerabilities the supply chain management should consider better resilient supply chains with taking into account: the sourcing flexibility, order fulfilment flexibility, capacity, efficiency, visibility, adaptability, anticipation, recovery, dispersion, collaboration, organisation, market position, security, and financial strength.

Table 2-1 shows key SC resilience enablers. Although SC resilience research is still spare, I try to group the common supply chain resilience enablers that have been recommended by various authors. It is an effort to build a comprehensive analysis around their theoretical and practical application.

Table 2-1: Main SC resilience enablers

SC resilience enablers	**Paper**
Flexibility	(Chopra, Sodhi, 2004; Christopher, Peck, 2004; Ponomarov, Holcomb, 2009; Tang, Tomlin, 2008)
Collaboration	(Christopher, Peck, 2004; Christopher, Peck, 2003; Pettit, 2008; Pettit *et al.*, 2013; Pettit *et al.*, 2010; Simchi-Levi, 2010; Waters, 2007)
Visibility	(Brandon-Jones *et al.*, 2014; Christopher, Peck, 2004; Pettit, 2008; Pettit *et al.*, 2013; Pettit *et al.*, 2010)
SC redundancy and re-engineering	(Christopher, Peck, 2004; Rice, Caniato, 2003; Scholten *et al.*, 2014; Sheffi, Rice, 2005)
SC risk management	(Christopher, Peck, 2004; Scholten *et al.*, 2014; Waters, 2007)

2.2.1.1 Flexibility

Flexibility is a well-known term in SC management literature. Vickery *et al.* (1999) mention a list of SC flexibility dimensions where the meaning of flexibility is varied based on the time horizon. In the short time horizon, it refers to how fast a SC could perceive and counter issues and opportunities such as the increase/decrease in the demand, the change in the customers' preferable packaging, and the late supply. In the long term, it refers to how the SC adjusts and implements new plans to support variations in the whole company or marketplace. Christopher and Peck (2004) describe the flexibility, from a resilience perspective, like the ability to react quickly to ‘risk events’, and to maintain the SC ability to fulfil its requirements in an uncertain environment. Pettit *et al.* (2008, 2010, and 2013) have distinguished between source flexibility and order flexibility to maintain the resilience. However, in the SC management literature, there are still theoretical and practical challenges around the measurement and the estimation of the SC flexibility (Moon *et al.*, 2012; Stevenson, Spring, 2007). Stevenson and Spring (2007) argue based on their review of the SC flexibility literature that “despite this attention, measuring flexibility is hard to achieve, and existing measures are often criticised: Measures are subjective and situational, i.e. lack generality” (Stevenson, Spring, 2007, Page: 691). The observations of Stevenson and Spring (2007) mean that building flexibility to improve the resilience can counter difficulties in judging if the SC is flexible enough to the propagation of adverse consequences or not. It stresses the importance of the quantitative resilience analysis to understand the contribution of the flexibility to the resilience level.

Some endeavours such as the work of (Moon *et al.*, 2012; Tang, Tomlin, 2008) try to advance this area of research by suggesting ways to estimate the flexibility of a SC. Mainly for mitigating ‘risk sources’. Tang, Tomlin (2008) propose strategies to enhance the flexibility. These strategies are flexible supply via multiple suppliers or supply contracts to counter the supply risk, flexible process via flexible manufacturing process such as shift production quantities across internal resources (plants or machines) to combat the process risk, flexible product via postponement and flexible pricing via responsive pricing to counter the demand risk. An analytical quantitative solution can then be generated. The solution is based on attaining the optimal level of flexibility, with taking into account the manufacturer expected profit. For example, what is the expected level of the profit that the manufacturer can gain if they have one supplier, two suppliers, or three suppliers? Although the suggested strategies have been directed to what Tang, Tomlin (2008) called a ‘risk source’, the calculation process does not clearly show how this risk source impacts the flexibility. The suggested optimal levels of flexibilities might be affected by the consequences of adverse events. These consequences might eradicate this flexibility and consequently influence the resilience of SC. For instance, if multiple suppliers have same second tier suppliers or their facilities are located in the same geographical hazard zone, how would the SC flexibility be affected? The latter requires deeper analysis around SC interdependency to understand the real flexibility.

2.2.1.2 Collaboration

Collaboration refers to the level of joined work to make operational, tactical and strategic decisions (Jüttner, Maklan, 2011). It also denotes a form of the integration between the supply chain members (Świerczek, 2013). According to Christopher and Peck (2004), high levels of collaboration across SCs can mitigate ‘risk’ and consequently improve the SC resilience. Sheffi (2001) asserts that collaboration is an essential element for fabricating SC resilience. He stresses that the importance of collaboration is not only before a catastrophe but also after, to share experiences among SC members.

Collaboration requires sharing some sensitive data about the internal processes of SC members, which increase the visibility in SC (Scholten *et al.*, 2014; Soni *et al.*, 2014). It can take different forms based on the type of information and with whom this information are shared. For example, in the vertical collaboration; supply chain members at diverse value chain phases (suppliers, manufacturers, customers) are working together in operational, tactical or strategic levels. The horizontal collaboration, on the other hand, collaboration involves organisations working at the same level or can be departments within the same organisation (Scholten *et al.* 2014). The collaboration can drive, as similar as the visibility, to avoid overreactions, needless interventions and ineffective decisions (Christopher, Peck, 2004). However, it necessitates turning the win-lose mentality to win-win attitude. The latter involves more work around the incentives and the benefits gained through the collaboration.

2.2.1.3 Visibility

Francis (2008) defines SC visibility comprehensively, depending on many empirical and theoretical pieces of evidence, as “the identity, location and status of entities transiting the supply chain, captured in timely messages about events, along with the planned and actual dates/times of these events” (Francis, 2008, Page. 182). The primary interest to achieve the visibility in the SC is to obtain the timely information about the entities processes, orders progress, etc. From SC resilience management the achievement of visibility aims to get evidence about the exposure of SC members to ‘risk events’ (Jüttner, Maklan, 2011). Many researchers emphasise on the value of visibility as one of SC resilience enablers. Brandon-Jones *et al.* (2014) suggest that “visibility is a specific capability that allows the organisation to mitigate threats in their supply chain to safeguard organisational performance”. Christopher and Lee (2004) state that SC visibility in a ‘risk event’ avoids overreactions, unnecessary interventions and ineffective decisions.

The study by Blackhurst *et al.* (2011) on seven firms reveals the need to increase the visibility within SC. The results of the cross-case analysis show that six companies indicate the importance of real-time monitoring of SC through shared information, to make strategic decisions to avoid disruption and improve the resilience. However, Francis (2008, Page: 184) reports that SC visibility is “widely used but is open to interpretation, it means different things to different people, thereby adding to miscommunication and confusion, especially between vendors and those who seek the supply chain visibility capabilities they provide”. While he argues that noteworthy progress has been made to build the theory around SC visibility, he has listed many empirical pieces of evidence from different research groups about the inherent challenges in achieving the visibility in many cases. The latter shows that visibility is still hard to achieve in practice despite the extensive literature on the topic. The SC characteristics such as the integration level that I discussed in Chapter 1, might have an effect on the visibility. So, it is worth checking what is the interrelation between the visibility and SC characteristics that might steer towards a better resilience analysis?

2.2.1.4 Interconnection between Collaboration, Visibility and Flexibility

From the above discussion, it appears that the fundamental principle to achieve collaboration in the supply chain is to share the information and knowledge between the supply chain partners or at least the critical partners in the chain. This data and knowledge sharing would increase the visibility across the chain. On the other hand, the increase in visibility enhances the collaboration in the supply chain. Theoretically speaking, improved visibility and higher levels of cooperation result in a more resilient supply chain.

Another critical dimension of supply chain collaboration is that it can steer towards flexible relationships and a flexible role of inter-organisational information systems (Stevenson, Spring, 2007). The flexibility in SC relationships means linking the firm to the wider supply chain. This clearly needs a vertical type of collaboration between the company and its partners in the SC. The flexible role of inter-organisational information systems and internet technologies is the implementation of real-time information systems that allow organisations to coordinate efficiently at the supply chain level (Stevenson, Spring, 2007). The inter-organisational information systems enhance the visibility that leads to a better flexibility level. For example, if a SC member is disrupted then the other members in the collaborative SC can work together promptly to fulfil its requirements or the firm will try to contact a secondary member immediately.

As can be seen Figure 2-1, the collaboration, visibility and flexibility are interconnected and one can lead to another by different means. The collaboration can lead to the more visibility in the SC or the visibility can create the collaboration in SC. Collaboration and visibility can also result in a more flexible SC, through providing any unexpected requirements and timely information for better management. However, not all forms of flexibility are based on the collaborative style. They might stem from the lack of confidence around members of the supply chain, such as having business relations with multiple suppliers for the same materials as discussed by (Tang, Tomlin, 2008). This is to ensure the sustainability of the supply in case that an adverse event impacts a supplier.

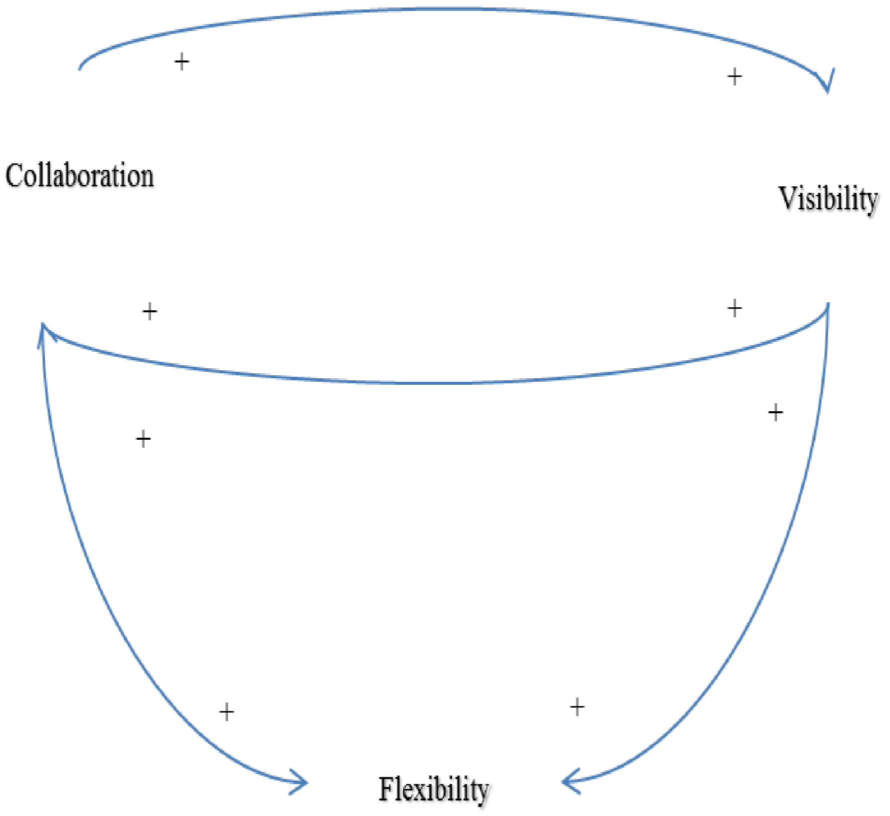


Figure 2-1: The positive causal relationships between visibility collaboration and flexibility

2.2.1.5 Redundancy and Re-engineering SC

“Redundancy is a concept of keeping some resources in reverse to be used in case of disruption”(Sheffi, Rice, 2005). Redundancies come in various forms such as safety stock, planned use of multiple suppliers when the cost of adding a supplier is high, low utilisation rate for the capacity, and backup sites (Sheffi and Rice 2005). The redundancy offers the time for a firm to cover its requirements wholly or partially during and after the disruption. It is primarily an internal decision for a business to be equipped for a hazard. In contrast to other supply chain resilience enablers, a firm can increase or decrease their redundant resources based on their strategy.

Redundancy has been suggested to be a conventional resilience enabler (Christopher, Peck, 2003; Sheffi, 2007). However, it confronts the lean and just–in-time (JIT) as two major well-accepted philosophies in the operations management field. The above modes of redundancies neither add value to customer nor reduce the waste in the SC. This drawback has driven suggestions that the SC needs to be re-engineered. The SC re-engineering is to build a balance between efficiency and the redundant resources in a way that maintains the SC capability to react and recover (Christopher, Peck, 2004; Jüttner, Maklan, 2011; Pettit *et al.*, 2013; Pettit *et al.*, 2010). To achieve this balance, an understanding of cost/benefit trade-offs should be obtained (Blackhurst *et al.*, 2011; Scholten *et al.*, 2014). However, the SC resilience literature does not answer what is the basis to explain the cost/benefit, and the trade-offs between the enhancement of the SC resilience and the cost of the redundancy. The latter could be studied through the quantitative analysis of the impact of redundant resources on the resilience of SC and explore if it is worth the additional costs to add more redundancy to improve SC resilience.

2.2.1.6 SC Risk Management (SCRM)

Jüttner *et al.* (2003a) define SCRM as “the identification of potential sources of risk and implementation of appropriate strategies through a coordinated approach among supply chain risk members, to reduce supply chain vulnerability”. The creation of SC risk management reduces the chance of some ‘risk events’ to occur, and results in improving SC resilience (Soni *et al.*, 2014). However, Rao and Goldsby (2009); Sheffi and Rice (2005) believe that the chief aim of the SC risk management is to enhance the resilience. Consequently, the SC ‘risk’ and ‘vulnerability’ will be reduced.

Research in SCRM has been escalated significantly since 2000 with a large number of journal articles, books and reports published. Despite this rapid flourish of SCRM domain, there is still no clear scope or boundaries with researchers from different fields, and many research methodologies attempt to expand this area (Sodhi *et al.*, 2012). This ambiguity and lack of clear boundaries are reflected by little consensus around the meaning of SC risk, its classifications and the unfettered use of terminology. For example, Zsidisin (2003) focuses on supply risk that can impact SC entities. He defines supply risk as “the potential occurrence of an incident associated with inbound supply from individual supplier failures or the supply market occurring, in which its outcomes result in the inability of the purchasing firm to meet customer demand or cause threats to customer life and safety” (Zsidisin, 2003, Page. 15). Spekman and Davis (2004) suggest a general probabilistic meaning for SC risk. They define SC risk as “the probability of variance in an expected outcome” (Spekman, Davis, 2004, Page. 416). The expected outcome can refer to several SC outputs such as the meeting of the customer demand.

The little agreement around the meaning of SC risk and the scope of SC risk management produces necessarily wealthy ‘risk classifications’. However, I argue that the majority of these classifications can be re-understood in the light of general risk management literature. Check section 2.3 for a critical review on the use of risk words and definitions of risk in SC. A well-cited SC ‘risk’ classification is the work of Jüttner *et al.* (2003a), who classified the risk in three categories. These are the environmental risk (earthquake, hurricane), network-related risk, and organisational risk. Christopher (2005); (Christopher, Peck, 2004) improve Jüttner *et al.* (2003a) risk classification by considering five categories of SC risks. These are processed risk, control risk, demand risk, supply risk, and, environmental risk. The process and control risk are related to organisational risk, and the demand risk and supply risk are linked to network sources. The environmental risk remains as in (Jüttner *et al.*, 2003a). Congruently Bogataj and Bogataj (2007) classify the SC risk into supply, demand, process and control risk. Tang and Tomlin (2008) group supply chain risk into supply, process, demand, behavioural, intellectual property and political/social risks. The latter two risks can be related to the environmental risk, whereas behavioural risks can relate to all categories. Wu *et al.* (2007) adopt a similar classification when they categorise the risk into internal and external to the SC. Then, they consider to what extent the risk can be controllable (controllable, partial controllable, uncontrollable). Apart from these similar classifications, Kleindorfer and Saad (2005) classify the risk based on their triggers into terrorism, political instability, natural hazards and operational contingencies. Chopra and Sodhi (2004) concentrate on disruptions and delays as SC risk consequences. Then they identify what the risk drivers can be for each consequence, such as system and forecast errors. Spekman and Davis (2004) cluster what can be the ‘risk trigger sources’ in a SC. They state that these sources can be the inbound supply, information flow, financial flow, the security of a firm’s internal information system, relationship with partners, and corporate social responsibility.

Overall the brief description around the SCRM primary constructs appears to confirm the general thoughts that SCRM concepts and boundaries are still unclear and do not provide a well-founded picture of the domain (Sodhi *et al.*, 2012). The supply chain risk has been defined loosely, and some terms such as vulnerability and risk triggers have been used interchangeably. While the generous SC risk classifications can significantly influence the scope of where the SCRM and its interconnected fields can focus, there is still need to differentiate between risks primitive elements for a better judgement of SC risk. This distinction also leads to a better comprehending to the supply chain resilience as it is considerably interrelated to SCRM. Heckmann *et al.* (2015) point out the latter problem to shape the definition for risk quantification purposes. They conceptualise the SC risk as "the potential loss of a supply chain regarding its target values of efficiency and effectiveness evoked by uncertain developments of supply chain characteristics whose changes were caused by the occurrence of triggering-events" (Heckmann *et al.*, 2015, Page. 131). Heckmann *et al.* (2015) notice that up to date, there has been a lack of a clear and adequate measure for SC risk that respects the attributes and characteristics of 'supply chains'. The importance of acknowledging SC characteristics is to analyse the consequences of 'risk event' on the SC. The latter leads to evaluate what Liu and Nagurney (2011) call a supply chain tolerance to risk. The reader is referred to Heckmann *et al*. (2015) for more detail about the literature review for the terminology in general, the consequences of the risk and the current analytical work in SCRM. In this research, I focus on specific terms that are interrelated to the quantitative SC resilience analysis, as we will see in section 2.3. Then, I will refine them further through my empirical data.

2.2.2 SC Resilience Analysis

Researchers have proposed many SC resilience enablers. I have shown above that the suggested enablers to enhance SC resilience have some theoretical and practical challenges. The literature has principally concentrated on them from a high-level view of the phenomenon. This view discourages the research from 'drilling down' to guide how SC resilience can be analysed and estimated. It could be attributed to the belief that SC resilience enablers should enhance SC readiness to all adverse events initiated by hazards. The principal shortcoming concerning SC resilience enablers could be the lack of ground to examine their impact on boosting the SC resilience. This observation has been confirmed by Kim *et al*. (2015) who argue that some resilience enablers are being assumed to have a conventional value. However, they do not necessarily contribute towards this aim. Kim *et al.* (2015) doubt the influence of redundancy in improving SC resilience through their analysis on SC theoretical structures utilising graph theory. Kamalahmadi and Parast (2016) confirm the need for quantitative analysis to shape knowledge about the current level of SC resilience and examine the impact of some resilience enablers on this level.

Some attempts have emerged that explore how the SC resilience can be analysed and measured such as (Christopher, Rutherford, 2004; Klibi, Martel, 2012; Simchi-Levi *et al.*, 2014; Wang, Ip, 2009) and (Kim *et al.*, 2015; Soni *et al.*, 2014). Christopher and Rutherford (2004) state that the resilient SC should be able to deal with all types of variation in the input, whereas the robust SC can deal only with reasonable variation in SC input. On this basis, they suggest that the analysis of the supply chain resilience can be performed through six-sigma. In six-sigma, the change between SC output variations before and after the disruption can be checked. Then, the time that the SC output needs to recover to its previous variations can be examined. However, six-sigma does not intend to explore the relationships between the 'causes' and variations, as well as, such analysis falls short in reporting how the supply chain characteristics and configurations can influence the variations.

Wang and Ip (2009) use graph theory to evaluate ‘the resilience’ of an aircraft logistic service. They analyse the resilience based on the reliabilities and the capacities of suppliers and edges (paths). For instance, the resilience function of a network with one supplier, one route and one demand node is [((the reliability estimation of the supplier * the reliability of the route) * min (demand, supply node capacity, route capacity)) / demand]. The resilience with multiple sources is [the sum of ((the reliability estimation of the supplier * the reliability of the route) * min (demand, supply node capacity, route capacity)) for all suppliers and their routes/ demand]. For this method, the ratio does not have to be below or equal one. It can be bigger to encode the surplus in the capacity of SC. However, this case mainly scopes down the resilience to the ability to fulfil the demand on time with no consideration to the hazards and their impact on the resilience. It does not show how the SC absorbs the shock and recovers to its state before the disruption.

Klibi and Martel (2012) propose several stochastic programming models to design more resilient supply chains. The capacity of suppliers and distribution centres (DCs), the demand fluctuation, and their recovery time to their regular level have been adopted as signs of SC resilience. However, in this method, there is no consideration to the causality and propagation of the adverse event consequences through the SC. Therefore, they study separate indicators for each SC member resilience (The capacity of suppliers and DCs, the demand fluctuation and their recovery time to normal levels).

Simchi-Levi *et al.* (2014) suggest a methodology for defining the influence that a node disruption has on the overall performance of the focal firm. The methodology studies the geographical facilities locations, facility recovery time, financial position, and cost of losing a node. The data about these characteristics were gained through a survey handed to an intended node. Simchi-Levi *et al.* (2014) state that the methodology also counts for the cost of adding alternative nodes or an extra buffer to run the processes smoothly during the recovery time of the disrupted node. A real application of the methodology to Ford automobile company has found that the central nodes that influence the resilience are the suppliers of low-cost commodities (Simchi-Levi *et al*., 2014). However, this methodology falls short in reporting the propagation of adverse events consequences due to its deterministic nature. The focus is only to quantify the financial loss if a node is out for a particular time interval.

Kim *et al.* (2015); Nair and Vidal (2011); Soni *et al.* (2014) introduce a deterministic approach based on graph theory to analyse the impact of disruption on SC. This method fundamentally concentrates on the SC structural configuration with the assumption that the flow of the materials between the SC is deterministic. The SC disruption for this approach has been defined by “a situation where there no longer exists a walk between the source(s) and sink node as a consequence of a disruption(s) in nodes or arcs” (Kim *et al,* 2015, Page 50). As a result, the resilient SC is the network, which remains connected. Kim *et al*, (2015) formally define the SC resilience by the ability of the SC to withstand the failure of nodes and arcs. Although Kim *et al.* (2015); Nair and Vidal (2011); Soni *et al.* (2014) consider the SC structure as one of the SC characteristics to recognise the resilience, their approach overlooks many other SC characteristics. They have also overlooked the dynamicity of SC resilience. The resilience in Kim *et al, (*2015) measured by the ability to withstand the failure of nodes and arcs, where they have the same probability to fail (static measure). This measurement neglects the recovery time that has been seen as a vital element to explain the resilience by many authors across various domains.

Depending on the discussed work to analyse supply chain resilience, there is a clear absence of a consensus around how the resilience should be estimated. Klibi and Martel (2012) have focused on the capacity of SC members, so for them, the resilience is measured by the ability of the supply chain node to maintain its capacity and how long it would take to recover to this capacity if it is affected. Wang and Ip (2009) measure the resilience by a ratio of the available supplies to the demand considering the capacity and the reliability of suppliers and paths. (Christopher, Peck 2004) propose that the resilience can be estimated by the ability of the SC to maintain and recover to the same variations in the output before and after the 'disruption'. (Simchi-Levi *et al*., 2014) consider the financial impact of losing a node on the focal firm. Kim *et al.*(2015) attempt to capture the resilience of SC by considering the total number of arcs and nodes that do not result in a disruption of the SC to the total number of arcs and nodes that lead to a disruption.

In addition to the lack of consensus about how to estimate the resilience, there is less harmony around the suitable matrix to estimate the resilience, as the current resilience models have not reflected the SC characteristics in order to understand their impact on the propagation of adverse event consequences or the resilience of SC to this propagation. Although Kim *et al.* (2015); Nair and Vidal (2011); Soni *et al.* (2014) try to capture the structure of SC, their approach is still underdeveloped because their models have been taken from a general network theory and applied in a theoretical way. There is no clear picture about how such models can work in practice and data required to operationalise them.

2.3 SC Risk and Resilience: Re-definition and Estimation

From the above discussion, it can be noticed that there is a lack of clarity around the definitions and terms that have been employed in SC risk and resilience domain. This ambiguity can be a reason for the absence of operational resilience measures that are mentioned by Kim *et al.* (2015), Kamalahmadi and Parast (2016). In this section, I critically assess the current terminology and definitions of SC risk and resilience in the light of general risk management field where the risk concept and its core constructs are well-developed. It is an attempt to propose a broad perception of terminology that might advance the analysis side of SC resilience.

2.3.1 Generic Risk Management View of Risk and Resilience Terminologies

The disagreement around the meaning of the SC risk and its main elements can partially find its root in risk management literature where there has been disagreement about the meaning of the risk, and how it can be estimated. See for example Aven (2011a); Haimes (2009). Haimes (2009) defines the risk as "the probability and severity of adverse effects (i.e., the consequences)" (Haimes 2009, Page. 1647). Aven (2011a) conceptualises the risk as "Uncertainty about and Severity of the Consequences of an Activity". Kaplan (1997) argues that the problem of loose definitions is because the risk is heavily entwined with probability. Scholars have argued about the probability meaning for hundreds of years. According to Kaplan (1997), the problem is two folds; either people use the same words to describe different meanings or use different words to describe the same meaning. Kaplan (1997); Kaplan and Garrick (1981) state that risk is bigger than a number or a curve to describe the probability. They mention three questions, which are interrelated to describe the risk. These are "What can happen? How likely is that to happen? If it does happen, what are the consequences?" The risk is equal to (scenario/event, the likelihood of this scenario, consequences). Aven (2011a); Vose (2008) define the risk in the same way. Vose (2008, Page 3) state that the risk as "a random event that may possibly occur and, if it did occur, would have a negative impact on the goals of the organisation. Thus, a risk is composed of three elements: the scenario; its probability of occurrence; and the size of its impact if it did occur".

Unlike SC risk management literature, the general risk management research has a clear guide around the majority of risk constructs, although there are slight variations of how some researchers view them. The principal terms defined by many risk standards such as ISO 31000 and Glossary of Risk Analysis Terms by Society for Risk Analysis (SRA)

(SRA, n.d). In addition, many academics such as Aven (2011b); Christensen *et al.* (2003) reflect on standards to build a universal appreciation of the terminology. Table 2-2 shows the definitions of some key terms in the risk management area. These terms will be employed to comprehend and classify the SC risk elements.

These definitions of popular terms in the risk management and analysis domain might contribute to SCRM literature due to two facts. The first one is that they clearly distinguish between what is called a hazard, risk source, risk event and their consequences. The second fact is that the relations between these terms are explainable. Regarding SCRM, as I have explored and confirmed by Heckmann *et al.* (2015); Sodhi *et al.* (2012), there is a lack of clarity due to the interchangeable use of different terms. For example, if I adopt the generic risk management terminology; a flood will be called hazard. A SC with a single supplier or a warehouse in the area where the flood can usually occur has the inherent property that can result in a susceptibility (vulnerability) to the hazard. The vulnerability of SC and hazard from a risk source can lead to an adverse event such as the inability of supplier and warehouse to fulfil their orders. This event can lead to consequences such as the financial loss due to order cancellation, where the magnitude of this financial loss can refer to its severity. The uncertainty can be about hazard, the vulnerability of SC, the consequences of the adverse event, and the severity of consequences.

Figure 2-2 describe how risk might be recognised. The vulnerability can be associated with a hazard from a risk source; then an adverse event can be initiated. This event might generate consequences that affect something humans place value on, such as life or money. The magnitude of these consequences determines its severity level. The uncertainty as I mentioned is everywhere. This interpretation of the risk is consistent with the belief of Kaplan (1997); Kaplan and Garrick (1981). While, the emphasis of Kaplan (1997); Kaplan and Garrick (1981) is of the risk event, its probability, and the consequences, more detail has been given about the hazard and vulnerability, that can result in an adverse event. I stress that the identification of hazards and vulnerabilities has a clear impact on identifying which circumstances can lead to adverse events.

Table 2-2: The main terminology in generic risk management domain

Term	Definition	References
Risk source	‘‘Element which alone or in combination has the intrinsic potential to give rise to risk” (ISO, 2009). “Activity or agent that has a potential to cause unwanted or harm consequences” (Aven, 2011, p725).	(Aven, 2011b; ISO, 2009)
Hazard	The inherent property/properties of a risk source are potentially causing consequences/effects.	(Aven, 2011)
Consequences	The impact of the risk event on the objectives (ISO, 2009). Aven (2011) states that the consequences of risk event are deeper than their impact on the objective. The outcome of risk event can be a financial loss, fatalities, etc.	(Aven, 2011b; ISO, 2009)
Severity	Expression of the weight allocated to a consequence/effect based on type and degree (Christensen *et al.*, 2003). The severity refers to the measure of a magnitude such as the size, the intensity, and the scope of something that human values such as the life and money (Aven, 2011b).	(Aven, 2011b; Christensen *et al.*, 2003)
Vulnerability	Intrinsic properties of something resulting in susceptibility to a risk source that can lead to an event with a consequence.	(ISO, 2009)
Risk identification	The designed procedure to identify and list risk sources and their related hazards/threats.	(Aven, 2011b; Christensen *et al.*, 2003)
Risk event	“Occurrence of a particular set of circumstances.”	(ISO, 2009)
Exposure	‘‘The object being subject to a risk source or an event’’.	(ISO, 2009)
Risk analysis	“An analytical process to provide information regarding undesirable events; the process of quantification of the probabilities and expected consequences for identified risks.”	(SRA, n.d)
Threat	A threat is similar to hazards. However, (Aven, 2008) argues that hazard is used for accidental events (safety) associated with risk sources whereas threats are more related to intentional acts (security).	(Aven, 2008)
Risk management	It is coordinated activities to direct and control an organisation about risk. Risk management typically includes risk assessment, risk treatment, risk acceptance and risk communication.	(Aven, 2008)

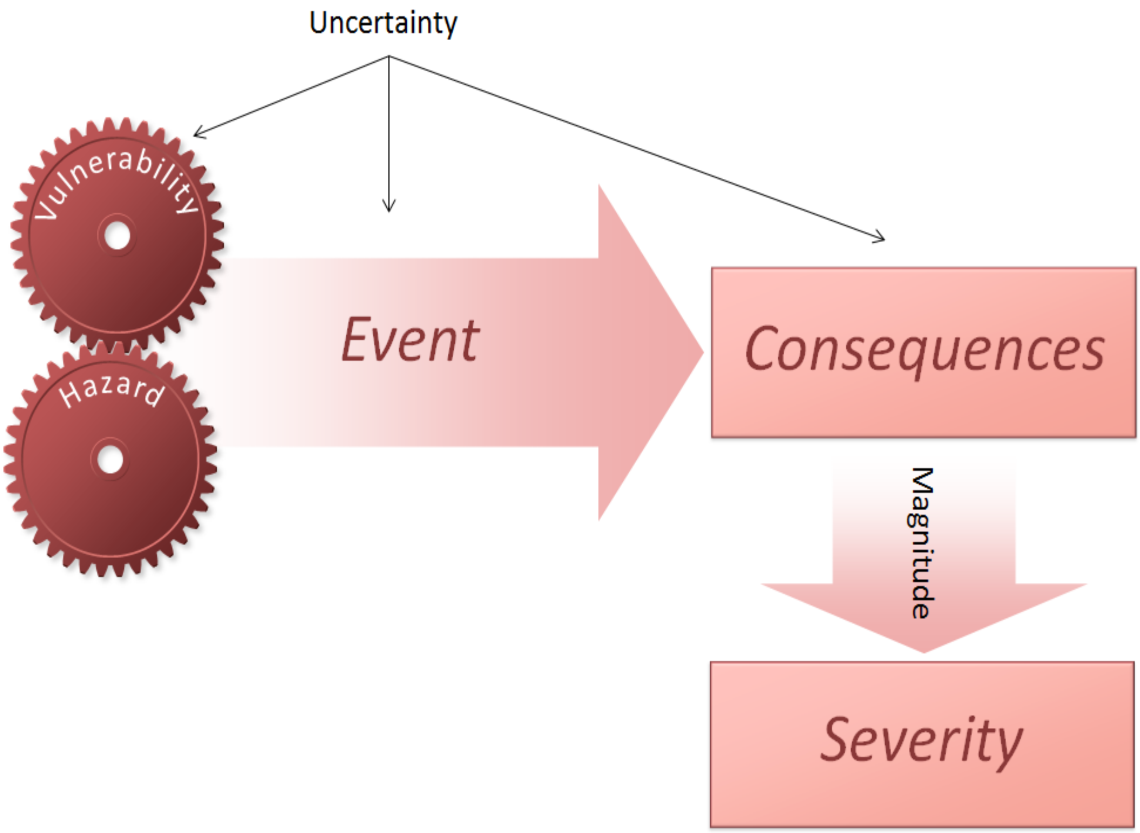


Figure 2-2: Main elements to understand the risk and their interrelationships

2.3.2 SC Risk Analysis in the Light of General Risk Management View

I analyse the key supply chain risk definitions based on Kaplan (1997); Kaplan and Garrick (1981) risk components. Table 2-3 shows the well-cited definitions of SC risk with a reflection of how these definitions have captured the Kaplan (1997); Kaplan and Garrick (1981) risk elements. Table 2-3 illustrates that the supply chain risk has been defined in a way that lacks generalisation. Some authors give a level of detail of risk sources that can be countless and different from one context to another as in Peck (2006). Others mix up risk sources and uncertainty, as in Heckmann *et al*. (2015). Another issue is the ill-differentiation between opportunity and risk as in Spekman and Davis (2004). However, some of the definitions below appear to describe the event, uncertainty and consequences in various ways despite the problem with the level of detail and loose terminology.

Table 2-3: Review of current risk definitions in SCRM domain based on the (Kaplan, 1997; Kaplan, Garrick, 1981) risk elements

Paper	**Definition**	**Risk elements**		
		Event/ scenario	**Uncertainty**	**Consequences**
(Jüttner *et al.*, 2003a)	"The possibility and effect of mismatch between supply and demand."	Not included	The possibility of a consequence	The mismatch between the supply and demand
(Spekman, Davis, 2004)	"The variance in an expected outcome".	Not included	The variance	The variance
Zsidisin, 2003)	"The potential occurrence of an incident associated with inbound supply from individual supplier failures or the supply market occurring, in which its outcomes result in the inability of the purchasing firm to meet customer demand or cause threats to customer life and safety."	Inbound supply risk	Not included	Financial loss for the purchasing firm and customer safety
(Peck, 2006)	"Anything that [disrupts or impedes] the information, material or product flows from original suppliers to the delivery of the final product to the ultimate end-user."	Any event affects the product and information flow	Not included	End-user does not receive the product
(Heckmann, *et al.* 2015)	"The potential loss of a supply chain in terms of its target values of efficiency and effectiveness evoked by uncertain developments of supply chain characteristics whose changes were caused by the occurrence of triggering-events."	Triggering events	Uncertain development of SC	The potential loss of a supply chain regarding its target values of efficiency and effectiveness.

Given the above ambiguity and taking into account the general narrative of the risk, I consider the supply chain risk as "The probability of an event that affects the ability of SC to achieve their objectivities and leads adverse consequences". This meaning of the SC risk includes three primary constructs. These are a) 'hazards and vulnerabilities identification', b) 'understanding the uncertainty' and c) 'the consequences of an adverse event'.

2.3.2.1 Hazards and Vulnerabilities Identification

As I have discussed and shown in Figure 2-2, the perception of the adverse events that lead to consequences requires the identification of hazards that come from the risk sources as well as identifying the inherent vulnerabilities in the system. I have stated that hazards can steer adverse events by themselves or in combination with SC vulnerabilities. However, in SCRM literature; terms such as hazards, vulnerabilities, risk drivers have been utilised interchangeably. Table 2-4 shows the classification of SC risk and how these ‘risk groups’ can be understood in the light of a generic risk management framework. The majority of the risk categories mentioned can be re-classified as risk sources, hazards from the risk sources, and the vulnerabilities of SC to these hazards. However, in the literature of SCRM, there is clear mixing up between these terms.

Re-check the vulnerabilities examples in Table 2-4. I can also notice that the structure of SC (For example, how many suppliers and warehouses), the geographical dimension, the rules that control the supply and the inventory, the available slack in the chain show the vulnerabilities in SC. The latter affix to the SC characteristics such as the operating system, the level of integration and the structure configuration. Therefore, the latter are the SC distinctive features that I aim to show their influence on SC resilience as I mention in Chapter 1.

Table 2-4: Re-understanding the SC risk classification in the light of generic risk management framework

Paper	**Given classifications**	**Proposed re-understanding**		
		Risk sources	**Hazard examples**	**Vulnerability examples**
(Jüttner *et al.*, 2003a)	1) Environmental risk (earthquake, hurricane) 2) Network-related risk 3) Organisational risk.	1) Environment sources 2) Network sources 3) Internal process sources	1) Earthquake, hurricane. 2) Supplier low performance 3) Inventory shortages machine breakdown	1) Geographical location 2) Single supplier 3) Long lead time to replenish the inventory
(Christopher, 2005; Christopher, Peck, 2004)	1) Process risk 2) Control risk 3) Demand risk 4) Supply risk 5) Environmental risk	1) Process sources and Control sources 2) Demand sources 3) Supply sources 4) Environment sources	1) Inventory shortages machine breakdown 2) Demand shift 3) Supplier low performance 4) Earthquake, hurricane storms	1) Long lead time to replenish the inventory, long waiting time to fix the machine 2) Inadequate Forecasting system and marketing research 3) High level of integration 4) Geographical location
(Spekman, Davis, 2004)	Inbound supply, information flow, financial flow, the security of a firm's internal information system, relationship with partners, and corporate social responsibility.	1) Material flow source 2) Information flow sources 3) Partnership source 4) Environmental source	1) Supply shortage 2) Wrong information transmission 3) Contracted supplier low performance 4) Suppliers unethical image	1) Maintain low inventory level 2) Information system 3) Single supplier 4) Supplier selection matrix
(Kleindorfer and Saad 2005)	Terrorism, political instability, natural hazards and operational contingencies.	1) Environment risk sources 2) Operational risk sources	1) Terrorism, political instability, natural hazards 2) Machines breakdown	1) Geographical location 2) Machines age

Paper	**Given classifications**	**Proposed re-understanding**		
		Risk sources	**Hazard examples**	**Vulnerability examples**
(Wu *et al.*, 2007)	Internal and external risks to the SC and to what extent they can be controllable	1) Risk sources from whole SC process including supply and demand zone 2) Environmental sources to whole SC (Controllability can be identified for the hazards and vulnerability rather than the sources)	1) Earthquake: Uncontrollable external hazard 2) Inventory shortages: internal control hazard	1) Geographical location of a warehouse 2) Information system
(Tang, Tomlin, 2008)	1) Supply 2) Process 3) Demand 4) Behavioural 5) Intellectual property 6) Political/social risks	1) Supply sources 2) Process sources 3) Demand sources 4) While, Political/ Social, Intellectual property can be hazards initiate from environment sources, behavioural hazard can be fit in all previous categories	1) Low quality 2) Inventory and manufacturing problem 3) Customer dissatisfaction 4) Unethical supplier, wars	1) Fragile quality inspection system 2) Periodic inventory check 3) Lake of marketing research 4) Centralised warehouse in one geographical location

2.3.2.2 Understanding the Uncertainty

SCs processes and decisions are exposed to uncertainties. According to Klibi *et al.* (2010), the source of uncertainty in SCs can be classified into three broad categories. These are endogenous assets, SC partners, and exogenous geographical factors. Endogenous assets encompass human resources, product inventories, the equipment, vehicles, distribution, recovery, revalorization, and service centres. SC partners include energy and material suppliers, customers (demand zones), third-party logistics providers (3PLs), and subcontractors. These sources of uncertainty are affected by business- as-usual events such as the changing of the market price, exchange rate and catastrophic 'risk events', such as industrial accidents or fires, which may have more severe impact on these sources and contribute more to the uncertainty. Additionally, SC members are located in specific geographical locations and regions (location within network dimension). These areas and their associated public infrastructures are themselves exposed to natural disasters (hurricanes, earthquakes) major accidents (epidemics, chemical/nuclear spills).

Tang (2006) uses the uncertainty to describe the uncertain demand, uncertain supply and uncertain supply capacity. Vorst and Beulens (2002) state that the lack of information about SC processes and its environment is a major factor that contributes to the uncertainty in SC. Samaddar *et al.* (2006) confirm that by asserting that the uncertainty in SC is related to little or no information about SC processes or this information is not visible. On this foundation, I argue that the uncertainty in SC can be due to the lack of knowledge about the hazards that might initiate events that hit SC and the random behaviour of some SC members and variables. This classification is compatible with one widely agreed uncertainty classification. In general risk analysis field, two main types of uncertainty have been reported by Winkler (1996) Abrahamsson (2002), Vose (2008). These are epistemic uncertainty and aleatory uncertainty. Epistemic uncertainty is the phenomenon that represents our lack or incomplete knowledge about one variable or more in the system (System is a generic term. For example, the supply chain can be called as a system). The second type of uncertainty is the stochastic uncertainty or aleatory uncertainty. It can be presented as variability "which is the effect of chance"

(Vose, 2008, Page: 3). For example, the demand can be at any level within a month time interval.

The only satisfactory answer to the modelling of uncertainty is the use of probability (Bouchon-Meunier *et al.*, 2008; Lindley, 2006). Others such as Pearl have the same view (Pearl, 1996). Winkler (1996) considers that the accepted mathematical language for uncertainty is using probability theory because the mathematical rules for this theory are well developed and almost no debate on them (Winkler 1996). There are many interpretations of the probability. The primarily dominated ones are the frequentist interpretation and the subjective interpretation. The frequentist interpretation means that the probability of a particular experiment outcome is the relative frequency of outcome occurrence after repeating the experiment a large number of times under similar conditions. Cooke (2004) calls this aleatory probability. From SC perspective, it means that the probability captures the random behaviour of a SC member or variables. For example, the distribution of the demand shows the different demand levels probabilities based on the historical data about the demand. Regarding the epistemic uncertainty, the subjective probability is the dominated one (Aven, 2011a). The subjective probability has been interpreted as a degree of belief on a rational subject (Cooke, 2004). This subjective belief is needed when there is a lack of historical data about the hazards, event, and consequences. So, their probabilities can be assigned by relevant stakeholders.

As the above probabilities represent the uncertainty around a variable, they are obviously not fixed. The more evidence obtained about the variable; the less uncertainty around the actual value of the variable. Thus, there should be a theory that can capture these probabilities based on the obtained evidence. Bayesian theory has been seen as a useful way to update the probabilities based on the obtained evidence (Abrahamsson, 2002; Aven, 2011a). It has been seen as a way of learning how the probability modified by new pieces of testimony. The celebrated inversion formula (Bayes rule) is the main approach to updating the prior probability by the testimonies. This formula is

$$\mathrm{P}(\mathrm{B}|\mathrm{D}) = \frac{\mathrm{P}(\mathrm{D}|\mathrm{B})\mathrm{P}(\mathrm{B})}{\mathrm{P}(\mathrm{D})} \qquad (2.1)$$

- P (B): the prior probability of B.
- P(B|D) is the probability of B, having taken D into account
- P(D|B), is the probability of D considering the occurrence of B

The above formula is at the heart of Bayesian theory (Pearl, 1989) due to its various utilities to run many models such as Bayesian Belief Networks. Pearl (1989) argue that the best theory to capture the uncertainty is probability theory. However, these uncertainties change based on pieces of evidence, so Bayesian theory is the most appropriate theory to update these probabilities based on evidence. In Chapter 3, I will explore some differences between deterministic modelling approaches that have been practised to analyse SC resilience and DBNs that make use of Bayesian theory.

2.3.2.3 Adverse Consequences

An extensive list of how the supply chain literature papers recognise the consequences of an event that affects the SC. Some of which are presented in Table 2 3. Examples are the financial loss (Zsidisin and Smith 2005, Zsidisin and Ritchie 2008), customers' dissatisfaction (Kull and Closs 2008), and lost thevalue of the efficiency and effectiveness (Heckmann, Comes *et al*. 2015). Jüttner *et al.* (2003), Zsidisin (2003) consider the main aim of SC to describe the consequence of adverse events. Zsidisin (2003) state that the result of 'supply risk' is "the inability of the purchasing firm to meet customer demand or cause threats to customer life and safety". Jüttner, *et al.* (2003) explain that the principal consequence of the supply chain is the mismatch between the supply and demand. Although Zsidisin (2003) mentions the customer life and safety, this could be beyond the SC management responsibility, and more related to safety, operations and quality management teams. However, health and safety problems can be one of SC hazards that paralyses its ability to fulfil customer demand.

The financial loss and customer dissatisfaction, on the other hand, are apparent consequences of the inability to meet the demand on time. However, apprehending the failure of SC to meet its demand is not straightforward as this depends on the acceptable lead time before the demand can be considered as missing, and results in a financial loss and customer dissatisfaction. For example, in a grocery supermarket chain, the acceptable lead time to fulfil store orders are short compared with the lead time to satisfy the demand of the plane orders. Therefore, the demand fulfilment and inability to meet the demand should be defined to consider the financial loss and customer dissatisfaction.

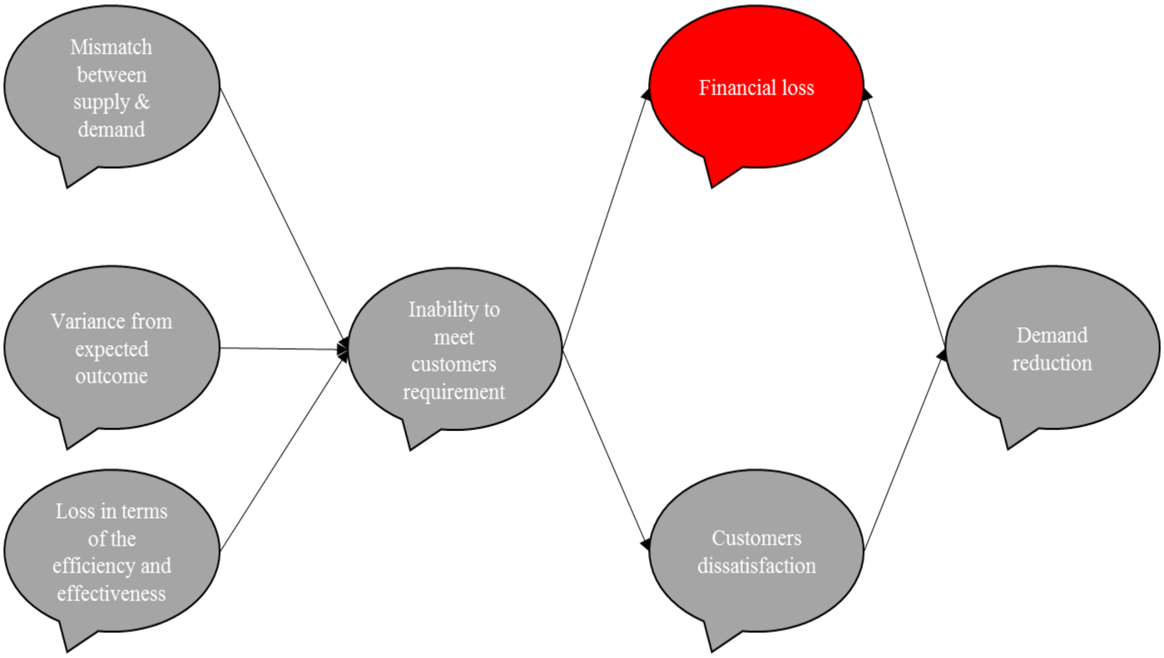


Figure 2-3: The primary adverse SC consequences and the relation between them

Figure 2-3 shows how the literature expresses the consequences of SC risk. While the research reports these consequences in different terms, I notice that all of them lead to the financial loss from inability to meet the customer demand. Therefore, in this research, I will focus on the failure to meet the demand and financial consequences of this disability to explain consequences of adverse events.

2.3.3 SC Resilience Analysis Conceptualization

The discussion in the previous sub-sections only covers three fragments of SCRM (i.e., the identification of hazards and vulnerability, recognising the uncertainty and understanding its consequences). The supply chain risk management does not stop at this point as there is a need to understand managers attitudes toward the risk events and their consequences, the suitable actions that be taken to reduce the chance of the events and to monitor the impact of these actions in reducing the risk. However, the latter steps are beyond the research scope, as the primary interest for this research is to contribute to the analysis stage of the resilience, where the hazards and vulnerability identification, recognising the uncertainty and event consequences add to this analysis.

2.3.3.1 The aim of SC Resilience Analysis Compared to SC Robustness and Responsiveness

The discussion about the similarities and differences between the resilience of SC and other terms that describe the capability of the SC to react to adverse events is requisite to learning what SC resilience analysis should produce. SC resilience, robustness, and responsiveness can give a comparable indication. These terms have been discussed widely in the network and engineering system theory literature including the fault tolerance (Al-Kuwaiti *et al.*, 2008; Hosseini *et al.*, 2016). Although SC literature is not keen on the meaning of fault tolerance, its use in this section is only to give an overall view about the interdependencies between the resilience, robustness and responsiveness.

While the resilience of the system is described by its ability to resist and spring back to its normal state after a disturbance Strigini (2009), the fault tolerance is considered as the capacity of the system to continue to perform its mission in the presence of some failures (Al-Kuwaiti *et al.*, 2008). Accordingly, the system resilience can be regarded as a shift forward from fault tolerance (Strigini, 2009). It includes a fault tolerance property (remains available) and a recovery from degradation. It is not just about having the ability to tolerate a failure but is also concerned about the reaction to that. Considering SC resilience, it is the ability of SC to react and restore to the normal equilibrium if it is being affected (Rice, Caniato, 2003). In essence, the items of SC and general system resilience are the same. However, some researchers such as (Kim, *et al.* 2015) describe resilience as the ability of the SC to withstand the disruption. (Kim, *et al*. 2015) have captured only the fault tolerance property of the SC resilience. I can argue the same for all other attempts that tried to capture the resilience in a static way.

Robustness is another term that often correlates with the resilience. Robustness is expressed as the ability of the system to continue to perform its function in the face of uncertain events (Dekker, Colbert, 2004; Tizghadam, Leon-Garcia, 2008). It stands for the valuable flexibility that leaves many options to be made in a case of adverse events (Rosenhead *et al.*, 1972). The robust system refers to the ability of a system to preserve its functionalities under expected and unexpected failures of some components (Brandes, Erlebach, 2005). Singpurwalla (2006:1) state that “Robustness encapsulates the feature of the persistence of some attributes in the presence of an insult, such as a shock, or an unexpectedly significant change, such as a surge in electrical power, or an encounter with an unexpectedly large (or small) observation” (Singpurwalla, 2006 Page 1). Concerning SC, Snyder (2003) states that the SC robustness represents the strength of SC in the face of uncertain conditions in the demand side whereas, Bundschuh, Klabjan *el at*. (2003) define SC robustness as a measure of a good performance in meeting unexpected events. Klibi, Martel *et al.* (2010) give a generic explanation of robustness. They define SC robustness as the capability of SC to provide a sustainable value creation in the face of all uncertain future events.

A robust system and a robust SC describe the ability to maintain stable outputs in the face of all events. However, Christopher and Rutherford (2004) argue that the robust SC will maintain a stable output with a reasonable variation in the input. For (Christopher and Rutherford 2004) the robust SC does not have the strength to maintain its stable output with all events. This meaning of robustness intersects with the definition of responsiveness. Responsiveness means that how SC retain its outcomes in business as usual cases (Klibi *et al.,* 2010). Therefore, if (Christopher and Rutherford 2004) definition has been granted, SC responsiveness and robustness would have almost identical meanings. However, the consensus between system theory and SC shows that responsiveness is a subset from the SC robustness. It refers to the capability to maintain the outputs in business as usual conditions.

Definitions of system robustness and resilience suggest a link exists between them. A possible explanation for this link can be through considering that the resilience has two sub-elements. The first element is the ability to maintain the stable output (Fault tolerance) and the second one is the recovery in case of the disruption. On the other hand, the robustness is the ability to maintain stable outputs in the business as usual and adverse event cases. Accordingly, the overlap between the robustness and resilience is the fault tolerance. This link proposes that the enhancement of resilience would improve the robustness and vice versa. However, the resilience contemplates the recovery from the disruption to the normal situation, whereas the robustness does not include this dimension.

The difference between the robustness and resilience can impact the type of enablers and how SC can be analysed. SC robustness enablers should aim to maintain the stable outputs in all events. In the resilient SC, the fact that the disruption of outcomes might occur is acceptable, so enablers should be customised for maintaining the ability to react and to enhance the recovery in case of the disruption. Consequently, in SC robustness analysis; the stability of the SC behaviour is checked, so the SC cannot be called robust if its outputs have been affected by adverse events. However, a SC can be still resilient if its outputs have been shifted from its stable state and then recovered.

2.3.3.2 Theoretical Elements to Analyse SC Resilience

In the risk analysis, the primary concern is to learn the consequences of an adverse event on the objectives of SC, while resilience analysis in principle queries ‘the capability of SC to react and recover’. Although researchers seem to agree on the ability of SC to respond and retrieve as the components to describe the resilience, there are differences in tackling four questions. These are: The ability to react to what? Moreover, recover from what? How can we judge that SC is resilient enough, given we know its capability to respond and the recovery time? And how can we compare between the resilience of two SC designs and study the influence of resilience enablers?

2.3.3.2.1 Hazard Scenarios and Adverse Consequences Identification

To answer the first two questions, I analyse the definitions of SC resilience in Table 2-5. I explore the resilience benchmarking issues (i.e. the third and fourth questions) in the next sub-section. As can be seen Table 2-5, the resilience to what and recover from what have not been communicated in the same way. However, they stress the same point that the resilience of SC is the ability to counter and recover from a disruption (expected and unexpected) apart from Kim *et al.*, (2015) with a primary assumption that an adverse event occurs and causes disruption. From a probabilistic view, this means that the probability of the event to happen is 1. It donates the ‘if –scenario assumption’. The reader can notice here the first difference between risk analysis and resilience analysis. In the former, I examine the consequences of the adverse event that can happen or not with a probability value between 0 and 1. However, in resilience analysis, the event is assumed to occur and then I examine the ability of SC to react and recover through the time. In other words, I test the preparedness of SC to that adverse events.

Table 2-5: The main SC resilience definitions and their answers to the ability to react to what? And recover from what?

Paper	**Definitions**	**The ability to react to what? And recover from what?**
(Rice, Caniato, 2003)	“Ability to react to an unexpected disruption and restore its normal operations.”	The sudden disruption. Through the paper, they mention that the unexpected disruption is the "risk" that has low probability to happen
Christopher and Peck, 2004)	“Ability of the supply chain to return to its original state or move to a new, more desirable state after being disturbed.”	The disruption
Ponomarov and Holcomb, 2009, Page: 131)	“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.”	The unexpected events and respond to the disruption
(Kim *et al.*, 2015)	The ability of the SC to withstand with the failure of nodes and arcs.	The failure of nodes and arcs. The recovery is not included

In the literature, there is an argument that a resilient SC should be able to deal with all adverse events. However, this could not be applicable. Although (Rice and Caniato 2003) mention the unexpected disruption, they link that to the disruption that can be caused by low probability events. To recognise the 'resilience' of SC, the hazards, vulnerabilities and the consequences of adverse events should be identified. It is to illuminate the ability of SC to absorb the consequences of particular events and the recovery from them. Decisions to improve the resilience against the hazards can be made. Aven (2011a) state that the resilience conceptually is related to all events although in practice, we have to draw boundaries for which events to include.

If 'arguably' we said that there is no need to identify the hazards that we analyse the SC resilience against; how can decisions be made about suitable resilience enablers such as the SC members that we need to collaborate with and the level of flexibility. A similar analogy is that different diseases require different medicine. It is not relational to say that someone should take medicine for everything with no identification of an illness. Although the medical attention in the majority of the cases is reactive, there are some cases where diseases have been identified and our white blood cells (leukocytes) cannot defend the body against them, so we get vaccinated against them from our childhood. It is for the sake of improving our immune system against them. Therefore, the resilience analysis should incorporate the identification of hazards/ vulnerabilities, check if the current SC configurations can maintain the SC targets, then a decision can be made (there is a need to get a vaccine or not).

2.3.3.2.2 Resilience Measures and Benchmarking

In the previous sub-section, I try to answer the ability of SC to react to what? And recover from what? Also, I have proposed that resilience analysis should have a hazards identification stage. In this section, I endeavour to answer How can we judge that SC is resilient enough, given we know its capability to respond and the recovery time? And how can we compare between the resilience of two SC designs and study the influence of resilience enablers?

While the SC resilience measures tend to be overlooked in the literature of SC Kamalahmadi and Parast (2016), the resilience measures for engineering system appear to be more mature, and several resilience matrices have been recommended (Hosseini *et al.*, 2016). Hosseini *et al.* (2016) have classified them into probabilistic and deterministic measures, and which can be either static or dynamic. The static ones mainly try to draw a picture about the ability of a system to absorb the consequences of adverse events, while the dynamic ones investigate the absorbability and recovery of the system. Although Kim *et al.* (2015) consider a static matrix for SC resilience, I believe that the static measures contribute only partially to understanding the SC resilience due to its limitation in predicting the recovery of the SC. Therefore, the focus of this research is on the dynamic measures only.

The resilience triangle is one way to present the resilience dynamically (Figure 2-4). It has been suggested as a technique to appreciate the resilience of a system and comparing between the resilience of different designs (Zobel, 2011). Resilience triangle is a familiar means to understand the infrastructure resilience. It has been initiated by (Bruneau *et al.*, 2003; Bruneau, Reinhorn, 2007). "Because of its simplicity, the resilience triangle of Bruneau *et al*. (2003) provides a solid foundation for developing quantitative measures that can be applied to resilience in this more general context, as well as in a more focused fashion" (Zobel, 2011, Page. 395).

As can be seen in Figure 2-4, the vertical axis of resilience triangle manifests the strength of the system in maintaining its steady state and the horizontal axis exhibits the recovery speed. The smaller size of a resilience triangle indicates that the system has a better resilient level. Therefore, the improvement of the resilience should aim to reduce the size of the resilience triangle.

In addition to the system strength and the rapidity of recovery, resilience triangles show

- Resourcefulness: the level of capability for dynamically responding to an adverse event,
- Redundancy—the extent to which components of the system are substitutable, and therefore able to be replaced

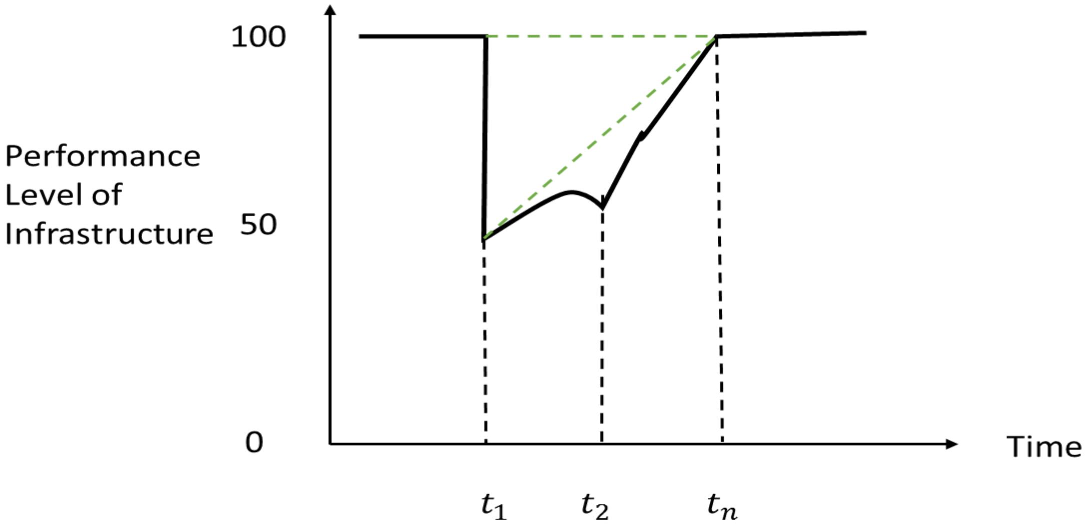


Figure 2-4: The resilience triangle adopted from (Bruneau, Chang et al. 2003)

The resourcefulness and redundancy are means to improve the resilience (Bruneau and Reinhorn 2007). The resilience triangles can be used to inspect the resilience of a supply chain, compare between the resilience of different configurations, and to check the impact of some decision on the supply chain resilience (Agha *et al.*, 2012a; Agha *et al.*, 2012b). However, the vertical axis (Figure 2-4) refers to the level of operation of the infrastructure. It is different from the objectives of SCs. For the SC in particular, Barroso *et al.* (2015) adopt as in (Agha *et al.*, 2012a; Agha *et al.*, 2012b) the fulfilment rate instead of the total quality in the vertical axis. The fulfilment rate is the percentage of units fulfilled comparing to the actual demand in a certain time horizon. However, Barroso *et al.* (2015) do not consider the uncertainty around the fulfilment rates.

The inoperability of the sector and the economic loss have also been considered as resilience indicators of a system by (Barker, Santos, 2010; Pant *et al.*, 2014a; Pant *et al.*, 2014b; Santos, Haimes, 2004b). Santos and Haimes (2004a) uses the normalised inoperability matrix and how this inoperability is propagated across the economy to investigate the effect of the disruption. The inoperability is the percentage of economic loss that is being normalised by the planned production. It can be expressed as:

$$\mathbf{q_i} = \frac{\mathbf{x_i^0 - x_i}}{\mathbf{x_i^0}} \ \forall \mathbf{i} \qquad (\mathbf{2.2})$$

$0 \leq q_i \leq 1 \ \forall i$

x_i^0: As planned output (production)

x_i: The reduced level of output due to disruption

$x_i^0 - x_i$: The economic loss due to disruption

The (Santos and Haimes (2004) is improved by the work of Lian and Haimes (2006). Lian and Haimes (2006) insist the importance of weighing the time element to estimate the inoperability and the resilience of the economy. The value of taking the time element is to see how the system will recover over the time and economic loss associated with the recovery through time. Then, decisions can be made to improve preparedness and minimise the loss. For a particular industry (i) at specific time interval, the inoperability can be measured as:

$$\mathbf{q_i^t} = \frac{\mathbf{x_i^0(t) - x_i(t)}}{\mathbf{x_i^0(t)}} \ \forall \mathbf{i} \qquad (\mathbf{2.3})$$

$\mathbf{x_i^0(t)}$: As planned output (production) at particular time interval

$\mathbf{x_i(t)}$: The reduced level of output due to disruption

$\mathbf{x_i^0(t) - x_i(t)}$: The economic loss due to disruption

To measure the resilience of infrastructure, Ouyang *et al.* (2012) suggest the use of a time-dependent expected annual resilience (AR) metric that has a probabilistic nature. It is "the mean ratio of the area between the real performance curve and the time axis to the area between the target performance curve and the time axis during a year" (Ouyang *et al.*, 2012, Page: 25). Another probabilistic measure was proposed by (Ayyub, 2014). Ayyub (2014) examines the resilience of a system based on probability density functions of the age of the system, the time to failure and the time to recovery. He states that the time to failure denotes the robustness of the system whereas time to recovery represents the redundancy of the system.

Despite the differences between the above measures, they all stress the value of comparing the steady state outputs of the system and its outcomes during and post hazard scenario occurrence to explain the resilience. Therefore, it can be said that to analyse the SC resilience, its base behaviour should be first described. The study of SC base behaviour of the system and its resilience requires digging into the distinctive characteristics of SC system. Hosseini, Barker et al. (2016) mention the importance of studying the distinctive characteristics of the system. For example, I believe that Ayyub (2014) matrix would not be appropriate for SC due to its central focus on a technical system where the age of this system is vital to understand its resilience. In Chapter 3, I will introduce some SC features that might affect its resilience analysis.

2.3.3.2.3 The Recovery Function of Affected Member

Baghersad and Zobel (2015); Zobel (2014) point out the significance of comprehending the recovery of affected system member by the adverse event to recognise the system. Zobel (2014) proposes three parametric recovery functions that are related to the level of preparedness. These are the exponential recovery to donate a well-prepared situation for affected member. It can be expressed mathematically as:

$$\mathbf{k_i^t = 1 - \gamma[exp(-\frac{(t-t0)\ln(n)}{T}) - \frac{(t-t0)}{nT}]} \qquad (\mathbf{2.4})$$

The linear recovery to show the average prepared situation as in (2.5):

$$\mathbf{k_i^t = 1 - \gamma\left[1 - \frac{(t-t0)}{T}\right]} \qquad (\mathbf{2.5})$$

and the inverted exponential recovery to illustrate the ill-prepared situation.

$$\mathbf{k_i^t = \ 1 - \gamma[1 - exp(-\frac{(T-(t-t0))\ln(n)}{T}) + \frac{(T-(t-t0))}{nT}]} \qquad (\mathbf{2.6})$$

$\mathbf{k_i^t}$ refers to the resilience coefficient at time t. It is the ratio of recovery to planned output each time interval. For example, $\mathbf{k_i^2}$ equal to 0.7 mean that in the second time interval, after adverse event occurrence, the affected supply chain member will be able to deliver 70% from its planned output before the occurrence of the adverse event

$\boldsymbol{\gamma}$ shows the initial impact of the adverse event on the output of a sector

$\mathbf{n}$ donates the level of concavity in the recovery curve

T is the time horizon for a full recovery

Baghersad and Zobel (2015) employ the mentioned recovery functions to estimate the recovery of the economy if a particular sector has exposed to an adverse event. The parameters of the recovery functions have to be assumed. In practice, the use of these functions raises questions about how their parameters of the recovery functions can be estimated. This research will explore these types of recovery in Chapter (3) briefly. However, the recovery for affected SC members for DBNs in this research is nonparametric. It relies mainly on the uncertain relationship between the hazard scenario states and the affected SC member output states as I will see in the case studies chapters.

2.4 Concluding Remarks

The SC resilience literature is still in its infancy and interconnects with SCRM literature in many approaches. Although many SC resilience definitions and enablers have been discussed in the literature, there is still a level of ambiguity around how the SC resilience can be estimated while considering the uncertainty around the SC processes. The main consequence of this incertitude could be the little work around the quantitative resilience analysis side. Similarly, for the SC risk management, many definitions conceptually have been suggested with no critical recognition of how these definitions can help to support the analysis of risk. Through this chapter, I have tried to illuminate this ambiguity by considering a wide range of literature on system risk and resilience. I have critically assessed the definitions of the risk, resilience and the terminology that have been used to describe them.

I have shown through discussing the interrelation between SC resilience, robustness, fault tolerance and responsiveness that the resilience analysis should focus on understanding how the SC absorb the consequence of adverse event and recover from them considering the available resilience enabler. So, the SC resilience analysis aims to understand the level of resilience through the consideration of adverse events that might affect the ability of SC to meet its target and the available resilience enablers to maintain this ability and enhance the recovery. This stresses the importance of 'hazards and the vulnerabilities identification’ to analyse the SC resilience. I have illustrated that for resilience analysis the adverse event is assumed to occur. Then, I examine how the SC react to this occurrence with taking into account the uncertainty about that reaction. Different matrices to measure the system resilience have been studied. These matrices, in principle, focus on learning the steady state of the system, and then check the output of the system if an adverse event occurs to find out its resilience level. I point out that system distinctive characteristics are vital to understanding its resilience level due to their contribution to understanding the behaviour of system prior, during and post event occurrence.

In Chapter 3, I will try to draw a picture around how SC has been modelled as a complex system to understand its resilience. Then, I will show the theoretical suitability of DBNs to understand SC resilience based on its characteristics and the uncertainty around its processes.

3 Modelling SC Resilience Based on their Characteristics: The Potential Role of Dynamic Bayesian Networks

3.1 Introduction

Chapter 2 has shown that SC resilience analysis is still in its infancy with a lack of main pillars that can guide the modelling process. The few attempts to advance the SC resilience analysis show that scholars from different backgrounds try to approach the field. Some of these models dealt with the supply chain as any other engineering or network system with implicit or explicit assumptions about the visibility to whole SC structure as in Kim *et al*. (2015) and Garvey *et al*. (2015) respectively. However, I have shown in the previous chapter and point it out by Hosseini *et al. (*2016) that the system distinctive characteristics play a role in understanding its resilience level. In this chapter, I will illustrate where the generic network theory models fall short in understanding the resilience of SC. Then, I will introduce Dynamic Bayesian Network as a model that can assist to understand the SC resilience based on its characteristics.

3.2 Modelling Supply Chain Resilience as a Complex System

Some authors such as Soni *et al.* (2014), Kim *et al.* (2015) consider SC as a complex system to analyse the SC resilience. However, the latter attempts refer to the resilience as a static concept that does not measure the recovery of SC. Similarly, Osadchiy *et al.* (2015) study the complex SCs system to understand the systematic risk (i.e. the correlations between the output of the affected industry by an adverse event and the market outputs of other industries during and after the occurrence of this event. Osadchiy *et al.* (2015) make use of Input-Output (I-O) data to find out the correlations. I-O analysis is an economic term that symbolises the investigation of the influences that different sectors have on the economy either as whole or for a particular region. Thekdi and Santos (2015) use the Dynamic Inoperability model to understand supply chains resilience with taking into account the dynamic nature of the resilience. Dynamic Inoperability model is an extension of Input-Output analysis. The Inoperability and Dynamic Inoperability model of Lian and Haimes (2006); Santos and Haimes (2004a) have utilised in many applications with regard the resilience. For example, Pant *et al*. (2014) deploy the model to explain the disruption in inland waterway networks. The model has also been applied to understand the impact of the workforce on pandemic recovery (Santos *et al.*, 2009), the effects of the August 2003 Northeast Blackout (Anderson *et al.*, 2007) and the economic impact of port closure (MacKenzie *et al.*, 2012). However, for a micro level view for the SC as in my research, the use of I-O model and its Dynamic Inoperability extension ignores the SC primary attribute as a sequential system. The supply chain is a network of members that transform the materials into a final product and deliver this product. The underlying assumption is that the flow of the material is in one direction. The flow is from the raw material suppliers to final customers. For example, the manufacturers' processes are dependable on their suppliers' output and not vice versa. However, in the I-O model, the assumption is that there are interdependencies between the sectors in both directions. The output is seen from a macro level where the final demand of each sector contributes to the total economy output. Figure 3-1 shows the I-O relationships at the micro supply chain.

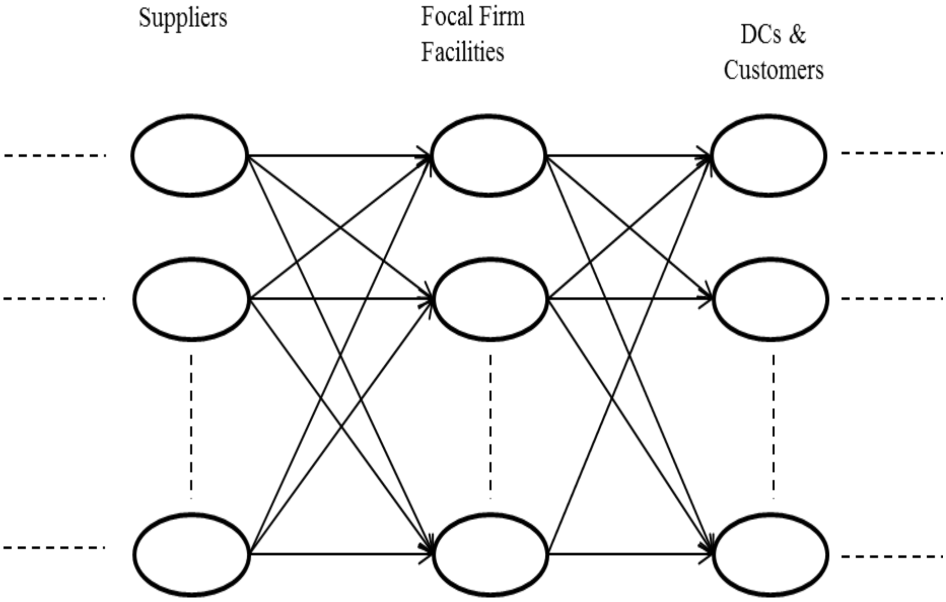


Figure 3-1: I-O relationships for the SC from material flow perspective (Micro level)

Table 3-1 shows how models that consider SC as a complex system deals with the identified SC characteristics and resilience analysis. These models are a deterministic view of the SC. They ignore the uncertainty around the flow in the SC. They also ignore the uncertainty about the impact of adverse events on the output of the affected SC member. The other major shortcoming of this type of models is that they deal with assumed recovery functions of SCs members with no actual consideration of how these recoveries can be elicited in a sensible way. To illustrate how the deterministic recovery functions, I employ the three parametric recovery functions in Section 2.3.3.2.3. I assume that the initial impact is 0.6, n=200 and T=6. The three recovery functions (k_A^t) are visualised in Figure 3-2. The recovery curves in these cases show how the preparedness of the supplier (A) affects the recovery. Instead of predicting the recovery of SC members, the model focuses on generating the economic loss based on different recovery functions of the affected SC member. This is by comparing the output of each member before and after the disruption to find out the economic loss.

Table 3-1: Factors that can help to evaluate the role of DBN in informing the resilience analysis in comparison to complex system models

Factor	**Models that consider SC as complex system**
Deal with interdependencies (Dependency level)	It shows the dependencies by understanding the ratio of the output of the member to the input of other members
Understanding the impact of SC structure	It provides a simpler way to deal with structure through a direct computation. So end to end SC can be modelled when there is a visibility to whole SC.
Show the impact of some decision rules in triggering the flow (operating system)	Deterministic view of the material flow, so the information plays no role across the time intervals
Deal with the uncertainty	No
Understanding the recovery	Deal with Recovery functions, so there should be an assumption about the time to recover and how the recovery curve are going to be.
Factors that contribute to understanding the occurrence of adverse event	No consideration of such factors
The impact of adverse event	It considers the deterministic value about the initial impact of hazard occurrence on the output of the affected SC members and the type of the recovery function (k_i^t)

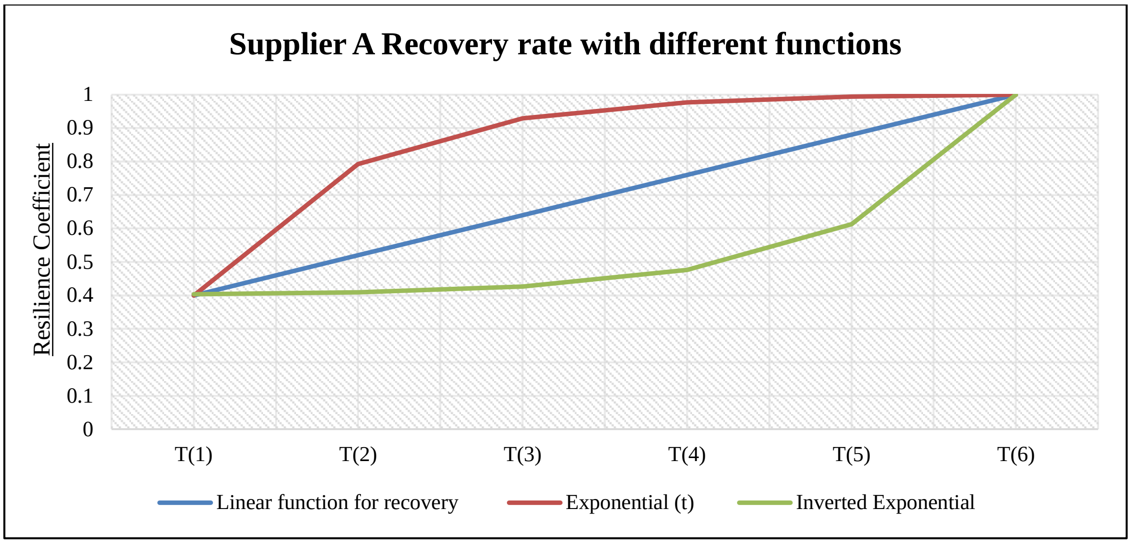


Figure 3-2: Supplier (A) recovery with three types of recovery functions

On the other hand, complex theory models are capable of dealing with complex SC structures based on several assumptions. However, it pays no attention to the role of information and decision rules in controlling the material flow in the SC. It also assumes that the visibility to SC structure and the input and output of each member. It is similar to the work of Soni *et al*. (2014), Kim *et al*. (2015) who exploit the graph theory to appreciate the critical nodes in the SC and check the effect of their disruption on the connectedness of the network. They assume that there is static material flow between the SC members that can be used to capture the criticality of nodes and arcs. However, in the reality, these types of assumptions need further research to evaluate their viability.

3.3 DBNs to Inform SC Resilience Analysis

In the literature of modelling static and Dynamic Bayesian Networks (BBNs and DBNs) are increasingly popular methods for reasoning under uncertainty. While static Bayesian Belief Networks aim to analyse/ make inference about a problem at a particular point of the time, Dynamic Bayesian Networks seek to understand the uncertain consequences through the time. These networks employ the probability theory and Bayes rule to capture the interdependencies between a set of random variables. One benefit of these networks is that the partial knowledge about one variable helps to update the uncertainty about other variables in the network

Some attempt to use DBNs and BBNs to analyse the resilience of complex engineering system from an operations management view have been proposed. Hosseini *et al.* (2014) employ Bayesian network as a quantitative tool for the assessment and analysis of electric motor supply chain and design. They propose that the quantification and analysis using Bayesian networks would empower system designers to have a better grasp of the weakness and strength of their own systems against system disruptions induced by adverse failure events. Similarly, Yodo and Wang (2016) use Bayesian network (BN) a quantitative tool for the assessment and analysis of the resilience of engineered systems. They conclude also that resilience quantification and analysis approach using BNs would empower system designers.

In contrast to the complexity theory models that assume the visibility about to the whole network and deterministic nature of the material flow, Dynamic Bayesian Networks is an uncertainty modelling approach that considers the knowledge of decision makers about the system and aims to support particular decisions to improve the resilience of SC in the presence of uncertainty. By examining DBNs to analyse SC resilience, I aim to predict the uncertain absorbability and recovery of SC. Therefore, DBNs do not assume particular recovery functions. This makes also DBNs different for simulation models such as discrete events simulation (DES). In DES , the primary assumption is that a work centre will be down due to shock for a particular period to generate the statistical measures of the SC resilience as in (Brintrup *et al.*, 2013). Therefore, the recovery is deterministic. In addition, in simulation models as the discussed complex theory models, there is no consideration to how adverse events affect the output of particular work centre and the uncertainty around this influence.

3.3.1 DBNs Graph

Bayesian Belief Networks (BNNs) use Bayesian theory to run the probabilistic inference and learn about the uncertain situation. BBNs model uncertainty by showing the conditional dependencies between different variables (Pearl, 1989). DBNs are an extension of BBNs that take the time into consideration. They represented by a directed acyclic graph (DAG). DAG is one type of graphical models with no loops from a variable back to itself is allowed in the same time interval. Nodes in the graph represent uncertain variables and arcs represent causal links between variables (Mihajlovic, Petkovic, 2001; Murphy, 2002; Neil *et al.*, 2009; Neil *et al.*, 2007; Oliver, Horvitz, 2005; Wu *et al.*, 2015). DBNs combine the graph theory and probability theory to provide a model for representing and dealing with two problems: the uncertainty through the time and complexity. The uncertainty of event outcomes captured by a prior probability distribution. This probability may be subjective or empirical. Parent nodes (i.e. initiating events with no influencing variables) is represented by direct probabilities, while the conditional probabilities depict the child nodes (i.e. one having at least one parent node or some dependency on another variable).

Dynamic Bayesian Networks introduce the concept of time-based dependencies that capture the dynamic behaviours of variables (Cuaya *et al.*, 2013; Murphy, 2002; Wu *et al.*, 2015). If I consider a set of random variables $X_1, X_2, X_3 \ldots\ldots X_n$. A DBN model is defined to be a pair (L, L'). L is a BBN defines the prior $P(X_t)$. L' is a two-time stage BBN labels by $P(X_t|X_{t-1})$. The latter means the probability of X_t given the states of some variables in the previous time interval. In the equation (3.1), the conditional probability distribution of a variable is shown. X_t^i represents a particular random variable at time t, $Pa(X_t^i, X_{t-1}^i)$ stands to the parents of this variable in time t.

$$P(X_t^i | X_{t-1}^i) = \prod_i^n P(X_t^i | Pa(X_t^i, X_{t-1}^i)) \qquad (3.1)$$

The nodes in the first time interval of a DBN do not have meaningful parameters due to the obvious non-consideration of the time-based dependencies. Thus, the parameters in the first time interval are usually assumed to run the analysis (Li, 2007; Murphy, 2002). However, each node in the second time interval of the DBN has a conditional probability distribution that defined by $P(X_t^i|Pa(X_t^i, X_{t-1}^i)$ for all $t > 1$. In other words, the conditional probability distributions for the DBN have two elements. The first one is the 'within time interval distribution' that dispense the relationships between variables in the same time interval. The other distribution is the 'across time intervals distribution' that illustrates the probability of $X_t$with parents at time $t-1$. According to Wu *et al.* (2015), the parameters of DBN can be assumed to be time invariant or variant depends on the case. Similarly, the time intervals of the model can be homogeneous or nonhomogeneous. The 'time variant parameters' and 'nonhomogeneous time intervals' means extra quantification burden. However, the parameters and the time intervals in the majority of the cases are assumed to be time invariant and homogenous (Wu *et al.*, 2015).

3.3.2 Example of DBN Graph

My example is necessarily very simple since my goal is to illustrate the principles of DBN graph and the moving from BBN to DBN.

3.3.2.1 Example Assumptions

First, I assume that the SC has the following properties:

1. A single tier SC;
2. Independent transportation routes;
3. Variables states are discrete;
4. The demand is fulfilled directly from the supply nodes. So, the role of inventory has not considered;
5. The decision rules (information) that trigger the process in the SC is ignored;

I further assume that the SC is to be modelled within a single time interval under normal conditions. Finally, I assume that the variables representing supply, transportation and demand each have three states of nature. These are defined as:

1. Supply
    a. State 1: 100% of demand supplied
    b. State 2: 50% of demand supplied
    c. State 3: 0% of demand supplied
2. Transportation
    a. State 1: 100% of the material from the supplier can be transported
    b. State 2: 50% of the material from the supplier can be transported

    c. State 3: 0% of the material from the supplier can be transported

3. Demand
    a. State 1: 100% of the demand is satisfied
    b. State 2: 50% of the demand is satisfied
    c. State 3: 0% of the demand is satisfied

3.3.2.2 DBN Structure for a Dyadic SC (One time interval)

Figure 3-3 (a) shows the dyadic SC with one supply and a demand node for which the qualitative DBN (BBN) for one time interval is given Figure 3-3 (b). The DBN captures the logic that both the supply and transportation will together influence demand, even though the state of transportation is statistically independent of the state of the supply node.

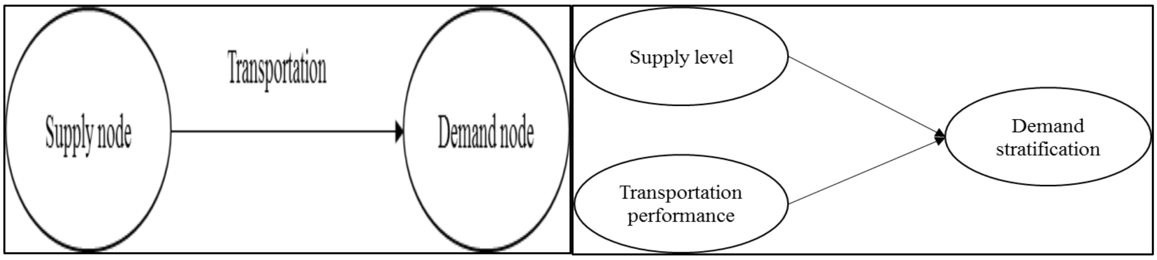


Figure 3-3: Figure 3-3 (a): Simple dyadic SC, Figure 3-3 (b): “One time interval DBN” for figure 3-3 (a)

The uncertain behaviour of the SC can be quantified by assigning probabilities to all states of all root nodes (i.e. nodes have no parents) over the specified time window. For states 1, 2, 3 of each of the root supply and transportation nodes (*i* =1, 2, 3, 4) I can denote these probabilities by p_{i1}, p_{i2}, p_{i3} respectively, where $\sum_{j=1}^{3} p_{ij} = 1$ Each probability represents the average uncertainty in the state of each node over the time horizon. For nodes that have parents (i.e. demand node in Figure 3-4 (b)), then we need to specify the conditional probabilities. In my examples in this sub-section, the values will be Boolean logic variables where 0 [1] denotes off [on] setting. An example of the conditional probabilities of the state of one demand node is shown in Table 3-2. As both nodes are required to provide products to satisfy the demand, we say that they are complementary.

In contrast, when either node can provide products to satisfy the demand, we say that they are alternates.

Table 3-2: Conditional probabilities for demand satisfaction node in figure 3-4 (b)

Supply level	**Transportation performance**	**Demand satisfaction**		
		100%	50%	0%
100%	100%	1	0	0
100%	50%	0	1	0
100%	0%	0	0	1
50%	100%	0	1	0
50%	50%	0	1	0
50%	0%	0	0	1
0%	100%	0	0	1
0%	50%	0	0	1
0%	0%	0	0	1

3.3.2.3 DBN Structure for SC with Multiple Dyadic Relationships

I extend my simple dyadic network by allowing two supply nodes to supply a demand node. This requires an additional transportation route as shown Figure 3-4 (a). It also requires me to articulate the capacity of supply nodes and the transportation route. It is implicit that when in state 1 (100% of supply), supply node 1 has the capacity to fulfil the total demand of a demand node. Similarly, when the node at state 2, it has the capacity to fulfil 50% from the demand. The main difference between the DBN for the SC in Figure 3-4 (b) and the simple dyadic network, as in figure 3-4 (b), is that the state of demand node 2 depends on the state of supply nodes 1 and 2 as well as transportation 1 and 2.

Table 3-3 shows the conditional probabilities for demand node and shows that the introduction of a new route between the supply node 2 and the demand node increase the chance that the level of demand satisfaction will be at state 1. This can be attributed to the increase of the redundancy level in the SC.

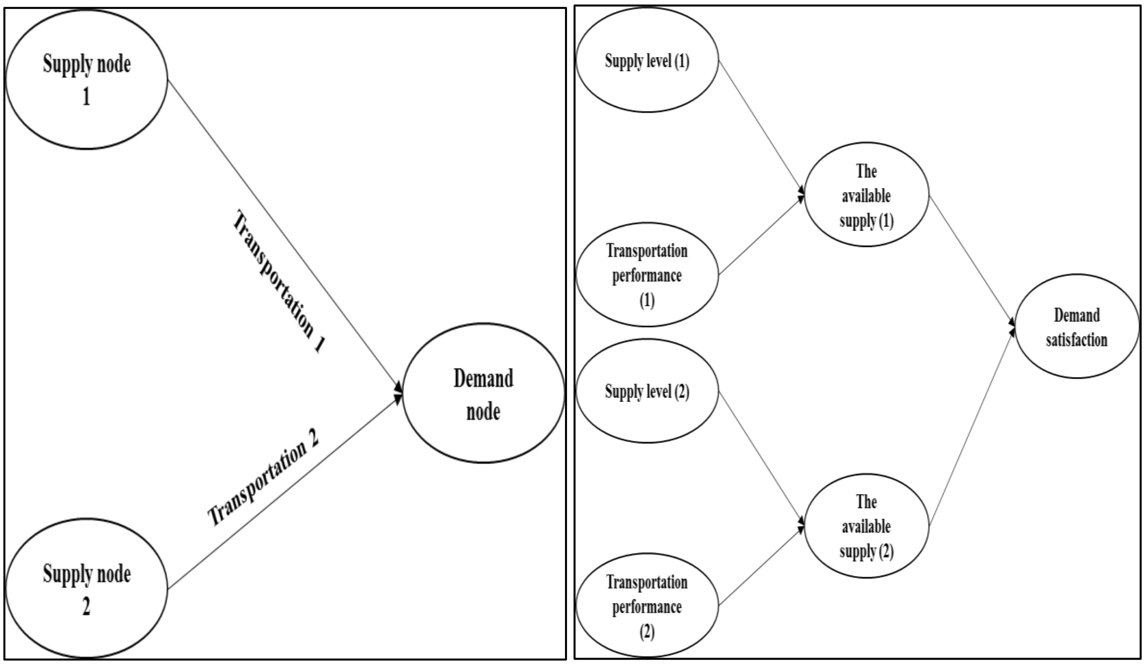


Figure 3-4: Figure 3-4 (a): Simple SC with two supply nodes, Figure 3-4 (b): “One time interval DBN for (a)

Table 3-3: Conditional probability for demand satisfaction node in figure 3-5 (b)

Supply 1 and Transportation 1 (The available supply 1)	**Supply 2 and Transportation 2 (The available supply 2)**	**Demand Satisfaction**		
		100%	50%	0%
100%	100%	1	0	0
50%	100%	1	0	0
0%	100%	1	0	0
100%	50%	1	0	0
50%	50%	1	0	0
0%	50%	0	1	0
100%	0%	1	0	0
50%	0%	0	1	0
0%	0%	0	0	1

3.3.2.4 Modelling Supply Resilience Using DBN

Now let us consider an example of how Dynamic Belief Network (DBN) can be used and assists in examining the impact of external events on the performance through time. To monitor dynamic effects, the state of a node in the previous time is considered to provide an assessment of the state of a node in the current time interval. Hence, we require obtaining the probabilities that a supply node is in a particular state at time point T+1 conditional upon it being in a given state at time point T, as well as the probabilities of the parent and child nodes. DBN allows me to measure the impact of hazards on the SC and to monitor its recovery. In this way, I can gain insight into SC resilience.

Assume that the SC in Figure 3-4(a) with two supply nodes and one demand node operating in the same geographical area which is at risk of experiencing major external natural hazards. Figure 3-5 shows the DBN for this SC. The main difference between the presentation of DBN in Figure 3-5 and 3-4 (b) is that the causalities across the time intervals have been shown by dashed arrows. Note that the available supply (1) and (2) nodes are interim nodes (only used for visualising calculation purpose). Therefore, they do not depend on their state in the previous. Using the DBN model, we can examine the behaviour of the SC to compare its recovery rate and its ability to react under different scenarios. In particular, the effects of a natural hazard, which I label a catastrophe in Figure 3-5.

Figure 3-6 shows output from the DBN for the example. Figure 3-6 (a) displays the base behaviour of SC before the catastrophe is assumed to occur. Figure 3-6 (b) exhibits the behaviour of SC in meeting the demand where the catastrophe is supposed to happen. The ability of SC to react to the demand decreases sharply immediately after exposure to the catastrophe then begins to recover gradually at T3 and T4. The SC reaches its typical pre-catastrophe behaviour by the fifth time interval. In the next section, I will explore the property of DBNs and their building process to create a picture of how they can apply for real SCs.

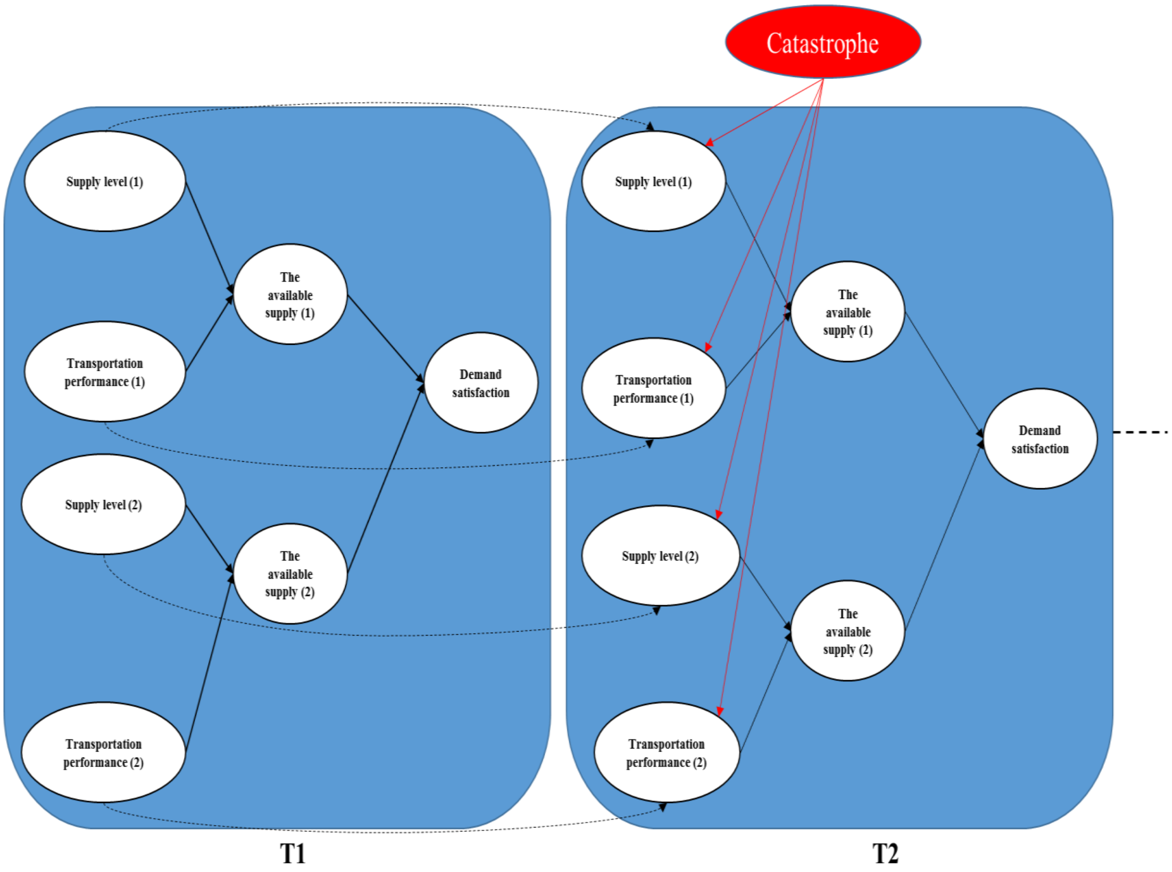


Figure 3-5: DBN for a SC that can be affected by a catastrophe

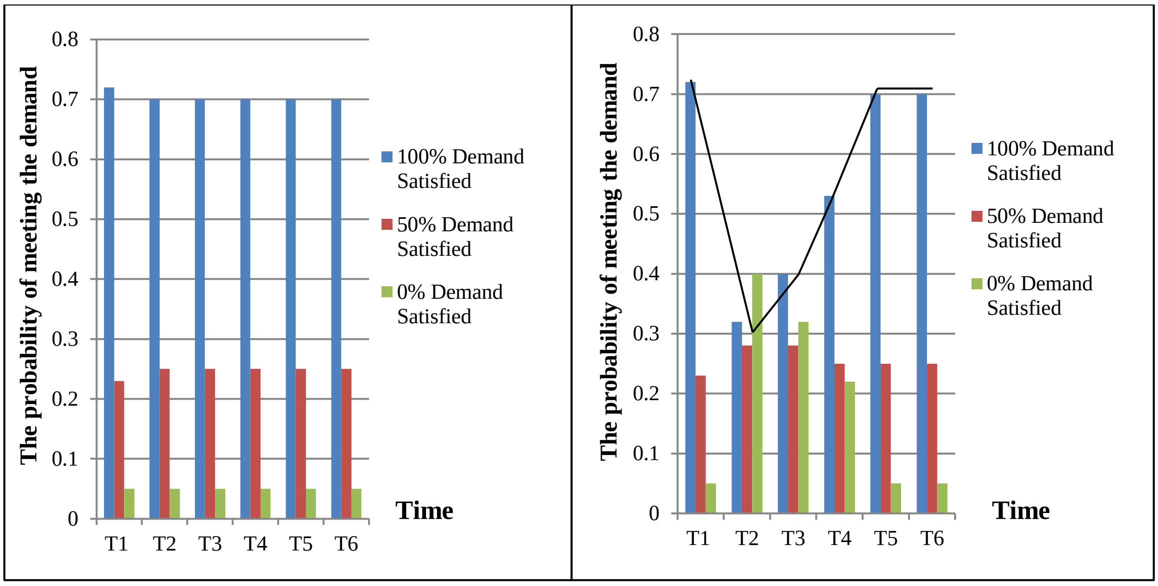


Figure 3-6: DBN output for the example

(a): SC base behaviour (b): Catastrophe effect and resilience triangle

3.3.3 Conditional Independence Property of DBN Graph

The conditional independence assumption is the main property of DAG. The conditional independence assumption reduces the burden of the computation and helps to order the variables especially in the complex application by considering how the knowledge about two events impacts each other. Independence and conditional independence are familiar concepts in the probability theory. They form the basis of several areas of study, such as limit theorems, Markov chains and statistical inference (Dawid, 1979). Two events are said to be independent if the occurrence of one of these events gives no information about whether or not the other event will occur; that is, the events have no influence on each other. In the probability theory, two events (A and B) are independent if the probability that they both occur is equal to the product of the probabilities of the two individual events (Kadane, 2011).

In the literature, three cases have been shown to illustrate the conditional independence in the DAG (Bishop, 2006). These are a tail-tail, head-tail and head-head relationships. In DBN, all these below relationships can be within the same time interval or across time intervals.

3.3.3.1 Tail-Tail Relationship

Figure 3-7 shows three random variables A, B and C at a time interval $\mathbf{t}$. Tail to tail relationship purports that $\mathbf{C_t}$is a parent of $\mathbf{A_t}$and $\mathbf{B_t}$ or a common cause for two effects $\mathbf{A_t}$ and $\mathbf{B_t}$. As can be seen Figure 3-7, the arrows are going from $\mathbf{C_t}$ towards $\mathbf{A_t}$ and $\mathbf{B_t}$. Assume that $\mathbf{C_t}$ has been observed. The observation of $\mathbf{C_t}$ will block the path between $\mathbf{A_t}$ and $\mathbf{B_t}$. It indicates that no knowledge about $\mathbf{B_t}$ can be obtained if $\mathbf{A_t}$ has been occurred given $\mathbf{C_t}$ and vice versa. The below relation can be cross the time intervals. For example, $\mathbf{C_{t-1}}$ (the remaining inventory level for example) can affect $\mathbf{A_t}$and $\mathbf{B_t}$ (the current supply and the inventory level).

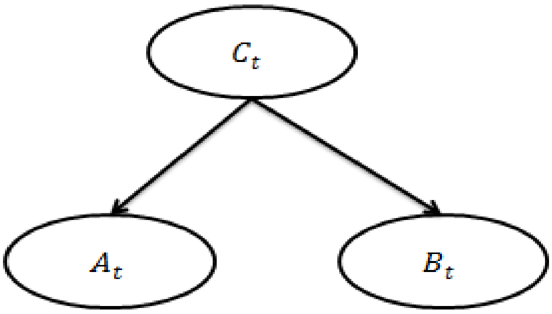


Figure 3-7: Tail-Tail graph

Example 1:

Assume that a single stage multiple dyadic SC configuration has one supplier that supplies raw material for two factories A and B Figure 3-8. In our mental model, we sometimes know that the monthly deterioration of factory A performance is associated with the monthly deterioration of factory B performance. So, there can be a positive statistical correlation between degradation of two factories performances. In other words, they can be statistically dependent on each other. However, the introduction of a supplier performance node proposes that the cause of the deterioration for the two factories performances is that the monthly performance of their shared supplier. Therefore, their monthly performances are conditionally independent giving the monthly supplier performance.

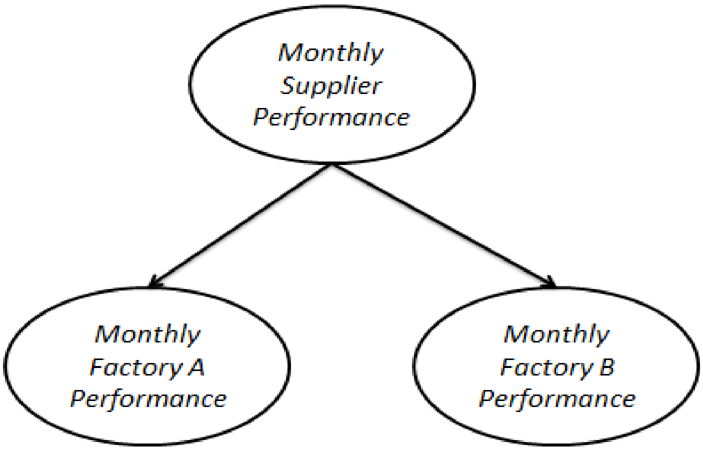


Figure 3-8: Tail -Tail relationship for single stage multiple dyadic SC configurations

3.3.3.2 Head–Tail Relationship

In Figure 3-9, the node C_t is said to be head-to-tail with respect to the path from $A_t$to B_t. Before the observation of C_t such path implies that A_t and B_t are dependent. However, if C_t has been observed then A_t and B_t become conditionally independent because C_t will block the path between them. However, as in the previous case; this relationship can be understood through time intervals. For example, the probability distribution of supplier performance at current time interval can be related to its performance probability distribution in the previous time interval.

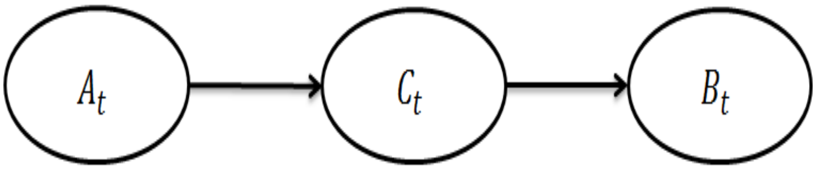


Figure 3-9: Head-Tail graph

Example 2:

Figure 3-10 shows two stages dyadic SC that consists of two tiers suppliers. Supplier B supplies to supplier A that supplies to the factory A. The inclusion of 'supplier A monthly performance' for this case blocks the path between 'factory (A) monthly performance' and 'supplier (B) monthly performance'. Thus, factory (A) and supplier B monthly performance are conditionally independent considering the performance of supplier (A), although there might be a statistical dependency between factory (A) and supplier B monthly performance.

The monthly distribution of the factory (A) performance is also affected by its previous monthly performance distributions. The observation of factory (A) monthly performance in time t will block the path between the factory performance at time t_1 and the other time intervals beyond the monthly performance at the previous time interval. The latter again steer less calculation burden by the ability to ignore the relation between factory

(A) monthly performance in time t_1 and its monthly performance at time $\mathrm{t}-1$ and backwards.

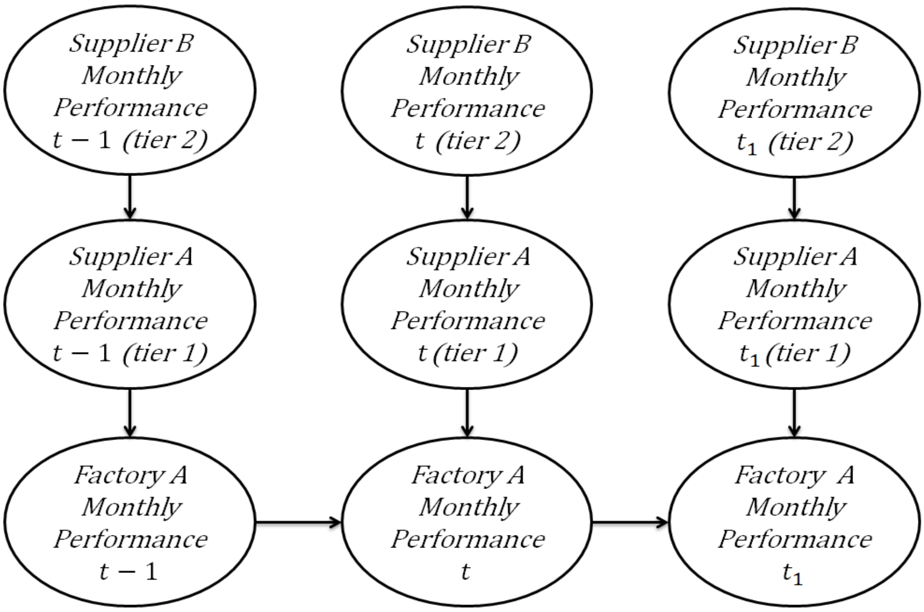


Figure 3-10: Head-Tail relationship for two stages dyadic SC

3.3.3.3 Head-Head Relationship

The third possibility about the relation in the directed acyclic graph is 'head to head' relationship where a node is a child of two parents as in Figure 3-11. This relation as above relation can be within one-time interval or cross two-time intervals. The interpretation of this relationship is that the child node is a joint effect of two causes. Thus, the knowledge about the child node blocks the path between the two causes. It means the knowledge about one cause does not contribute to the knowledge about the other reason if the effect to be observed.

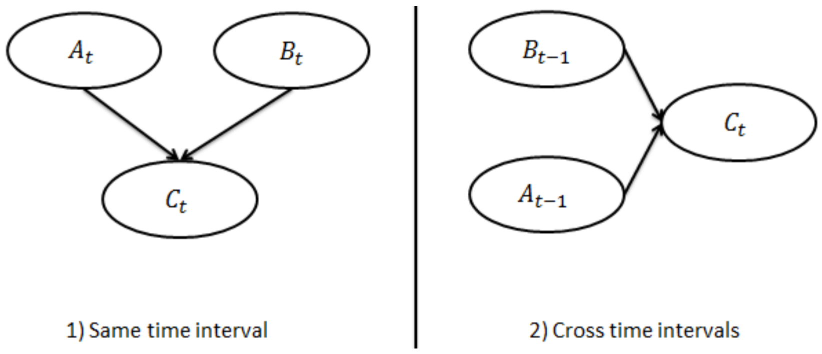


Figure 3-11: Head-Head graph

Example 3:

Let us consider a partial representation of a SC material flow. In this case, instead of representing the structure of the SC by its members, we present random variables that refer to material flow from each member such as the supply, demand and inventory level. As can be seen, Figure 3-12, the level of remaining inventory (an interim node for calculation) at any time interval is a joint effect of two causes; these are the available inventory within a time interval and the demand at the same time interval. In this case, it is clear that the level of inventory and demand has a negative correlation if the remaining inventory node has not been introduced. However, the introduction of the remaining inventory node blocks the path between these two nodes. Thus, the knowledge about demand does not contribute to our understanding of the inventory level given the knowledge about the remaining inventory level.

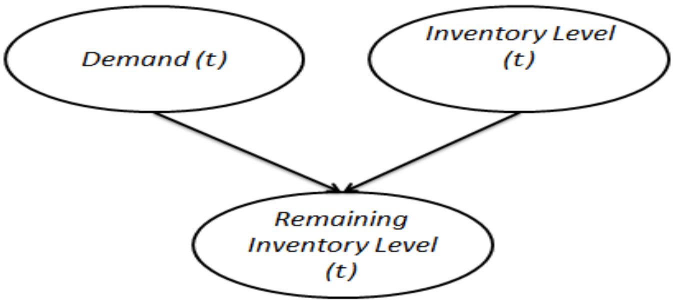


Figure 3-12: Head-Head relationship for a part of SC material flow representation

3.3.3.4 Conditional Independence Formal Definition

Let X_1, X_2 be random variables. I denote by $P(x_1, x_2)$, $P(x_1)$ and $P(x_1 \mid x_2)$, the joint probability distribution of X_1, X_2, the marginal probability distribution of X_1 and the conditional probability distribution of X_1 given $X_2 = x_2$ respectively. I write $X_1 \perp X_2$ to denote that X_1 and X_2 are independent. The mathematical expression of independence:

$$X_1 \perp X_2 \Leftrightarrow P(x_1, x_2) = P(x_1)P(x_2) \quad (3.2)$$

$$\Leftrightarrow P(x_1 \mid x_2) = P(x_1) \quad (3.3)$$

$$\text{Also if} \quad X_1 \perp X_2 \text{ Then } X_2 \perp X_1 \quad (3.4)$$

To explore the conditional independence, I add another random variable X_3. I denote that X_1, X_2 are conditionally independent given $X_3 = x_3$ as $X_1 \perp X_2 \mid X_3$ for any value x_3. This property has several equivalent mathematical expressions:

$$X_1 \perp X_2 \mid X_3 \Leftrightarrow P(X_1, X_2 \mid X_3) = P(X_1 \mid X_3)P(X_2 \mid X_3) \quad (3.5)$$

$$\Leftrightarrow P(X_1 \mid X_2, X_3) = P(X_1 \mid X_3) \quad (3.6)$$

$$\text{Also If } X_1 \perp X_2 \mid X_3 \text{ then } X_2 \perp X_1 \mid X_3 \quad (3.7)$$

The above means that no more information can be obtained about the probability of $P(X_1 \mid X_3)$ giving that X_2 has happened and vice versa.

The conditional independence assumption for a DAG means that the number of parameters required to be estimated is fewer because the probability distribution for each variable depends only on its parents (Kjaerulff, Madsen, 2012; Pearl, 2000). Therefore, the conditional independence concept allows factorising the network. It is by seeing each variable (node) and its parents in an isolated form from the rest of variables (nodes) in the graph (Murphy, 2002). For example, if the fulfilment rate has been considered as a node in the graph, then the knowledge about this node will be only dependent on nodes that have direct arcs to the fulfilment rate node such as the demand and inventory level. However, the level of the inventory is related to the supply and the remaining inventory. The latter suggests that the introduction of the 'inventory level' node isolates the knowledge about the fulfilment rate node from the supply and the remaining inventory level. From a DBN point of view, this means that fulfilment rate at a time interval is only dependent on the demand and the inventory level at that time interval. It leads to less elicitation and computation.

3.3.4 DBNs Building Process

The current research mainly focuses on learning DBNs from datasets as in (Mihajlovic, Petkovic, 2001; Murphy, 2002; Wu *et al.*, 2015; Zhu, Collette, 2015). There is no clear picture of how the model is constructed based on the expert knowledge and the decision maker knowledge. Recently, Wu, *et al.* (2015) have described stages of applying DBN to support decisions about the safety standards in a tunnel construction. The steps comprise of identifying the potential hazard scenario, the variables and their states and the relationships between them considering cause-effect logic. The structure of DBNs and the parameters can be then shaped and learned. The variables that have Markov chain property through the time should be described to show the inter-time relationships. Therefore, the causality in DBNs is two types. They are 'within time interval causality' (i.e. the variables affect each other within the same time interval) and 'inter-time intervals causality' (i.e. some variables are influenced by their state or the state of other variables in the previous time interval). Once DBN structured and quantified, it can be used for predicting the distribution of variables or to diagnose the difference between the prior and posterior distributions. The above steps are similar to the steps that suggested by Sigurdsson *et al.* (2001) to form BBNs. They propose three main stages to build BBNs. These are: finding the model qualitative structure, quantify the model and run the inference where the verification and validation can be considered at each stage. However, all these processes are generic and do not give clear guidelines of how to apply the model in particular context. There is always need to dig into the characteristics of the system and generate lessons for proper applications.

3.3.4.1 Model Qualitative Structure

This stage contains mainly the identification of the model variables and structure and expresses the variables statistically.

3.3.4.1.1 Variables and Network Structure Identification

Variables and network structure identification include identifying variables that within the scope of what the model tries to represent/predict and building a visual representation of casualties between the defined variables. The identification of the variables and the causalities have been looked from two different perspectives in the literature. The first one is to build the model from the datasets where the structure is learned from the associations between the variables in the datasets. The other way is to identify variables and the structure of the network through the interviews with relevant domain experts (Kjaerulff, Madsen, 2012; Oniśko, 2008). However, the reader might face many cases where the model structure has been built based on identified variables from the related literature to the research problem under consideration. See for example (Constantinou *et al.*, 2014; Marquez *et al.*, 2010; Neil *et al.*, 2009; Sun, Shenoy, 2007).

Considering the necessity to customise the model through identifying hazard scenarios that a SC resilience is examined against them, this thesis mainly focuses on DBN construction using interviews with relevant stakeholders. Additionally, at this stage, the SC resilience analysis is still a new phenomenon. Thus, there is an absence what types of datasets are required to learn a model that can be used to understand the resilience of SC. It is different from the work of Sun and Shenoy (2007); Neil *et al.* (2009); Marquez *et al.* (2010), Constantinou *et al*. (2014) where the problems are well-defined.

3.3.4.2 Express Variables Statistically

Once we identify the variables and finalise the DBN structure, the possible states of variables should be defined. Variables to model the SC resilience can be discrete or continuous. Examples of continuous variables are the variables that characterise the performance of a supplier, the supply level and the demand level. These variables can take any value between its minimum to maximum limits at any point in the time. An example of a discrete variable is a hazard that can either occur or not. This type of DBN model called Hybrid Dynamic Bayesian network. It contains both discrete and continuous marginal/conditional probability distributions as numerical inputs (Neil *et al.*, 2009).

The simplest form of the Hybrid Network is the Conditional Linear Gaussian (CLG) model (Cowell *et al.*, 2007; Lauritzen, 1992; Lauritzen, Jensen, 2001). However, the limitation of this model is that discrete nodes cannot have continuous parents (Cobb, Shenoy, 2006). Discretization has been suggested as one way to solve Hybrid Bayesian Networks. Discretization is used to divide the range of continuous variables into intervals. It is according to Cobb and Shenoy (2006) allow approximate inference without limitations on relationships among continuous and discrete variables.

A number of methods have been employed to map a continuous variable into discrete values to approximate the distribution with minimal loss of information. They are mainly based on static discretization. According to Marquez *et al.* (2010), in static methods, the number of partitions needs to be determined before starting the inference. They also remain the same during the inference process. In the static discretization, the more intervals the variable is discretized to drive to more accuracy and less loss of the information. However, the main limitation of these methods is that the increase of intervals number makes the computation intractable (Marquez *et al.*, 2010).

Extension to current static discretization models for BBN has been proposed by Kozlov and Koller (1997) and improved by (Neil *et al.*, 2007). Kozlov and Koller (1997) use the relative entropy to identify sub-regions with high density. See (Appendix A, Page 255) for further detail about the mathematical meaning of the entropy function. The Binary Split Partition tree has been, then, employed to represent the recursive binary decomposition for each high-density interval (the dynamical decomposition). The main limitation of Kozlov and Koller (1997) is that the current standard algorithms for the inference and evidence propagation in BBNs need to be extended which makes their approach complex to be applied (Marquez *et al.*, 2010; Neil *et al.*, 2007). Neil *et al.*

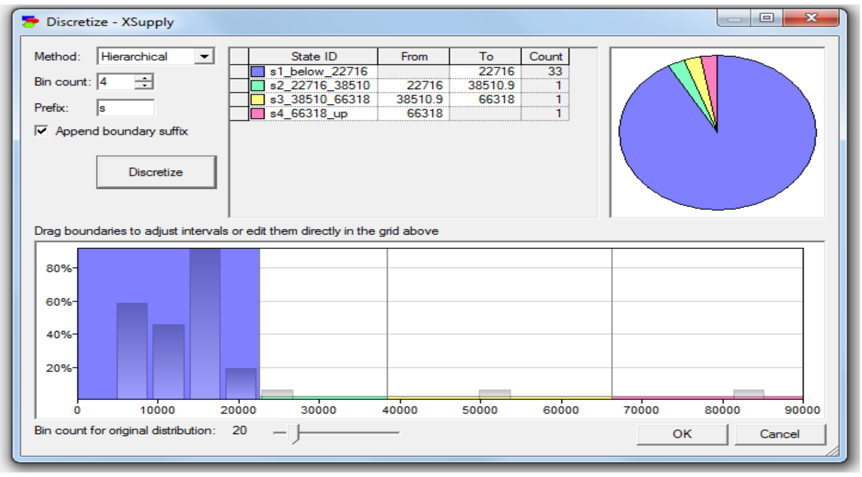
(2007) suggest an easier technique for a dynamic discretization where there is no need to introduce new extensions to the current algorithms. The dynamic discretization of Neil *et al.* (2007) has the following steps:

1. Creating an initial discretization for each region node Ω,
2. Run the model with evidence propagation.
3. For each node, we need to check the intervals (sub-region) with high density (high entropy error) and low density (low or zero entropy error).
4. We discretize the intervals that have high density and merge the intervals with low density
5. Run the model again and repeat the process from step 2 till reaching a convergence level.

The use of dynamic discretization helps to accommodate all kind of mathematical relations between two variables that can contribute to producing the joint probabilities distributions. Therefore, it reduces the burden of assigning the conditional probabilities manually for a child of discretized variables when there is a known mathematical relationship (Neil, *et al.*, 2007).

3.3.4.2.1 Static and Dynamic Discretization Examples

Let us consider the supply data of X supplier that has been obtained from one of this research case studies. The data follow a lognormal distribution with mean 9.495 and standard deviation 0.541. Figure 3-13 shows the discretized supply data for X supplier (A) using a hierarchical method as an example for a static discretization. The use of the hierarchical method requires identifying the number of bins for discretization. The number of bins is specified heuristically. The data is clustered depending on the number of bins and the distance between the data points. As can be seen Figure 3-13, if the bin count has been considered to be 4, the static discretization will lead that majority of the observations about the X supply will be group one the state “from 0 to below 22716”. The increase of bins drives to change the boundary of this state. It means that some observations are fitted in other states.



Discretize - XSupply

Method: Hierarchical

Bin count: 4

Prefix: s

☑ Append boundary suffix

	State ID	From	To	Count
	s1_below_22716		22716	33
	s2_22716_38510	22716	38510.9	1
	s3_38510_66318	38510.9	66318	1
	s4_66318_up	66318		1

Drag boundaries to adjust intervals or edit them directly in the grid above

Bin count for original distribution: 20

Figure 3-13: The result of static discretization for X supply

On the other hand, Figure 3-14 shows the dynamic discretization for the X supply. The distribution has been discretized into 29 states. There is no need to guess the state ranges before running the calculation and pre-supposing that the resulting probability distribution is known beforehand. The use of dynamic discretization for X supply leads to split the area with high density ("from 0 to below 22716") in Figure 3-13 into smaller bins to reduce the loss of information. Also, it can be noticed that the use of dynamic discretization results with non-uniform states of X supply.

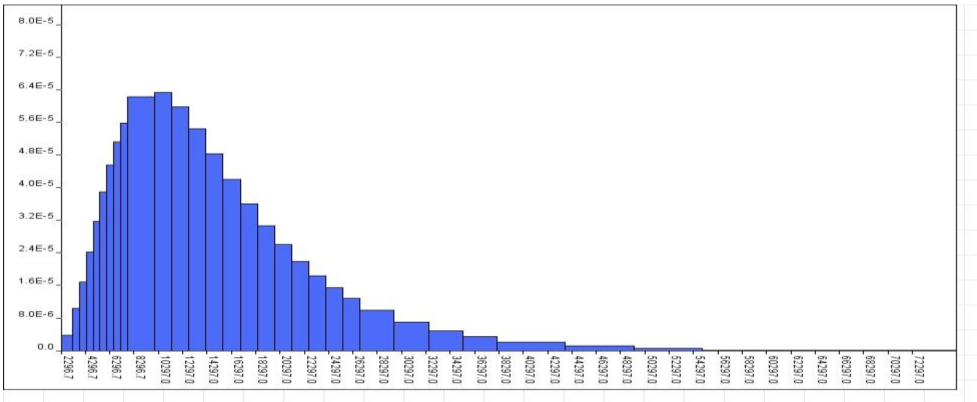


Figure 3-14: The result of dynamic discretization for X supply

Another example of the use of dynamic discretization is when the performance of a supply network member (D) is following a normal distribution with mean= 50 and variance=100. As can be seen Figure 3-15, the use of the dynamic discretization with this distribution will result with many states to minimise the loss of information. However, the question is about the suitability of this large number of states within a small variable range.

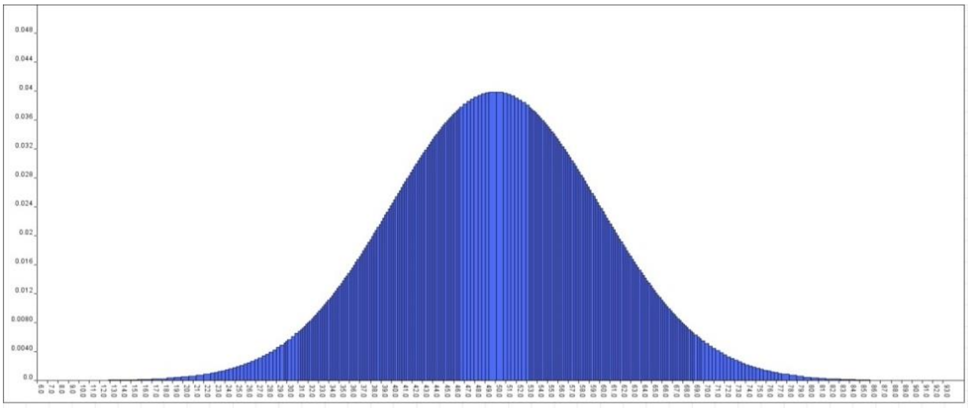


Figure 3-15: The dynamic discretization for the performance of a SC member (D)

The main difference between the static discretization and dynamic discretization is that when a piece of evidence about the value of a variable is obtained, in the static discretization the whole state where the value of the variable fits will be updated, whereas the dynamic discretization deals only with the exact observation. Recall the states in Figure 3-13, if the level of X supply has been predicted to be 2000 units, the probability of the whole state from 0 to below 22716 will be updated to be 1. The evidence will not make a notable difference for the model running, having known that, the majority of observations are within the limits of this state. In contrast, if a piece of evidence about the value of the distribution in Figure 3-15 has been obtained, the exact value of distribution will be used for re-running the calculation in the model. See Figure 3-16 where the distribution of SC member performance (D) has been updated to the value of 10. A state with value 'ten' will only appear and be used to re-run the calculation in the model.

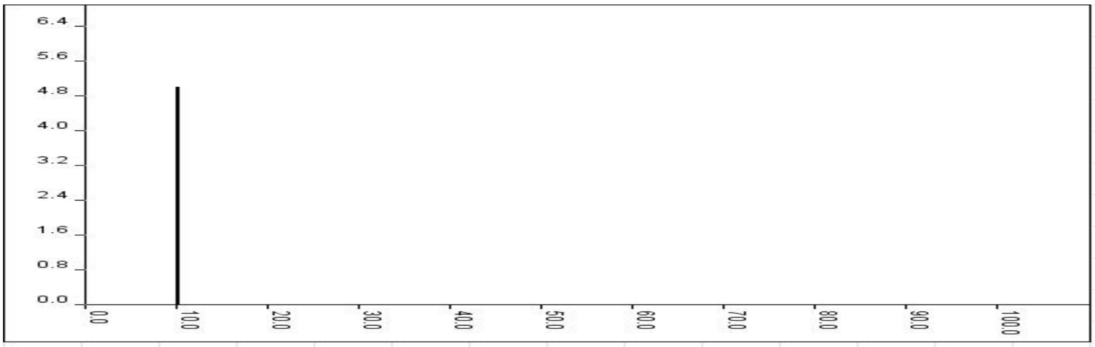


Figure 3-16: The updated result of the performance of SC member (D) by value 10

This advantage of Dynamic Discretization in dealing with numerical distribution as it is and update the distribution by the exact value have a notable difference regarding the description and analysis the result of the model when there are continuous variables.

3.3.4.3 Model Quantification

The model quantification aims to assign prior probabilities to the root nodes and conditional probabilities for child nodes Sigurdsson *et al*. (2001). However, the use of dynamic discretization involves inevitable overlap between this stage and the discretization stage. The discretization of continuous variables means that its prior distributions have been obtained. Thus, it is not possible all the time to distinguish between the statistical expression of variables and the description of their probabilities distribution.

From probabilities elicitation point of view, Kjaerulff and Madsen (2012) mention three ways to obtain the required probabilities to run the model. These are: the identification of the probabilities through mathematical relationships, expert judgement and databases about the variables included in the model. If two variables or more has clear mathematical relationships such as arithmetic relationships and logical relationships, then these relationships can be utilised to produce the joint probability distribution for a child node. In the SC context, some mathematical relationships between variables that represent the flow of the materials are obtainable. For example, the distribution of inventory level at any time interval is an arithmetic relation between the supply level in the current time interval and the remaining inventory from previous time interval. Another example is when two suppliers are complementary for a factory. If there is no supply from one of them, the factory will not be able to produce. The latter is a clear And logic gate relationship where both suppliers are needed.

The second way is to elicit the probabilities from experts. The expert judgement has been discussed widely in many fields, especially in the risk analysis area. The expert opinion provides a way to obtain data that cannot be acquired from the database, or the collection of this data is costly. Theoretically, the use of expert judgement has been proposed. However, it requires a thorough design to the expert selection and elicitation process. See Cooke (1991); Meyer and Booker (1991) for more information about expert judgement. Cooke (1991); Kjaerulff and Madsen (2012) report that experts are facing difficulties in stating their knowledge as probabilities. Thus, the training of experts has been suggested for many cases. However, the genuine experts' participation time is always restricted. Therefore, there should be a practical focus on critical data that expert can provide (Oniśko, 2008).

A third way of eliciting the probabilities in a BBN is through the existing databases. Bedford *et al.* (2006) propose the use of some databases in their review for expert judgement elicitation for reliable system design. They state that "historical data may be obtained from generic databases or company-specific event databases" (Bedford *et al.*, 2006, Page 442). In the SC context, some databases are inevitably available such as the supply and demand data that can be used if these variables are included in the model.

3.3.4.4 Inference

DBNs and BBNs are built to support reasoning under uncertainty where some variables are updated by observations to update a belief about unobservable variables (Neil *et al.*, 2001; Oliver, Horvitz, 2005). The inference is the process of computing the posterior distribution of variables given evidence about some other variables. Bayes theorem that has been presented in Chapter 2 is the heart of Bayesian inference. Many efficient algorithms have been recommended to run the inference. They are associated with the availability of much powerful computing software. The latter enables the inference to be conducted for very large scale models (Neil, Fenton *et al.* 2001). A considerable body of the literature has been devoted to improving different algorithms. However, this discussion is out of this research scope due to that the primary focus of this research is the SC resilience and discussed the role of DBNs in informing the SC resilience analysis.

The inference for this research has been executed using GeNIe 2.0 and AgenaRisk. GeNIe 2.0 was a free software during its utilisation for this research. However, this software does not support the dynamic discretization for the numerical variables. It is not compatible with the use of mathematical relationships where there are continuous variables. Thus, GeNIe 2.0 has been only used to conduct the inference for the Atlantic Canada food SCs case studies in this research. In that case, the static predefined states for the continuous variables have been considered where there was a clear focus from decision makers in specific performance categories. Therefore, the use of many states to describe variables has no added value. In the other two cases, the material flow with many numerical variables to check how the SC meets its demand has been used to describe the SC system. Therefore, the dynamic discretization has employed to work with numerical variables directly and accommodate the majority of mathematical relationships that appeared. For this purpose AgenaRisk software has been contracted as a supportive tool to conduct the inference.

3.3.4.5 Model Verification and Validation

Model verification refers to a test to check that its input: output relationships are the same as those in the usual sense (Pidd, 2009). The states of discretized variables should also be checked if they are exhaustive and exclusive and their probabilities are added up to one. It is to make sure that the model has been built correctly. On the other hand, validation, theoretically, aims at assessing the behaviour of the model comparing to the performance of the real system within some defined experimental frame (Pidd 2009).

While the verification of BBNs and DBNs can be a straightforward process, there is no doubt that their validation is a difficult task because the majority of the applications are using the experts' knowledge in structuring and quantifying the models (Pitchforth, Mengersen, 2013). The model also in many cases tries to make inference about some variables that have not been observed, or they are unobservable. So, there is an absence of a genuine value that model is trying to predict or make inference about it (Pitchforth and Mengersen 2013). For example, my application of DBNs is mainly focused on predicting the SC resilience. The real value of SC resilience is hard to be realised because the model would not count for all factors that affect SC resilience. The value is going to be different based on the considered hazards scenarios. Korb and Nicholson (2003) state that the validation should consider the cost and time. Some experimental data, for example, may be prohibitively expensive or time-consuming. Therefore, the validation process should stem from the case where the model is built and applied.

The aim of validating the model is to ensure that the model is useful (answer the research question or meet the research aim), and is being validated under identified conditions (Pidd, 2009). Revie (2008); Revie *et al.* (2011) argue that the model should be practical (i.e. it is simple to use) and meet the project aims. However, the practicality of the model could be related to a project case study where the main focus is the client problem rather than the research problem. Similarly, the meeting of project aims is related to one case study project.

The validation methods that have been suggested by the literature is to ask 'experts' who involves in developing the model to comment on the model structure and behaviour which has been called a face validity (Korb and Nicholson 2003, Pitchforth and Mengersen 2013). Zitrou (2007) states that model should involve a meaningful representation for the people who committed to the model construction. Experts can comment on variables definitions, the relationships between the variables, the need to add more variables and the outputs of the model are logical comparing with the input. Apart from the expert above role, Bedford and Cooke (2001) state the BBNs can be validated through checking the conditional independence in the model. In their view, the domain experts should comment whether the conditional independences that are embedded in the graphical model are valid or not. The graph must be altered if the expert does not accept the stated conditional independence.

Korb and Nicholson (2003) stress the role of the sensitivity analysis to validate the model where the distributions of the model variables can be tested against the variations of provided evidence, or changes in the network parameters. Pitchforth and Mengersen (2013) propose studying the nomological validity and content validity. Nomological validity means how the model fits in the current literature of the research where variables consistency with knowledge about the research can be reviewed. The content validity ensures that the model incorporates relevant variables to the problem. The nomological validity is related to the transferability of the model to similar problems in the literature, whereas the content validity is combined to the face validity where experts can suggest adding or removing variables. However, the latter two validity tests are similar to the ones that should be respected in doing case study research as we will see in Chapter 4.

To build a cross understanding for the conducted case studies, I will briefly reflect on the model validation for each case. After that, I will analyse how the model meets the research aim in capturing the SC resilience based on its characteristics and where are the learning points.

3.3.5 Issues Related to DBNs and Their Use for SC Resilience Analysis

3.3.5.1 Time Definition

DBNs provide extensions to BBN where the model aims to capture not only the dependency and the uncertainty in one-time interval but over several time intervals or instances. However, from an application point of view, the use of DBN can raise two central intuitive questions. These are how can we specify the time-space and how many time intervals are required to capture the dynamicity of a particular system? There is no clear picture in the literature of how the time-space should be defined for DBNs. The importance of a precise definition of the time space is that variables prior probability distributions which are elicited either from experts or datasets change based on the time window. For example, the monthly supply probability distribution is different from the weekly supply probability distribution. Similarly, the prediction of the recovery time is related to the length of the time interval. Therefore, a clear description of the time unit should be considered. The latter two questions will be visited in Chapter 8 where I will try to answer how the time-space of DBN can be appreciated in the light of the case studies.

3.3.5.2 Theoretical Advantages of DBNs Comparing with Other Models

The second issue can be raised is that the benefits of DBNs comparing with other modelling approaches. This question has been theoretically answered by the above discussion about the shortcoming of the complexity theory in modelling SC resilience and will be tackled further by the empirical work of this research. The work of Leerojanaprapa *et al.* (2013); Leerojanaprapa (2014) also draws a theoretical comparison between several modelling approaches. Leerojanaprapa *et al.* (2013); Leerojanaprapa (2014) have compared a set of modelling approaches that can be used to model SC risk such as fault tree, discrete event simulation and system dynamics. They conclude that Bayesian Belief networks have advantages over the other modelling by its ability to capture complex relationship via non-deterministic dependence. BBNs also make use of probability theory and Bayes rule to capture the uncertainties and update them based on new evidence about some variables. However, BBNs fall short to model the SC resilience because of the dynamic nature of the resilience. That why DBNs can be theoretically a good modelling type to analyse the resilience. Still, DBNs practical role to inform the resilience analysis is to be explored in the empirical work for this research.

3.4 Concluding Remarks

In this chapter, the view of SC as a complex system to analyse its resilience has been critically assessed. I have shown that despite the latter modelling approaches can deal with complex structures of SCs, they ignore the role of information in triggering the flow in the supply chain, the uncertainty around the flow and the uncertain impact of the adverse events on the output of the affected members. Moreover, the visibility across the SC is a vital element of such approach. Based on that, in this chapter I propose the examination of DBNs as a model that can deal with uncertainty through the time. This chapter has shown the basic steps to build DBNs and their theoretical constructs. I have illustrated that the dynamic discretization can help to accommodate the continuous variables to model SC resilience and the mathematical relationships between them. Dynamic discretization can result in reducing the burden of eliciting required data to run the model. Furthermore, the issues of the DBNs time-space have been highlighted to shape a basis for a further discussion in the light of cross-case analysis in chapter 8. Theoretically, DBN can be a suitable model to analyse SC resilience based on the SC resilience proposed definition and nature where the uncertainty through the time should be taken into account. However, the useful role of DBNs to inform the resilience analysis and to reveal the influence of some SC decision characteristics on the resilience needs to be explored. The rest of this thesis will be revolved around studying empirically this role and the steps to build DBNs to analyse the SC resilience. I try to dig further into issues regarding the discretization of variables, time intervals definitions and mathematical relations that control the SC material and information flow and lead to reduce the elicitation burden.

4 Research Setting: Philosophy and Methodology

4.1 Introduction

In the previous chapters, I have mentioned that the analysis of SC resilience is a new phenomenon. As well as the use of DBNs as a modelling tool to understand this phenomenon is a new applicability for DBNs. This chapter is devoted to explaining the philosophical and methodological stance to investigate the role of DBN to inform the SC resilience analysis. I will discuss how the current knowledge about the SC resilience that I have discussed in chapter 1 and 2 and the state of knowledge about DBN draw the direction to select an appropriate research methodology that fits the philosophical stance of this investigation. Then, a data collection and analysis protocol will be discussed to highlight where the enquiry of SC resilience should focus and what are the primary forms of data analysis.

4.2 Nature of the Research Problem

To advance 'SC resilience literature', there is an inevitable need to consider attempts to analyse the resilience as I discussed in chapter 2. The resilience analysis assists in building a deeper thinking about the current level of resilience to adverse events and the effectiveness of some SC resilience enablers that have been seen from a high theoretical level. For example, Kim *et al*. (2015) argue based on their analysis to a set of SC structures that the redundancy in SC does not imply a better resilience. It clearly contradicts the conclusion of Sheffi and Rice (2005) about the conventional value of redundancy to improve the resilience. Therefore, this research is concerned about SC resilience analysis to explain such issues and the role of DBN modelling approach to inform this analysis. The need for attempts to analyse and measure SC resilience to support the decision-making process has confirmed by (Kamalahmadi and Parast 2016).

Another issue to be studied is the influence of SC distinctive characteristics on the resilience analysis. It has been identified in Chapter 1 and 2 that SC structural configuration, the level of integration, visibility and operating system can contribute to how SC resilience can be understood. Thus, the analysis of SC resilience is more complicated than just matching the general steps to build DBNs from an engineering network level. There is an ambiguity of how DBN or any other formal modelling approach can apply to analyse the SCs resilience based on their characteristics. Also, there is no clear picture of how different set of SC features can impact this resilience. This ambiguity requires a broad investigation of the phenomenon. It is for the sake not only to generate new theories but also to discuss some theoretical constructs that appeared in chapter 1 and 2 from a practical point of view.

4.3 Research Philosophical Perspective

The research philosophical perspective concerns about designing the knowledge claim for this research. This knowledge claim should show the researchers' assumptions about how they will learn and what they will learn during their research inquiry (Creswell, 2013). The philosophical standpoint consists of four main elements (Crotty, 1998). These are the belief of researchers about the phenomenon (ontology), how we know it or how we make claims about it (epistemology), how we gain knowledge about the world (methodology) and then the models are used to collect data about the phenomenon (research methods).

As this research is interested in the SC resilience and the role of a modelling approach to understand this resilience, a theoretical base about SC resilience and the appropriateness of DBN to analyse the SC resilience based on its characteristics have been grounded in chapter 2 and 3. I believe that there is a reality exists about the SC resilience analysis based on its characteristics (research ontology). It is clearly different from interpretivism ontology which according to Mingers (2006) diminishes the reality of the world due to the limitations of my knowledge about the world. This research ontology fits broadly with two major philosophies of science. These are the positivism and critical realism. The ontological stand of the positivist and critical realist insist on the independent existence of the structure and mechanism that generate the events that we observe (Mingers, 2006). However, there is a difference in how we make a claim about this reality and how we obtain the knowledge about the reality. The positivist narrows down the reality to an observable level, regular causation and emphasis on the independent role of the researcher. On the other hand, the critical realist claims that what we can observe is only a subset of events, so there might be some hidden events might cause the phenomenon with an emphasis on the observer role in accessing to the world (Creswell, 2013; Mingers, 2006).

In the following two sections, I will discuss the positivism and critical realism primary constructs briefly. I will show why critical realist view of the research can be better than to stick to a positivist view considering the flexibility of obtaining the knowledge. However, there is surely no best way to conduct the research (Saunders *et al.*, 2007). So, different researchers can be attached to different philosophies.

4.3.1 Positivism

Positivism has been extensively discussed in various research areas especially the ones that are related to science (Lewis, 2003). For positivist-oriented researchers, the ontological viewpoint is that the reality exists and is driven by immutable natural laws and mechanism. Human players are assumed to be passive agents. They are doing nothing rather than observing and coding the phenomenon (Creswell, 2013). According to what it is attempting to achieve, research within this philosophical viewpoint should be assessed based upon the objectiveness and generality of the outcomes. It means that the evaluation is concerned with: collecting objective data about SC resilience and the predictive power of DBN to predict this resilience. This is with taking into account the appropriate selection of the sample of SCs and the right building and application of statistical methods to determine the significance of the findings. The positivist view states that this value-free observation of the objective reality is considered to be the only valid approach. Therefore, the methods which will be selected should consider as non-subjective and depend on only the empirical data. There is no role for values and normative judgements from either the participant or the observer.

The positivist thoughts have been enriched by the causation property (This is called post-positivism). David Hume was the first one who introduced the causation in the positivist tradition (Creswell, 2013; Crotty, 1998). However, there are some conditions should be met here. The most important one is the existence of the perfect empirical regularities. Burrell and Morgan (1979) explain that the presence of such regularities allows making a causal statement. For example, if it has been observed many times that a bad SC ability to fulfil its demand occurs after a shortage of the supply from a supplier A. Then, it can be said that the shortage from supplier A will cause a bad SC performance. This statement can be figured out by using cross-sectional data between the performance of SC and the shortage from supplier A.

This epistemological positivist position has serious limitations for conducting this research. First of all, it is not able to address the social values in different scenarios analysis to understand SC resilience using DBN. The recognition of various hazards situations depends on the subjective judgment of the human partially or entirely. For example, the epistemological positivist position will not tolerate the inclusion of hazards to the model if they have not happened before or have been elicited from the human who participated in the research. The second issue is that the perfect regularity in the positivist view implies an always conjoined of some events and their consequences. This perfect regularity is not possible in many cases in SC. The system is supposed to be an open system where some unobservable causes and consequences can affect the resilience. They drive the absence of the real value of many variables including SC resilience. Concerning DBN, this means that DBN structure should be only learned from data about the SC resilience. Learning DBN from data requires that the casual relationships should have been observed many times to have a significant association level. Learning DBN from the data is similar to any other statistical methods where the associations between the variables observations will be the primary factor in determining the causality between them. However, as I have shown in Chapter 3, learning DBN is not appropriate for this research. The third issue is that the positivist epistemology also adopts the observer independence for social science (Burrell, Morgan, 1979; Mingers, 2006). It means that some attributes of this research which are about generating theories about SC resilience analysis and the reflection on DBN input, output and the process to understand SC resilience will be excluded. So, the research will tend only to test the theory or learn theory with a rigid separation between the researcher and the context.

4.3.2 Critical Realism

If a positivist standpoint has been chosen, then the aim of the research should no longer be to explore the SC resilience analysis based on their characteristics and the investigation of the role of DBNs to advance the quantitative analysis of this resilience. It can be either to use DBNs to predict the exact SC resilience or to test one formal approach to building DBNs for SC resilience in a control experimental design. The previous two aims are not valid because they do not fit with the state of knowledge claims about SC resilience and DBN application at this stage as a new phenomenon. Many theoretical constructs should be explored, and new ones should be generated before such positivist thinking might come to the life. Therefore, this research focuses on exploring some parts of the reality mechanism and causalities that lead to understanding the SC resilience and how DBN can advance this understanding. This is with admitting the role of empirical data and human judgement in interpreting this reality. Thus, from an epistemological point of view, the critical realism can be best fit the exploration purpose of this research.

Critical Realism (CR) is a philosophy of science that prioritises ontology over epistemology in the sense that, for the critical realists, the way the world is should guide the way knowledge of it can be obtained (Ackroyd, Fleetwood, 2000). The work of Bhaskar (1989) was the main base for the Critical Realism. According to Ackroyd *et al.* (2000), critical realism fulfils the intellectual 'space' between the many forms of interpretivism and positivism. This is by considering that there are rational grounds for preferring one theory over another (e.g., comprehensiveness, explanatory power, the degree of supporting power, coherence with other bodies of knowledge) and considering the observer non-independence role (Mingers, 2000; Mingers, 2006). Critical realism is illustrated by Figure 4-1 where the reality consists of causal and structure generative mechanisms. This causal generative mechanism produces actual events. Some of these events are conceptually mediated in empirical experience, impression and observation (Johnson, Duberley, 2000). Thus, the critical realist view advocates the role of the human attributes along with the role of the grounded theory. Also for the critical realists, the research design will not be static, but it will be improved by the obtained experience.

The critical realist philosophical stance enables the researcher to adopt multiple case study as an appropriate research methodology. Case studies have been suggested by many authors where there is little existed theories about a phenomenon. Their employment to test the current knowledge and generate new novel theories (Eisenhardt, 1989; Ketokivi, Choi, 2014; Yin, 1994). The use of case studies aims to understand part of the actual world about SC resilience and how DBN contribute this understanding. This is by making use of multiple data collection methods to collect objective and subjective data about the research study. Further discussion about the rationale of using case studies is given in next sections.

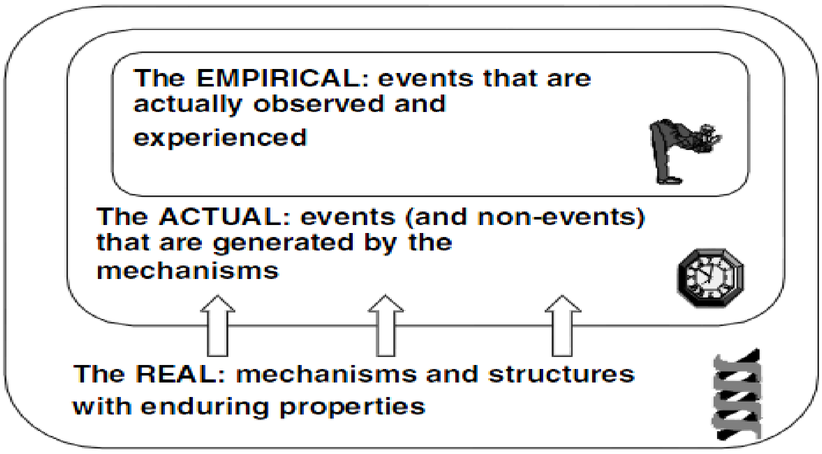


Figure 4-1: The domain of the knowledge from a critical realist point of view adopted from (Mingers, 2006, Page: 204)

4.4 Multiple Case Study Methodology

4.4.1 Multiple Case Study Rationale

Many factors guide the choosing of the research methodology including the research philosophy such as the research questions, the propositions and the state of the knowledge about the research. Ketokivi and Choi (2014) argue that the case study research methodology can be exploited for three purposes in Operations Management based on the available knowledge about the research area Figure 4-2. These are theory generation, theory testing and theory elaboration. In the latter three cases, the starting points are the general knowledge about the phenomenon. As can be seen Figure 4-2, the contribution of general theory and empirical knowledge have been symbolised by the width of the arrows. The arrows widths reflect the contribution of empirical context to the theory comparing to the available general knowledge about the theory and vice versa. For example, in the case of the little foundation of general theory; the contribution of the empirical research is more towards generating new theories or/and elaborating on the current theories. Considering this research, as I discussed in chapter 2 and 3 that SC resilience is a new topic as well as the exploration of DBN to understand more about SC resilience, therefore, case studies methodology for this research is a suitable methodology to achieve this research aim.

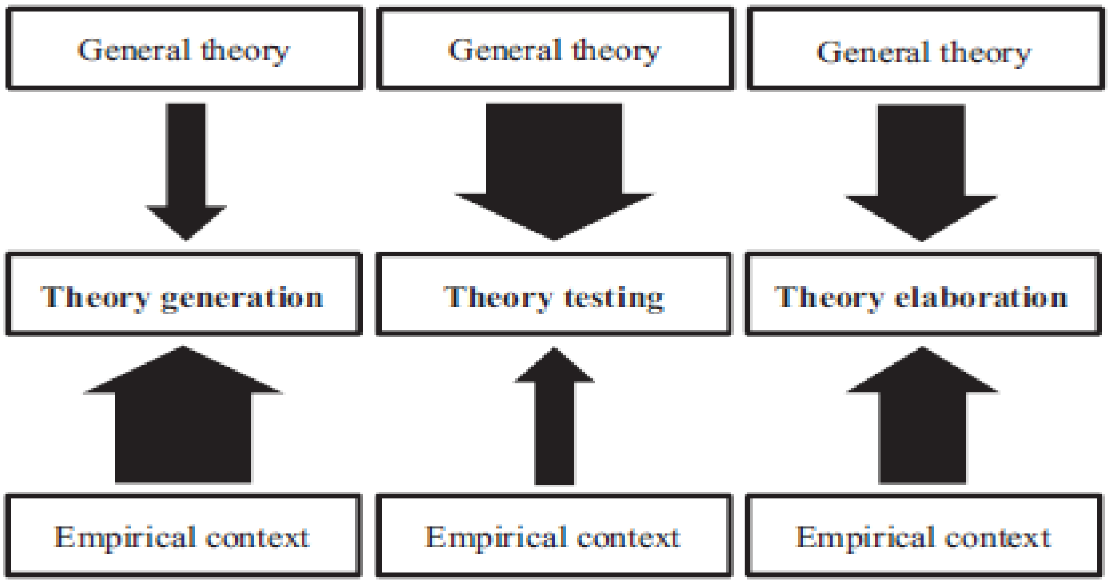


Figure 4-2: The role of case studies methodology in operations management adopted from (Mikko and Choi, 2014, Page: 233)

According to Willig (2013), case studies methodology is a research methodology that focuses on gaining an in-depth understanding of a phenomenon. Therefore, case studies are not categorised by the data collection and analysis methods rather than by their focus on a particular unit of analysis which is the case. In the literature of research methodologies, some explain that there is a difference between the single case study and multiple case study methodology. However, Eisenhardt (1989); Yin (1994) do not seem to differentiate between the setting of a single case study and multiple case study research from a methodological level. Yin (1994) states that case studies can include either single or multiple cases with many levels of analysis. Also, he stated that within one context different cases can be considered. However, a single case study is more oriented towards a specific deep context (Yin, 1994). Thus, in a single case research no cross cases analysis can be drawn to inform a general discussion about the area of investigation. Instead of that, the aim is a context informed discussion. See for example Leerojanaprapa *et al.* (2013); Leerojanaprapa (2014); Sachdeva *et al.* (2007) where the aim is to examine the model approach to a specific case study context. In many instances, such studies are a project-oriented study where the research problem stems from the case itself.

If a single case study had been adopted for this research, the aim of this research would have been to examine the resilience of one type of SC such as Atlantic Canada food SC using DBN. Then, a conclusion needs to be drawn about the benefits of using DBN to understand the resilience only for this context based on Atlantic Canada SC distinctive characteristics. The aim of this research would no longer be to produce a sort of generalisation about analysing SCs based on their characteristics and a reflection on the input, output and the process to build DBN for a better understanding of SC resilience. Therefore, multiple case study can fit better to the purpose of this research at this stage because as I have stated in chapter 2 that there is a lack of generic theories that can guide the study of SC resilience. The pieces of evidence from multiple cases have been considered by Yin (2013) to be more compelling and robust that contribute to the theory generation. Once the knowledge about SC resilience theory and DBN have been flourished, then, one case study might be used to examine the knowledge of a particular unexamined context and produce more knowledge about a specific context.

4.4.2 Steps to Conduct Case Studies

Yin (2013) illustrates basic steps to conduct the case studies research. They start by obtaining theoretical propositions, selecting the case studies, designing the data collections protocol, individual case study analysis and cross-case analysis Figure 4-3.

One of the important constructs in Figure 4-3 is the possibility of using the feedback from each case to reflect on the design. Eisenhardt (1989) states that the researcher within case studies methodology should consider an iterative process where the research questions and design can always be revisited based on the experience from conducting the cases.

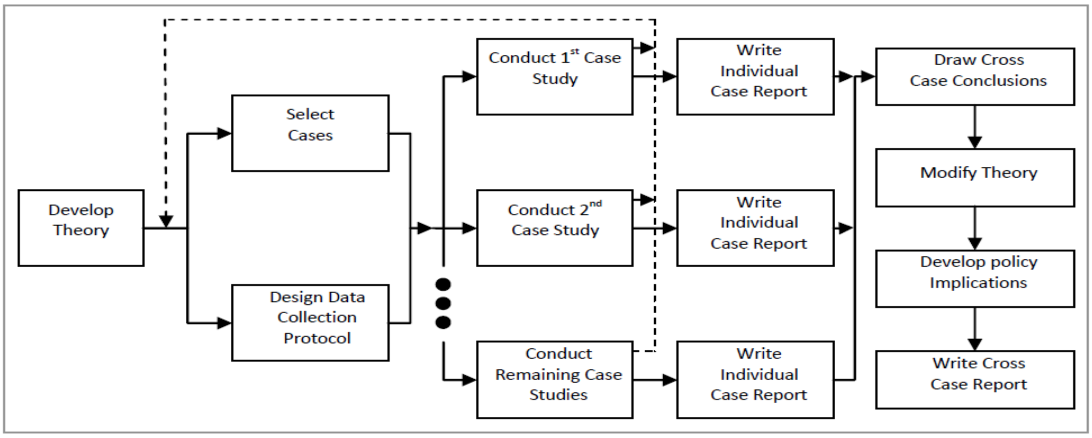


Figure 4-3: Case studies research generic steps adopted from (Yin, 2013, Page: 49)

4.4.2.1 Research Propositions/ Case Studies Direction

Eisenhardt (1989); Ketokivi and Choi (2014); Yin (2013) argue that cases studies research methodology should start with some propositions that describe the general theory to guide the data collection process and the analysis. Yin (2013) explains that although some areas of research have legitimate reasons for not having propositions, there should be stating purposes for the study and criteria to compare the case study output to them. Eisenhardt (1989); Ketokivi and Choi (2014) insist on the role of the literature to shape the research questions and some theoretical propositions. Eisenhardt (1989) argues that theoretical propositions should also be used to reflect on the level of agreement and disagreement between the literature and the empirical evidence. While the agreement means further support to the existing theory, the difference triggers the building of new ideas that needs additional research. Another important factor to describe the current knowledge about the phenomenon is to show where the empirical pieces of evidence reveal new insights that have not discussed in the literature before. Recall Figure 4-2 for more detail about the role of theory in case studies research. The missing of such theoretical propositions will lead to collect data about everything, which is impossible (Eisenhardt 1989).

The main theoretical propositions that they are related to this research have been developed in Chapter 1 and 2. It can be clearly that this theoretical knowledge is at two levels. The first one is the role that DBNs can play in informing the resilience analysis and show the impact of SC characteristics on the resilience. The second one is that the steps that can be taken into consideration to apply DBNs. In Chapter 1, I have illustrated that some distinctive SC characteristics can influence its resilience analysis. These features can play a role not only in guiding the direction of SC resilience analysis enquiry but also provide a ground to compare case studies outputs.

I have identified in Chapter 1 that the integration level and span has an association with the propagation of adverse event consequences through the SC. This association have been reported by (Jüttner, Peck *et al.* 2003, Peck 2005, Świerczek 2014). In this study, I seek to examine these associations using DBN. I also try to find why there could be a connection between the integration and the propagation of adverse event consequences. Then, I try to find out the resilience level that the focal firm has to this propagation. Regarding the SC structure, Nair and Vidal (2011), Soni *et al.* (2014), Kim *et al.* (2015) have considered this structure with a static flow of the material. Their view is consistent with general network theory. In this research, I examine the role that structure can play in understanding the interdependency in the SC and identifying the vulnerabilities. This study leads to an important question about the role of the SC visibility can be played in tracing the SC structure, processes and vulnerabilities? The visibility as has been shown in Chapter 2 has two levels. The first one is the operational level where the SC members share information about the day-to-day processes (Francis 2008). The second one is the strategic level where the SC members have information about the vulnerabilities and hazards that can hit the SC (Christopher and Lee 2004). However, it is not clear how the latter visibility can be achieved in practice and how this affects the resilience level to adverse events and the modelling process to understand that resilience. In the same hand, the operating system as I have shown in Chapter 1 should reveal insights about the level of redundancies concerning the inventory, the ordering strategy of the focal firms and the triggers to the material flow in SC. From this research point of view, the interest is how can different operating systems with their decisions rules contribute differently to SC resilience? And what is the role DBN can play in revealing their impact on the resilience of SC?

The generic standard modelling process to run DBNs have been discussed chapter 3. Recall that this process started by identifying the potential hazard scenario, the variables and their states and the relationships between the variables considering cause-effect logic. The structure of DBNs can be built, and the parameters can be learned. The variables that have Markov chain property through the time can be defined to show the inter-time relationships. Thus, the causality in DBNs is two types. Once DBN structured and quantified, it can be used for predicting the distribution of variables or to diagnose the difference between the prior and posterior distributions. However, how this standard process can be used to build and run DBNs to analyse SC resilience needs a further investigation. It is with taking into consideration the influence of SC characteristics on this process and how the outputs of DBNs can be presented in the light of resilience triangles, economic loss and inoperability.

4.4.2.2 Case Studies Selection

Yin (2013) has described the selection of case studies as a difficult task. It does not only depend on the scientific methodological selection criteria that related to the level of general theories that can be developed but also related to practical issues related to the access to the case studies and the time to conduct the case studies. According to Yin (2013), there is a need for a sufficient access to the potential data in different forms such as people interviews, documents and records, or make observations in the field. If the access has been granted to more than a single candidate case, the research should choose the cases that will most likely illuminate his/her research questions (Yin 2013). From a methodological point of view Eisenhardt (1989) argues for the use of theoretical sampling to choose the case studies rather than the random sampling where the case studies are selected for statistical reasons because there will always be a limited number of cases that the research can have access to them. The theoretical sampling is based mainly on choosing cases that are likely to extend the emergent theory or represent extreme situations where there is a likelihood to capture rich information about the phenomenon (Eisenhardt 1989). However, the design of the case study research is not static. Therefore, the choosing criteria can always be refined based on the feedback from other cases (Figure 4-3).

As has been stated above, SC resilience analysis, as well as the application of DBN for a better perception of this phenomenon still in an early stage. There are no clear criteria can be employed for the theoretical sampling to extend the current theory. Moreover, some information about SC characteristics that have been reviewed in Chapter 2 such as the structure of SC cannot be figured out prior the study. Therefore, to increase the likelihood of capturing different SC characteristics, hazards and produce sort of generalisation about the resilience analysis and the exploration of DBN; I propose that theoretical sampling should focus on selecting SCs from different industry sectors, diverse business types and different geographical locations. These criteria should allow drawing cross analysis through various SCs sectors and companies, capturing more rich information about SCs characteristics and highlight the problems that affect SCs resilience. Table 4-1 shows a summary of the criteria for selecting the case study for this research. It also shows the case studies for this research which will be discussed further in the next three chapters.

Table 4-1: Case studies selection criteria

Criteria for selecting cases		**Context 1**	**Context 2**	**Context 3**	
		Case study 1	Case study 2	Case study 3	Case study 4
Pragmatic selection	Access for interviews and meetings	X	X	X	X
	Willing to share confidential data	X	X	X	X
Methodological selection	Industry sector	Tubes industry	Pipes coating industry	Food industry	
	Geographical dimension	UK	Malaysia	Canada	
	Focal firm business type	Distributor	Manufacturer	Retailer	Producer and Retailer

4.4.2.3 Research Methods

Research methods illuminate specific models to generate the data (Bryman, Bell, 2011; Greener, 2008). It is different from research methodology, which describes the researcher attitudes and strategy to answer the research questions. The research methods are very important part of the study design because they influence the type of data collected, the analysis of the data and the conclusion of the study. According to Yin (2013), in the case study methodology, there are several data sources such as primary and secondary documents, archival records, interviews, direct observations and participant observations. The rationale behind using diverse data sources is to make the triangulation possible for the sake of providing a stronger validity for the case output. However, the researchers do not have to use all of these sources as they might select some of them based on the case (Eisenhardt 1989).

The evidence to answer the research questions in case study methodology can be qualitative (e.g., words), quantitative data or both (Eisenhardt, 1989, Ketokivi and Choi 2014). It is consistent with the critical realist view for this research where events are observable and non-observable. Observable events are safer to verify them through quantitative data. However, the collections of statistics and quantitative data are not able to understand the non-observable meanings, beliefs and experience that are better explained through qualitative data (Creswell, 2013). Therefore, according to Creswell (2013), there is a need to mix methods. This section will illustrate the research methods used within the case studies methodology.

Notice that as I mentioned in the case study selection, there are pragmatic issues related to the utilisation of the case studies. Any research should weigh issues such as establishing contact with appropriate people in a suitable time scale to give access and build trust either through word of mouth or through a legal confidentiality agreement for not revealing distinctive data about the case study. I will go through these practical issues in the actual data collection process for each case study.

4.4.2.3.1 Literature Review

According to Hart (2001), the literature review can show several issues such as the significant research problems, the debate about the topic, the key sources, the ontological and epistemological view of the domain. The role of literature review for this research has been described from a methodological point of view in section 4.4.2.1. I have shown in section 4.4.2.1 that the literature review plays a vital role identifying gaps and make sense about basic principles and concepts about SCs characteristic and resilience (chapter 1, 2). Then, in the second stage of literature analysis, I consider how SC resilience might theoretically be better understood using DBN. In the third stage, the use of the literature will be as a base for comparing the case studies output.

4.4.2.3.2 The Model

The model can be seen as a simple image of a well-defined sector of the real world and it includes a set of equations or another mathematical structure that represents the relationship between the different elements and variables. According to Pidd (2003, page:12), the model is “an external and explicit representation of part of reality as seen by the people who wish to use that model to understand”. Thus, the modelling approach links well with the case study research methodology because according to Pidd (2003), it can be employed to illustrate the uniqueness of the context under the study. Notice that the use DBNs for this research is exploratory in nature as there are no earlier DBN models in the SC resilience field can be used as a basis. Other ways to use the models exist. However, they are out of this research scope.

It is evident from the above that a model is a tool of thinking. It would fit within the analysis stage of the data rather than the data collection stage. However, the reason to mention the DBNs here is that the planning to use of DBN for a better understanding of SC resilience can draw guidance for data collection process to structure and operationalise the model. As I have shown in Chapter 3, DBNs require identifying the variables and map the model structure. Then, the qualitative structure needs to be discussed with the participants to verify that the model captures correctly their thoughts about the variables that impact the resilience of SCs. Similarly, the model requires numerical data for quantification purposes. These data could be available from the datasets, primary and secondary documents. Other variables such as hazards might need subjective judgements of participants /decision makers to be quantified. Therefore, the model requirements should be considered during the data collection stage due to its role in guiding the data collection process.

4.4.2.3.3 Semi-structure Interviews

Semi-structure interviews are a useful tool where specific data need to be obtained (Bernard, 2011). They might also offer reliable and comparable qualitative data (Bernard, 2011). They are preceded by observations, informal and unstructured interviewing and accessing to some information to allow the researcher to develop an in-depth knowledge of the context. This perception is imperative to ask relevant and meaningful semi-structured questions. According to Bernard (2011), semi-structure interviews are also useful tools when the relation between the interviewer and respondents are formal, and there is a chance for inability to have several runs of interviews. In this type of interviews, the interviewer has a guide that he or she needs to follow to obtain the required data. However, the interviewer has sort of flexibility to elaborate based on the guidelines. The key inquiries for this research interviews are shown in Figure 4-4. The process starts with building the contact with the case study holder and identifying the concerned SC. In addition to that, the inquiry of this research revolves around understanding the SC characteristics and the relevant hazards scenario that affects the SC.

Informal meetings and access to some documents in the focal firm have preceded the semi-structure interviews for research case studies. The main aim of the informal meetings is to establish the contact with ‘the case study holder[2]’ in the focal firm and specify the concerned SC from the perspective of resilience analysis. The case study holders were supply chain managers for tubes and pipe coating spare parts SCs and the

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[2] Case study holder refers to the main contact point in the case study. He facilities the access to other interviewees and confidential data.

transportation manager for Atlantic Canada case. Interviews have focused on probing for information necessary to map the knowing structure of concerned SC, understand the visibility to other SC members, decision rules about the stock and re-orders (this is to understand the operations system) and the concern hazards that might impact the SC. It is also necessary to comprehend the primary indicator that assists in predicting the resilience of SC at the strategic level. After building DBNs structure, the model should be validated with the case study holders and interviewees.

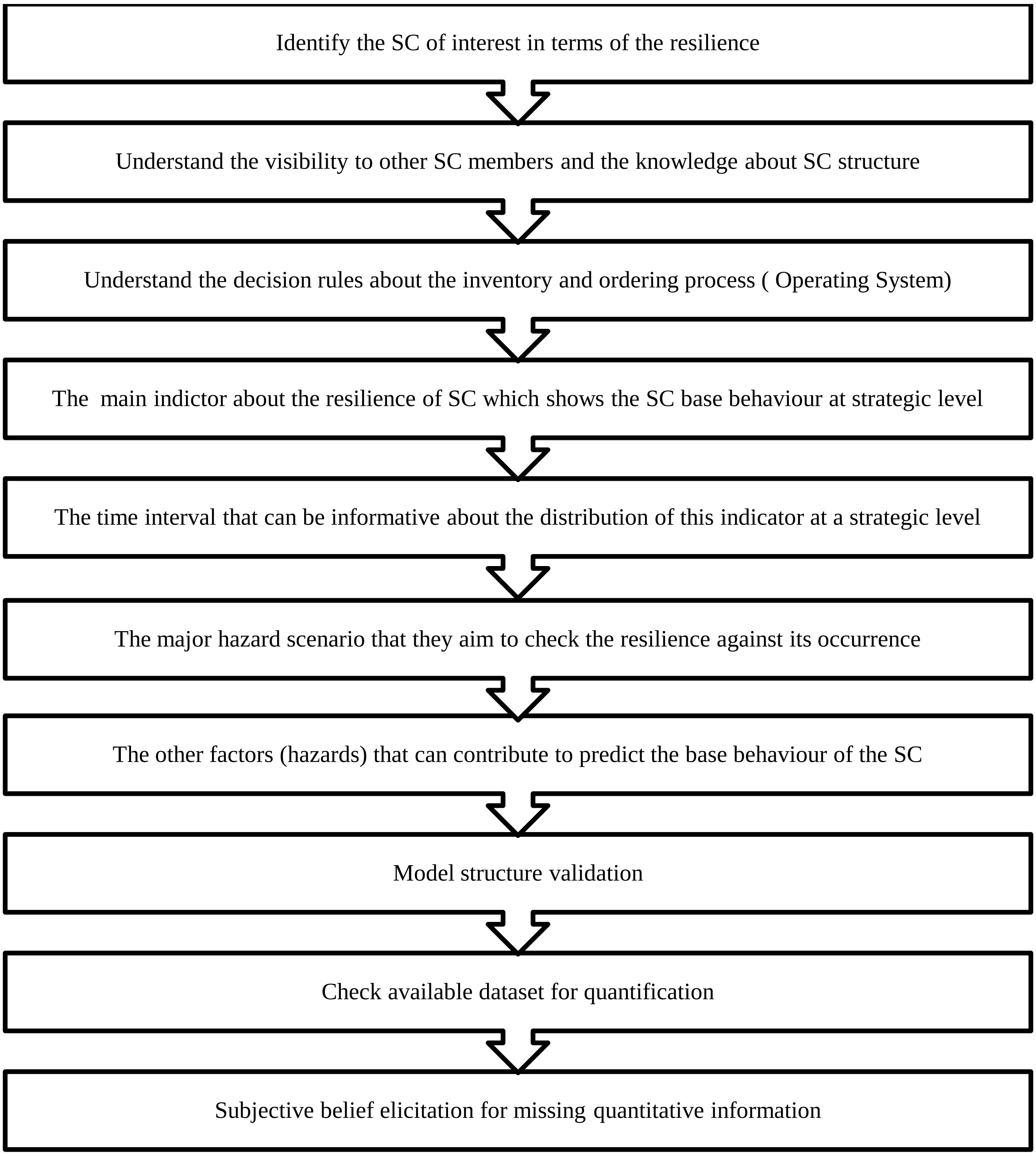


Figure 4-4: The main interviews' inquiries

In addition to the transportation manager and supply chain managers, other interviewees have been selected based on claims from the case study holder about their expertise in the concerned SC. The interviews have been recorded when it is possible after seeking the permission from the interviewee.

Table **4-2** shows the case informants and their titles with the name of interviewers and mode of interviews and their numbers and the content.

The interviews and meetings with case studies informants have been run sequentially based on the needed information. However, they can classify in three phases. These are (1) building contact and understand the concerned SCs, (2) understand the main SC characteristics, hazards, the resilience indicator and enablers (3) validation of the obtained information where feedback from case study participants about the model qualitative structure has been sought. The latter stage has been taking into consideration the suggestions to introduce or remove some factors that help to better analysis of SC resilience.

Table 4-2: SC Cases: interviewees and their positions, mode and number of interviews, interviewers, content

Case	**Informant corporate title**	**Mode and number of interviews**	**Content**
Tubes SC	SC Manager, Procurement Supervisor,	• Face to Face interview (1)	• Initial contact, concerned SC • Tubes SC known structure, visibility to other suppliers processes, • Decision rules in terms of the inventory and orders, • Main hazard scenario, • Strategic indicator about their resilience with its time interval.
		• Telephone Interviews (2) • Online Interviews (2)	
Specialised spare parts	SC Manager,	• Face to Face interview (1)	• Initial contact, concerned SCs, • Concerned hazards, • SC description, • Inventory and ordering strategy, • Actions to maintain the ability to react and recover.
		• Online interviews (3)	
	One inventory team member, One maintenance team member	• Face to Face interview (1)	• Spare parts classifications, • Spare parts suppliers.
		• Online interviews (1)	
	Operations Manager	• Online interviews (2)	• Production sequences description, • Relations between production and the spare parts demand.
	Procurement Manager	• Face to Face interview (1)	• Spare parts suppliers ordering process.

Atlantic Canada food SCs	Transportation Manager (Case holder)	• Telephone interview (1) • Face To Face Interview (2)	• Initial contact, • general information about company supply chains networks and the concerned SCs, • Known chickens and non-perishable food SC structure, • Main hazard scenario, • Other hazards the affect the identified SCs, • Validation of SC and model structure, • Subjective judgement for ferries, performances, • Strategic indicator about their resilience with its time interval,
	Procurement Manager	• Face To Face Interview (1)	• Decision rules regarding the inventory and ordering, • Performances of the suppliers, • Suppliers locations, • The contribution of suppliers to the performance of DCs • Validation of SC and model structure.
	VPs	• Face To Face Interview (2)	• Insights about the plan to maintain the resilience • Confirmation of the information that has been obtained • Visibility to other SC members processes • Validation of the SCs and model structure
	VP Agricultural Marketing and Product Development Division (currently CEO)	• Face To Face Interview (1)	• Insights about the chickens SC process • Packer and farms management rules. • Validation of chickens SC structure

4.4.2.3.4 Documents and Datasets

According to Love (2003), documents are an essential part of our world fabric. The main advantage of these documents is that they are created with no involvement of the researcher. Thus, they could be a more reliable source for the research data (Peräkylä, 2005). These documents can vary from auditor reports to meeting notes. Similarly, for available quantitative datasets, they provide a rich source of data that arise with no involvement of the research and might show many important facts about the situations that can be reported back to the interviewees to understand why for example some data have a particular pattern.

The purpose of using the primary and secondary document for the research as it has mentioned briefly above is to get an overall view of the SC and its suppliers, possible structure of SC and the current procedures about inventory and ordering. The location of some suppliers and their facilities can also be figured out through the primary and secondary documents. On the other hand, the quantitative datasets have been requested after the building of model qualitative structure due to the prominent role of the model structure in determining the required data for the quantification. Table 4-3 shows the documents and datasets that have involved in this research. The datasets and documents are case based. It suggests that the availability and the level of data that can provide to fulfil the research inquiry differ from one case to another. For example, in pipe coating case there is an absence of the suppliers' performance reports. So, suppliers for the specialised spare parts have been identified from the "transaction reports" and "PO detail reports".

Table 4-3: Case studies obtained documents and datasets

Case	**Documents and datasets**
Tubes SC	Supplier Performances reports
	Performance calculation matrix
	Suppliers financial data and auditor s' report
	Facility locations of the suppliers (suppliers websites)
	Demand, Inventory, and supply data (4 years span)
Pipe coating specialised spare parts SCs	Production Datasets (2 years span)
	Transaction reports
	Spare parts Demand (3 years span)
	PO detail reports (2 years span)
Food Atlantic Canada SCs	Weekly Suppliers performances datasets (6 years span)
	Performance calculation matrix
	Weekly DCs performances (6 years span)
	Service history reports
	Stores locations map

4.4.2.4 Case Studies Analysis

"Analysing data is the heart of building theory from case studies, but it is both the most difficult and the least codified part of the process" (Eisenhardt, 1989, Page. 539). According to Eisenhardt (1989), it can be attributed to the little discussion around the case studies analysis process in the literature as the primary focus remains to describe the context and the data collection methods. The analysis of case studies is usually conducted on two levels. These are within case level and cross case level (Eisenhardt 1989, Yin 2013). While Within case study analysis focuses on situational groundedness of the case study, cross-case analysis focus, according to Ketokivi and Choi (2014), on similarities and differences between the cases to shape propositions. Ketokivi and Choi (2014) state that case study should have duality criterion to have a sort of generalisation to another context. Otherwise, the results of the case studies will be so situational oriented and will not contribute to the emergent theory. Ketokivi and Choi (2014) insist on the role of incorporating the general theory which I discussed before in 4.4.2.1. However, the priority should be given all the time to the empirical evidence.

4.4.2.4.1 Within Case Analysis

‘Within-case analysis’ for this research concentrates on two phases. The first one is a problem orientation stage. The focus at this stage is to apply DBN to a particular problem that affects the resilience of SC based on the actual data about SC characteristics, decision rules that trigger the flow of the material and hazards/vulnerability identification. The coding of the terminology from these cases is based on the discussed concepts in chapter 2 and 3. For example, in chapter 2 I have distinguished between the vulnerabilities and hazards. In each case study, this terminology will be used to classify the data that have obtained with this regard. The results of this stage should show the facts about the case study and the analysis of the SC resilience based on its characteristics to the studied problem. They contribute to explaining the unique context of the case and the viability of DBN to analyse the problem and predict the resilience of the SC in that context. The results of this stage should also offer an interpretation of how some the relationships in the model can be operationalised considering the case characteristics and the people involved in the study. However, as I deliberate previously that the model itself is a tool for thinking and analysing the particular situation. Therefore, the model the input and the output play a significant role in understanding the causalities between the input, how adverse events consequences can propagate in the SC and how SC characteristics affect the resilience level to the problem.

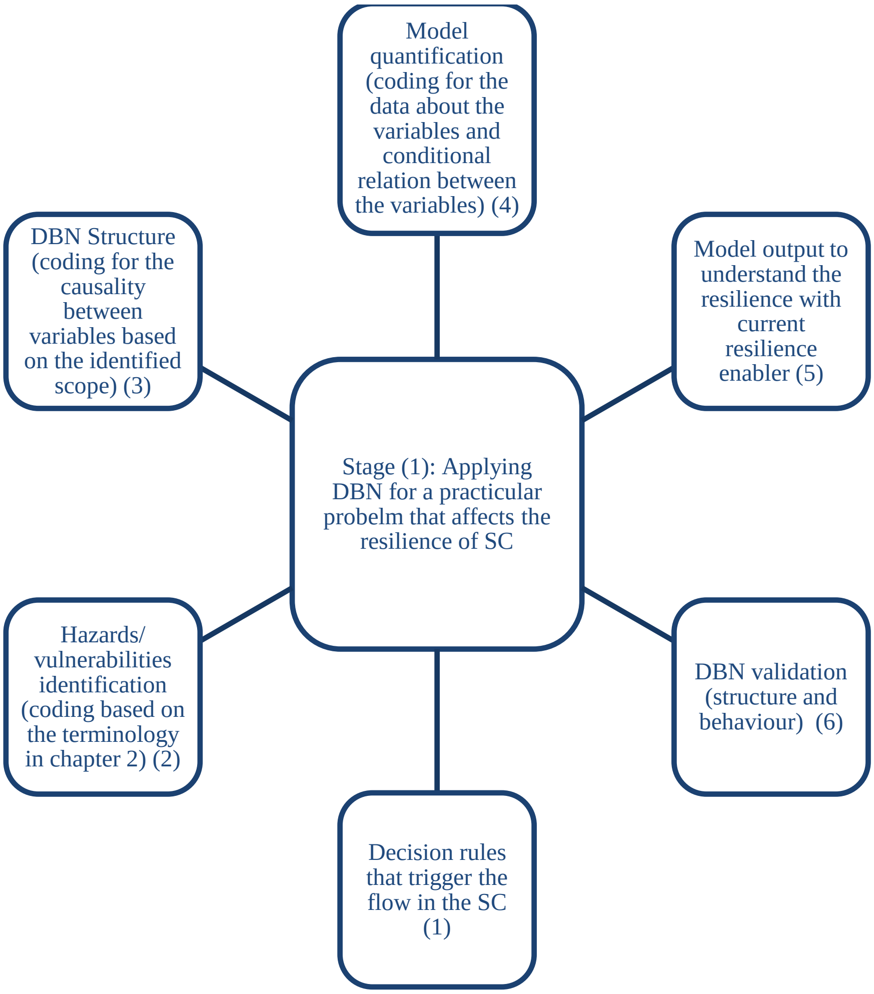


Figure 4-5: The first stage of within-case study analysis (Case problem orientation)

The second stage of "within-case analysis" is to answer three central questions that can contribute to fulfilling the objectives of the research regarding the practical application of DBN and the relations between the SC characteristics and the resilience level. These questions are: Is DBN able to capture the resilience by its definition that has been discussed in chapter 2? What are the relationships between the SC characteristics and the standard process to build the model? What the outputs of the model show about the relationships between SC features and its resilience? The analysis of these questions based on the case study will lead to drawing observations from each case about the DBNs role in informing the resilience analysis, the influence of SC characteristics and the relationships between the standard model process and SC characteristics. The latter analysis is a primary pillar to build theory from the cross-case analysis.

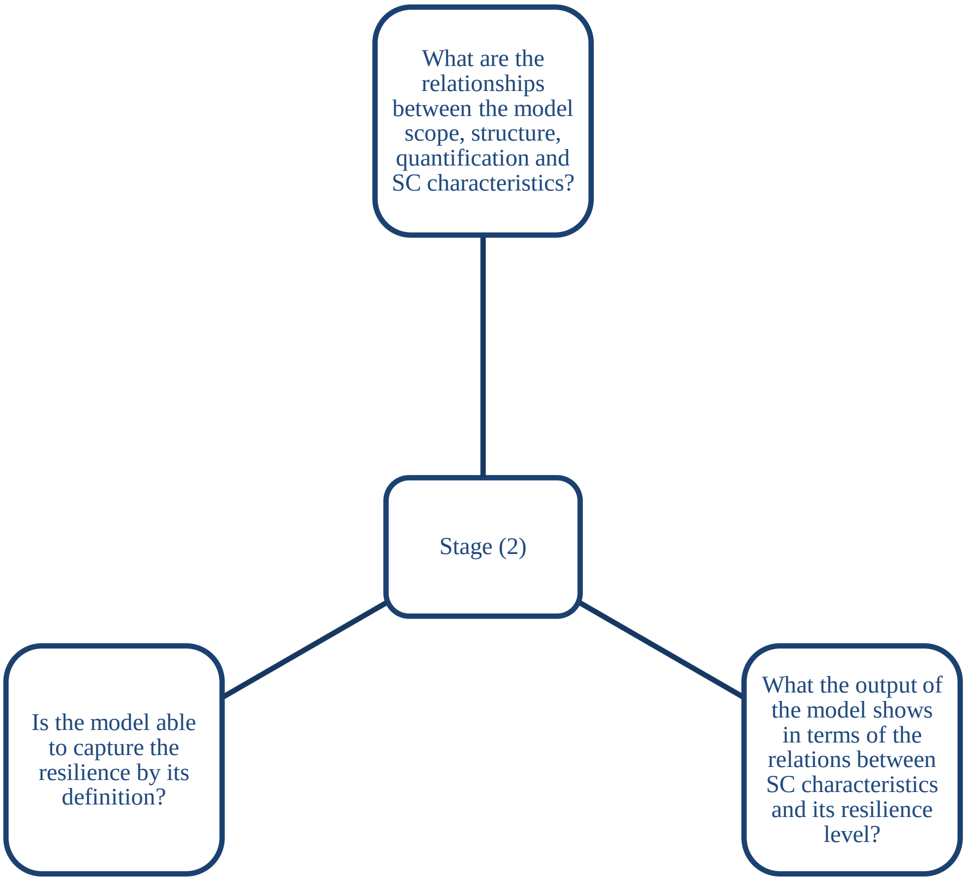


Figure 4-6: The second stage of within-case analysis

4.4.2.4.2 Cross-Case Analysis

‘Cross-case analysis’ focuses on similarities and differences between case studies to check if there is an emergent pattern through the case studies. The tactic for conducting cross cases analysis as proposed by Eisenhardt (1989), Yin (2013), Ketokivi and Choi (2014) is to select categories and dimensions from the general theory and the case studies and then check the similarities and the differences between the cases. In this research, three main categories for theory building in addition to one category that related to refining the terminologies that have been used in chapter 2 based on the empirical pieces of evidence.

The first category is the role of DBN in informing the resilience analysis. I will try to reflect on how DBNs predict the resilience of SCs to different problems arisen in the case studies. I will also show what contribution DBNs can make to understand the resilience comparing with the approach of complexity theory that has discussed in chapter 3. The second main category of the analysis is to produce a general view about DBNs process, input and output. This is to report key lessons that modellers can be considered when DBNs are employed to analyse and support decisions about SC resilience analysis Figure 4-7. In this stage of analysis, I try to answer what the influence of SC characteristics, discretization methods and time element on the standard modelling process that have been reported in chapter 3 and how this process can be refined if the SC resilience to be analysed.

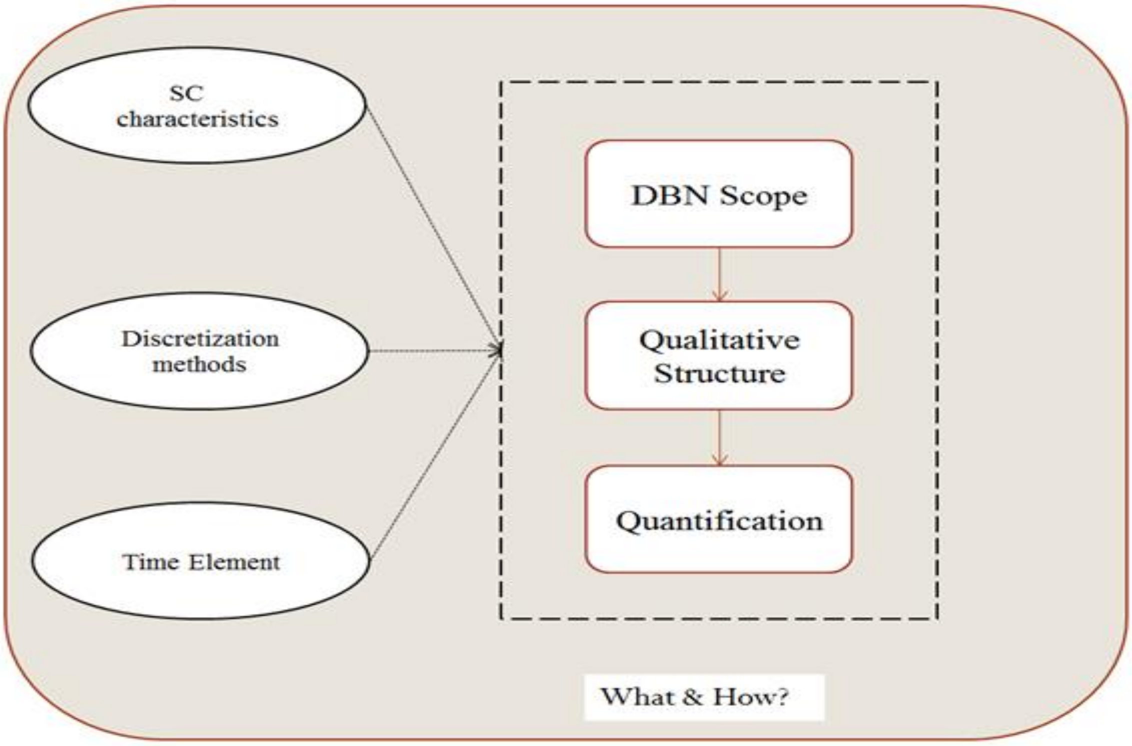


Figure 4-7: Cross-case investigation about DBN process to understand SC resilience

SC characteristics and their relations to resilience analysis based on DBN output Figure 4-8. Through the literature exploration in Chapter 2 and 3, some authors have reported that they are relationships between some SC characteristics and their risk analysis such as the role of SC structure (Nair and Vidal 2011, Soni *et al.,* 2014, Kim *et al.*, 2015), the operating system (Tang, 2006), and the integration (Jüttner *et al.,* 2003, Świerczek 2013). Apart from the visibility where the authors argue with their positive relation with SC risk management; there is no clear indication in the literature about what the nature of the relationships between the SC resilience and SC characteristics. Therefore, in this research, I try to understand the nature of these relationships. I try to tackle why there can be a relationship between SC resilience and a particular supply chain characteristics and how these characteristics can affect the resilience. The answer to the latter question will be mainly coming from interpreting the output of DBN for case studies.

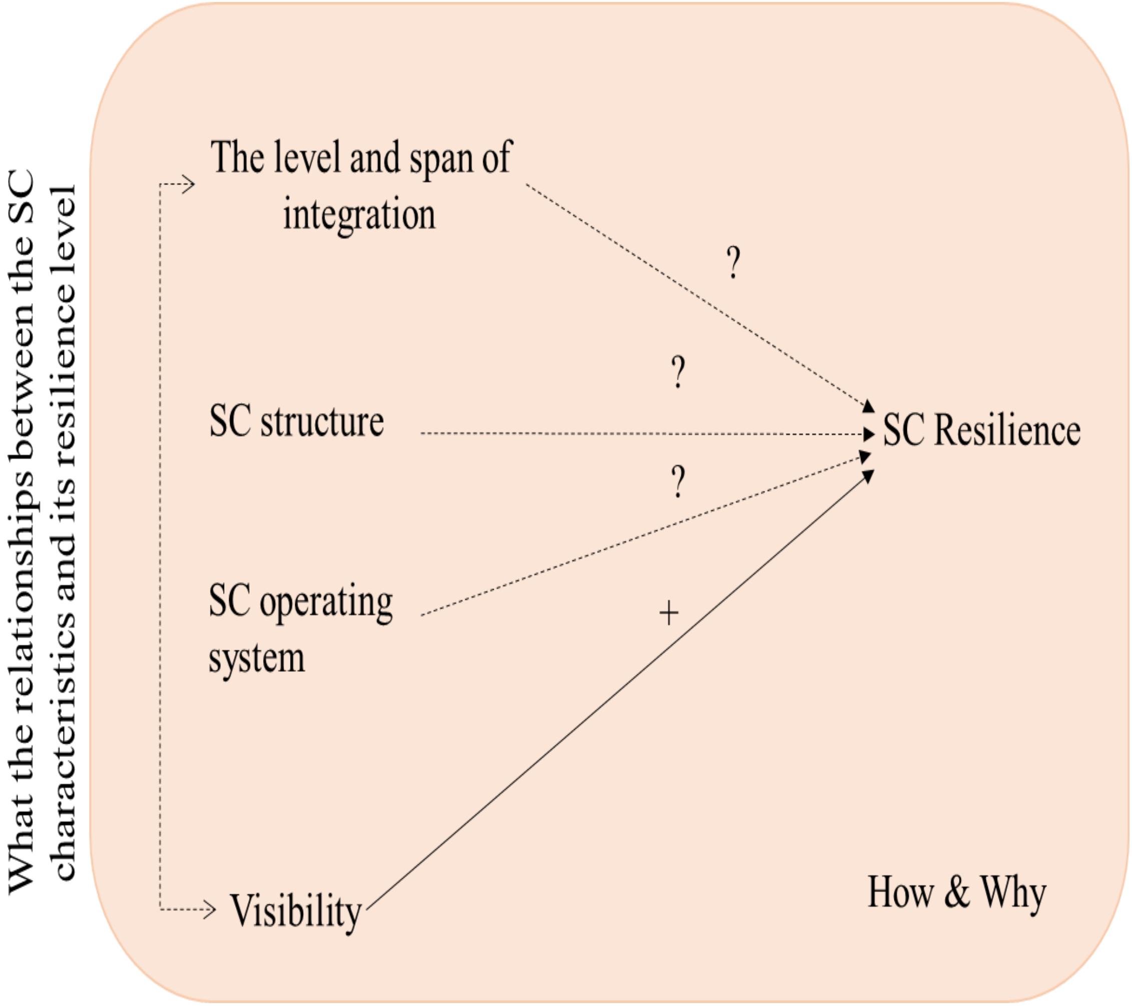


Figure 4-8: Cross-case investigation about SC characteristics and their resilience

4.4.2.5 Validity

In this section, the type of validation that can be carried out through the cases studies will be illustrated briefly. The reader should notice that this validation inevitably overlaps with the model validation. In the case studies literature, four types of validity have been highlighted. These are: Construct validity, internal validity, external validity and reliability (Yin, 2013). The internal validity is not a part of this case studies research because of the exploratory nature of this investigation. Internal validity has been suggested specifically for explanatory case study type where the aim is to test the theory in the literature.

Construct validity includes mainly the use of multiple sources of evidence and has feedback from the key participants about the output of the case. It is obviously one part of the modelling process for this research. The map of variables that affects the resilience is taking back to participants for validation and different sources of data to identify and quantify the variables are utilised. While the external validity seeks to define the domain to which a study's findings can be generalised, the reliability reveals the processes of the case study such as the data collection methods (Yin, 2013). The external validity will be addressed by stating how the results of this research should give insights for SC resilience analysis as well as for the using of DBN to inform this analysis based on SC characteristics. On the other hand, I try to improve the reliability level by declaring in this chapter steps to conduct the case studies and the aim of each data collection methods. Moreover, the data analysis protocol to generate the research propositions has been illustrated. Further insights into the processes to conduct each case study will be given in the case studies chapters. It is to address that there are slightly distinctive differences from one case to another.

4.5 Concluding Remarks

This chapter has shown the philosophical and methodological stance for this research. I have illuminated why the critical realist view of the world can contribute further to understand the phenomenon of SC resilience. By adopting the critical realism philosophy, I believe in the actual phenomenon rather than the observed one, although there is no denial of the existence of the real world.

The multiple case study methodology that is a justified research methodology by my philosophical stance has been discussed in detail. The methodology has three main phases to generate new knowledge for this investigation. The first one is the data collection phase where the aim is to understand SC characteristics, generate a map for the variables that can drive to understanding the resilience of SC to a particular problem, seeking feedback from participants and obtain numerical data to run the model. The second phase is to analyse the data based on a case level to show the characteristics of SC, DBNs input, DBNs output, DBNs process and get insight in the distinctive practicalities for the case problem and decisions. The similarities and difference between the cases in relation to the theories in Chapter 2 and 3 are considered for the cross-case analysis. This is to generate a common ground about the role of DBNs in informing the resilience analysis, induce a learning process to build DBNs and shape the research propositions about the role of SC characteristics in its resilience analysis.

5 Tubes SC Case Study: Suppliers Evaluation based on their Business Continuity to Understand the Resilience of Tubes SC

5.1 Introduction

This chapter investigates the use of DBN to evaluate the suppliers of a tubes SC based on their business continuity and examine the resilience of tubes SC to the business continuity of its suppliers. Tubes perform a significant role in many applications mainly for transmission of fluids and as structural elements in construction, automotive and aerospace industries. According to Hashmi (2006), any shape of hollow material with a uniform wall wideness called tubes. The typical supply chain of tubes consists of raw material suppliers, manufacturers that have facilities to produce tubes called mills and then distributors or customers. The raw materials for constructing tubes can be principally cast iron, wrought iron, steel, copper, aluminium, concrete, clay, wood, glass, paper and many others. This chapter will focus on exploring tubes SC for a leading distributor in the UK. I will investigate the tubes SC characteristics from the distributor perspective, DBN input/output and the analysis of how the confidence in the model results is built.

5.2 Relevant Literature: Suppliers Evaluation and Selection

The issue of evaluating suppliers based on their business continuity has been stated as the primary concern of decision makers concerning tubes SC resilience. They are interested in understanding the chance of a supplier to go out of the market and its effect on the monthly company response to customers demand. Suppliers' business continuity has been discussed briefly in the literature of supply chain risk management. Tang (2006) argues that the supplier business continuity can be an important criterion for the supplier evaluation and selection. Supplier selection and evaluation is a strategic process that determines the sustainability of a company. It is not only related to suppliers offering the lowest cost (Ng, 2008). It is highly dependent on selecting good suppliers based on different criteria (Ng, 2008). Ho *et al.* (2010) report that the quality is the most popular criterion for the supplier selection process, then the delivery time after that the price. Besides the quality, delivery and price that are operational criteria, many other tactical and strategic criteria have been discussed in the literature such as manufacturing capability, service, financial position, supplier location, management, technology, research and development and flexibility. See for example (Choy *et al.*, 2005; De Boer *et al.*, 2001; Ng, 2008; Perçin, 2006; Ramanathan, 2007; Saen, 2007; Talluri, 2002).

Recently, there is an increasing trend in the literature to deal with the supplier selection process under operational and catastrophic risks. Sawik (2011a); Sawik (2011b); Sawik (2013) proposes three different mix-integer programming for an optimal selection of supply portfolio in the presence of local and global supply chain disruption scenarios such as labour strike and bankruptcy and then he extended that to multiple periods of time. Hammami *et al.* (2014) make use of mixed integer stochastic programming for the supplier selection under price discounts and uncertain fluctuations of currency exchange rates scenario. However, the business continuity issue is still under research. According to Tang (2006), the business continuity of the supplier can be a fundamental problem when a firm suddenly has to increase the sourcing from other suppliers in its current supply chain design or find new suppliers with similar quality and immediate capacity. The issue of business continuity and the resilience of tubes SC to its suppliers' business continuity will be checked in detail for this case where I can share some insights with the current literature of supplier selection and evaluation.

5.3 Brief Description on the Actual Data Collection Process for UK Tubes SC

The data collection process and analysis had lasted for five months starting from December 2013. The initial telephone meeting with a decision maker led to building the contact and gave an overview of the company supply chains. The semi-structure interviews with two decision makers assisted in identifying tubes supply chain as a strategic one for the company and mapping some of its structure. The suppliers' continuity in the market had been identified as the main hazard scenario that the company aims to check their resilience against its occurrence and consequences.

Once the qualitative structure of the model had been validated with supply chain manager, the company provided their tubes demand, supply and stock data for the last four years starting from 2010. The principal reason for collecting this data is that the SC system for this case had been described by the flow from the suppliers to meet the demand. A secondary search had been focused at this stage on obtaining data from in-house financial companies, annual reports and suppliers’ websites to demonstrate the ability to populate and update the model based on some pieces of evidence. In-house financial companies provide business, accounting and director information on businesses mainly registered in the UK and Ireland. They also offer information about the mother companies in case they have subsidiaries registered in the UK.

5.4 Tubes SC Characteristics

The company current tubes supply chain design consists of five direct suppliers. Three of them are big suppliers who are also the principal suppliers for the global market of tubes. They own mills in various locations in the world. The other two suppliers are local with one facility. Figure 5-1 shows the identified structure for this SC. The exact facility locations for each supplier have been recognised from secondary data sources. I code the facilities location here as F China, F US, etc. I make them anonymous for confidentiality reasons. Between 2010 and 2013 Supplier (A), (B), (C), (D) and (E) supply 77%, 10%, 7%, 3% and 3% from the company tubes respectively. The importance of this distinction between suppliers is that the disruption of a big supplier can significantly affect the sourcing from other suppliers whereas the small suppliers usually have a negligible impact on the market as I will see in the resilience analysis of this case.

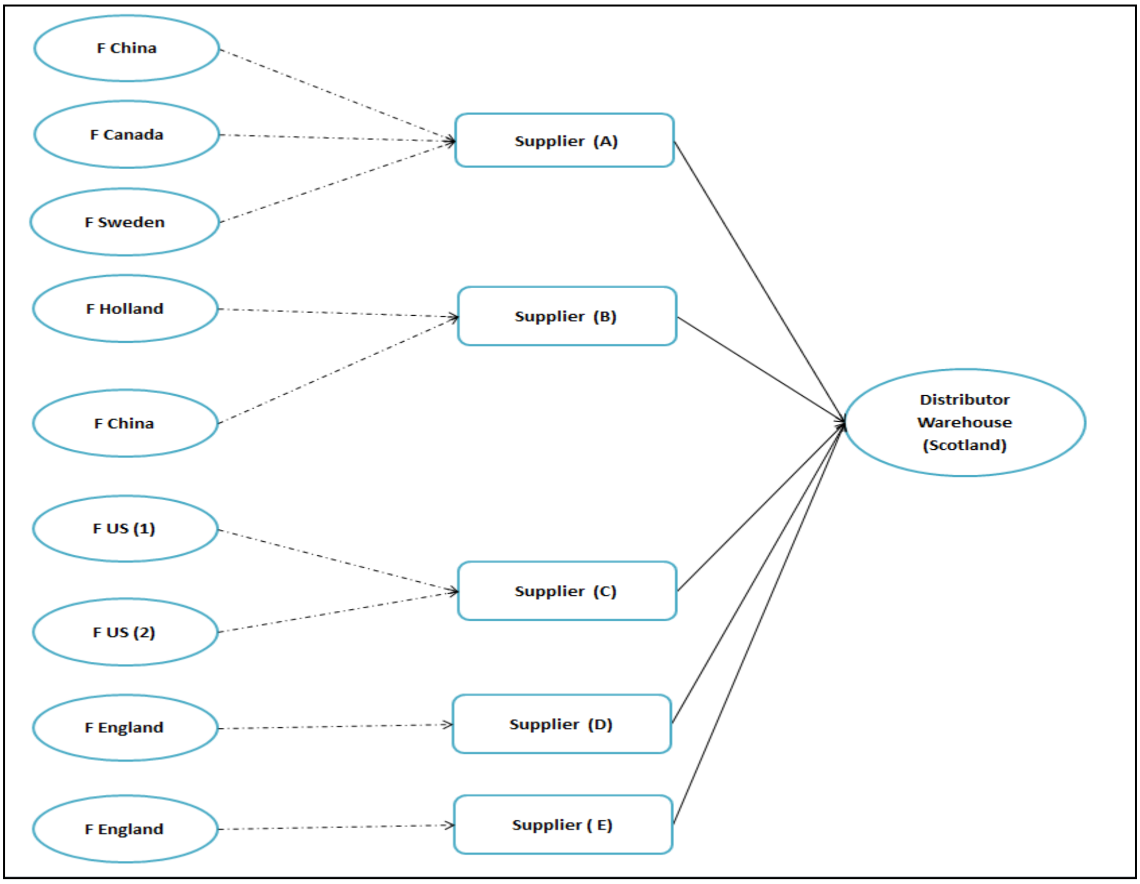


Figure 5-1: Known structure of the tubes supply chain

The distributor has market relationships with their suppliers where buyers at the company main hub order based on the negotiated price and delivery time. Based on (Świerczek, 2013) classification for the integration level, the tubes SC can be classified as non-integrated SC. The suppliers are the main responsible for organising the shipment and any late shipment will affect their calculated performance. The distributor and suppliers do not share essential information about the processes in tubes SC. The exchanged information revolve around the orders and shipment notifications. The lack of visibility to big suppliers is justified by a substantial number of customers that a big supplier has in the global. However, one key point that this case study raised is that the visibility across the SC can be improved when there is no integration between SC members. It is mainly through collecting some data from public sources that aid to understanding and assessing the level of hazards that a supplier can face.

The company push-pull operating system is decoupled by a one-month redundant inventory Figure 5-2. The goal of this excess inventory is to stabilise the supply chain and reduce tubes shortages which can cause customers to go elsewhere to make their purchases. The adoption of this system is justified by the stated value creation of the company that mainly stems from the high and speedy response to the customer orders. With the push-pull system, the triggers for ordering is the difference between the actual inventory level and target inventory level, which is 35000 units.

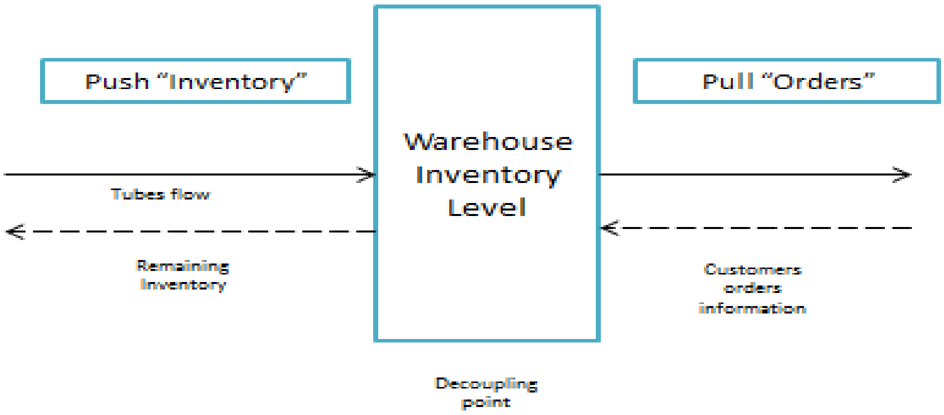


Figure 5-2: Tubes SC push-pull operating system

5.5 DBN Qualitative Structure

5.5.1 Resilience Index and Variables that Represent the SC System

The 'inability to meet the demand' has been seen by the company as the main consequence of the adverse event. They express this inability by the number of units that they are not able to fulfil monthly (i.e. the shortages). The ability to satisfy the different levels of demand as a resilience index is expressed by the distribution of the units that has been fulfilled and shortages in meeting the demand. To predict the resilience index, the variables that represent the tubes flow have been studied. Table 5-1 shows the variables that have been used to describe the flow of the material in tubes SC. These variables are the supply from the five suppliers, the demand distribution, the inventory and the replenishment quantity. The current flow in the SC is controlled by the information flow and decision rules in terms of the target level of inventory and the orders allocation between suppliers. The SC capacity is only a figure to show two indicators about the resilience of the SC. The first indicator is the ability of the tubes SC to maintain its base behaviour in fulfilling the customers demand if a supplier has left the market. The second indicator is how long supply chain needs to recover to its normal capacity in meeting the client's demand.

Table 5-1: Variables that represent the tubes SC system

Factors	**Description**
Demand	It describes the uncertain distribution of the company demand during a particular time interval
Supply (X)	It shows the distribution of the supply level from X supplier within a time interval
Inventory	It represents the fluctuation of the company stock due to the demand and supply
Replenishment quantity	It manifests the distribution of the company orders that triggers the supply process
SC capacity and remaining inventory indicator	It refers to the ability of tubes SC to response to the customers' demand for their inventory

5.5.2 Early Warning Factors to Evaluate Suppliers Business Continuity Hazard

Table 5-2 summarises the descriptions of the business continuity as the prime hazard that concerns the company. It also illustrates the early warning factors to understand the chance of this hazard to occur that have been refined with the decision maker in the company. Wagner and Bode (2006) explain that supplier business risks relate to the various events that affect the continuity of the supplier and result in the temporary or permanent perturbation or termination of the buyer–supplier relationship. According to Wagner and Bode (2006), the threat of financial instability of suppliers and its consequences are vital events that can lead a supplier to go out of the business. Simchi-Levi *et al.* (2014) employ the financial position of the supplier as a factor to assess the supply chain resilience to unpredictable risk events. In the supplier selection literature, the supplier financial position has also been acknowledged in a number of papers. See for example, Bottani and Rizzi (2008); Braglia and Petroni (2000); Muralidharan *et al.* (2002); Pei-Chan *et al.* (2007). Therefore, the supplier financial stability is considered as one of early warning factors that can guide to understanding the business continuity of the suppliers. The other factor arises in this case and affects the business continuity of the supplier is the environmental hazards due to facility locations. Some geographical locations are hazard-prone areas more than others (Kahn, 2005). Supplier business continuity will be affected if its facilities are located in hazard-prone areas. Thus, the location of supplier facilities should be checked (Chan, Kumar, 2007; Simchi-Levi *et al.*, 2014).

The financial stability by itself has had a meaningless interpretation for decision makers, as the financial stability should be understood by the financial indicators. There has been a need to figure out what the financial indicators that their values can give a picture to the company to understand the financial stability of a supplier. Many financial indicators have been found where the changing of their values can show the supplier financial stability. Through refining the model with the decision makers, two indicators have been adopted. These are the net worth and profit changing rates. The net worth of a supplier equals the total assets (what the supplier owns) minus the total liabilities (Bernanke, Gertler, 1989). The net worth changing rate shows if the company assets are expanding comparing with their liabilities and if the suppliers business helps to reduce their liabilities or not. Therefore, it gives a clear indication about a supplier financial stability. On the other hand, if a company is not profitable or their profit decrease dramatically, it likely will not stay in business for long. Thus, the profit changing rate can give a further aid to anticipate the financial stability of a supplier because it shows if the profit decline, improve or remain steady during the time.

Table 5-2: The identified hazards that can affect the Tubes SC

Hazards	**Description**
Facility location environmental hazard	It summarises the level of hazard that a facility might face due to its location such as the natural and political hazards.
Financial stability	It refers to the hazard that arises from the financial status of a supplier.
Supplier business continuity	It describes the chance of the supplier to continue in the market.
Net worth changing rate	It exhibits how the net worth of the supplier changes from a year to another.
Profit changing rate	It illustrates the growth or the declined of the profit from one year to another.

5.5.3 Notation

$(\mathbf{S_t^i})$: The supply from a supplier $\mathbf{i}$ at time $\mathbf{t}$

$(\mathbf{D_t})$: The demand at time $\mathbf{t}$

$(\mathbf{\Phi D_t})$, $(\mathbf{\Phi S_t^i})$: The distributions of the demand and supply that can take any form of a continuous distribution.

$(\mathbf{I_t})$: The inventory level at time $\mathbf{t}$. It is an arithmetic function of the inventory level remains from the previous time interval and the distribution of supply from suppliers at time t

$(\mathbf{\Phi I_t})$: The continuous distribution of the inventory that indicates the uncertainty around the supply and the level of inventory in the previous time interval.

$(\mathbf{R_t})$: It is the replenishment quantity at each time interval, which distributes between the suppliers according to predetermined strategy in sourcing. Mathematically $\mathbf{R_t}$ is the difference between the target inventory level and the actual level of the inventory at any time interval. At the operational level, the reorder point should be included.

$(\mathbf{\Phi R_t})$: The continuous distribution of the replenishment quantity that shows the uncertainty around this quantity.

$\boldsymbol{\alpha}$: The allocation coefficient of the replenishment quantity between the suppliers

$(\mathbf{G_v^i})$: The environmental hazard that affects the geographical facility locations of a supplier, which takes $(\mathbf{v})$ states. It is a function from each facility geographical location environmental hazard $(\mathbf{g_v^u})$. $(\mathbf{u})$ denotes the exact location of the facility.

$(\mathbf{F_v^i})$: The financial stability of a supplier. It is a function of the net worth changing rate $(\Delta\mathbf{N_v^i})$ and profit changing rate $(\Delta\mathbf{P_v^i})$ of the supplier $\mathbf{i}$. It takes $(\mathbf{v})$ states.
$\mathbf{C_t}$: The remaining inventory and capacity indicator

5.5.4 Cause –Effect within and Cross Time Intervals

Figure 5-3 shows the general qualitative structure for DBN to analyse the resilience of tubes supply chain considering the business continuity ($\mathbf{B^i}$) of two suppliers (B and D) as an example for a clear visualisation. The actual DBN includes the company five suppliers. DBN for this case mainly concentrates on two levels of estimations. In the first one, I try to understand the chance of supplier business continuity states at a node level. Then, in the second stage, I examine the effect of the business continuity at the SC level. The arrows between nodes indicate the causal and influential relations between the variables. The dashed arrows between business continuity of the suppliers and the supply from different sources refer to the influence of supplier business continuity on its supply and the supply from other suppliers. These latter relationships will be used mainly to understand the impact of a supplier goes out of the market on other suppliers in the SC. This influence can be reflected in different forms. It can lead to increase sourcing from other suppliers (orders reallocation strategy). On the other hand, the failure of a supplier can also drive less supply from other suppliers. The node $\mathbf{C_t}$ shows mainly the shortages and the surplus of the inventory in comparing to the demand within a time interval. Using the figures from this node is essential to understand the ability of the SC to meet the demand. The main dynamic factors that affect how the situation will be in the next time interval are the remaining inventory and the replenishment quantity. The latter needs to be ordered based on the remaining inventory level to the target inventory level. The replenishment quantity is assumed to be split between the suppliers based on the ratio of the dependency that I have discussed in 5.4 (e.g., supplier A supplies 77% of the company needs).

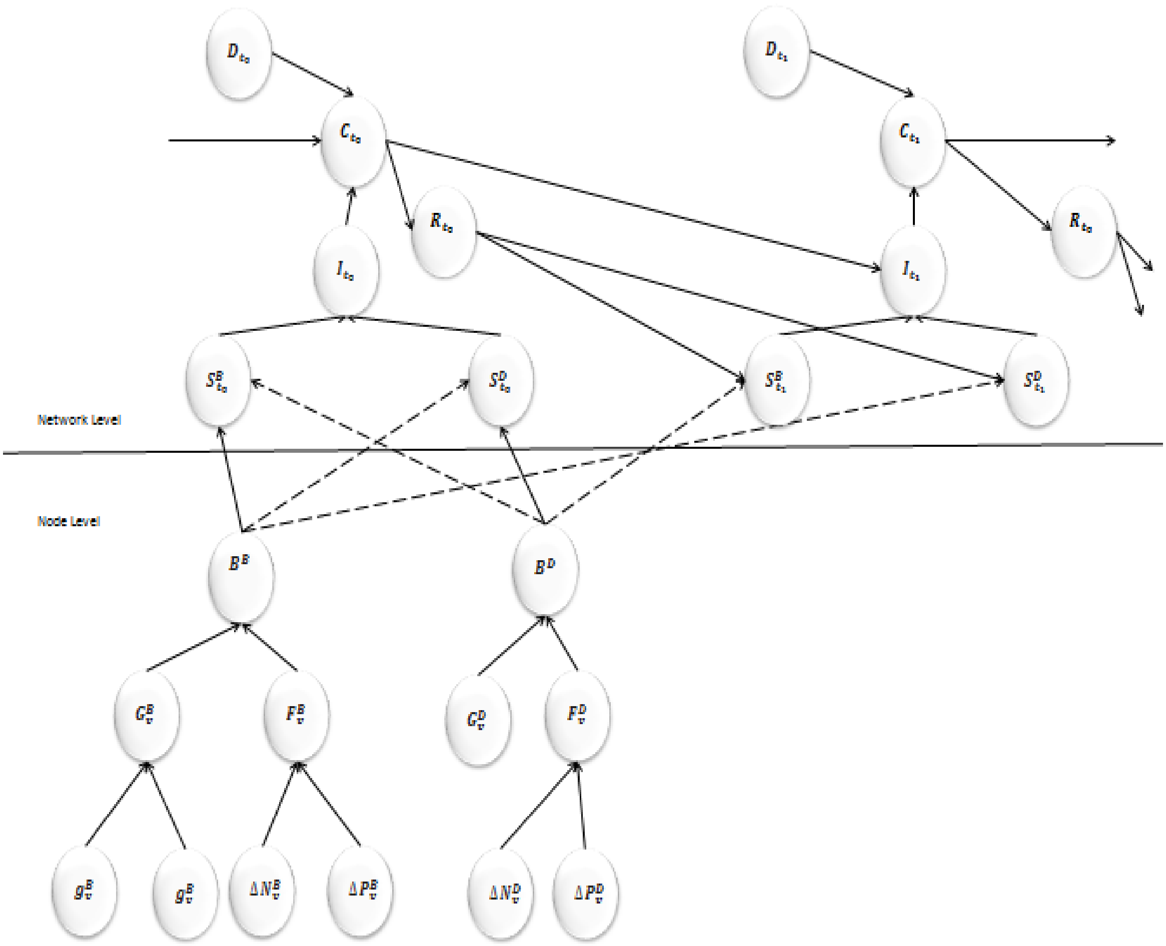


Figure 5-3: DBN general qualitative structure for tubes SC resilience analysis

5.6 Quantifying DBN of Tubes SC

5.6.1 Time Space

The monthly time intervals are the central pillar to understand how the tubes SC can maintain its monthly responses to demand and its ability to recover when an adverse event occurs as I have stated above. However, the chance of the supplier not to continue in the market is assessed by a longer time interval. Mainly, it can be estimated based on a yearly time window because the data about some the financial indicators are obtained from auditing reports. This different assessment of the time space between the hazard scenario and the variables that describe the SC system has raised a dilemma about how the interaction between the hazard scenario and SC system can be highlighted.

This interaction can be understood in two ways. The first one is simply to think about the chance of the hazard to occur as the expected number of occurrences per unit of time. Then, half the time, half the expected number of occurrences (Twice the time, twice the expected number of occurrences). Therefore, the analogy for this case is the chance of supplier to go out of the market within a particular month will be understood by its yearly chance divided by 12. This is with taking into account the homogeneity through the time. For example, the chance of supplier to go out of the market will not be different from one month to another (Figure 5-4). However, this is neither the aim of identifying factors that help to understand the chance of a supplier to go out of market nor the hazard scenario for a particular supplier can occur several times (supplier will not go out of the market several times).

By identifying the factors to predict the hazard, the aim is to evaluate the chance of the supplier to go out of the market. Then, examine the impact of this scenario occurrence on the base behaviour of tubes SC at a particular point of a time interval. Recall for the resilience analysis, the hazard is examined as a scenario. Therefore, whatever is the time window to understand the chance of the hazard scenario, it will not conflict the time intervals of the base behaviour. The reader can draw here a comparison with Atlantic Canada case studies that I am going to discuss in Chapter 7. In Atlantic Canada case study, some hazards such as the storms and the ferries breakdown can occur every week. Therefore, they have been included in the model base behaviour. On the other hand, the hurricane has been explored as a hazard scenario (it occurs at a particular point in the time) to understand the resilience of SC to this scenario.

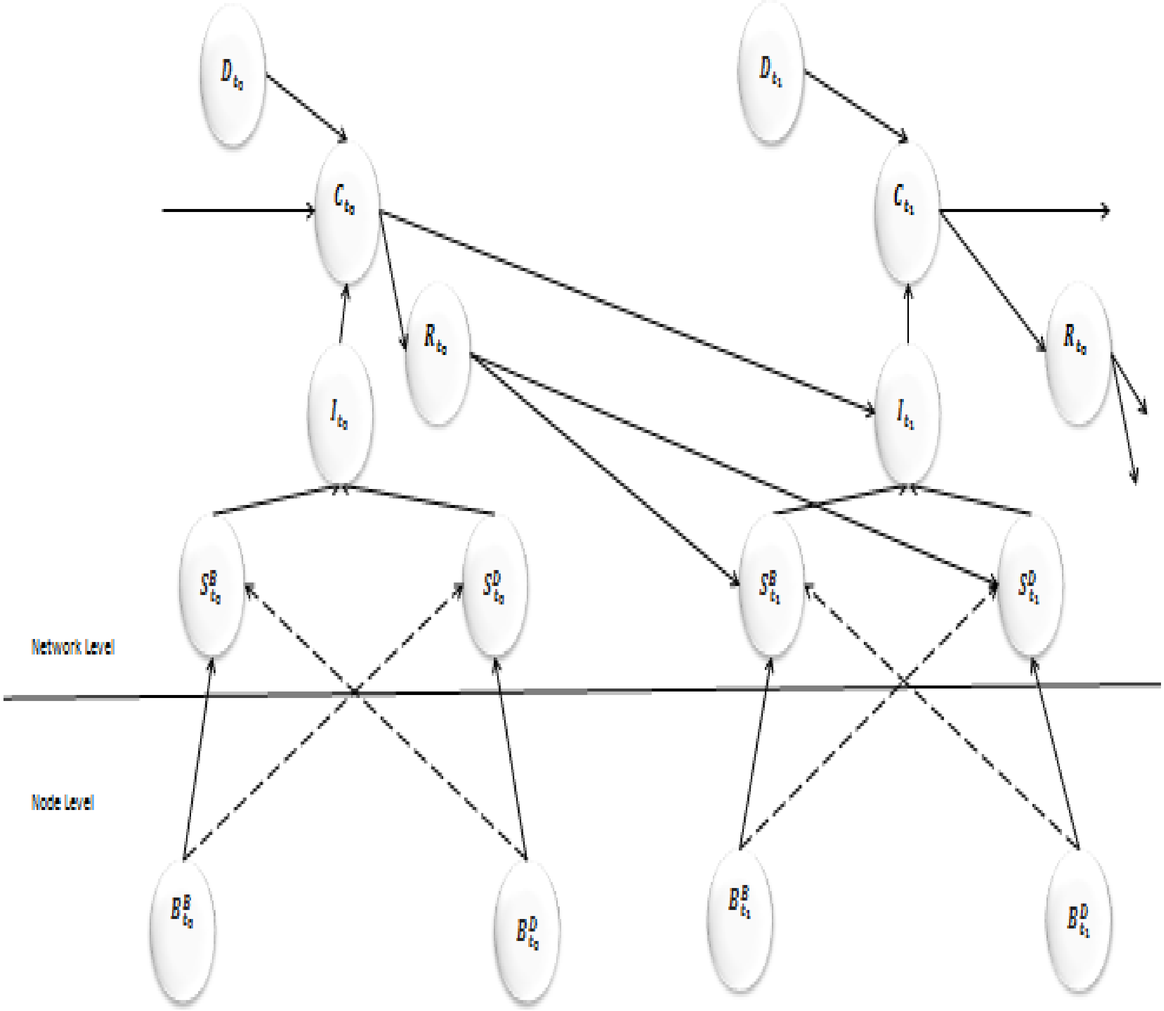


Figure 5-4: The interaction between the hazard scenarios based on one-month time chance description

The above discussion also illustrates how the decision maker is updating the model at the planning stage. While the base behaviour can only update by a new probability distribution of demand, supplies, etc. due to random uncertainty, the evaluation of suppliers can be updated by a new piece of information about the early warning factor. The latter can be obtained at any point of the time.

5.6.2 Describing the Variables States and Their Probabilities

Table 5-3 shows the descriptions of the model discrete variables and demand as a parent node with no roots nodes.

Table 5-3: Variables states descriptions

Variables	**Distribution /States**
$(\mathbf{G_v^i})$, $\mathbf{g_v^u}$	〰 = Low, High
$\mathbf{F_v^i}$	〰 = Good, Bad
$(\Delta \mathbf{N_v^i})$, $(\Delta \mathbf{P_v^i})$	〰 = Highly Positive, Positive, Negative, Highly Negative
$\mathbf{B^i}$	Continue, Not continue
$(\mathbf{\Phi D_t})$	LogNormal $(9.65208, 0.424987)$
$(\mathbf{\Phi I_{t_0}})$ **(initial inventory distribution level)**	Normal (10000, 530625)

The monthly demand distribution has been figured out from the company data. As can be seen Figure 5-5, the company monthly tubes demand is approximately between 5000 units and 28000 units with few outliers.

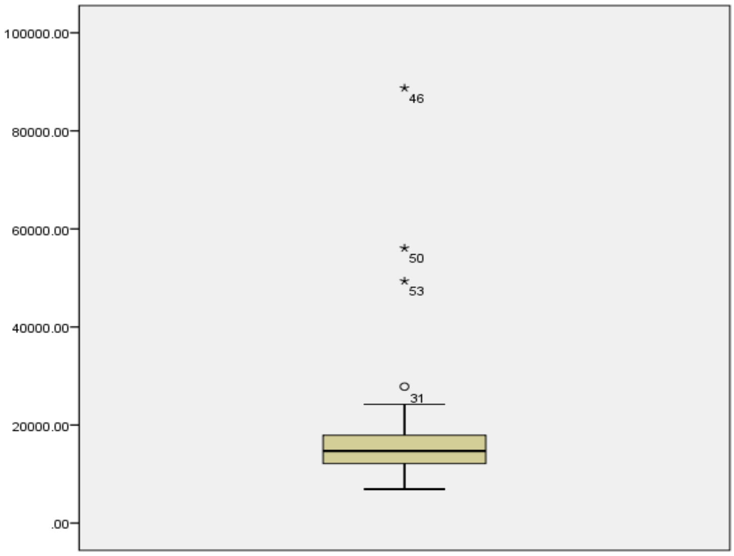


Figure 5-5: Demand distribution between 2010 and 2013

The demand has been fitted to different distributions. The best fit is that the monthly demand has a log normal distribution with $(\mathbf{9.65}, \mathbf{0.43})$. Figure 5-6 shows the lognormal distribution fit for the monthly demand data. The good of fit has been confirmed using a chi-squared test. The reason why this demand distribution has to be parameterised is to enable the use of dynamic discretization algorithm. For the parent node with no roots, the use of dynamic algorithm requires fitting data to distribution. The current algorithm of dynamic discretization does not learn the distribution from the available dataset. However, this issue has no impact on the continuous child nodes as their probability distributions are determined from the joint probability distributions of their parents. They do not have to take any particular distribution form.

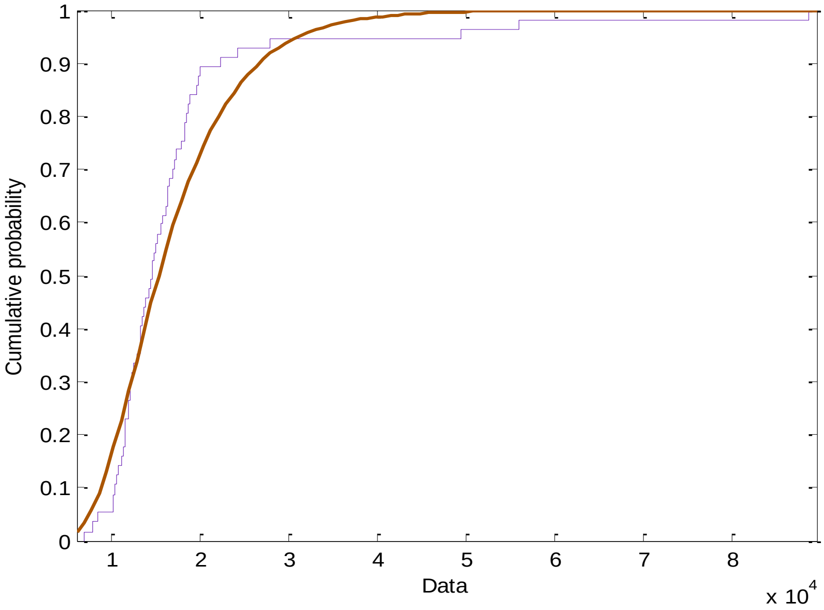


Figure 5-6: Cumulative distribution fit for monthly demand data

The data about facilities geographical locations have been collected from the suppliers' websites and annual reports. Companies usually disclose this information to show their capacity to meet the customers demand. The environmental hazard of a facility location has been considered either to be low or high. Regarding the financial indicators, (Appendix B.2, Page 257) shows a sample of financial data that I have collected for all actual suppliers. The financial data are numerical and has clear continuous nature. This numerical nature can be noticed from the net worth chaining rate of the supplier C between 1997 and 2013 (Figure 5-7). In contrast to the variables that represent the system where the dynamic discretization aids to reduce the elicitation burden, the dynamic discretization of financial datasets results in many states that make the meaning of these states are hard to describe. The importance of having a limited number and distinct description of discrete states is to inform the state of financial stability that can be good and bad. One percent decrease or increase in the net worth will not add any value for this description.

To deal with this issue, I have used a non-uniform static discretization similar to the one that will be utilised for the Atlantic Canada case. Non-uniform static discretization means that a static discretization will be run with no target state. Then, in the same analogy to dynamic discretization, I will manually merge the states with low probability and discretise more the states with high probability.

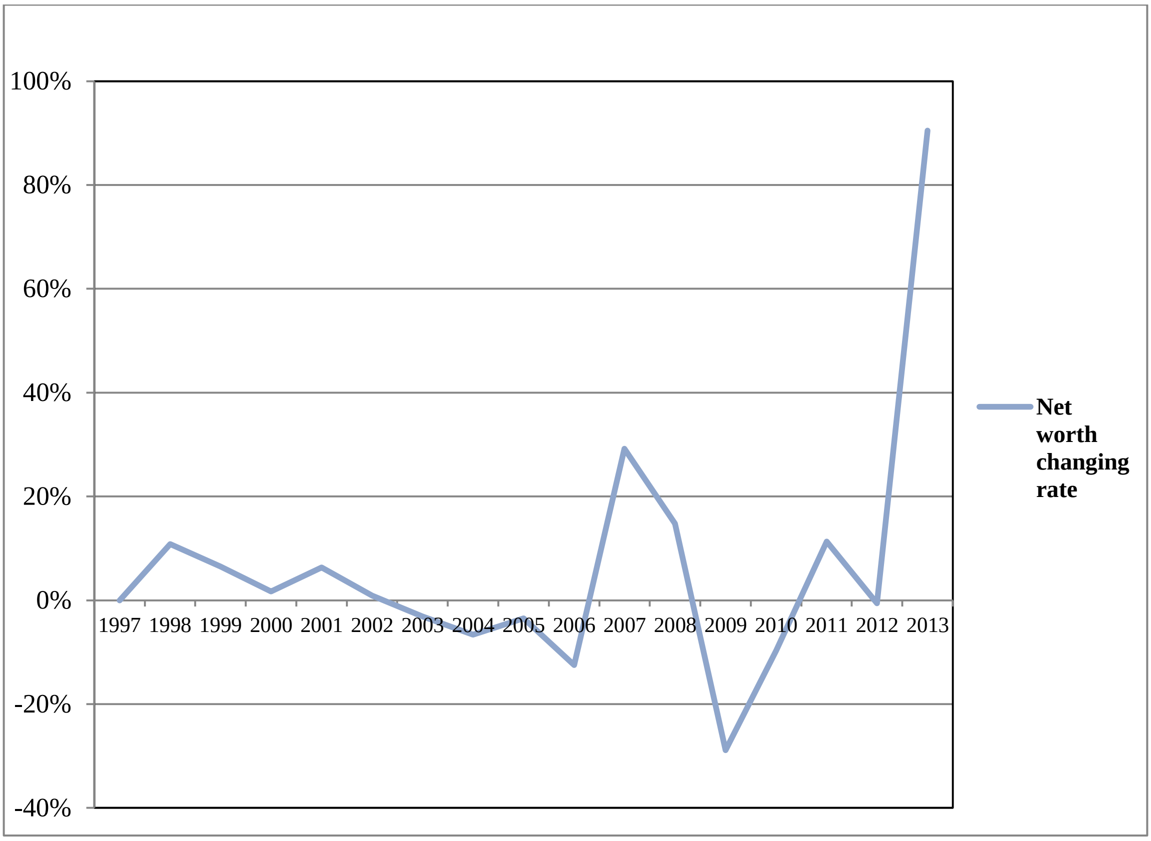
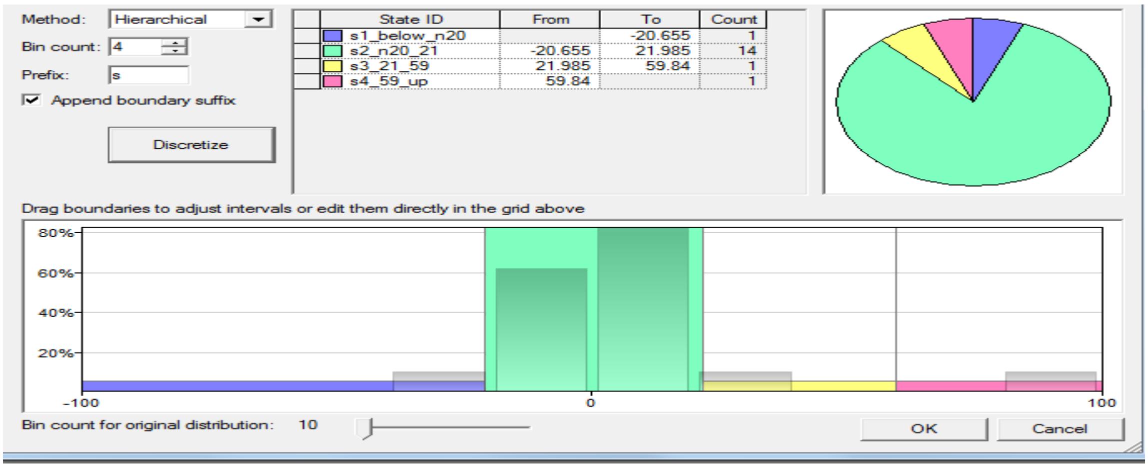


Figure 5-7: The net worth changing rate for supplier C

Recall the example about the net worth changing rate for supplier C. The initial static discretization of this net worth changing rate revolves around the -20% and +20% value (Figure 5-8). However, this discretization still is non-informative and has meaningless due to that the category from -20.65 to 21.98 includes the 83% of the observations between 1997 and 2013 and has negative and positive observations. This category has been discretised more to be "-20.66 to <0" and "0 to 21.98". The other two positive categories have merged to be "<21.98" due to their low probabilities. Table 5-4 displays the threshold values for the suppliers net worth changing rate states and their probabilities. The states of other variables are delivered in the next section as part of DBN run.



Method: Hierarchical

Bin count: 4

Prefix: s

☑ Append boundary suffix

	State ID	From	To	Count
🟦	s1_below_n20		-20.655	1
🟩	s2_n20_21	-20.655	21.985	14
🟨	s3_21_59	21.985	59.84	1
🟥	s4_59_up	59.84		1

Drag boundaries to adjust intervals or edit them directly in the grid above

Bin count for original distribution: 10

Figure 5-8: The initial static discretization for supplier C net worth changing rate

Table 5-4: The discretized states for supplier C net worth changing rate

States	Description	Probability
Highly positive	<21.985	0.12
Positive	0 to 21.98	0.44
Negative	-20.66 to <0	0.38
Highly negative	<-20.65	0.06

The importance of such clear description is that when a value of the financial indicator is obtained there should be precise which variable state is going to be updated by this observation. The updating of financial indicator states will lead eventually to update the belief about the financial stability of the supplier.

5.6.3 Assign Probabilities and Mathematical Relationships

In this case study, the description of some variables states and assign probabilities for them are intertwined due to discretize the data. As I have shown above, the demand distribution and the states of financial indicators are associated with prior probability distributions. It is mainly due to the use of available data to run the discretization. The rest of variables are child nodes where their conditional probability distributions are formed by the joint distribution of their parents.

Table 5-5 demonstrates the mathematical relationships that employed to find out the conditional probabilities for the variables that represent SC system. As the SC system is expressed by the distribution of the tubes flow in the system and the information and decision rules that control this flow, the conditional probability distributions for the variables that represent this system can be formed depending on the arithmetic relationships between the variables that describe the SC system. The supplies from suppliers (S_t^i) are triggered by the replenishment quantity. Therefore, their conditional probability distributions are functions from the replenishment quantity distribution and ordering strategy. Recall that 77%, 10%, 7%, 3%, and 3% from the orders go to suppliers A, B, C, D and E respectively. However, the supplies from suppliers are conditional also on its business continuity state. The business continuity has two states (i.e., continue or not continue). The supply will maintain its distribution if the supplier is going to continue in the market. Otherwise, the supply will be zero.

Table 5-5: The mathematical relationships to form the conditional probability distributions for variables that represent SC System

Variables	Distribution /States
Target inventory level	35000
$\mathbf{R_t}$	F (Target Inventory - Remaining Inventory)
$(\mathbf{I_t})$	$F(S_t^i + C_{t-1})$
$\mathbf{S_t^i}$	αR_{t-1} , 0
$\mathbf{C_t}$	$F(I_t - D_t)$

The inventory node is a complementary node that shows the conditional probability distribution of the inventory based on the distributions of the supplies and the distribution of the remaining inventory from the previous time interval. Therefore, its probability distribution is generated by an additive function of its parents. On the other hand, the conditional probability distribution of the remaining inventory and capacity node indicator $\mathbf{C_t}$ is produced by a function of the difference between the inventory level and demand level. Likewise, the replenishment quantity distribution is shaped by the difference between the target inventory and the remaining inventory. The conditional probability distribution to find out the chance of a supplier business continuity states, $(\mathbf{G_v^i})$ is assumed to have a logic relationship (OR gate). It implies that the environmental hazard tends to be lower if there is more than one facility due to the redundancy. Similarly, the states of the financial stability of a supplier ($\mathbf{F}_{\mathbf{v}}^{\mathbf{i}}$).

5.7 Tubes Suppliers Evaluation and Resilience Analysis

For running DBN, I seek to understand the chance of suppliers to go out of the market and if this scenario has occurred, how the tubes SC can be affected considering the current resilience enablers (excess inventory and flexibility of some suppliers). However, to answer the latter question SC current state (base behaviour) should be studied as we have learned from the literature in Chapter 2.

5.7.1 Tubes SC Base Behaviour

Figure 5-9 shows two consecutive time intervals of DBN for tubes SC. If the business continuity of suppliers has not been examined, tubes flow in the supply chain will maintain almost the same behaviour across time intervals. My use of continuous distributions as inputs for the model results in a continuous distribution to illustrated the ability to meet the demand that visualised by “the capacity and remaining inventory indicator” for each time interval.

Figure 5-10 shows the discretized distribution of capacity and remaining inventory indicator at $\mathbf{t_1}$. The categories that represent the shortages have very low chance to occur (less than 4% in total) whereas there is an approximately 86% chance that SC meets the tubes demand and have remaining inventory. The latter distribution reflects how the company manages their high response to the customer demand by holding redundant inventory all the time.

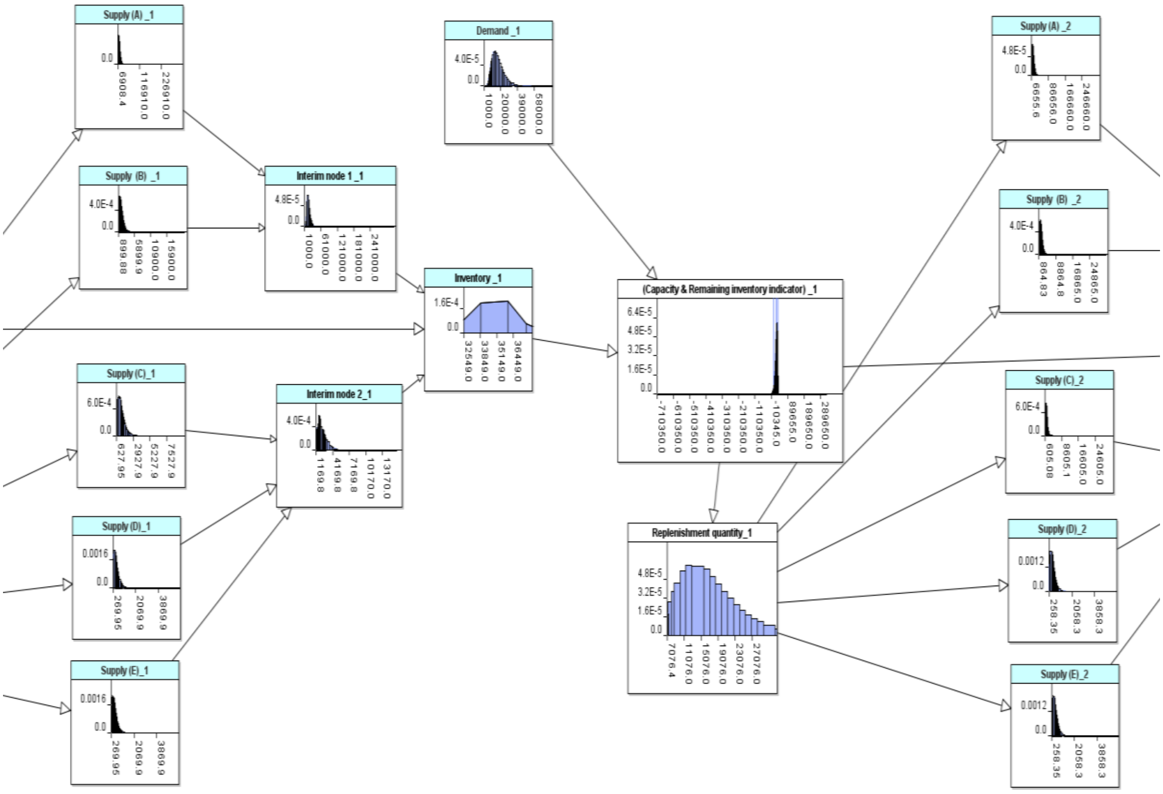


Figure 5-9: Base model for tubes supply chain when the business continuity has not considered

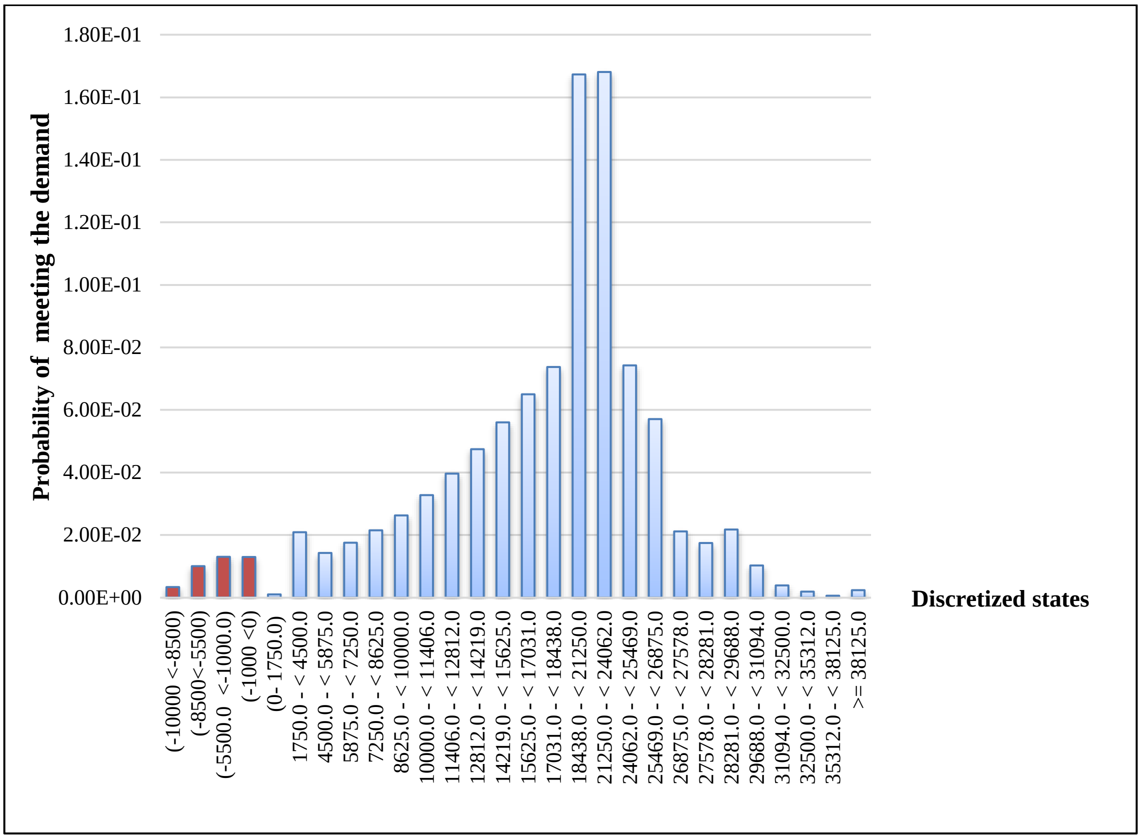


Figure 5-10: The discretized distribution of "the capacity and remaining node indicator" for one month

To visualise the tubes SC behaviour across the different time intervals, I have grouped the above categories that generated using the dynamic discretization in two categories Figure 5-11. These are 'shortages category or ‘demand has met with the remaining inventory category'. The behaviour across the time shows the stability of the SC behaviour in meeting the demand.

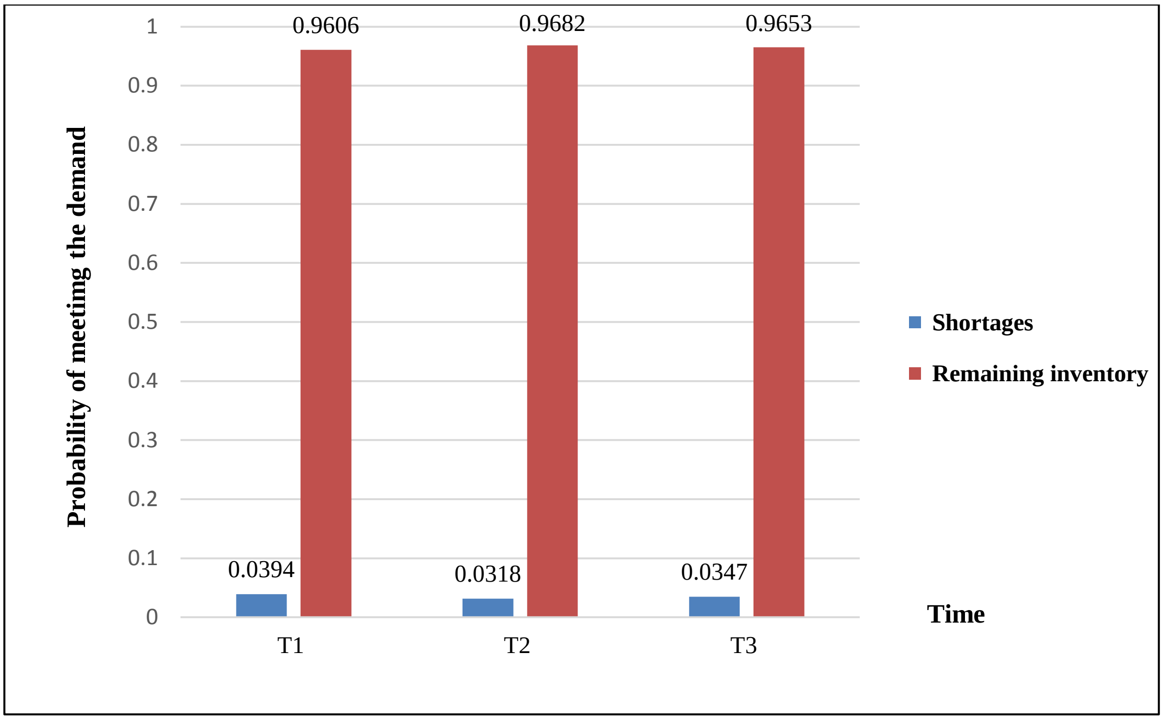


Figure 5-11: The base behaviour of tubes SC across the time intervals

Recall the economic loss, which has been addressed in Chapter 2 as a way to show the resilience of supply chain in maintaining its target. In this case study, the fulfilment of the demand in total has been considered as the planned situation, then shortages in meeting this demand are the economic loss (The deficit level represents the difference between the demand as planned situation and the actual fulfilment). The distribution of the shortages is shown in Figure 5-10 with red categories with probability to occur. However, these classes do not provide a predictive distribution based on demand different levels. To obtain the expected economic loss distribution (expected shortages distribution) using the latter definition, the probability of shortages might be used as in (5.1):

The expected shortages level (Expected Economic Loss) = (Shortages probability * the demand level) (5.1)

By using the (5.1), I argue that, at any level of the monthly demand, there is a particular level of demand will remain unfulfilled. This argument should be looked at from a strategic point of view. From the operational level of view, the SC might meet their demand all the time with no chance to shortages to occur.

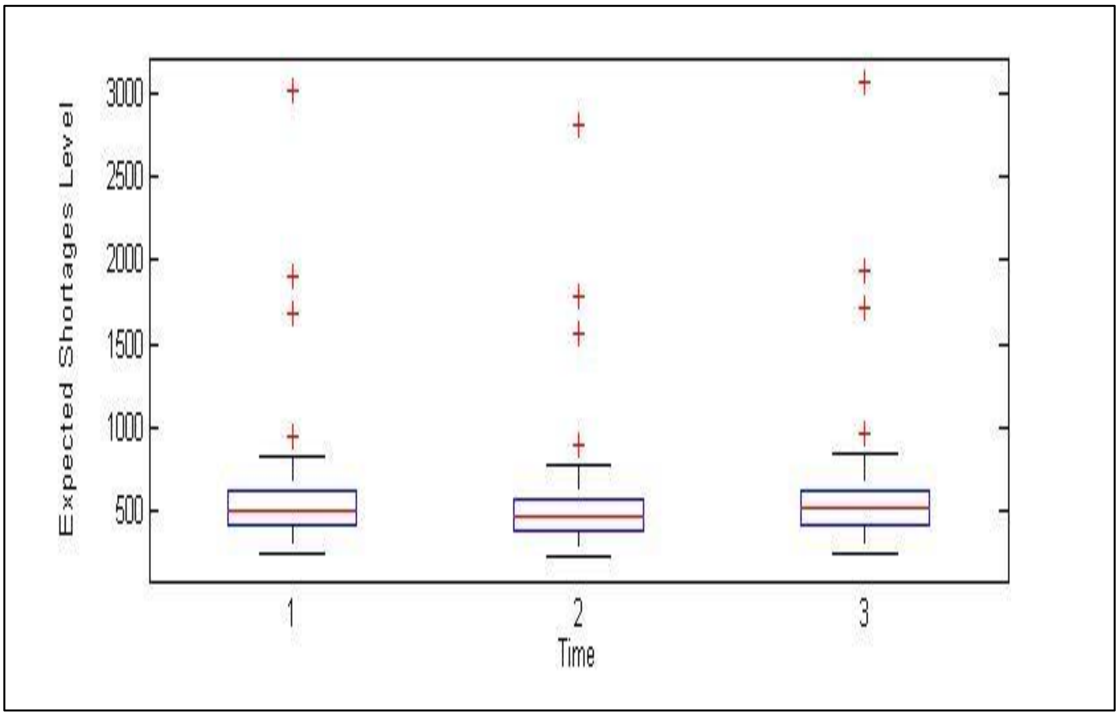


Figure 5-12: The expected distribution of shortages through the time when there is no consideration to business continuity hazard

Figure 5-12 illustrates the expected shortages distribution (i.e. the expected economic loss distribution) when there is no consideration for the business continuity of suppliers. The boxplots show that expected monthly shortages can be mainly between 200 to 1000 units with an average of 575 units. The outliers indicate that the increase of the demand level would increase the shortages level based on the current decision rules and the target inventory level. The latter economic loss figures can be used to obtain financial loss. It is by multiplying the economic loss distribution by the cost of unfulfilling one demand unit. I will get the distribution financial loss as well due to the uncertainty.

5.7.2 Resilience Prediction based on the Evaluation of Suppliers Business Continuity

5.7.2.1 Prediction Based on SC Current Decision Rules

Having studied the supply chain base behaviour. In this section, I try to predict the chance of a particular supplier to go out of the market in a particular point of the time based on the identified early warning factors. Then, I will show how DBN can be employed to predict the resilience of tubes SC to the business continuity scenario of a supplier. Figure 5-13 and Figure 5-14 show examples of the calculation of business continuity for supplier A and the update of this calculation based on assumed evidence about the environmental hazard in China. In Figure 5-13, the chance that the supplier will not continue in the market is approximately 16%. However, in Figure 5-14, this chance has been increased to 22.6%. There is no massive change regarding the business continuity of supplier A if the facility in China has stopped. The little difference in the business continuity state is due to the assumed redundancies in term of the facilities and their locations. The calculations of other suppliers' business continuity states are shown in (Appendix B.3, Page 258)

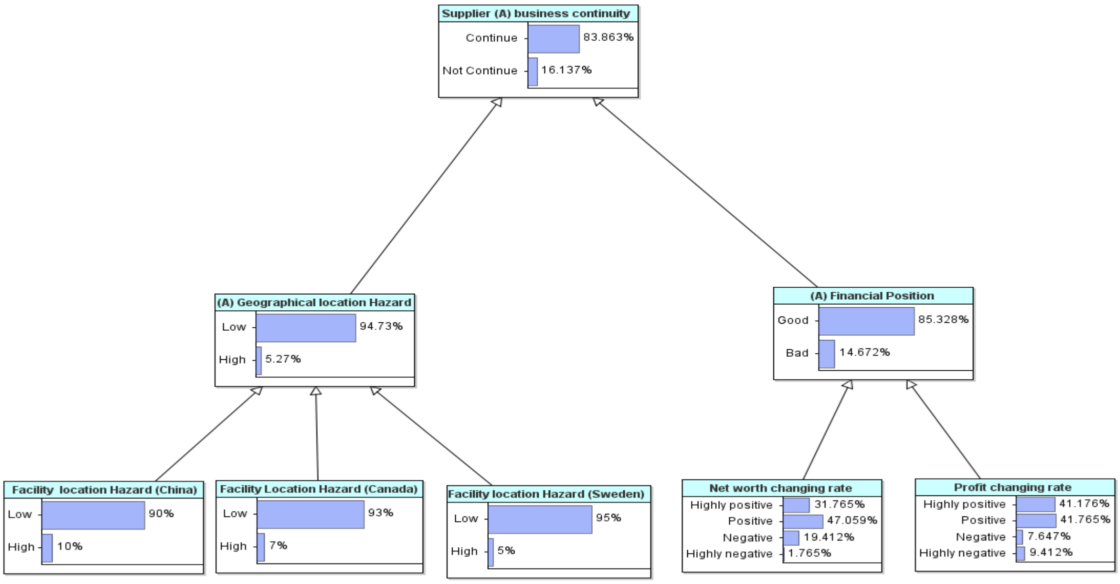


Figure 5-13: The business continuity of supplier A

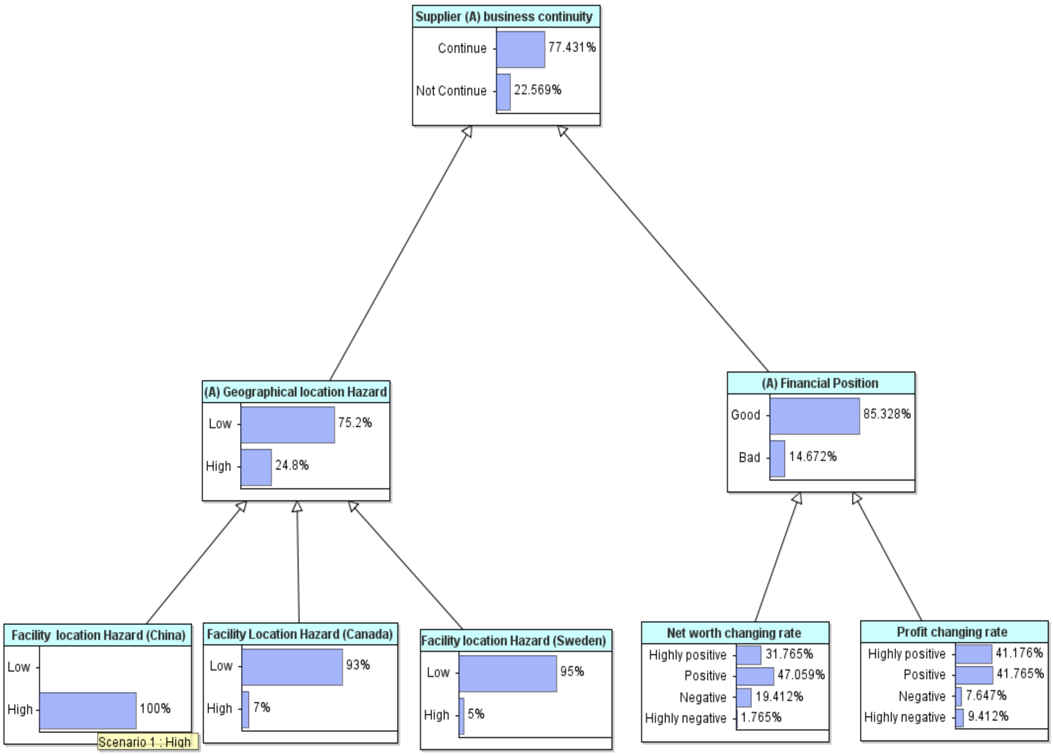


Figure 5-14: The business continuity of supplier A based on the evidence about the hazard in China

The impact of current suppliers' business continuity within the supply chain is examined in Figure 5-15. It is to check how the situation in the tubes SC will be changed when there is only soft evidence about the business continuity (BC) of the suppliers (risk analysis). Recall chapter 2, the difference between the resilience analysis and risk analysis is that in the resilience analysis, I assume that the hazard scenario is going to occur and examine the SC behaviour against its occurrence. Figure 5-15 shows that the distributions of supply nodes are now multimodal distributions. They are not clearly visualised because their ranges now are wide and have many discretized states with very low probability comparing with the zero supply state. Recall that the 'zero supply state' occurs when there is a chance that the supplier will not continue in the market. However, in interim nodes, the multimodal distributions are clearly visualised (The interim nodes are only used for factorisation purposes to improve the calculation efficiency).

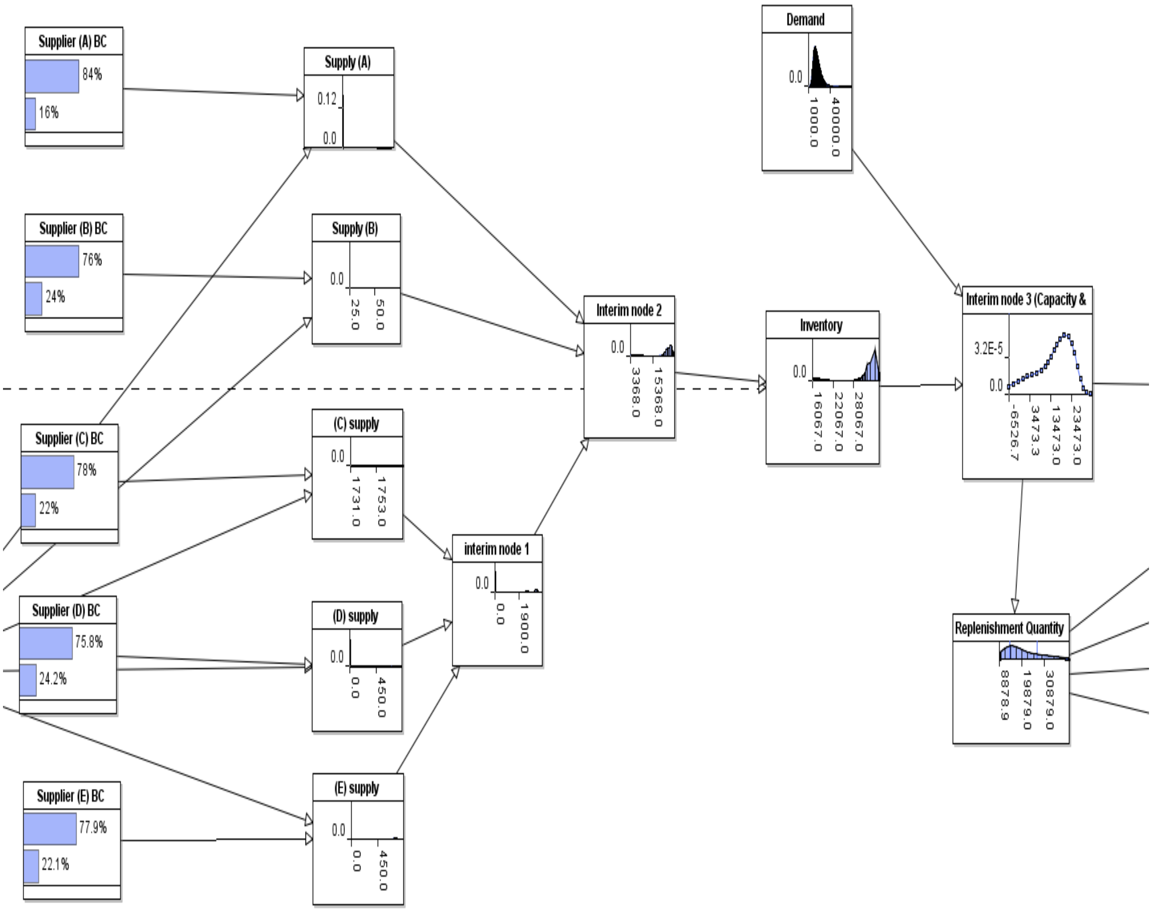


Figure 5-15: The impact of business continuity of the suppliers on the tubes SC base behaviour

The consideration of chance of suppliers to leave the market has resulted in increasing the chance of inability of the tubes SC to meet its demand and decreasing the chance of remaining inventory. As can be seen Figure 5-16, the chance of the categories where the shortages can arise has been increased from less than 3% to around 13%. The reason for this deterioration in the ability of the company to meet their demand is the assumption that the company has a passive behaviour. The passive behaviour means that the chance of supplier failure will not affect the sourcing strategy from other suppliers. However, this is not the real picture as I will see in the next section.

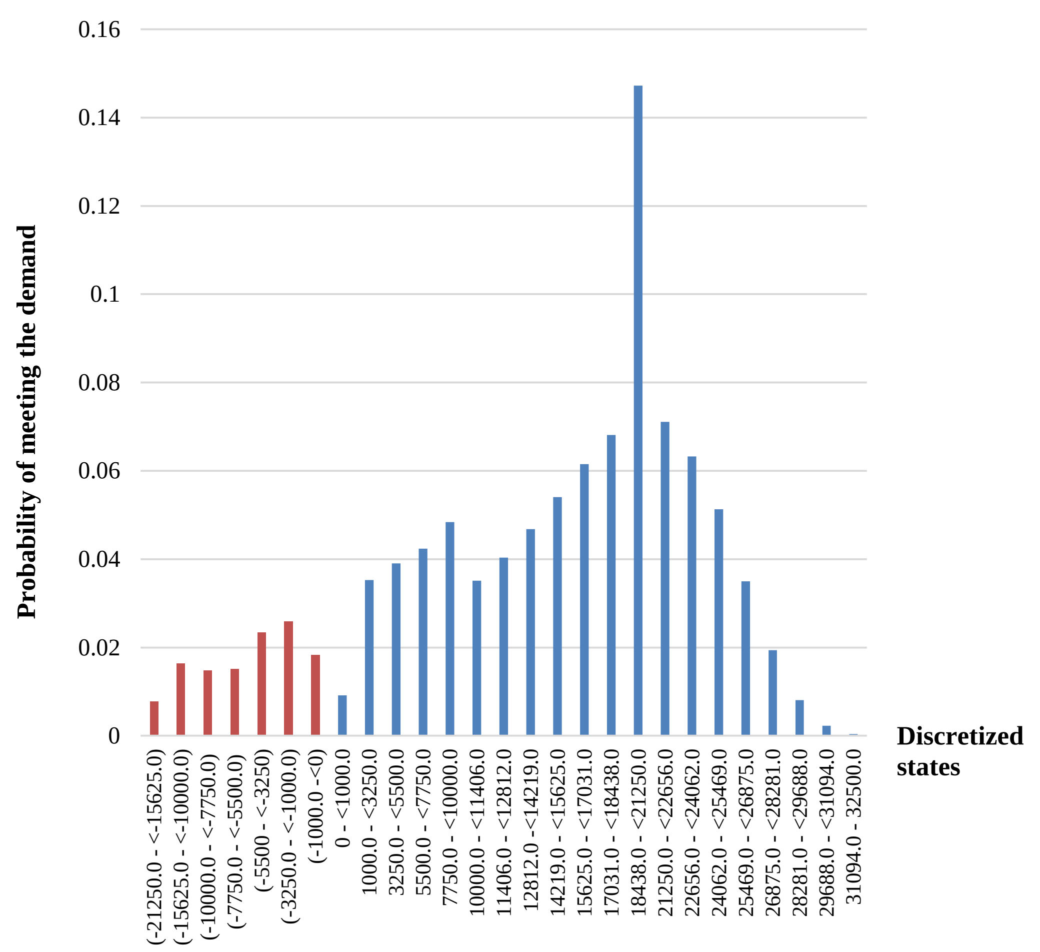


Figure 5-16: The discretized distribution of the capacity and remaining node indicator for one month after considering the chance of suppliers to go out of the market

5.7.2.2 Resilience Prediction: Supplier A to go out of the market with no flexible orders reallocation

The financial indicators of supplier A in Figure 5-13 has been updated by new pieces of evidence. The new evidence drives the chance of 'supplier A to leave the market' to be very high. This scenario has been utilised to update the DBN in Figure 5-15. In $\mathbf{t_2}$where the scenario (supplier A left the market) has been assumed to occur, the chance of not meeting the monthly demand has been increased from around 13% to about 57% (Figure 5-17). After that $(\mathbf{t_3})$, the chance of shortages will be around 90% and will continue like this for many time intervals if there are no changes in the current DBN parameters. The latter imply that tubes SC can be severely impacted by the failure of supplier A due to the high dependency on this supplier A. It is regardless of redundancies in terms of the inventory and the number of suppliers. However, these figures are limited to that there are no alternative strategies to maintain the resilience or there is no ability to increase the sourcing from other suppliers.

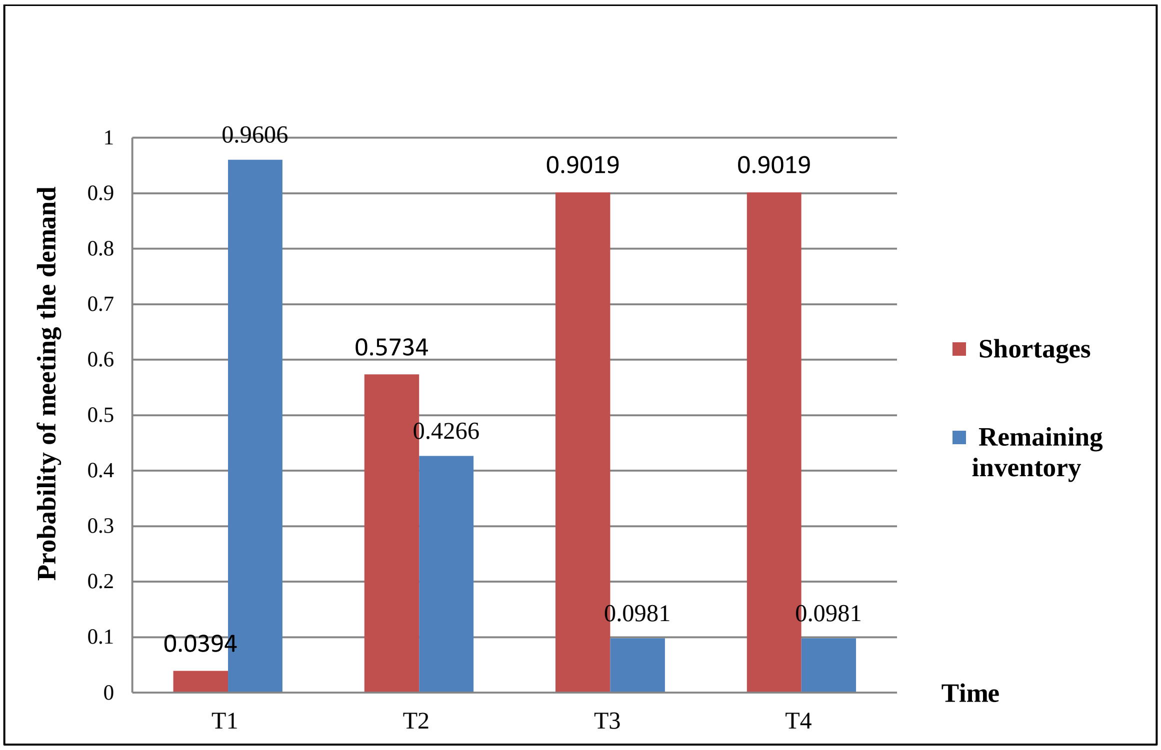


Figure 5-17: Tubes SC behaviour across time intervals if supplier A goes out of the market with no flexible sourcing from other suppliers

Figure 5-18 illustrates the expected shortages distribution (the economic loss). It has been generated by applying the formula (5.1). Figure 5-18 shows that 0.05 and 0.95 percentiles for the anticipated shortages distributions are (10047, 18435), (15803, 28997) respectively starting from the second time interval and forward. The averages expected shortages are 5680, 8935. It is clear that the redundant source represented by the inventory in the second time interval plays an interim role in reducing the immediate impact of the adverse event. However, this role fades away through the time where there is no ability to obtain proper supply from other sources.

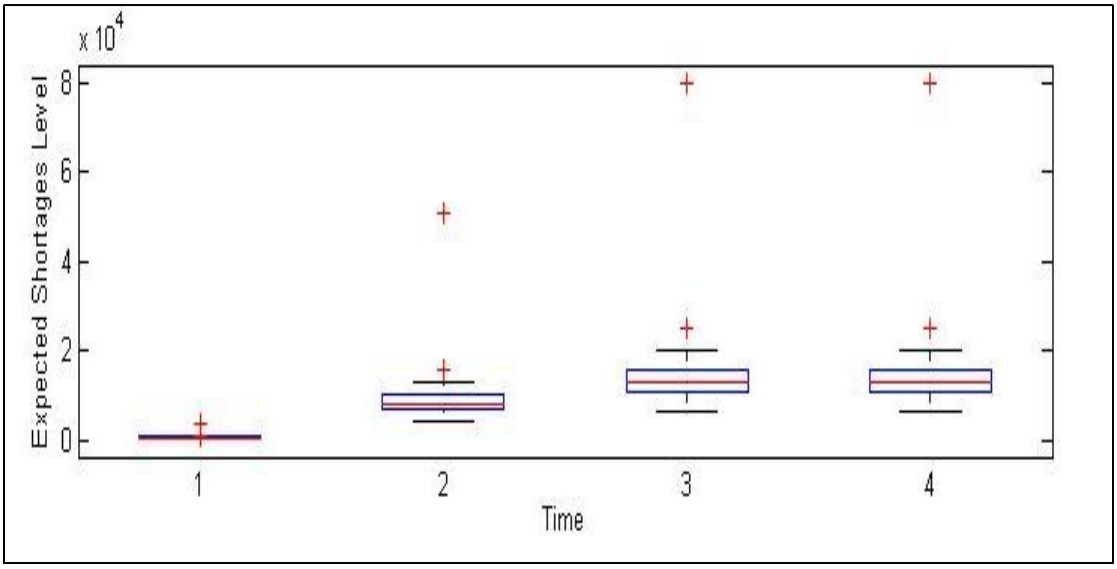


Figure 5-18: The expected distribution of shortages through the time when supplier A leave the market, and there is no flexible sourcing

5.7.2.3 Resilience Prediction: Supplier A to go out of the market with flexible orders reallocation

In this case, I explore how the available flexibility from the suppliers can influence the recovery of tubes SC. To predict the resilience for this situation, I assume that the failure of supplier A is associated with the ability to obtain flexible resources from other suppliers. It means from DBN point of view that there are considerations to the interdependencies between the business continuity of supplier A and the supply from other suppliers. These interdependencies have been shown with dashed arrows in Figure 5-3. In this situation, the functions to generate the conditional probability tables should be changed to respect how the joint probability distribution for the supply from a supplier will be linked with its business continuity states and other supplier business continuity states. Figure 5-19 shows the DBN with assuming that the company will be able to increase their sourcing from the supplier (B) and (C) gradually when the supplier (A) is not likely to continue in the market. The company is assumed to be able to increase the sourcing from the supplier (B) and (C) by 10% and 5% respectively after one month from the failure of the supplier (A). Then, they will be able to source 40% and 30% in total from the supplier (B) and (C) respectively. The reallocation of orders between suppliers is affected by the strategic view that the DBN has. At an operational level, the redistribution of orders should have a more precise description as the company will have an exact figure about how much inventory they have and what are their need. In other words, their need is so specific, and one supplier might be able to fulfil these requirements if the demand is low.

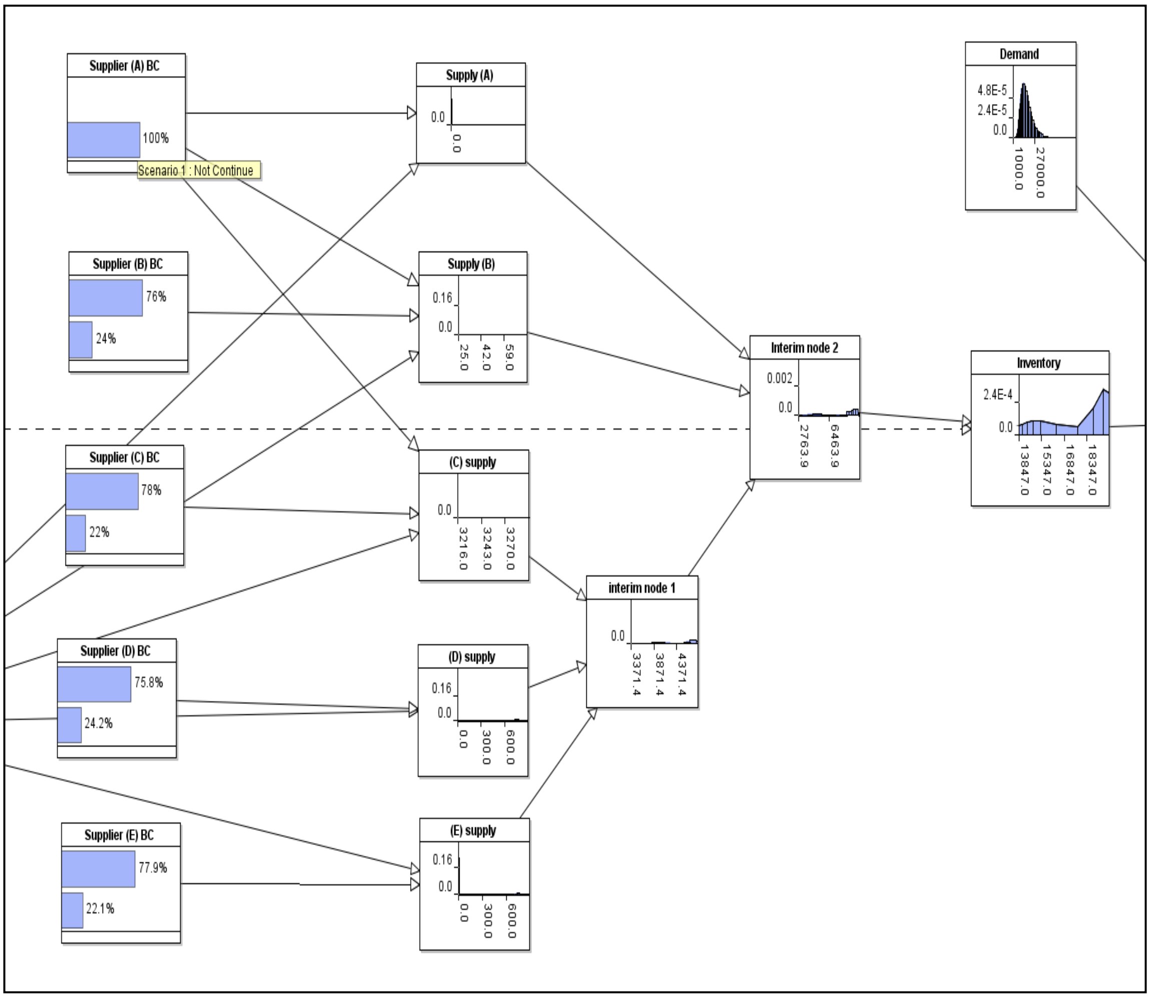


Figure 5-19: The dependency between the business continuity of supplier A and other suppliers

Figure 5-20 shows the resilience triangle for this case based on the probability of shortages and the probability to have remaining inventory. As can be seen, the probability of having shortages will increase from less than 3% in time $\mathbf{t_1}$ to around 57% at time $\mathbf{t_2}$. However, it will decrease at $\mathbf{t_3}$ to be around 40% due to assumed increase in sourcing from supplier B and C. Then, from time $\mathbf{t_4}$ and afterwards the behaviour will be stabilised around 13% shortages chance due to the assumption that the current suppliers have limited ability to react to all company orders.

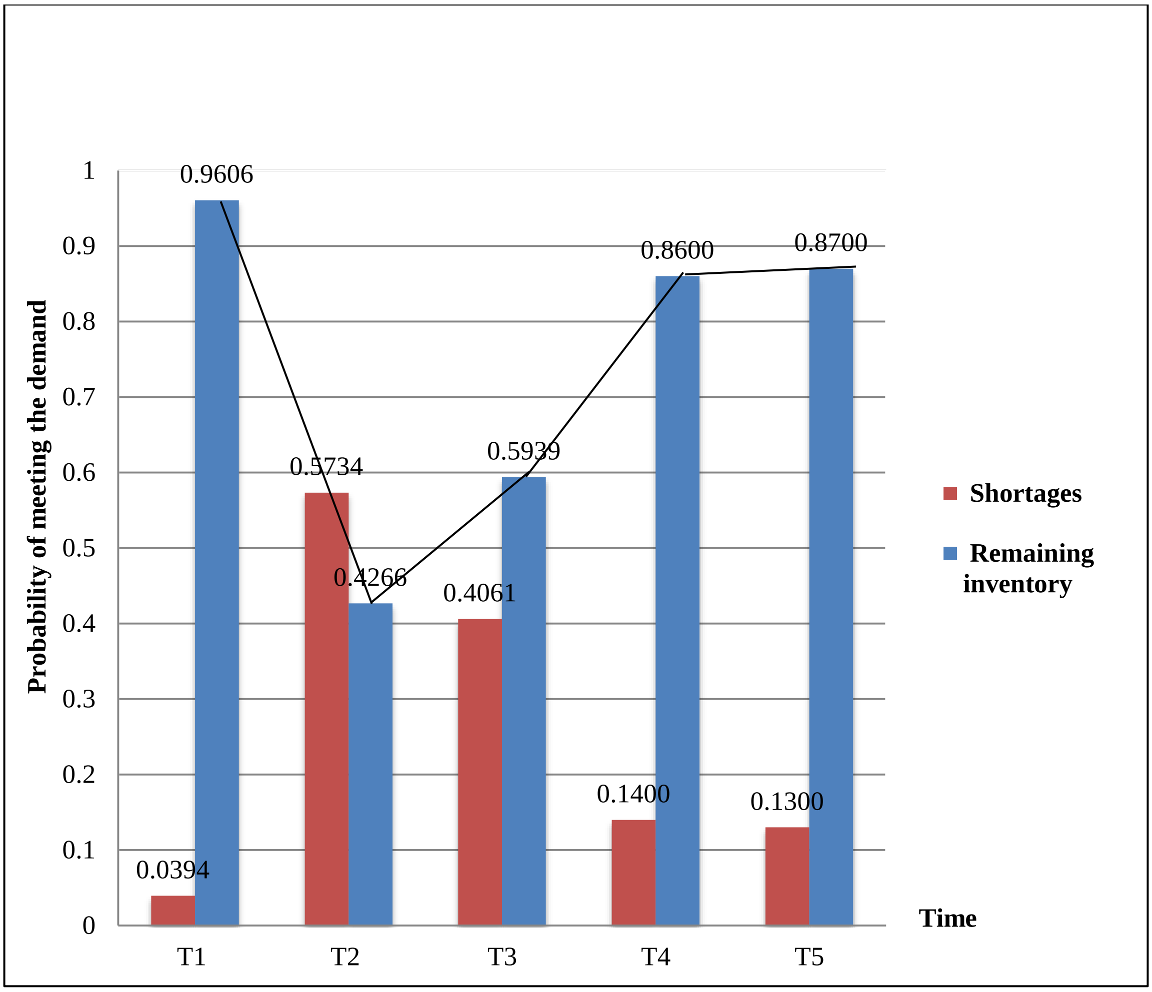


Figure 5-20: The resilience triangle of the tubes SC

Considering the mentioned outputs, it can be said that the tubes SC needs almost two months to recovery to a new stable behaviour if the supplier (A) goes out of the market and the focal firm can reallocate part of its orders to other suppliers. This recovery is associated with an economic loss that expressed by the expected shortages distributions at every time interval in Figure 5-21. DBN for this case shows the impact of flexible resources in reducing the economic loss and the recovery time of the SC. The average economic losses starting from the second time interval are 5680, 4022, 1386, and 1287 respectively. The 0.05 and 0.95 percentiles for the expected economic losses are (10047, 18435), (7115, 13055), (2452, 4499) and (2277, 4178) respectively. In view of the latter figures, further decisions can be made to reduce the distribution of economic losses if it is needed. For example, if the current suppliers are not able to increase their supply due to capacity limitation then, the company needs to make more strategic decisions to improve the resilience of their tubes supply. The role of DBN for this case is that the company can improve their prediction to the supplier business continuity. Therefore, decisions can be made to increase the sourcing from other suppliers based on, for example, contractual agreements if there is a belief that other competitors can influence the rest of suppliers.

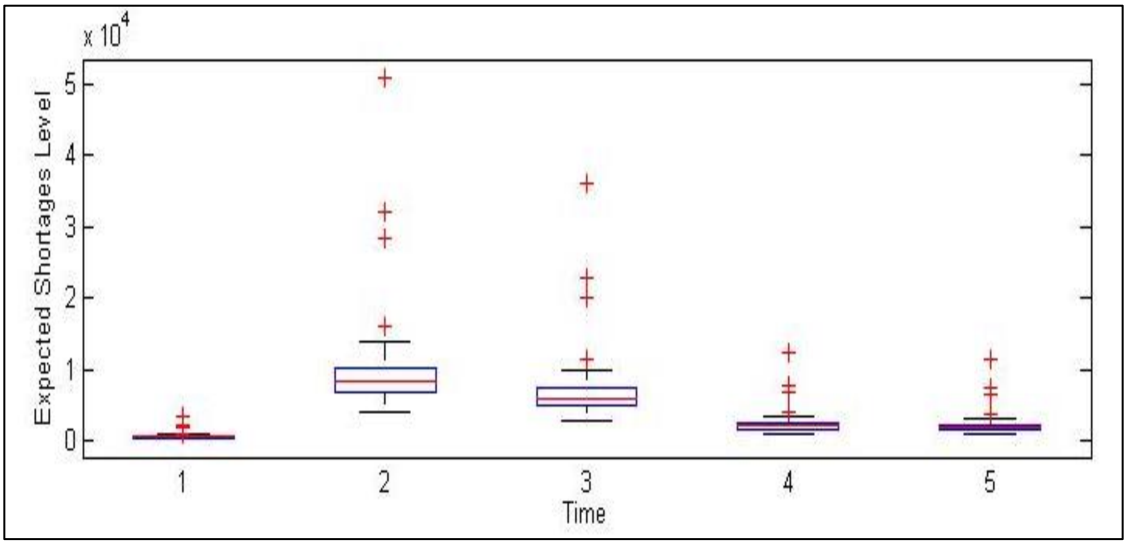


Figure 5-21: The expected distribution of shortages through the time when supplier A leave the market, and there is flexible sourcing

5.8 Building Confidence in Case Study and the DBN Results

The internal validity of this case study has been achieved through interviewing supply chain manager and purchasing manager, access to the tubes suppliers' performance reports, obtain primary data about tubes supply, inventory and demand and collect secondary data from the suppliers' websites and auditor reports. Regarding DBN, the next sub-sections will explore the steps that have been considered to validate the model and reflect on its usefulness to evaluate the resilience of tubes SC to the suppliers' business continuity.

5.8.1 DBN Validation for Tubes SC

The validation of the model to this case study has focused on ensuring that DBN satisfies the conditional independence property, gather feedback on DBN structure, check the model base behaviour with decision makers and explore the sensitivity of the model behaviour to extreme values.

Satisfying the conditional independence property has been assured by isolating factors that contribute to the financial stability of suppliers from the environmental hazard that can affect facility. Although the environmental hazards that have an impact on a facility can cause a noticeable fluctuation in the company financial indicators, the introduction of the business continuity node leads that these factors are conditionally independent with a head-head relation. Another example is the 'inventory level' nodes and the demand nodes. These nodes are clearly dependent within a time interval due to the negative correlation between the demand level and the inventory level. However, the introduction of the capacity and remaining inventory node has factorised these two variables by considering their joint conditional probability distribution to understand the shortages and the remaining inventory. Thus, the introduction of the capacity and remaining indicator node has blocked the path between the demand and the inventory in a head-head relationship. A similar analogy can be held for other relationships in the model.

The supply chain manager has been asked to give his feedback about the evolving of the model structure and the description of the variables. This step has resulted by removing the quality and the delivery performances from the initial model to predict the business continuity of the suppliers. It tends that the quality and the delivery can have operational meanings. The bad quality can reduce the number of customers for a supplier. It eventually can affect its financial indicators. However, the latter influence can be understood through the available data about the financial indicators. Similarly, the effect of delivery on the business continuity of the supplier can be learned in a longer time horizon by their impact on the supplier number of customers and consequently on its financial indicators.

The sensitivity of the DBN to extreme values can be spotted from Figure 5-11, Figure 5-16 and Figure 5-17. These figures show clearly how the model is producing a realistic behaviour and sensitive the extreme values of its variables. Figure 5-11 illustrates how tubes SC has very high responses to their demand due to a high level of inventory that the company holds comparing to the average of monthly demand. It matches the expectation about how the tubes SC behaves based on the current decision rules (the target inventory level 35000). While Figure 5-16 shows how the exposure of the tubes SC to suppliers goes out of the market scenarios increases the chance of the shortages, Figure 5-17 exhibits a major drop in the ability to meet the demand if the significant company supplier goes out of the market. These are also expected behaviours due to the high dependency between the company and its big tube supplier. The latter results indicate clearly that the current characteristics of SC are not able to absorb the consequences of hazard occurrence despite the high level of redundancy regarding the inventory if there is an absence of flexible resources from other suppliers.

In Summary, the model validation for this case focuses on gathering the feedback from the decisions maker about the structure of the model and the base behaviour of the SC in meeting its tubes demand. On another hand, the tubes SC behaviour if a supplier goes out the market has been checked through sensitivity analysis as its related to the prediction of the future consequences that the decision maker has no prior experience with them.

5.8.2 Model Usefulness Based on Tubes SC Characteristics

5.8.2.1 Capturing SC Resilience in Conjunction with SC Characteristics

The data collection and analysis for this case study has revealed that the company primary aim is to maintain a high response to their monthly demand if a supplier left the market. Thus, the judgment of the resilience, in this case, revolves around how the company can maintain a low level of shortages. Recall Figure 5-11 and Figure 5-20. While Figure 5-11 shows the base behaviour of the SC where there is a very low chance that SC will not meet its demand, Figure 5-20 displays that the tubes SC needs two months to recover to a new stable behaviour if supplier A no longer exists in the market. However, the new stable behaviour indicates that the chance of being shortages and shortages level is higher due to the limit flexible resources of other suppliers to react to the company orders. DBN has captured the response of the company to their demand in both cases. The outputs of DBN shows also how the resilience enablers (i.e. the flexible resources and the redundant inventory) can enhance the resilience.

5.8.2.2 Tubes SC Characteristics and the Resilience Modelling

5.8.2.2.1 SC Integration and Visibility

As has been discussed above, tubes SC is an entirely non-integrated chain from the distributor point of view. The limited span of integration has been reflected by the lack of visibility to and collaboration with other members of SC. It has limited the identified known structure of tubes SC to only direct suppliers and their facility locations. However, despite the high number of suppliers and low level of integration, there is still a high dependency on the resources of one supplier that might lead to severe consequences if this supplier has been affected. As has been shown in DBN outputs, this high dependency increases the chance of shortages from around 3% to nearly 90% if there is no orders reallocation strategy in a place. The evidence from the building and running DBN for this case indicates that SC can be severely affected by hazard occurrence despite the low level of integration because of the high dependency level. It also shows an association between the level of integration and the visibility to other SC members.

5.8.2.2.2 SC Operating System

This case study shows that the focal firm maintains a high level of the slack that is related to push supply cycle in their tubes SC. This high-level slack aims to decouple the pull cycle in the tubes SC from the hazards that might impact the supply. While the redundant inventory reduces the severity of the consequences when the supplier (A) assumed to leave the market for the first month, it has not been able to maintain the tubes SC small chance to be short in meeting the demand in the next time intervals (Figure 5-17). Thus, the high redundancy of inventory has no conventional value in maintaining the resilience of the SC for this case study, although it has an intermediate impact in reducing the expected economic loss.

The push-pull system also influences the forming DBN. The push-pull operating system has been recognising through the inbound and outbound tubes flow triggers and the functions to generate the conditional probability distributions. The inbound material flow is controlled by the conditional probability distribution of the supply. This supply distribution is triggered by the information about the replenishment quantity distribution and the level of dependency on a supplier. However, the replenishment quantity distribution itself is influenced by the information about the target and remaining inventory levels. On the other hand, the outbound flow of tubes is controlled by the uncertain distribution of the demand. This demand distribution affects the chance of different levels of remaining inventory and shortages.

The above discussion shows how important is to understand the rules that control the materials flow to build the DBN to understand the resilience of a SC. These rules have played a vital role in presenting the causalities in the model as well as in understanding some functions that will help to generate the conditional probability distributions. On the other hand, DBN can show the effectiveness of the current decisions rules in maintaining the resilience of SC such as the level of excess inventory.

5.8.2.2.3 SC Structural Configuration

The identified structure of SC has played a role in comprehending the hazards, vulnerabilities and how the consequences of initiating events might propagate from a facility location in some hazard prone geographical zones to affect the distributor ability to meet its demand. However, it has been revealed through the DBN modelling process that despite the redundancy in the structure, this redundancy cannot maintain the resilience if there is no flexibility from the suppliers and prioritisation of the distributor over other customers. Thus, the redundancy in terms of the number of suppliers should be accompanied by flexibility from the suppliers to increase their sourcing to the company when it is needed as I have shown through the orders reallocation strategy. It can also be noticed that the business continuity has an apparent effect on the structure of the tubes SC. In this case, differently from Atlantic Canada Chapter 7, once the supplier goes out of the market, it will not recover. Therefore, the recovery function, in this case, are mainly based on the ability of the remaining suppliers in the SC structure to increase their supply or adding new suppliers to the SC that can compensate the loss sourcing.

On the other hand, the application of DBN needed some simplification of the reality. For example, the concern, in this case, is about the impact of supplier business continuity on the resilience of tubes supply chain. However, tubes can have hundreds of specifications (Appendix B.4, Page 260). The consideration of each specification and modelling the uncertainty around them is unrealistic. Therefore, the assumption is to consider the flow of all specifications together to obtain the base behaviour of the system. The justification for this assumption is that all suppliers, generally speaking, provide same specifications with few exceptions. If a supplier goes out of the market this will affect all specifications from that supplier. Simultaneously, other suppliers can offer same specifications.

5.9 Summary of Key Insights and Concluding Remarks

DBN has formulated and applied to evaluate the suppliers based on their business continuity and examine their impact on the distributor's ability to maintain tubes SC base behaviour in fulfilling the tubes demand. This case study shows that DBN can provide a mechanism to evaluate the suppliers and contribute to the supplier selection literature. The model outputs about the chance that a supplier will not continue in the market could be a criterion to compare between different suppliers. Moreover, DBN has advantages of dealing with epistemic uncertainty in the supply chain. A prior distribution can be elicited, and then updated through the time based on available pieces of evidence. Therefore, DBN can be a good model for continuous evaluation of the suppliers and make a decision about them based on new evidence.

DBN outputs also show the ability of tubes SC to react and recover based on their current level of integration, operating mode and structure. They demonstrate that the redundancies about the number of suppliers and the inventory level might not have a conventional value to maintain the resilience in case that a big supplier goes out of the market, and there is no flexibility to source from other suppliers. The impact of redundant inventory and flexible resources have been captured through the shortages chance and the expected economic loss distribution. Table 5-6 shows the key insights that have been obtained about the influence of SC characteristics on the resilience and where they have been discussed in this chapter.

The process of the applying the model to understand the resilience of tubes SC shows how the use of Dynamic Discretization to explain the material flows can contribute to reducing calculation and elicitation burden due to the obvious arithmetic functions to produce the conditional probability distributions. However, for the financial indicators, a static method has to be used due to the number of meaningless categories result from the dynamic discretization. There has been a need to group these classes in some discrete states that give an indicator of the financial stability of the suppliers. The model process also shows the importance of distinguishing between the time intervals that represent the base behaviour of the model and hazard scenario that can occur at any point of the time. I conclude that the hazard scenario chance can be calculated based on the time window of early warning factors. Then, the exposure of the SC base behaviour to that hazard can be assumed to occur at a particular point of the time. Table **5-7** shows a summary of the key insights that have been obtained about DBNs process from this case.

Table 5-6: Key insights on the impact of some tubes SC characteristics on its resilience

Factor	**Insights**
The intensity of integration and the dependency	a) The tubes SC can be severely impacted by the failure of supplier A due to the high dependency on the supplier A resources, despite the low integration, b) The impact of flexibility in improving the resilience.
Operating system	The interim role of the inventory to adverse events from the supply side.
Visibility and span of integration	a) The limited integration span has been reflected by the lack of visibility to and collaboration with other members of SC. It has limited the identified known structure of tubes SC to only direct suppliers and their facility locations, b) The visibility has been improved by the secondary data collection.
SC structural configuration	a) Suppliers are complementary in terms of the capacity despite the redundancy in terms of the structure, b) Geographical locations of the suppliers' facilities are key to understand the environmental hazards.

Table 5-7: Key insights on the lessons learned about DBNs modelling process for tubes SC

Factor	**Insights**
DBN scope	a) The identified tubes SC structure leads to figure out the suppliers and their facilities locations that affected the model scope b) The focus on the suppliers' business continuity, so there is no need for the transportation to be included. c) The inclusion of variables to predict the hazard scenario occurrence (early warning factors).
Qualitative structure	a) The known structure shows clear causality between SC members (e.g., the tubes supply from different suppliers feed the inventory). b) The relationships between one supplier business continuity and the supply from other suppliers.
Quantification	a) The supplies from suppliers (S_t^i) are triggered by the replenishment quantity from one time interval to another. Therefore, their conditional probability distributions are functions from the replenishment quantity distribution and ordering strategy (operating system). b) Decision rules about inventory and ordering (the replenishment quantity distribution is shaped by the difference between the target inventory (35000) and the remaining inventory (push supply cycle). The latter triggers the supply in the next time interval. c) The current resilience enablers (excess inventory and flexibility of some suppliers) affect the conditional probability distribution for the supplies. d) The uncertain demand influences the material flow through the time.
Discretization	a) Dynamic Discretization: • Distribution fit for the demand as root variables • The use of arithmetic relations between the variables that represent the material flow reduces the burden of elicitation, b) Heuristic Discretization has been used for the financial indicators. The importance of having a limited number and distinct description of discrete states is to inform the state of financial stability that can be good and bad.
DBN output representation	a) The use continuous distributions as inputs for the model results in a continuous distribution to illustrated the ability to meet the demand. b) Resilience triangles formed based on the shortages states.

6 Pipe Coating Specialised Spare Parts SCs Resilience: Interdependent View of Their Management

6.1 Introduction

This chapter focuses on investigating the application of DBN to comprehend spare parts SCs resilience for a global pipelines coating company located in Malaysia. Pipelines coating industry is driven by the pipelines requirements or the customer specifications. The latter necessitates that the production for this industry is a project production type. For each project, the production set-up can be different as not all pipes need same requirements. To run the processes smoothly, three complementary inbound supplies are necessary. These are pipes, raw materials and spare parts. While the company receive pipes from customers, the requirements of pipes are the trigger for the raw materials are orders. Spare parts are vital because of the industry nature, which is heavy machinery oriented. Any spare part shortage results in stopping the whole production and create a bottleneck. However, managing the inventory of spare parts is a difficult problem due to their lumpy demand and the weather conditions of Malaysian coast that contribute to the supply uncertainty. DBN for this case will be employed to understand how the interdependent view of the supply, the inventory and the production can lead to a better management of the spare parts and support decisions about their resilience through After-Sales agreement.

6.2 Relevant Literature: Spare Parts Prediction and Classification Problem

The spare parts demand forecasting, inventory control and classifications has received researchers attention (Bacchetti, Saccani, 2012; Braglia *et al.*, 2004a; Deshpande *et al.*, 2006; Everingham *et al.*, 2008; Fleischmann *et al.*, 2003; Hassan *et al.*, 2012; Hishamuddin *et al.*, 2012). Spare parts have been classified mainly based on their movement (slow or fast move), their criticality and their demand volume (Bacchetti, Saccani, 2012). Bacchetti and Saccani (2012, Page: 722) explain that “several aspects concur in making demand and inventory management for spare parts a complex matter: the high number of parts managed, the presence of intermittent or lumpy demand patterns, the high responsiveness required due to downtime cost for by customers and the risk of stock obsolescence”. According to Lengu *et al.* (2014), spare parts demand is known to be intermittent. Such features led to significant problems concerning its demand forecasting and inventory control. The current inventory management model cannot directly apply to the spare part inventory (Botter, Fortuin, 2000).

Spare parts have been looked mainly from the seller point of view. See Bacchetti and Saccani (2012); Braglia *et al.* (2004a); Deshpande *et al.* (2006); Everingham *et al.* (2008); Fleischmann *et al.* (2003); Hassan *et al.* (2012); Hishamuddin *et al.* (2012). The primary concern is to maintain a level of inventory that can improve their after-sales service level. The mentioned papers consider the distributions that can fit the spare parts demand. In this case study, I look at the supply chain of spare parts from a customer point of view. The main aim is to create resilient spare parts SCs that maintain their production and reduce the downtime. This study will contribute to the literature of spare part inventory management through suggesting a new way to classify the spare parts and consider interdependence view between the production, the supply and the inventory level to predict their demand and improve their resilience.

6.3 Actual Data Collection for the Pipe Coating Spare Parts SCs

The data collection process and analysis took place between January 2014 and July 2014. However, the clarification about some data and the discussion about the model structure of the case study had lasted until August 2014 considering the time that some people have taken to correspond to emails.

Data for this case came from meetings/semi-structure interviews with a decision maker and staff from SC management, maintenance and operations management departments. The company document and data had been used as well to enrich the study and quantify the model. However, due to geographical location for this case study partner; the majority of communication had been done online apart from one week visit to the company by the researcher to scope the problem and to get face to face meetings and interviews.

Before the interviews and the visit to the company, there had been several discussions through emails with the company SC manager who accepted to provide access for this research. The confidentiality issues regarding using sensitive data to run the model had been addressed as well. The discussion with him assisted in learning the structure of the company supply chains and the nature of pipelines coating industry. It has turned out that the main concerned supply chains for the company are spare parts SCs. The responsibility of the supply chain management is to make these spare parts available so that they ensure that the production will continue in a smooth way.

The main interviews and meetings have been conducted firstly with supply chain manager and staff from his inventory and purchasing teams. Then, it appeared that there is a need to initiate a dialogue with employees from maintenance and operations management to understand the demand of spare parts and factors influence this demand. The supply chain manager facilitated the access for those people. He forwarded the questions and data requests to the suitable people from other departments.

A possible qualitative structure for the general DBN model built based on the above analysis. The general structure of the model has discussed and refined with company supply chain manager. It was to get his feedback as the main contact point. Once the model qualitative structure finalised, there was a need to obtain some datasets for quantification processes with a judgement about the storms that prevent the supply. The company provided data for their spare parts transaction between 2011 and 2013 with information about their suppliers and target inventory levels. In addition, the production data between 2012 and 2013 handed by operations management in a monthly format for each process.

6.4 Pipe Coating Spare Parts Classification

Boylan and Syntetos (2008) state that spare parts for durable products are highly varied, with variation regarding the costs, service requirements and demand pattern. A classification of spare parts, for that reason, is useful to maintain a high level of service, forecasting and inventory control decisions. There are several criteria for this classification pointed out by (Bacchetti, Saccani, 2012). These are part value/cost, criticality, supply uncertainty, Demand volume/value, Demand variability and life cycle. Bacchetti and Saccani (2012) show that ABC technique is the principal quantitative method for classification.

Similarly to the literature, the number of spare parts for the current case study tends to be very high that makes it appealing to find out how to classify them and what the company see the critical spare parts. To obtain a sort of classifications for the spare parts, I tried first to encourage the company participants to think about the classifications of spare parts using ABC generic inventory classification analysis as an example. Two participants one from the inventory team and the other from maintenance department who have direct expertise on spare parts have agreed on two categories for spare parts. The first type is the specialised spare parts that have particular specifications and quality. Therefore, it is very hard to get them from suppliers other than the manufacturers of the machines. The other category is non-specialised spare parts where there are many local suppliers for them.

This classification is different to classifications mentioned in the literature. The classifications in the literature do not consider the ability to obtain the spare parts from various suppliers rather than their machine manufacturer or not, although the supply uncertainty is one of the factors that have been considered by Braglia *et al.* (2004b); Partovi and Anandarajan (2002). From a resilience perspective, my classification of spare parts does not mean that some parts shortages can be ignored. The shortages of non-specialised spare parts also cause production disruption. However, the advantage of managing the later spare parts is the quick way to obtain them from local suppliers. Therefore, the supply is less certain compared with specialised spare parts where the suppliers are mainly international one.

6.5 Pipe Coating Spare Parts SCs Characteristics

The specialised spare parts SCs are dyadic supply chains where ordering from international manufacturers are based on the market price and the “After-Sales care policy of the manufacturer”. There is a low visibility and clearly low integration level with the manufacturer. The latter increases the uncertainty level around the suppliers’ processes and deliveries. In Figure 6-1 I show the identified specialised spare parts, their suppliers and the plants where there is a need for them and the processes that are carried out in the plants.

The specialised spare parts have five suppliers who are manufacturers of the machines. For example, the manufacturer of A group machines provides eight types of specialised spare parts. All these SCs can be complementary for one project that needs through the production processes and not for others. Therefore, it is an inevitable to understand the internal processes to appreciate the triggers for the demand. The other issue in the structure of spare parts SCs is that one supplier is providing several spare parts. Thus, the missing of the supply from a supplier will trigger severe consequences if it is correlated with a need for one or more parts from that supplier.

To maintain their ability to fulfil the internal demand of spare parts, the supply chain management previously had pull operating mode type across their internal and external SCs. They were ordering based on their consumption of spare parts with maintaining minimum levels of inventories. After suffering many shortages due to unexpectedly high levels of demand or disruption of the supply, the supply chain management has decided to move to a push supply cycle concerning their sourcing from spare parts Figure 6-2. They try to maintain the maximum number of spare parts. Their aim is to reduce the shortage chance in facing the demand from the spare parts. Consequently, this would lead to reducing the chance of a plant to be down. However, this maximum inventory strategy has driven that some spare parts can get rusty before it is consumed.

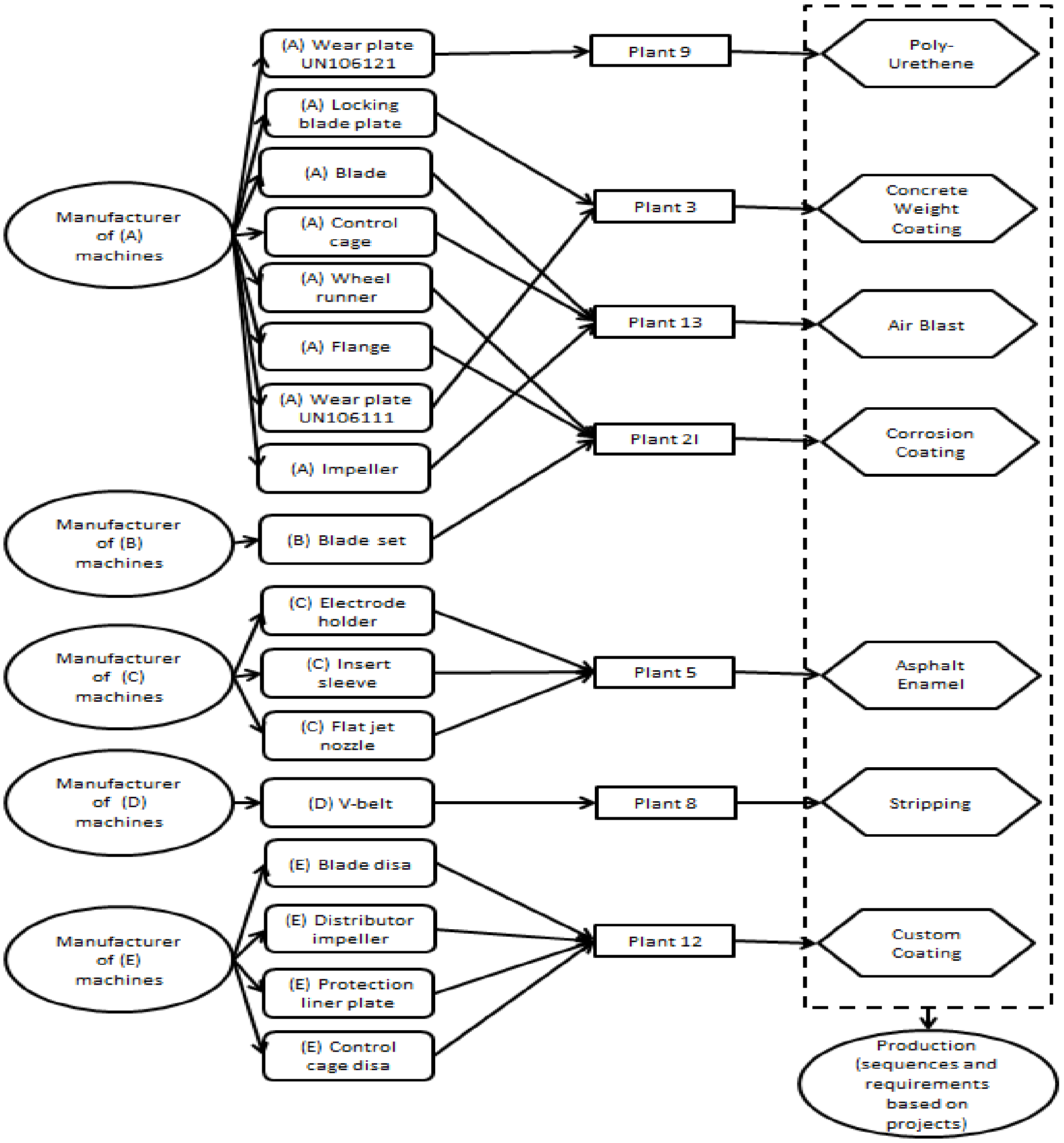


Figure 6-1: Company inbound supply chains and processes

Internally the processes are purely triggered by the pull demand of maintenance department, which is timely and reactive. The operations management informs the maintenance department about the need to replace a part once it occurs. Then the maintenance department places an order to the supply chain management to issue the required spare part. The inability to fulfil this demand directly lead to the machine to be down.

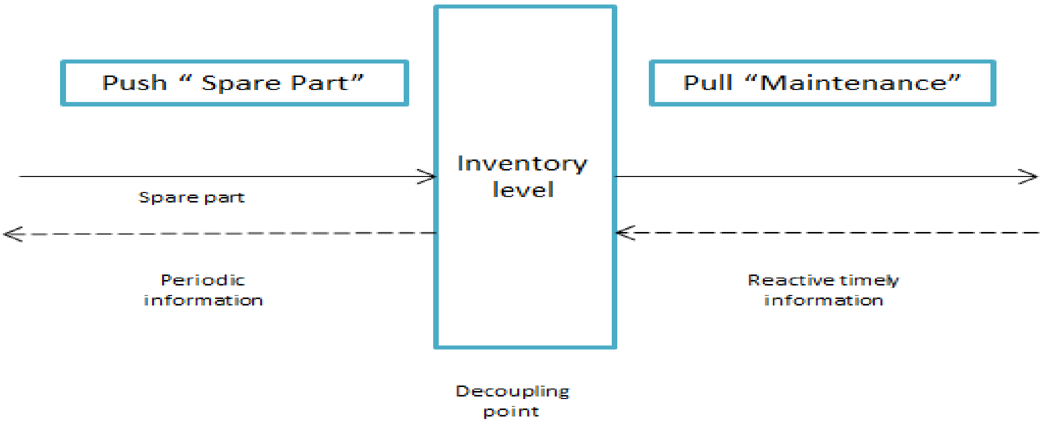


Figure 6-2: “Push–pull” spare parts SCs operating system

6.6 DBN Qualitative Structure

The aim of this DBN is to aid the SC management in enhancing their spare parts SCs resilience that leads to reducing downtime of the production. The enhancing of this resilience required an interdependent view of spare parts supply, the inventory management and their lumpy demand that trigger by a lumpy production. This interconnected view has not considered before by the literature from the user of spare parts point of view. In this section, I will explore the variables that represent this interdependent view of this problem.

6.6.1 Resilience Index and Variables that Represent the SC system

In contrast to the tubes case study, the demand pattern of the spare parts has a lumpy pattern. The shortages by its self cannot be an expression of the resilience if there is no need to the spare part. The shortages have a negative impact only if it is accompanied with a demand of the missing spare part. It represents the case where is the inventory is zero and demand is not zero. Therefore, the maintaining of a low chance of a plant to be down due to the shortages has been seen as the main resilience index for spare parts supply chains in this case. The high chance of a plant to be down is associated with a high expected number of unprocessed pipes. The latter mainly will create the financial loss in the pipe coating industry as the number of pipes that proceeded in a particular time interval generates the revenue of pipe coating industry.

To capture the above resilience index, the SC system has been described by the variables that show the material flow. Table 6-1 illustrates the main factors to explain the SC system for this problem. The material flow is controlled by the information about the target inventory level and the maximum level of supply that a supplier can offer from a spare part within a particular time interval. The latter is mainly related to After-Sales agreement with the manufacturer at the time of machines purchase. This level of supply can be artificially unlimited where the supplier is assumed to have an infinite capacity within a particular time horizon. However, the level of spare parts supply are always limited to a maximum point within a given period.

Table 6-1: Factors to understand the consequences of the initiated events

Factors	Description
Demand	It describes the demand for a spare part. It is conditional on the production volume.
Supply	It shows the supply of a spare part. It is conditional on the remaining inventory level and storms states.
Inventory level	The inventory level is a continuous variable that is conditional on the previous time remaining inventory level and the supply during the current time interval from a spare part. It also will be conditional on the flood state once it assumed to occur.
The replenishment quantity	The replenishment quantity displays the ordering strategy of the company based on the inventory level.
Capacity indicator	Shortages and remaining inventory visualisation node.
Plant status	It refers to the state of a particular plant. It is conditional on the ability to meet the demand from the needed spare parts.

6.6.2 Hazards and Vulnerabilities Identification

Through the analysis of interviews and meetings notes, it appears that three main hazards can impact the spare part SCs that related to the internal company production and its location in a hazard-prone area (Table 6-2). Flood has identified as a major hazard scenario that could influence the inventory of spare parts due to the location of the company in flood prone geographical area. It is all the time a possibility that the level of water can be high and destroys the inventory where nothing can be done about it. The production volume increases the deterioration of some machines parts. However, the requirements of this production and its volume vary due to the project type of operation. The latter leads to high uncertainty around the demand for the spare parts and eventually to less ability to manage them. The supply side also can be disrupted by the tropical storms that prevent the delivery of the supply. Tropical storms can occur very often.

Table 6-2: Main hazards that affect the spare parts SCs

Hazard	Descriptions
Tropical Storms	It defines the tropical weather conditions status in Malaysia which prevents the supply
Production volume	It describes the distribution of monthly production from a process which can be highly uncertain
Flood	It refers to a rare hazard scenario where the level of water can be high enough to destroy the inventory

The geographical location of the firm, production project type and single source of a spare part supply has a notable influence on the type of hazards that the spare parts SCs counter. The geographical location of the company is a high hazard–prone. However, the operations of the firm in the current location are due to two reasons. The first one is that the area is rich in raw materials (mainly ore) that are needed for the pipe coating. The other reason is that the port in that area is a typical stopping point for ships on its way from Japan (main pipes manufacturing hub) to all over the world. Thus, it is a convenient place for ships to unload and load the uncoated and coated pipes.

6.6.3 Notation

($\mathbf{S_t^i}$): The supply from a spare part **i** at time **t**

($\mathbf{D_t^i}$): The demand from a spare part **i** at time **t**

($\mathbf{I_t^i}$): The inventory level a spare part **i** at time **t**. It is an arithmetic function of the inventory level remains from the previous time interval and the distribution of supply from a spare part **i** at time **t**

($\mathbf{R_t^i}$): It is the replenishment quantity from a spare part **i** at time **t**. Mathematically ($\mathbf{R_t^i}$) is the difference between the target inventory level from a spare part and the actual level of the inventory at any time interval

($\mathbf{T_t}$): It refers to the tropical storms that influence the supply from one spare part or more at time **t**

($\mathbf{C_t^i}$): The remaining inventory and capacity indicator from a part **i** at time **t**

($\boldsymbol{\alpha}^{\mathbf{i}}$): The ratio of a part due to the level of production

6.6.4 Cause–Effect Within and Cross Time Interval

Figure 6-3 shows the proposed DBN qualitative structure for the base behaviour of this case study. In Figure 6-4, I show where the flood as a major hazard scenario can affect. This model is a general model to analyse the base behaviour of a spare part supply chain. It is with taking into consideration how the chance of shortages in fulfilling the demand from a spare part affect the status of a plant.

DBN represents two levels for this case. The first one is the behaviour of a spare part supply chain considering the decision rules of inventory, the demand, supply and the hazards the might affect the demand and the supply. The second one is the impact of shortages on the plant status and internal process of the company. The spare part SC level is the main interest of the supply chain management that aims to reduce the chance of being short in meeting the demand from the spare part. On the other hand, the internal process level of the model is the primary concentration of the operations management that seeks to minimise the chance of plant to be disrupted particularly when there are several projects are running in parallel.

At spare part SC level, the escalation of a process production increases the demand for the spare parts due to frequent deterioration of machines parts. This degradation triggers the demand for one type of spare part or more to replace the affected part. The SC management either can fulfil this demand from their inventory or be short and wait for a new supply to come. The supply might be affected by tropical storms that can prevent the delivery for a while. At this stage, I consider only the demand of a spare part due to production volume as it leads to deterioration of machines parts. The supply chain manager stated, “we may not use some parts for a year, then we get a project, and we go through dozens of them in one month”. Other causes can lead to the machines breakdowns, which affect the demand pattern. However, they are out of this case study scope.

Regarding variables with a dynamic property, the main two variables that affected by the cross time causal relationships are the supply ($\boldsymbol{S_t^i}$) and the inventory. The supply is affected by the replenishment quantity. On the other hand, the inventory is influenced by the remaining inventory in the previous time interval and the supply in the current time interval. The latter two dynamic relationships are the pillars to understand the triggers of the material flow over the time and how the reaction of the supply chain to a hazard.

At the company internal process level, the consideration of each process separately from others is justified by the project nature of the company production. The production volume from a process can be different from others at the same time interval. As well as some processes are needed for a particular project while others do not. Thus, the inputs of the model are process based. Each process triggers a set of specialised spare parts demand that attached to this process as have been illustrated in Figure 6-1. For example, if the model has been employed to understand the resilience of spare parts SCs that are attached to Air Blast process, three spare parts SCs will be considered. These are (A) Blade, (A) Impeller and (A) Control Cage. On the other hand, if 'custom coating process' to be considered (E) Control cage Disa, (E) Protection liner plate, (E) Distributor impeller and (E) Blade Disa SCs should be investigated. Similarly, the model should be customised for other specialised spare parts that are attached to a particular plant and process.

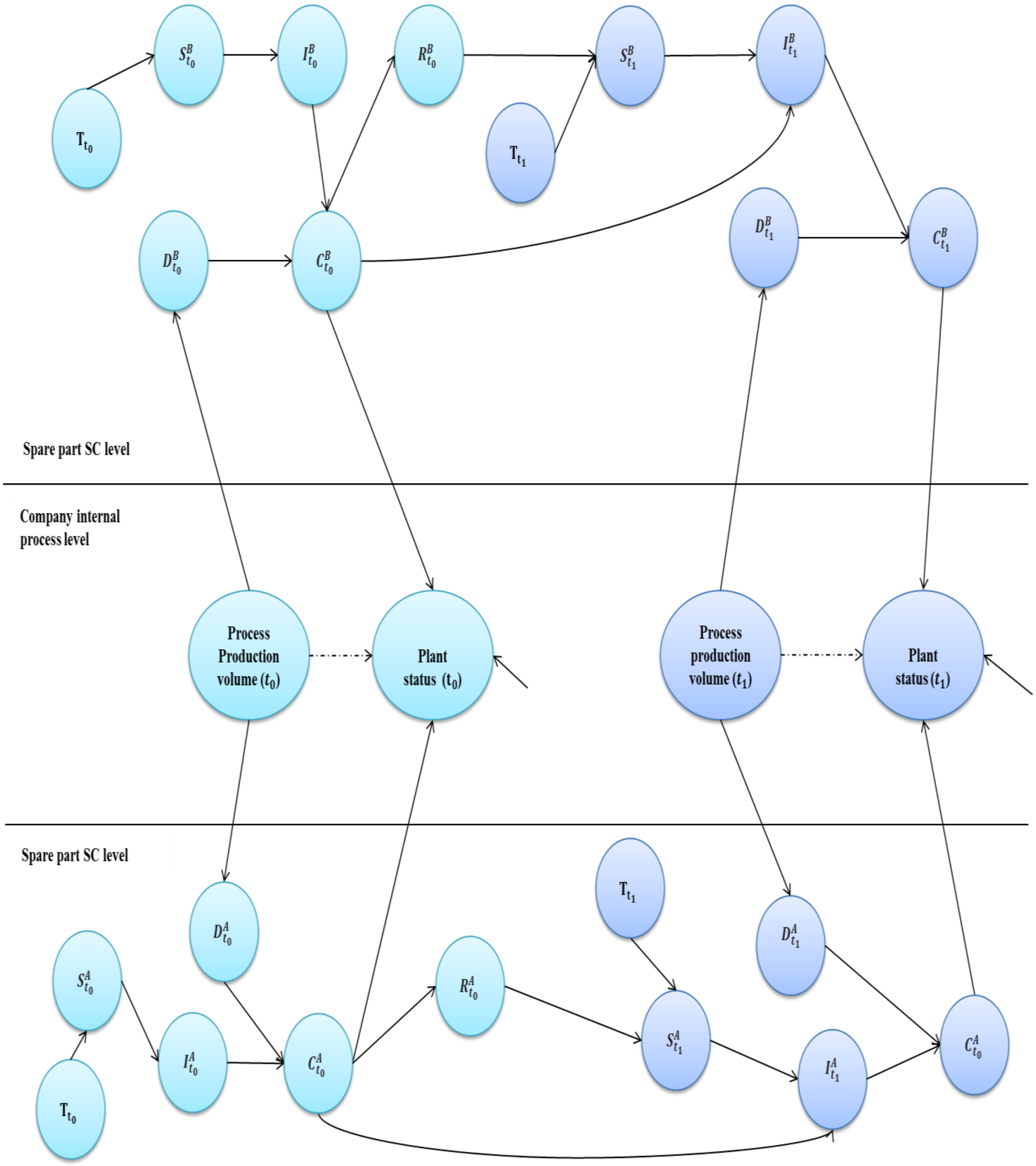


Figure 6-3: DBN qualitative structure at a spare part SC and company internal process level

6.7 Quantifying DBN of Spare Part SCs

6.7.1 Time Space

To support decisions about spare parts SCs resilience I seek mainly to understand the base uncertain behaviour at spare parts at SCs level and company internal process level.

Then, the impact of a flood as a major hazard scenario on the ability to maintain the base behaviour will be studied (Figure 6-4). From a base behaviour point of view, the SC management aims to see 0% shortage chance in fulfilling their spare parts demand whatever is the time interval to be considered. However, the SC management during the contacting of this case study did not have performance measures to rely on as in the tubes case. However, at operations management level; the primary interest at a strategic level is to see very low chance for a plant to be down within a monthly time interval. The low chance for a process to be down within monthly time interval means that they do not have to create extra strategic capacity such as redundant staff to reduce the consequences of the process to be down. Therefore, a monthly time interval has been considered as a suitable time interval to understand the base behaviour at the spare part SC level and the internal process level. The monthly view of the model has been reported to the supply chain management to agree on it. The importance of having same time interval at the SC level and internal process level is that the demand distribution at a time interval intertwines with production volume at the same interval. Similarly, the chance of the plant to be down at a time interval is related to the ability to meet the demand from the spare parts at the same time interval. Thus, it is inevitable to consider a consistent interval at the two levels because both of them contribute to understanding the base behaviour.

In the other hand, the chance of flood to be high to destroy the company inventory is different from above because it represents the interaction with the base behaviour at a particular point of the time. This chance is very low regardless of the calculation time window. The low chance has a negligible impact on the base behaviour. The significance of including this hazard as in other cases is to check the resilience of the spare parts SCs and internal process to its occurrence. It will lead to better management of spare parts. It can be noticed here the difference between the tropical storms and floods regarding the chance to occur. While the tropical storms have been considered to comprehend the base behaviour of the SCs due to its frequent occurrences at the monthly level, the flood has been explored as a scenario to occur at a particular point of the time. The latter stresses the importance of distinguishing between variables that contribute to understanding the base behaviour of SC and the ones contribute to understanding the hazard scenario.

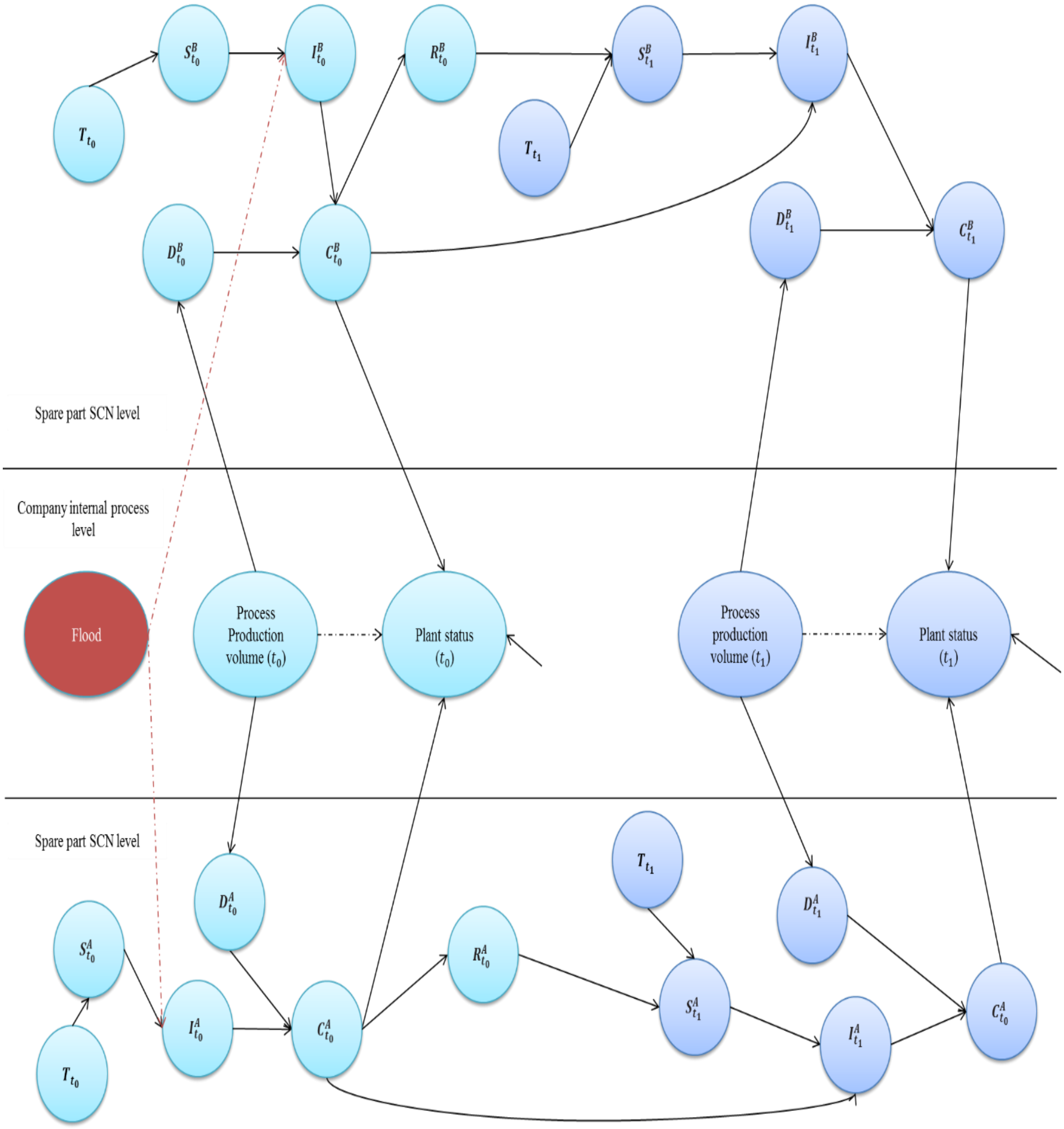


Figure 6-4: DBN structure with flood hazard scenario

6.7.2 Describing the Variables States and Their Probabilities

Table 6-3 shows the descriptions of the model variables states. The process production volume is a root node with no parent. Its probability distribution is different based on the process that I need to consider to customise the model.

Table 6-3: DBN variables probability distributions and states description

Variable	**Descriptions**
$(\mathbf{T_t})$	Low: it refers to that the tropical storm will not disrupt the spare part supply. High: it denotes to that the tropical storms will prevent the supply.
Process production volume	It takes any form of a continuous distribution that describes the uncertainty about the monthly production level from a process.
$(\mathbf{D_t^i})$	It is conditional on the production volume. The increase of production triggers the demand of a spare part by an estimated ratio. For example, the processing of every 400 pipes means a new spare part needed. Thus, when the production is 0, the demand will be zero. The ratio between the production volume and the demand is different from one spare part to another.
$(\mathbf{R_t^i})$	It is a continuous distribution that describes the difference between the target inventory level for each spare part and the actual level of inventory.
$(\mathbf{S_t^i})$	It represents the supply from the suppliers which affected by the occurrence of the tropical storm.
$(\mathbf{I_t^i})$	The inventory level is a continuous distribution that is conditional on the remaining inventory level from previous time interval and the supply during the current time interval.
A plant status	Up: If all demand from spare parts has been met, Down: If there is a shortage in meeting the demand from one spare part or more.
Flood	High: the level of water is high to destroy the inventory Low: the level of water has no effect on the inventory

The data about the production volume has been obtained from the operations management data. These data show that there is a big difference between the processes' production volumes. It confirms that the requirements of projects are different. See for example Figure 6-5 and Figure 6-6. These diagrams show the volume of production from ‘Air Blast’ process and ‘Concrete Weight Coat’ process. As can be noticed, there is a massive difference between them in many time intervals. There is also a fluctuation in the pattern of production from the process itself. This fluctuation indicates why the demand for spare parts is lumpy.

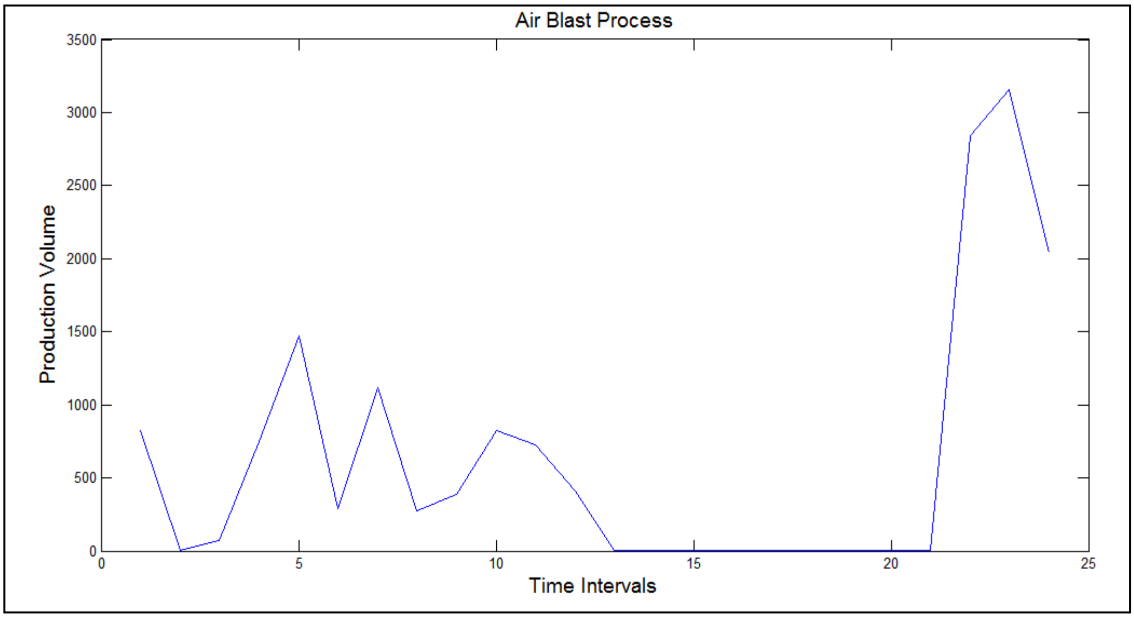


Figure 6-5: Air Blast monthly production volume for 24 months

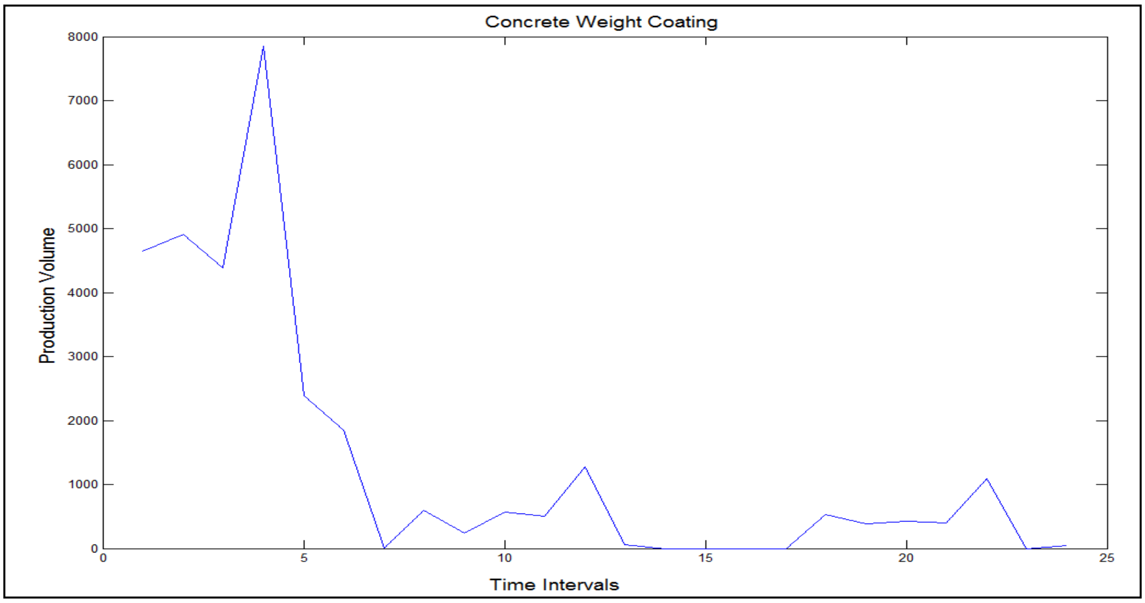


Figure 6-6: Concrete Weight monthly production volume for 24 months

To use the dynamic discretization algorithm to run the calculation, the above production distributions have to be fit to specific distribution form. For instance, the best fit distribution for air blast production volume is a gamma with (0.27, 2357.1), as can be seen Figure 6-7. Other continuous variables in the model such as the demand, inventory and the supply there is no need to consider the distribution fit as these are child nodes for other variables. For example, Table 6-3; the supply states are conditional on the storms states and the replenishment quantity. If the storm state is low, then the expectation is to receive the replenishment quantity on full. Otherwise, the storms prevent the delivering of the supply totally due to its international nature.

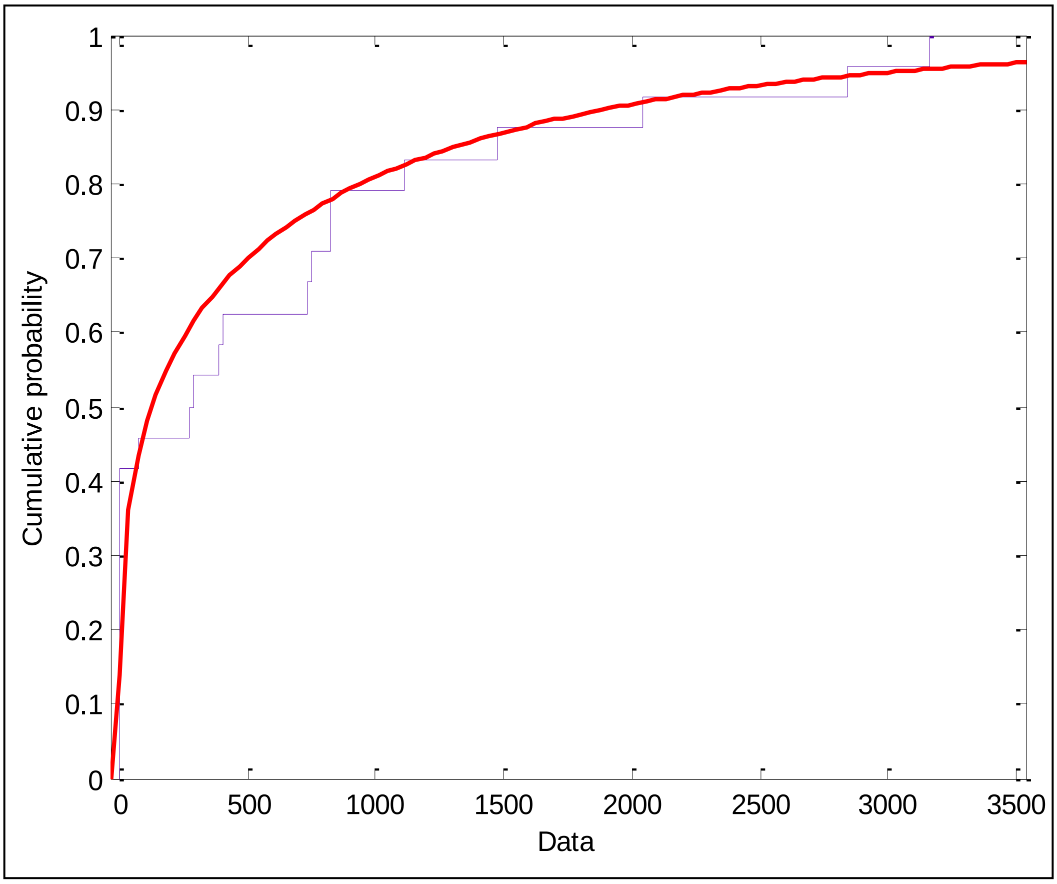


Figure 6-7: The gamma distribution CDF fit of air blast production monthly volume

Notice here that I do not assume that the internal process is insensitive to how long the shortage is going to be during one-time interval because to be short for one day is different from being short for a week, month or any other time interval. These issues need further operational level exploration. My focus here at the strategic behaviour where the chance of shortages and how the SC management can maintain a very low chance of shortage to occur is explored. Similarly at the company internal process level, if the processes are down for one day is different from one week. However, at a strategic level, they are looking to keep this chance at a low level. Having mentioned that, DBN time intervals can be one day if the interest is to see how many days the supply chain and the internal process are going to take to recover. This will not change the strategic nature of the model as the aim of such model to show the uncertainty at the strategic level.

6.7.3 Assign Probabilities and Mathematical Relationships for Spare Parts DBN

As in the tubes SC case study, the description of some variables states and assign probabilities for them are interrelated due to discretise their available data dynamically. I have shown above that the "production monthly volume" from a process has its continuous probability distribution that affects the demand from a spare part. There is no need to describe the production volume probability distribution again.

The conditional probabilities distributions control the rest of continuous variables. The replenishment quantity triggers the supplies from suppliers $(\mathbf{S_t^i})$. Their conditional probability distributions are either same as the replenishment quantity distribution if the tropical storm hazard state is low or it is zero if it is high. The latter means that the storms occurrence prevents the supply.

Table 6-4: The mathematical relationships to form the conditional probability distributions

Variables	**Mathematical relationships**
$\mathbf{R_t}$	F (Target Inventory - Remaining Inventory)
$\mathbf{I_t^i}$	$\mathrm{F}\left(\mathrm{S_t^i} + \mathrm{C_{t-1}^i}\right)$
$\mathbf{S_t^i}$	$\begin{cases} 0, \text{ if } (\mathrm{T_t}) = \text{High} \\ (\mathrm{R_t^i}) \text{ if } (\mathrm{T_t}) = \text{Low} \end{cases}$
$\mathbf{C_t^i}$	$\mathrm{F}(\mathrm{I_t^i} - \mathrm{D_t^i})$
$\mathbf{D_t^i}$	$\alpha^i * (\mathrm{ProductionVolume})$
Plant Status	$\begin{cases} \text{Up: If demand from the all spare parts fulfilled,} \\ \text{Down: If there is a shortage from at least one part} \end{cases}$

The inventory node is a complementary node that shows the conditional probability distribution of the inventory based on the distribution of the supply and the distribution of the remaining inventory from the previous time interval. Therefore, its probability distribution is generated by an additive function of its parents. The conditional probability distribution of "the remaining inventory and capacity node indicator $\mathbf{C_t^i}$ " for a spare part is formed by a function of the difference between the inventory level and demand level. Similarly, the replenishment quantity is decided by the difference between the target inventory and the remaining inventory. The conditional probability of a spare part demand at a particular time interval is produced by considering the deterioration ratio of the parts to the production volume from the process that leads to the deterioration of this part.

6.8 Resilience Analysis: Spare Part SCs of Air Blast Process

This section illustrates the use of the above model to understand the base behaviour of SCs that related to Air Blast processes. I check how the situation will be if a flood hits the inventory of the company. Three specialised spare parts should be available to react when the machines parts are deteriorated due to the production volume from the Air Blast process. These are (A) blade, (A) control cage and (A) impeller. The target inventory level for the blade, impeller and control cage are 38, 40 and 30 respectively. These represent the maximum inventories level that the company is holding. The order is placed by the difference between each part actual inventory level and the target level.

6.8.1 Air Blast Spare Parts SCs Base Behaviour

The base behaviour of (A) impeller and (A) blade SCs for three-time intervals are shown in Figure 6-8 and Figure 6-9. As can be seen, these SCs are shown stable uncertain behaviour cross the time if the hazards scenario have not been considered. From the figures, it can be noticed that there is a low chance for shortages to occur. However, this low chance of shortages associates with a high chance that the remaining inventory can be bigger than 24 items across the time intervals.

The model can be updated by the production volume that is usually a known quantity for a particular time horizon. So, the evidence about this volume can be used to check the probability of shortages and the remaining inventory. This is with taking into account the uncertainty around the supply of these spare parts. The updating of the production node can contribute to spare part demand forecasting and lead to a better inventory management for the spare parts.

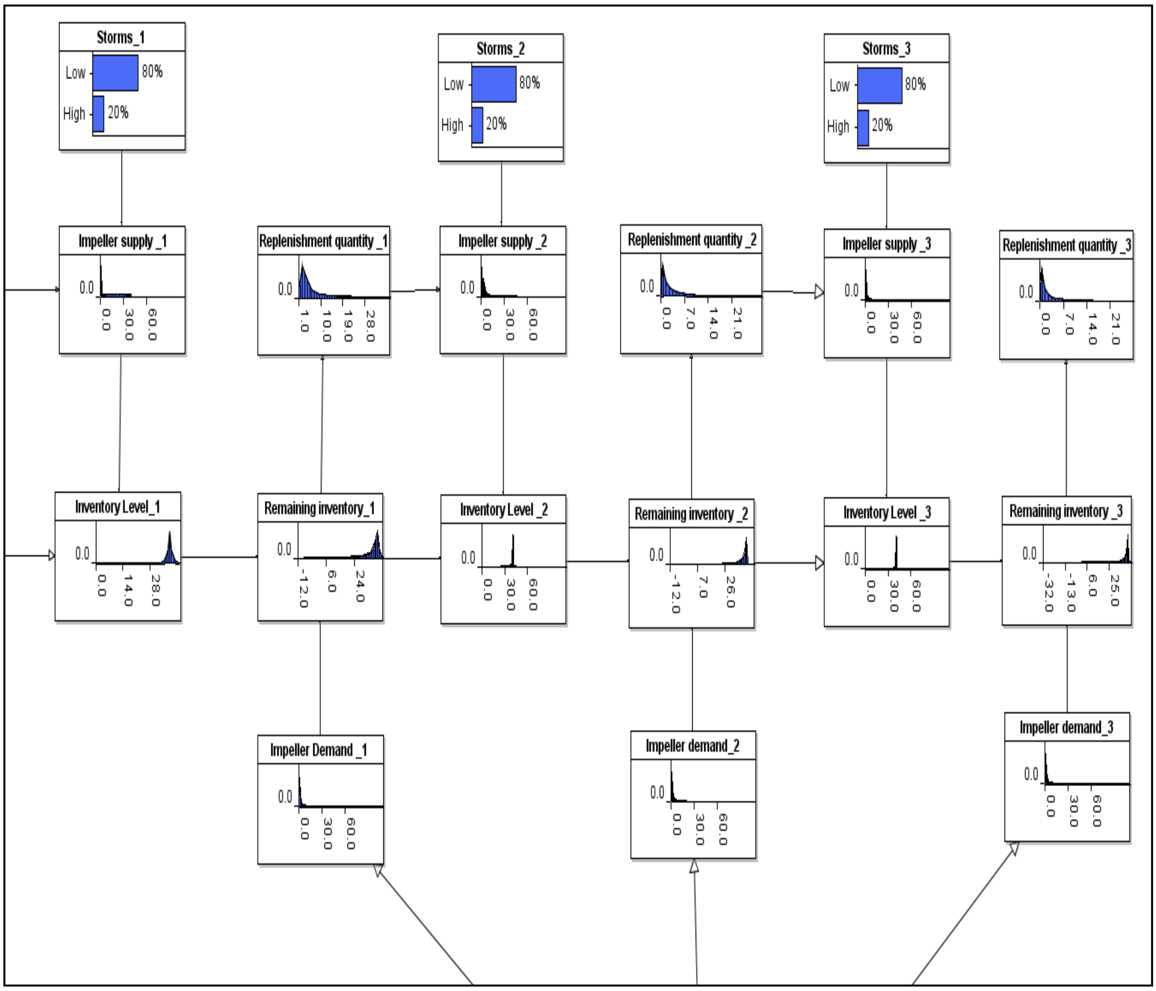


Figure 6-8: DBN for (A) Impeller SC base behaviour

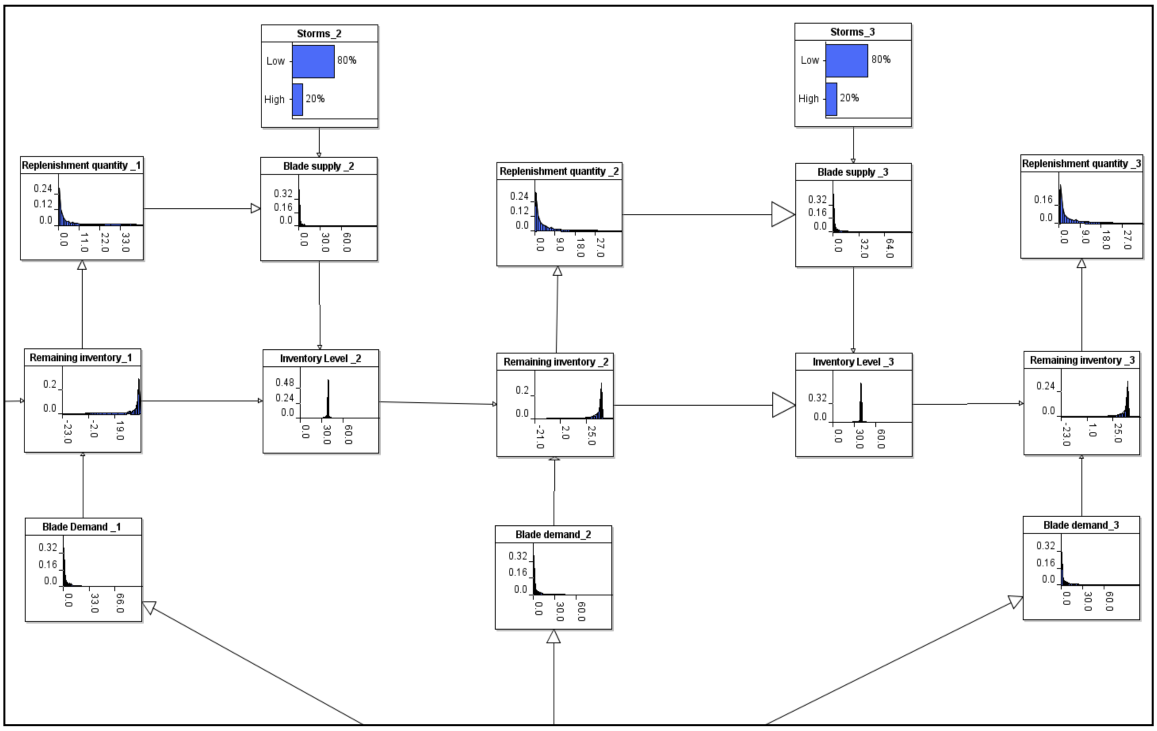


Figure 6-9: DBN for (A) Blade SC base behaviour

Figure 6-10 displays the blade capacity and remaining inventory node across the time intervals as an example of the behaviour of spare parts SCs. As can be noticed, the low chance of shortages at (A) blade SC level is associated by almost 70% chance that the remaining inventory across the time is more 22. It reflects the impact of SC management decision rules in maintaining the maximum inventory level as a strategy to reduce the shortages chance. However, this approach increases the chance of inventory to get rusty if there are no projects that required them.

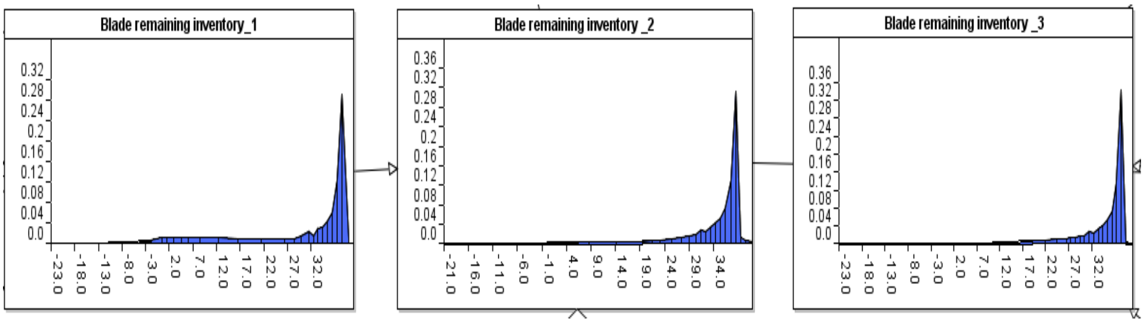


Figure 6-10: (A) Blade SC base behaviour across three time intervals

The base behaviours of three SCs that are vital for the air blast processes are illustrating in Figure 6-11 in a discretised way. These behaviours have been obtained by grouping the outputs of the model into two categories (meet the demand with remaining inventory or being short). As can be noticed, SCs maintain relatively stable base behaviours across the time intervals. While the base behaviour of (A) impeller shows that shortages have less than 2.5% in average to occur, the chance for shortages to occur at (A) blade and (A) control cage is around 4.5%. This means that the latter SCs are slightly more vulnerable than the former one in case no major hazard scenario is assumed to occur.

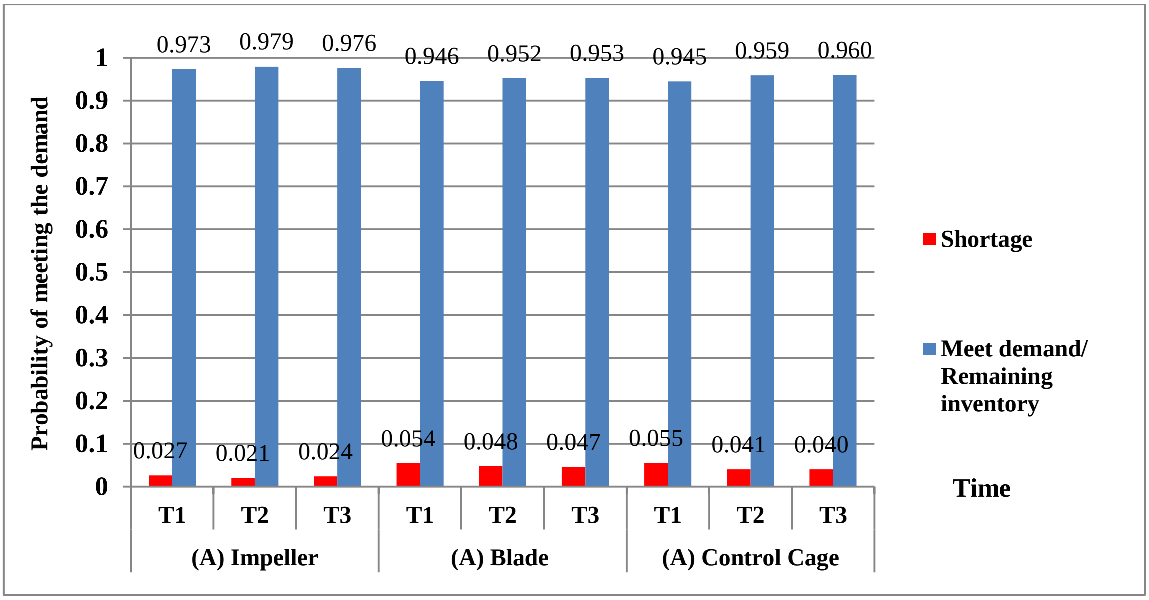


Figure 6-11: Base behaviours of Air Blast process specialised spare parts SCs

At the internal process level, the inability of SC management to respond to the demand of spare parts implies that the plant where the process production is taken place will be down. Thus, the plant status is "And logic gate" of the ability of each spare part SC to meet their demand. Figure 6-12 shows the chances of the Air Blast plant (plant 13) to be down within a monthly time interval. As can be noticed, this chance is an adding up to the chances of the shortages. It shows the significant vulnerability of production process to the shortages of the spare parts and the importance of the quick response to the demand from these spare parts.

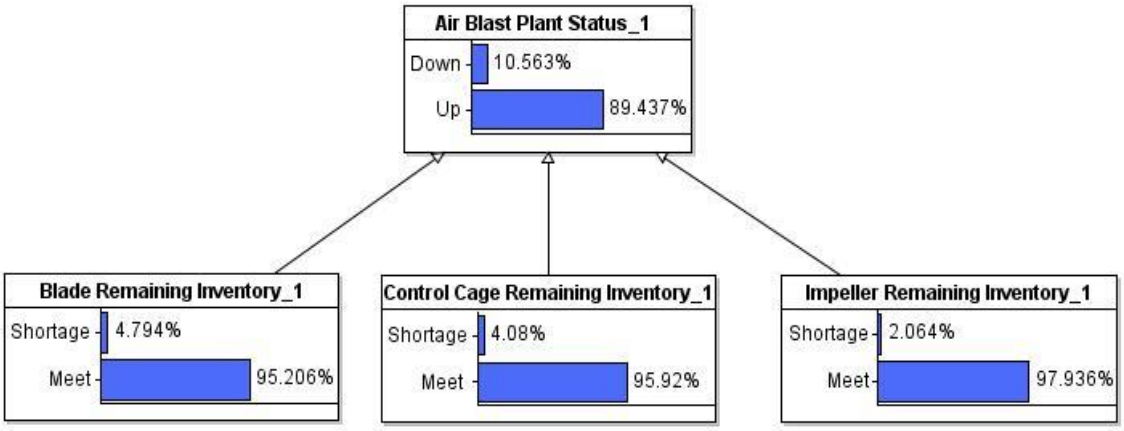


Figure 6-12: Air Blast plant status based on the chances of meeting the demand

The economic loss is related to the number of pipes that the company processed compared to the planned level. In other words, it is the number of unprocessed pipes (The unprocessed pipes level represent the difference between the planned situation and the actual situation). To obtain the expected economic loss distribution (the expected unprocessed pipes distribution) using the latter definition, the probability of plant to be down might be used to obtain the expected distribution of unprocessed pipes as in (7.1):

The expected unprocessed pipes level (Expected Economic Loss) = (The probability of plant to be down * the expected production level) (7.1)

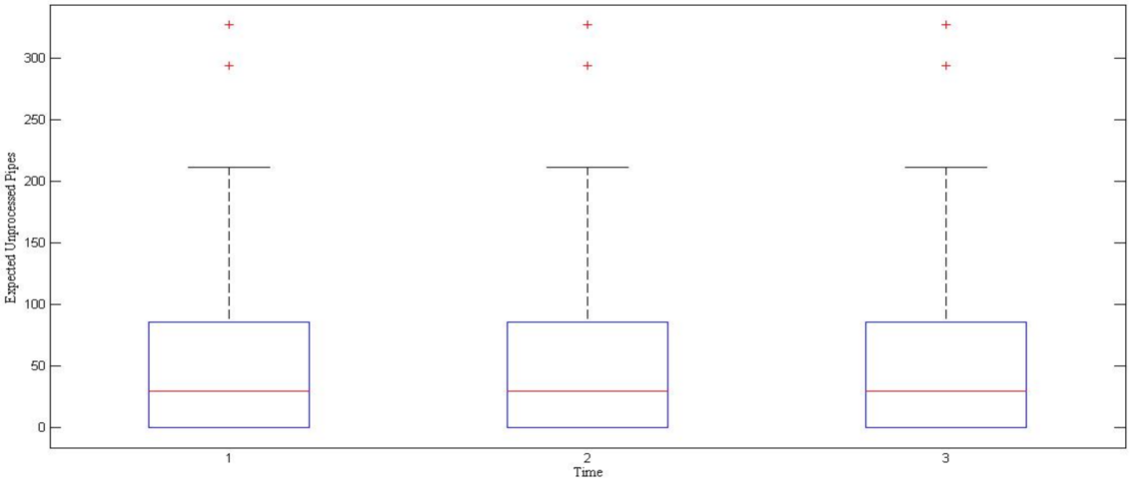


Figure 6-13: The expected distribution of unprocessed pipes in case of no flood

Figure 6-13 shows the expected distribution of unprocessed pipes for the base behaviour of SC. The boxplots show that the expected monthly distribution of unprocessed pipes can be mainly between 0 to 250 units with outliers represent the situation where there is a high production level.

6.8.2 Resilience Prediction Based on Flood Scenario

I explore the impact of flood scenario that destroys the inventory in two cases. The first one is that suppliers have no capacity limit within a time interval. The other one is that there is a maximum limit on what the company can receive from the supplier within a time interval. This reflects that either the supplier has unlimited flexibility to serve their "After-Sales care" or there limit on this flexibility. For both cases that the internal company production can recover to its normal operations level during the same time interval where the flood takes place. However, the production node of the model can be adjusted to reflect the case how the production volume is affected.

6.8.2.1 Case 1: Suppliers with Unlimited Capacity

The supplier with unlimited capacity indicates that the supplier has high flexibility. It implies that the company will receive all their orders with no maximum to what they order if the flood has assumed to destroy their inventory at a particular point of the time. See Figure 6-14 as an example for this case where the behaviour of (A) impeller SC is shown across the time. In this case, the chance of shortages from (A) impeller has been moved from around 2.5% before the flood to around 84.99 % at the same time interval where the flood occurs. The remaining 15.01% chance denotes the situation where there is no inventory and no demand (0:0 case). The (A) impeller SC would take only two months to recover to its normal state due to assumed flexibility from the suppliers.

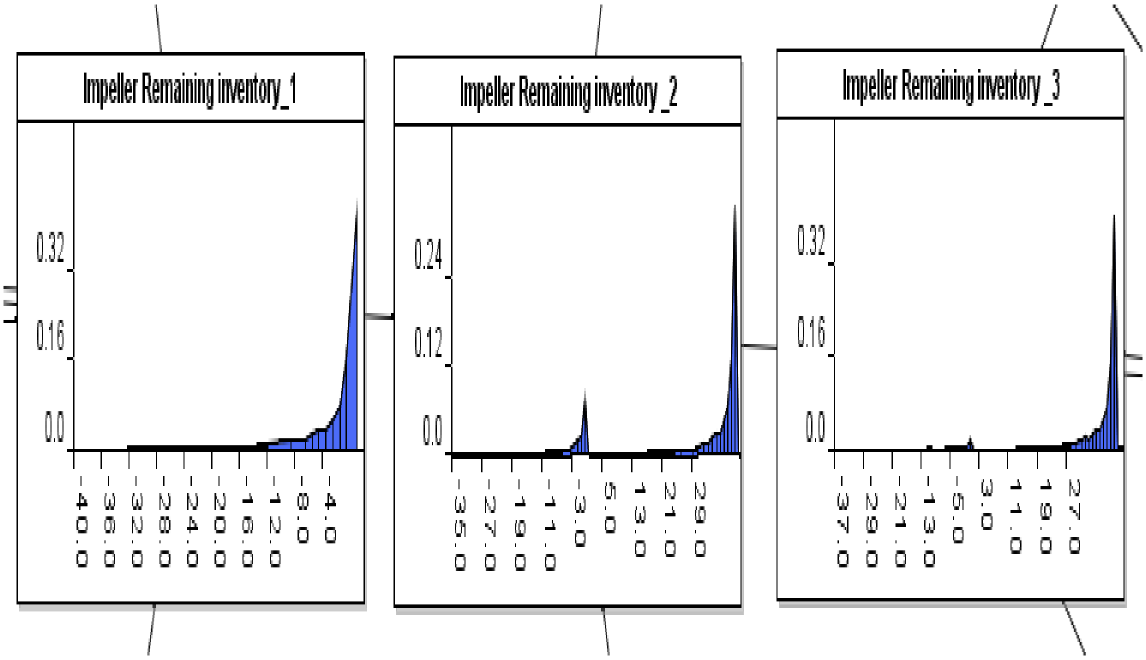


Figure 6-14: (A) Impeller SC behaviour when flood occurs and the supplier has unlimited capacity

The behaviours of the Air Blast spare parts SCs across time intervals are shown in Figure 6-15. As can be seen, SCs will be greatly affected during the month where the flood is assumed to occur. However, there is a particular chance that the effect of the flood is negligible. This is where there is no projects are running. At the second time interval, the probabilities of shortages will be significantly fell down due to the assumed flexibility and the only reason could prevent the supply is the storms. At the third time interval, the SCs behaviours will be stabilised again at the same level before the flood occurrence. The recovery time, in this case, will be almost two months. Figure 6-16 and Figure 6-17 show how the shortages chances are affected the plant chance to be down.

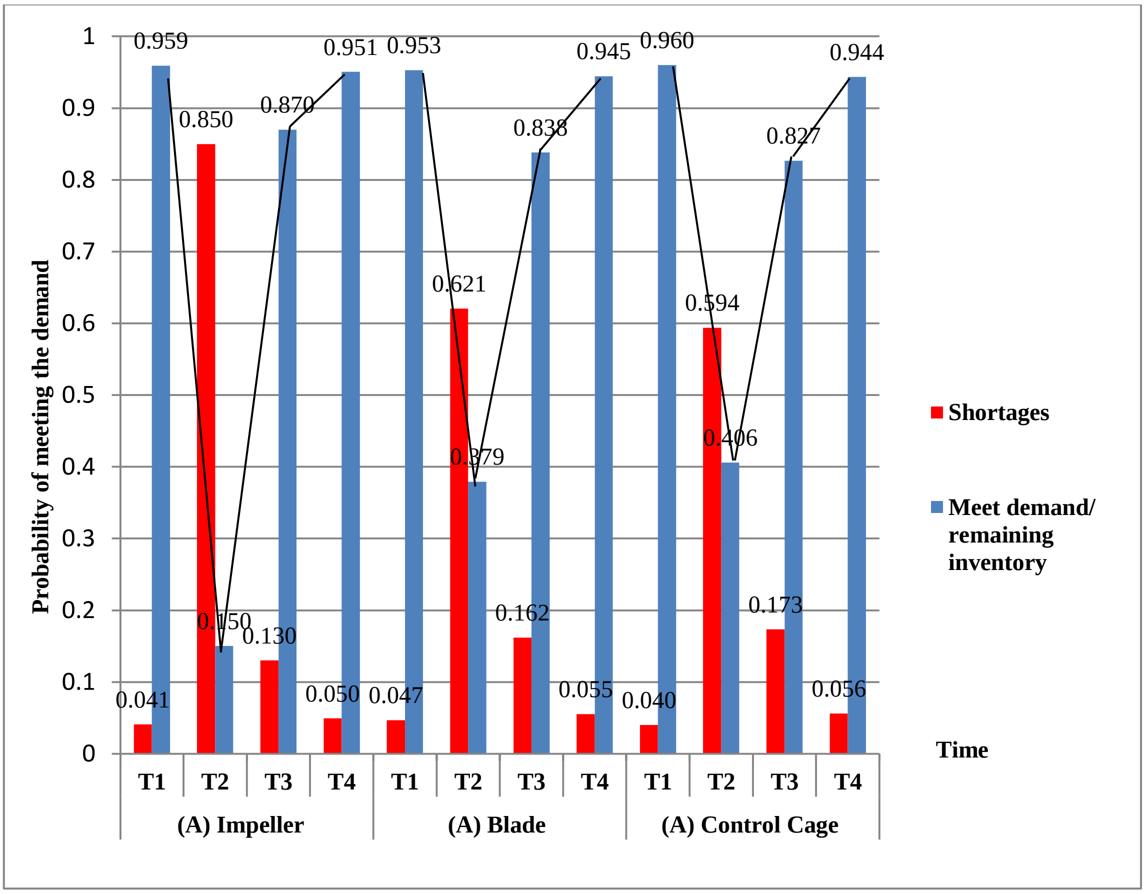


Figure 6-15: Resilience triangle of Air Blast process specialised spare parts SCs across the time when flood occurs, and the supplier has unlimited capacity

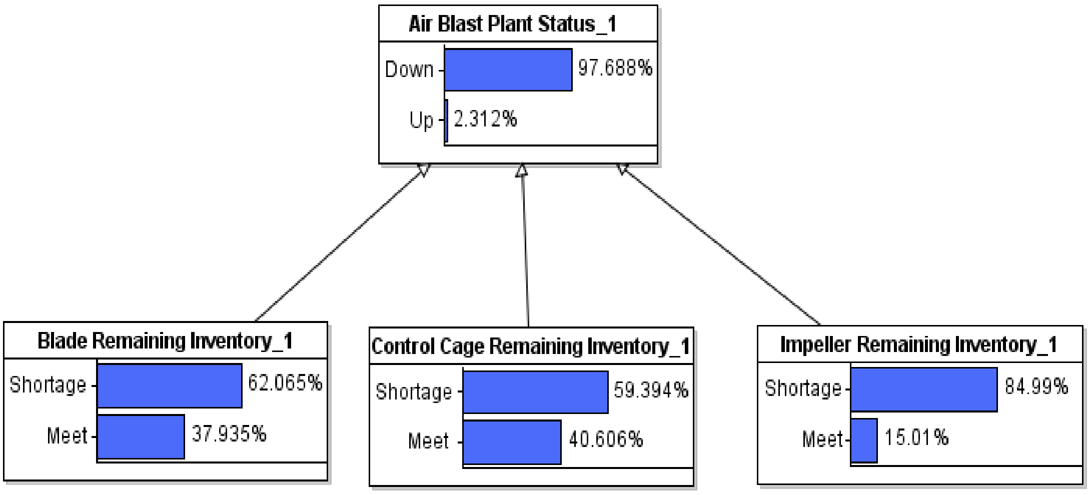


Figure 6-16: Air Blast plant status based on the chances of meeting the demand when there are no limits on the supplier's capacity (First-time interval)

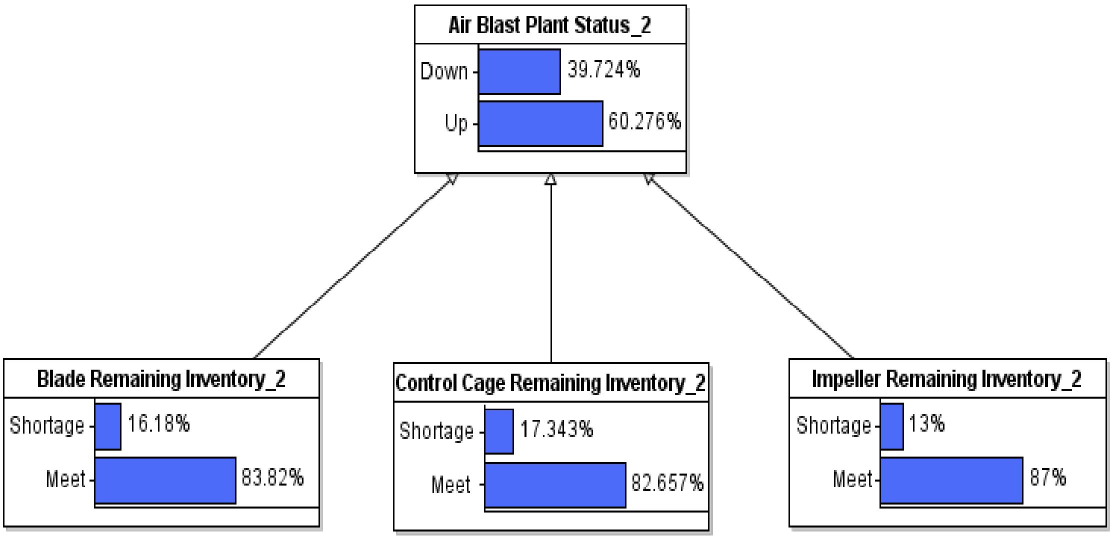


Figure 6-17: Air Blast plant status based on the chances of meeting the demand when there are no limits on the supplier's capacity (Second-time interval)

The above possibility of the plant to be down is associated with an economic loss that expressed by the expected unprocessed pipes distributions at every time interval in Figure 6-18. The latter figure shows the relationship between the loss that the company can incur and the production volume that needs to be processed. If there is no projects need the Air Blast process, the shortages of spare parts and its impact will be negligible. However, if there is a production, the total economic loss during the recovery time will be an additive function of the economic loss distribution at each time interval.

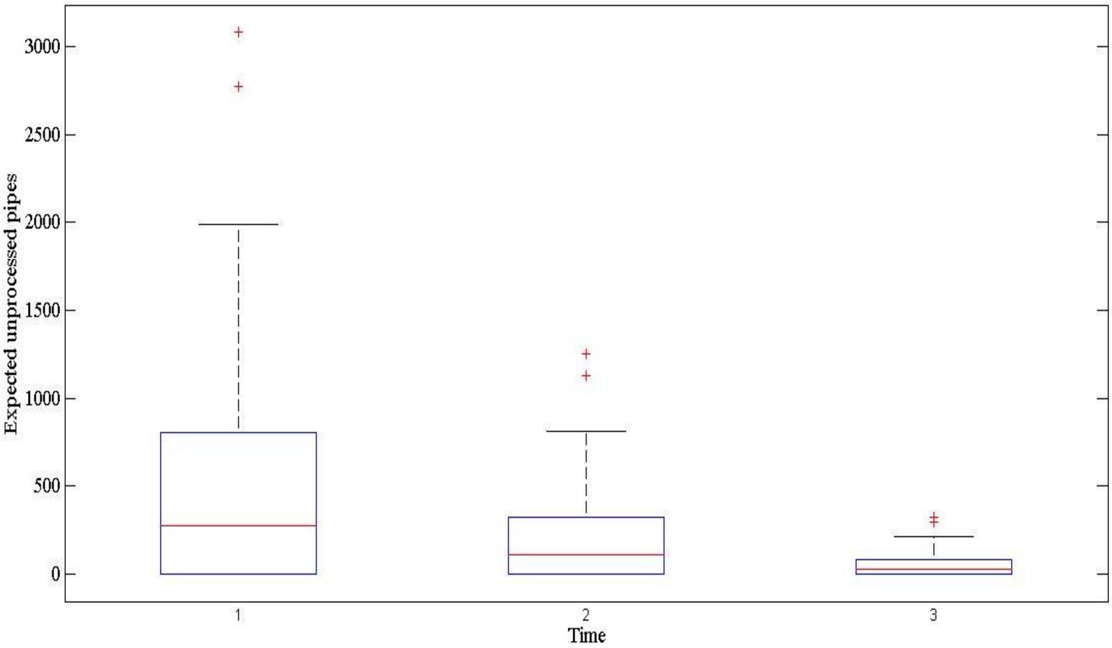


Figure 6-18: The expected unprocessed pipes distributions when the supplier has unlimited capacity

6.8.2.2 Case 2: Supplier with Limited Capacity

A supplier with limited capacity means that within a time interval they can only source the minimum of ($\mathbf{R}_{\mathbf{t}}^{\mathbf{i}}$, fixed maximum quantity). The maximum quantity can be related to the inventory that the supplier holds to react to "After-Sales" demand or the duration to produce or source more. Their inventory should be balanced between customers. The limited capacity clearly impacts the expectation about what the SC management able to receive after the occurrence of the hazard. The supply chain management cannot receive more than a specific limit of spare parts during a specific duration.

To explore the resilience for this case let us assume that the supplier (A) only supplies min ($\mathbf{R}_{\mathbf{t}}^{\mathbf{i}}$, 35) from (A) blades. DBN for this case has been run to understand the reaction of SC. The output of DBN shows that the blade SC needs one more month than the previous example to stabilise at its normal state (Figure 6-19). The behaviour of air blast SCs across the time with limited supplier capacity are shown in Figure 6-20. This figure is based on that the supply is limited to min ($\mathbf{R_t^i}$, 30) or the control cage and impeller for a one-month duration.

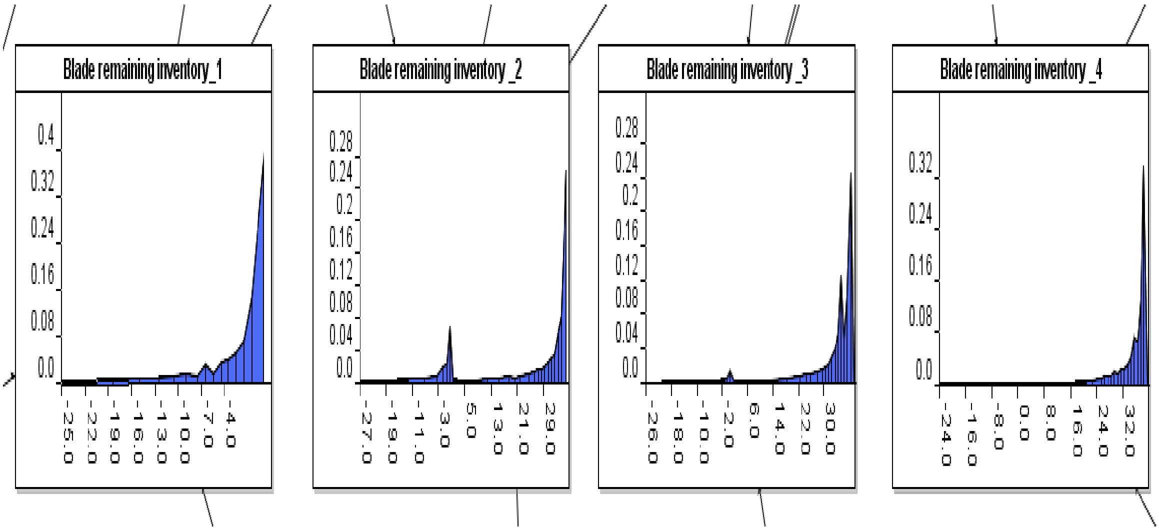


Figure 6-19: (A) Blade SC behaviour when flood occurs and the supplier has limited capacity

As can be seen, the impact of losing the inventory in this case due to the flood manifests by bigger chances of the shortages in time $\mathbf{t_3}$ and $\mathbf{t_4}$, as well as, an extra month from the SCs to recover to its normal behaviour before the flood.

Figure **6-21**, Figure 6-22 and Figure 6-23 show how the shortages chances with a limited capacity affect the chance of the plant to be down. Such figure might play a fundamental role in forming the contractual agreement with the manufacturer regarding “After-Sales care” if new machinery to be bought. The expectations about capacity limits from the spare parts can be studied in a way to check the resilience of the SCs for losing the inventory. The output of DBN demonstrates the value of the flexibility in maintaining a better resilience level.

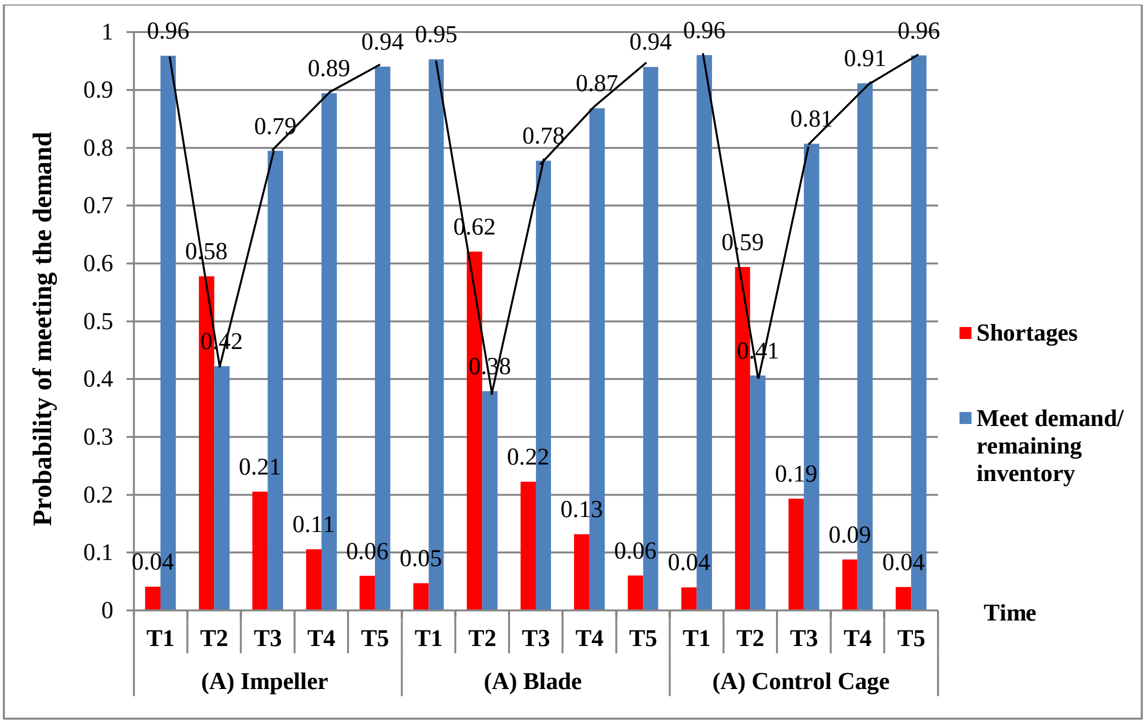


Figure 6-20: Resilience triangle of Air Blast process specialised spare parts SCs across the time when flood occurs, and the supplier has limited capacity

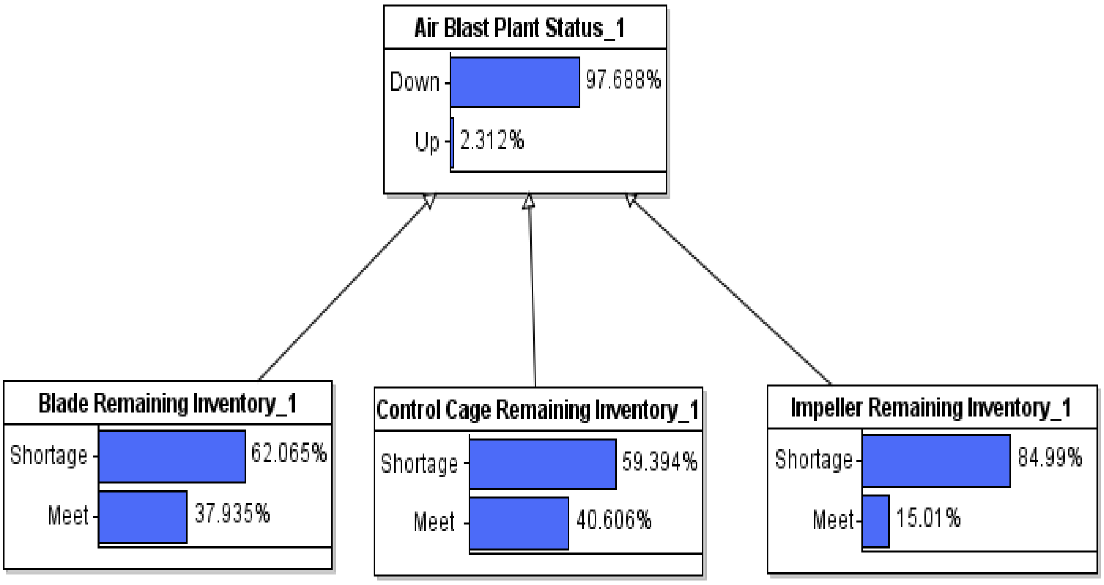


Figure 6-21: Air Blast plant status based on the chances of meeting the demand when there are limits on the supplier capacity (First-time interval)

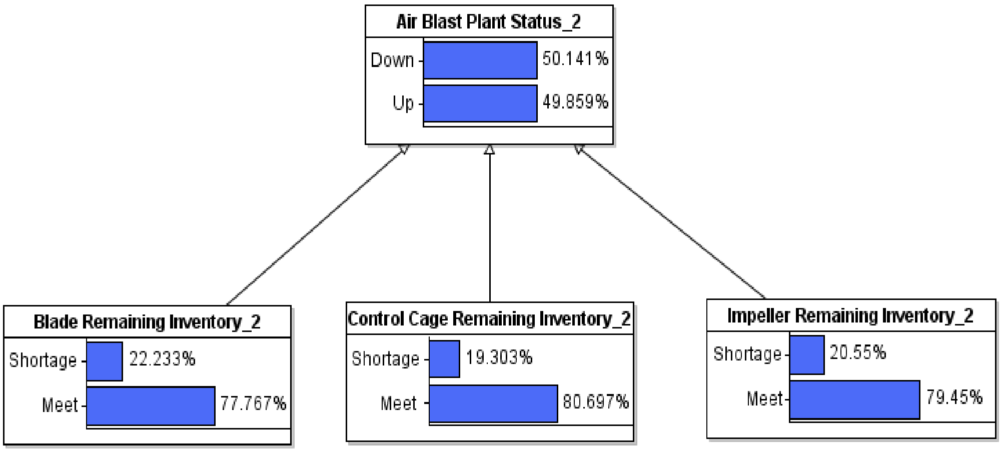


Figure 6-22: Air Blast plant status based on the chances of meeting the demand when there are limits on the supplier capacity (Second-time interval)

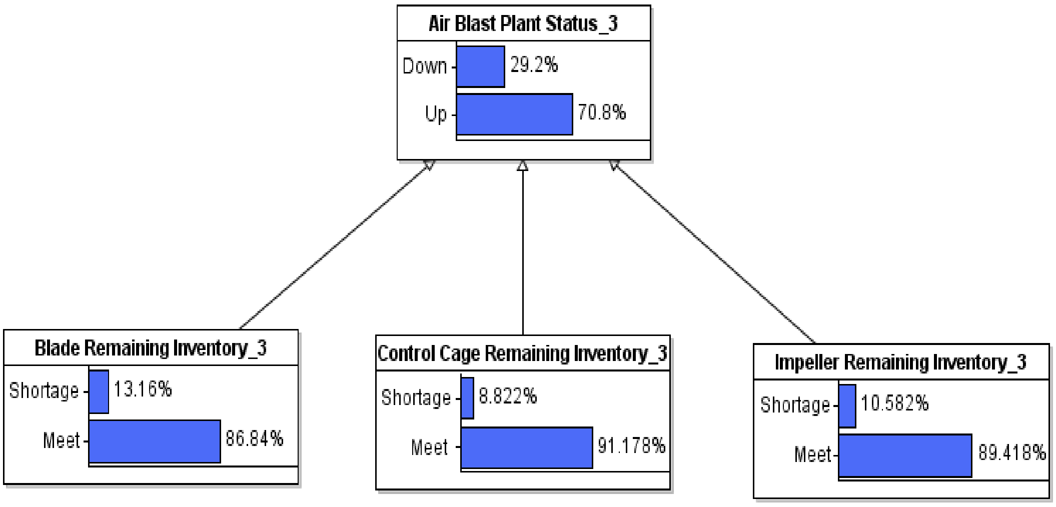


Figure 6-23: Air Blast plant status based on the chances of meeting the demand when there are limits on the supplier capacity (Third-time interval)

The economic loss that expressed by the expected unprocessed pipes distributions at every for this case is shown in Figure 6-24. The capacity limits, in this example, is contributing to a bigger economic loss. However, this loss can be zero with almost 20% chance due to code the case where there is no production.

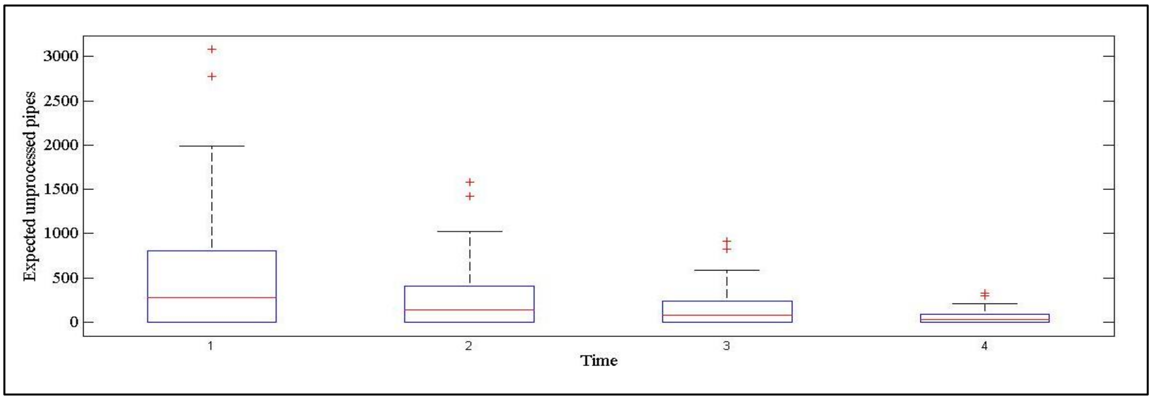


Figure 6-24: The economic loss distributions in the event of supplier has limited capacity

6.9 Building Confidence in the Case Study and Model Results

The internal validity of this case study has been built by ensuring the data are collected from different sources to enrich the case study. The complexity around the resilience of the spare parts SCs has led to contact staff from the maintenance, operations and supply chain management. I have collected datasets from operations and supply chain management for the sake of operationalising DBN and the conduct the analysis.

The validation and usefulness of the model, as for other cases, has focused on ensuring that the DBN satisfies the conditional independence property, collecting feedback on the model structure and the model behaviour, checking the sensitivity of the model behaviour to extreme values. The usefulness of the model has been understood by reflecting on DBN assists in predicting the resilience of SC and how the model can help to a better management of spare parts SCs.

6.9.1 Model Validation

The satisfying of the conditional independence property has been confirmed by the modeller at the internal process level and SC level. The first step to ensuring the conditional independence has been considered by understanding the structure of each spare part SC separately from the others (Figure 6-1). The mapping of internal and external SCs structures has assisted to comprehend whether there are common factors that affect the supply and demand for each spare or not.

At a spare part SC level, the conditional independence has been ensured through considering the D-separation between the variables that show the material flow in SC. For example, the demand and the inventory level are dependent for a particular spare part. However, the introduction of remaining inventory node has blocked the path between the demand and inventory level in “tail-tail” relationship. Similarly, the remaining inventory node and supply node within same time interval are clearly dependent. The increase of supply in any month leads to increase of the remaining inventory in the same month and vice versa when the demand is constant. However, the knowledge about the inventory level node blocks the path from the supply node to the remaining inventory node. Therefore, these two variables are conditionally independent with “head to tail” relationship. The supply chain manager has been asked to give their feedback about the evolving of the model structure, the description of the variables. Due to the complexity of the case study the model structure has been refined several times as it was firstly hard to understand the internal process of company processes and how these processes influence each other and their impact on the spare parts SCs.

The behaviour of DBN with various scenarios have been shown in Figure 6-8, Figure 6-9, Figure 6-10, Figure 6-11, Figure 6-15 and Figure 6-20. From latter figures, it can be noticed that the model is producing a realistic behaviour based on the current decision rules regarding sourcing and the inventory. For example, Figure 6-10 shows that there is a high chance for the inventory of blades to be more than 32 items cross the time, which consistent with the lumpy demand pattern of the blade and the decision rule to maintain 38 items all the time in the warehouse. Similarly, the output behaviour of the model has been consistent with the expectations when the supplier capacity issues have been taken into consideration (Figure 6-15 and Figure 6-20). The model produces a necessary reduction in the ability of the spare part SC to maintain a small shortage chance due to the imposed capacities constraints (Figure 6-20). The base behaviour of the model has been also confirmed by the observations of the decision maker. The decision maker states that the spare parts can go rusty before they are being used. However, this base behaviour of these SCs cannot be validated in a precise way as the consumption of spare parts are also related to the breakdown of the machines due to other factors than the production volume.

Figure 6-15 and Figure 6-20 how the sensitivity of the model to the extreme value regarding the inventory when the flood has been assumed to destroy the inventory. The extreme value of the inventory level at $\mathbf{t_1}$ has resulted in degrading the ability to maintain low shortages chance across the time intervals. This degradation has been considerably different based on the assumed flexibility from the supply side. DBN output shows that while supplier unlimited capacity leads to a greater absorption of the impact of the flood in the company, the limited flexibility from the supply side drives to amplify the impact of flood and delay the recovery for a month.

6.9.2 Model Usefulness Based on SCs Characteristics

6.9.2.1 Capturing SC Resilience in Conjunction with SC Characteristics

The outputs of DBN (Figure 6-15 and Figure 6-20) show the ability to maintain the low shortages chance and the recovery time in two cases. They also show the additive impact of shortage chances on the chance of the plant to be down and create a production bottleneck. DBN outputs illustrate that the focus of the supply chain management in maintaining the resilience should not be the inventory due to the location of their warehouse in a hazard-prone area. The model output reveals that the better ability to recover from a flood scenario is mostly based on the flexibility from the suppliers considering that they are a single point of the supply. However, this flexibility cannot be unlimited. There is always a maximum level that can be negotiated with the suppliers to maintain the resilience of the SC. On the other hand, the model outputs show the importance of considering the uncertainty about the production, supply and the inventory levels to enhance the management of spare parts SCs.

6.9.2.2 Spare Parts SCs Characteristics and the Resilience Modelling

6.9.2.2.1 SC Integration and Visibility

The low integration level has been reflected by a lack of visibility to suppliers' processes. It has limited the identified known structure of spare parts SCs to only direct suppliers with no information about the factors that can lead to the hazard from the supply side apart from the tropical storms in the Malaysian coast. DBN outputs highlights that despite the low integration level the company depends heavily on one supplier with no choice to source from other suppliers. It suggests that resilience of specialised spare parts can be significantly affected by the disruption from the supply side regardless of the integration level.

6.9.2.2.2 SC Operating System

As has been shown in Figure 6-8, Figure 6-9 and Figure 6-10, the supply chain management maintains a high level of the slack to improve their reaction to the lumpy demand of the spare parts. This high-level slack aims as well to counter the disruption of the supply due to tropical storms. While the high inventory has an apparent influence on maintaining their ability to have a low chance to be short in business-as-usual cases, the inventory is the primarily impacted resource when the flood scenario has been considered. For the case study where the firm facilities are in a hazard-prone area, the results of DBN shows that the maintaining of the resilience cannot be achieved by having redundancy in the inventory. The latter mainly can be reached through the flexibility in the supply side to increase the sourcing. However, this flexibility is usually limited due to the supplier capacity.

The influence of the push-pull system in forming DBN has been manifested by considering the company decision rules in forming conditional probability distribution functions in the model. As for the tubes SC case study, the material flow from the supplier is triggered by the information about the replenishment quantity distribution, which is influenced by the information about the target and remaining inventory levels for each spare part. The pull cycle, in the other hand, is controlled by the distribution of production volume that triggers the demand.

6.9.2.2.3 SC Structural Configuration

The identified structure of SC has shown a single point of the supply for each spare part where a common supplier supplies a set of spare parts. There is an absence of the redundancy concerning the structure, and this redundancy cannot be achieved due to the dependency on the exact machine manufacturer. The lack of ability to create redundancy regarding the structure leads to that the recovery from a flood is entirely dependent on the capacity of the single supply point to fulfil the firm orders. DBN outputs show that the limitation of the capacity of a single point supplier with the inability to create redundancy in the structure to increase the flexible capacity lead to amplifying the impact of the adverse event and longer time for the recovery (Figure 6-20).

From internal processes perspective, the spare parts SCs are complementary. It means that shortages from one spare part can lead to disrupting the production from a process as in Figure 6-11. The complementary nature of spare part SCs has two consequences from DBN modelling. The first one is to consider the common process production volume for the set of spare parts. The other consequences are to consider how the probability of shortages from different spare part affect the chance of the plant where the process is taken place to be down. It is by using And logic gate as in Figure 6-12.

6.10 Key Insights and Concluding Remarks

This case study focuses on supply chains resilience for a production firm. The nature of pipelines coating industry has led to focus on spare parts as the main concerned SCs. The hazards that affect these spare parts SCs are not only coming from the supplier side but also from the vulnerable firm location and its internal processes. The management of spare parts has been described in the literature as a difficult task. Several classifications and mechanism to forecast their demand has been suggested. However, the literature seems to look at the issue from a seller point of view.

In this case, my focus is how the resilience of the spare parts SCs can be analysed from a user perspective. Spare parts for this case have been classified into specialised and non-specialised spare parts. Then, DBN has been formulated to understand the resilience of specialised spare parts considering the interdependencies between the uncertain supply, inventory level and production volume. DBN modelling input and outputs for this case study illustrate the importance of having a flexible capacity from the supply side to maintain the resilience of spare parts SCs. It is mainly due to inability to create redundancy in the structure if this SC (single source of supply). I have also shown that having a high redundancy that related to a push supply cycle will be the primarily affected source if the firm is in the hazard-prone area. I also illustrate that firm has so little information about the hazards that affect the supply side (lack of visibility) that might be related to a low level of integration. Table 6-5 and Table 6-6 explain some key insights that have been gained in terms of the influence of SC characteristics on the resilience and DBN process.

Table 6-5: Key insights on the impact of some pipe coating specialised spare parts SCs characteristics on its resilience

Factor	**Insight**
Intensity of integration and the dependency	SCs has low integration level. However, the ability to meet the demand of to maintain the machines are very dependent on the resource of the single inevitable point of the SC.
Operating system	Inventory is the main affected due to the location of the focal firm in a hazard-prone area. Therefore, it plays no role in maintaining the resilience to the flood.
Visibility and span of integration	The limited integration span has been reflected by the lack of visibility to machines manufacturers (suppliers). This leads to an inability to identify hazards that might impact the supplier.
SC structural configuration	a) Focal firm is in a hazard-prone area (understanding the vulnerability), b) Inability to create redundancy in the structure, c) Internal spare parts SCs are complementary. It means that shortage from one spare part can steer to disrupt the production from a process.

DBN modelling approach contributes also to the discussion in the literature of spare parts management not only through considering the interdependent view to understanding their demand and the impact of inventory control decisions and supply uncertainty but also through reflecting on the impact of some hazard scenarios on the management of theses spare parts. Eventually, this can lead to identifying decisions rules that can enhance their resilience such as decisions about the level of After-Sales flexibility.

Table 6-6: Key insights on the lessons learned about DBNs modelling process for pipe coating specialised spare parts SCs

Factor	**Insights**
DBN scope	a) The identified suppliers and the internal process, b) Spare parts classification into specialised and non-specialised ones. c) The hazards due to the location of the focal firm (tropical storms and flood).
Qualitative Structure	a) The known internal and external structure (e.g. Air Blast processes), b) The impacted internal processes by SCs resilience, c) The impact of the hazards on the supply and inventory.
Quantification	a) Decision rules about inventory and ordering (maximum inventory level), c) The current resilience enablers (excess inventory and After-sale agreement flexible sourcing with limits) affect the conditional probability distribution for the supplies, d) Lumpy production volume influences on the demand for spare parts.
Discretization	Dynamic Discretization: • Distribution fit for the production volume (gamma distribution) as root variables, • The use of the arithmetic relations between the variables that represent the material flow of the spare parts.
DBN Output representation	a) The use continuous distributions as inputs for the model results in a continuous distribution to illustrate shortages of the spare parts, b) Resilience triangles are based on the plant status as the main resilience indicator.

7 Atlantic Canada Food SCs Resilience In the Presence of Critical Infrastructure and Extreme Weather Conditions

7.1 Introduction

This chapter examines Atlantic Canada food SCs resilience to the occurrence of hurricane scenario. It illuminates the influence of infrastructure restoration time and air shipment on the recovery of the SCs. Atlantic Canada is a region of Canada comprised of four provinces located on the east coast: New Brunswick (NB), Prince Edward Island (PEI), Nova Scotia (NS) and Newfoundland (NL) Figure 7-1. Newfoundland is a large island off the east coast. It is the most populated island in North America. Most wholesalers and supermarket chains in Atlantic Canada have stores in Newfoundland, and in some instances, suppliers of particular goods are located there; however, most goods must be imported.

The resilience of food SCs from and to Newfoundland has been considered an issue mainly because of Canadian weather conditions, which disturb the operations of SC members and the presence of critical infrastructure. In Atlantic Canada, there are three main big retailers/ supermarkets where the market is a highly competitive between them. The case study has been carried out on two SCs of one retailer who has provided access for this research. The case study retailer has supply chains originate from the mainland to Newfoundland. It also has a chickens SC that begins from Newfoundland. Therefore, this investigation would allow making inferences about the food SC resilience to and from Newfoundland.

Figure 7-1: Atlantic Canada provinces map

In contrast to previous two case studies where I have presented the SC system by the material flow and variables that represent this flow, in this case study, I have taken a structural view of the performances of different SC members to predict the resilience. In principle, it is similar to Garvey *et al.* (2015) theoretical work in BBN. Garvey *et al.* (2015) insist on the importance of identifying the whole SC structure to analyse its risk. In this chapter, I will show the characteristics of non-perishable food and chickens SCs. DBN input/output based on the structural view of the relationships in the SC and its complexity will be explored.

7.2 Brief Description on the Actual Data Collection Process for Atlantic Canada Case

The results of this case study as in other cases studies are mainly drawn from interviews, company data and documents. The interviews had been carried out with the transportation manager, procurement manager and three vice presidents (VPs) from the company board between February 2013 and June 2013. The telephone meeting with the transportation manager helped to identify the concerned supply chains for the company. They are mainly related to the inbound supply to Newfoundland and chickens outbound supply from Newfoundland. The company inbound and outbound supply from and to Newfoundland is vital. Regarding the inbound supply, it is clearly because of their stores' continuity in the market. However, the reason why the company has their chickens supply chain originates from Newfoundland in spite of their concerns about the resilience of this network is that there are federal quotas in Canada on how much chickens can producers market in. Federal quotas mean the number of kilogrammes of chickens, expressed in live weight that a producer is entitled under regulations to market in interprovincial or export trade, during the period referred to in the schedule. The company has their quota in Newfoundland that helps them to cover their needs from the chickens inside Newfoundland and in the mainland.

The telephone meeting followed by semi-structure-interviews aimed at getting information to investigate SCs characteristics and the hazards that can affect them. The models qualitative structures were mapped based on interviewees’ responses to questions.

Then, they were validated. (Appendix D.1, Page 263) shows an example of interview questions for the chickens SC. The interviewing and analysis process has been conjoined with gathering documents about the company suppliers and some available quantitative data that can help to populate the model. See (Appendix D.2, Page 264) and (Appendix D.3, Page 264) for examples of the company weekly performance data and calculation matrix for the performances respectively. The company has provided the performance weekly data of the majority of the SC members between 2008 and 2013 with some exceptions for the chickens SC, as I will discuss in section 7.7. In case there is no data about some root variables (variables have no parents), the transportation manager act as an expert to give a subjective judgement due to his direct knowledge of the situation.

7.3 Food SCs Issues and Model Focus

Food SCs are described to be very complicated SCs with many safety concerns over the food storage (Sarathy, 2006). The food security and safety have an inevitable impact on the resilience of SC and the ability to meet the demand of food (Figure 7-2). One of the potential hazards that have appeared during the modelling process is the recalls. Recalls often occur because of safety concerns over a manufacturing defect in food that may harm its users. It is one of company concerns that has not been captured by the model. The recall is linked to an area of the literature called food safety and security. Food safety is concerned with decreasing the likelihood that the consumption of food will result in illness, injury, death or adverse consequences to people. From SC perspective, safety problems can arise at transfers in the system, improper storage, handling and distribution of the product (Marucheck *et al.*, 2011). The product security refers to the aspects that arise during the delivery of a product by intentional contamination and damage within the supply chain (Sarathy 2006). The recall of one product or more leads to less availability of the product in stores or a DC. However, it requires a different DBN modelling structure to identify the potential hazards that might affect the food safety and security. This is out of the model scope from the beginning. The DBN mainly considers the resilience of the supply chain in making the food available in the presence of hurricane scenario.

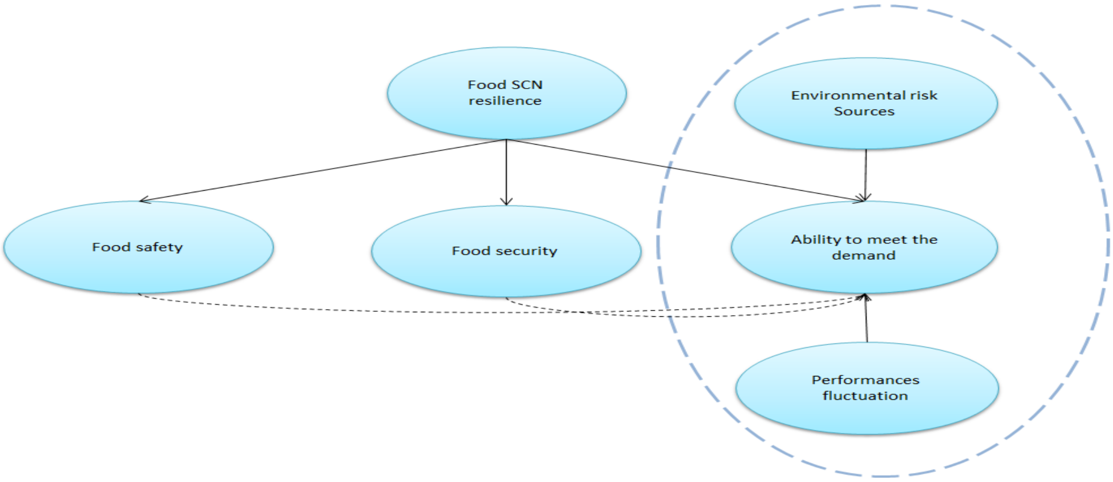


Figure 7-2: Implication of food supply chains resilience

7.4 Non-perishable Food and Chickens SCs Characteristics

Figure 7-3 shows the identified non-perishable food SC structure. The destination node in the case is a store in Newfoundland as an example of other stores. This known structure for SC starts with suppliers located in the USA and various locations in Canada. All food is supplied to a centralised distribution centre (labelled A) via 3PLs. Food is, then, sent to North Sydney port and via ferries onto Port aux Basques (Newfoundland) from which it goes to a second centralised distribution centre (labelled B). It is, then, distributed to grocery stores. The majority of suppliers located in Ontario (ON) where the company has a consolidation point there. All suppliers in Ontario send materials to that consolidation point. Other suppliers send their supply directly to the Distribution Centre (A).

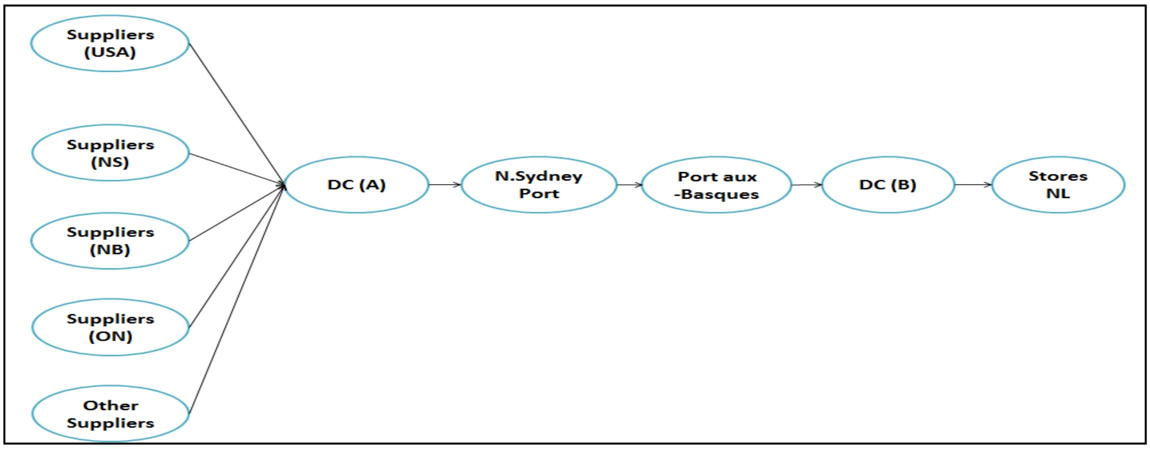


Figure 7-3: Non-perishable food SC structure

The known chickens SC structure starts from the hatchery where the eggs are hatched under controlled conditions, feed mill where the chickens feed are produced and then poultry farms where the chickens are raised. The poultry farms send the chickens to a centralised packer where chickens get slaughtered and packed. The packer uses a group of suppliers that they are located nearby to wrap the chickens. The hatchery, feed mill, poultry farms and the packer all located in Newfoundland. After that, the chickens are sent to a centralised distribution centre (C) in the mainland through the Port aux Basques (Newfoundland) and North Sydney port. Then, they are being distributed to the stores in the mainland Figure 7-4.

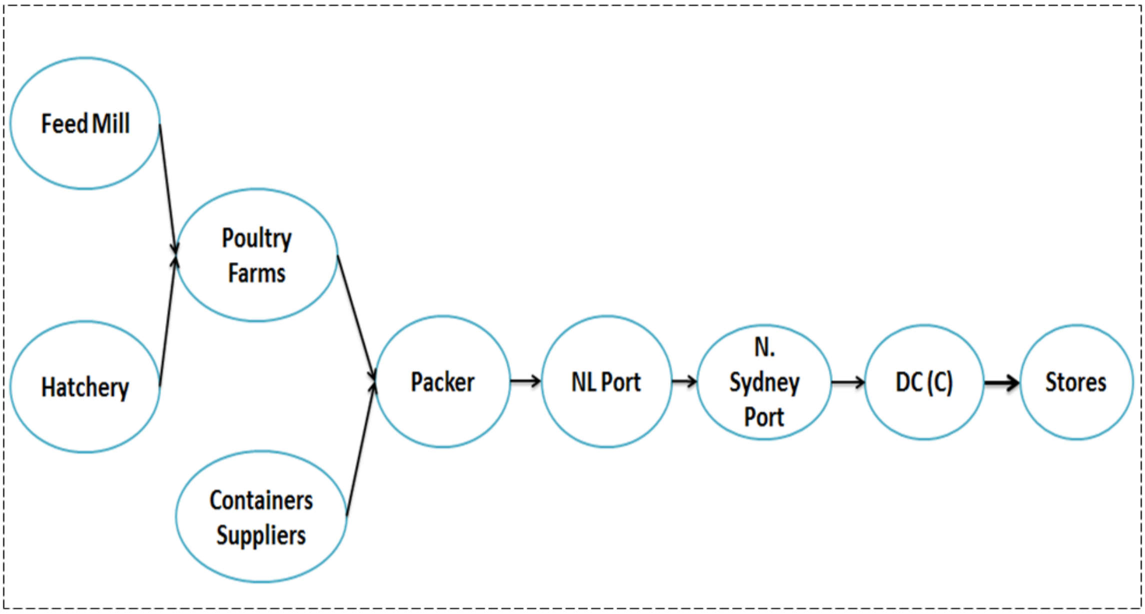


Figure 7-4: Chickens SC structure

For non-perishable food SC, the focal firm has market relationships with their suppliers and with the ferries company that move the food between the ports. So, it can be described based on Świerczek (2013) classification for the integration level as non-integrated SC. The chickens supply chain is highly vertically integrated SC apart from the ferries company. Although each SC member has its organisational structure and trademark, the SC members are controlled by the retailer due to its power over other members. Moreover, the retailer has shares in some of them, which vary based on the organisation. For example, the retailer owns 50% from the packer and poultry farms shares. According to (Świerczek 2013) classification, this is a fully-integrated SC and span of integration is extended as still there are SC members are not integrated such the containers suppliers. In contrast to the non-perishable food SC that has very basic visibility to the upstream SC members, the retailer has high visibility to the processes of Chickens SC upstream due to the vertical integration.

The non-perishable food SCs are mainly controlled by a "pull" operating system where the primary trigger for the processes in SCs is the stores orders Figure 7-5. In each stage, there one-week stock available where the orders might be partially or fully fulfilled from that stock. The stores are decoupling points in the system where the customers are expected to find their orders on the shelf all the time. The controlled “pull” operating system in SC with one-week stock level gives the non-perishables food flow flexibility to be adjusted to the variation in orders.

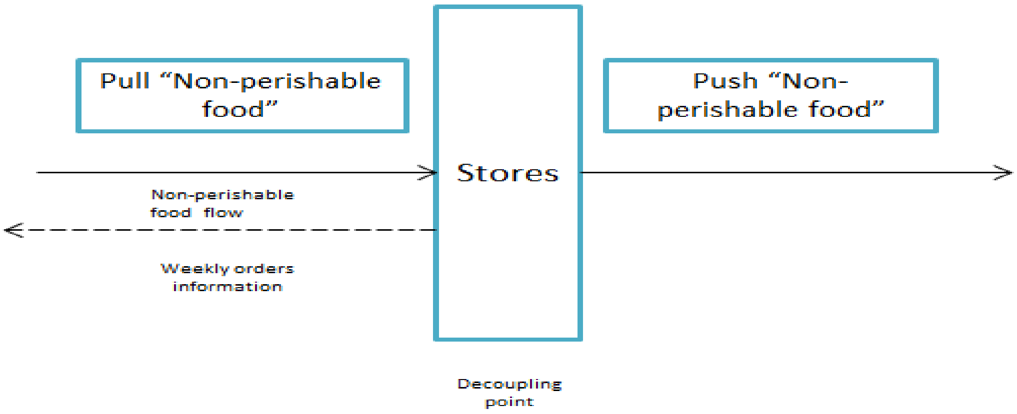


Figure 7-5: “Push–pull” non-perishable food SC operating system

The chickens SC consists of two cycles. These are the production cycle and trade cycle (Figure 7-6). The poultry farms production cycle is scheduled based on the expectation of the demand for the long term and the packer needs to slaughter and pack the chickens that they receive from the poultry farms. So, the supply conditions are controlled by a "push" operating system. Although the production cycle, in this case, is controlled by the push operating system and the trade cycle is controlled by pull system, the operation mode does not give an indication of the level of the slack in fresh chickens to meet the demand. This can be clearly attributed to the nature of chickens as a fresh product that cannot be stored for more than few days. Therefore, the redundant inventory cannot be a resilience enabler for this case.

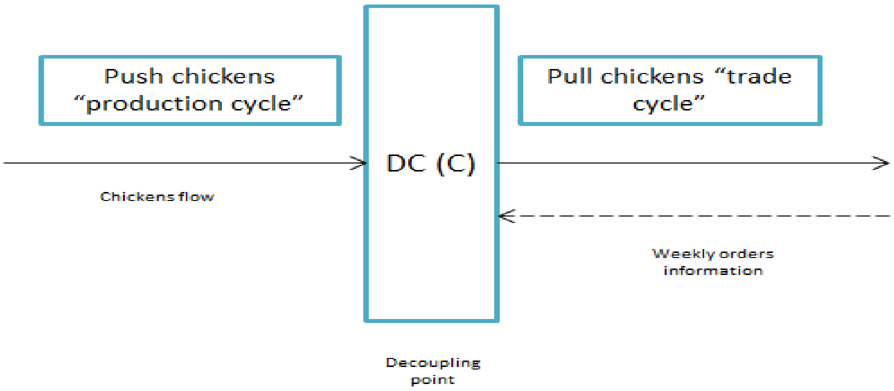


Figure 7-6:"Push–pull" chickens SC operating system

7.5 DBN Qualitative Structure

Recall that the building of DBN qualitative structure includes the identification of variables that represent the SC system and its resilience index and hazards, find out the cause-effect relation and check the variables that have dynamic property.

7.5.1 Resilience Index and Variables that Represent SC System

The main consequence of hazard propagation through the SC is the inability of stores as a destination point in SC to meet their demand. It is reflected by their fulfilment rate. The retailer wants to ensure that all SC members' weekly performances are 95% or above. In this way, they can maintain 95% or above fulfilment rate in the stores. The fulfilment rate has been considered as a resilience index for this case. It can show to what extent the SC is resilient to maintain the distribution of this rate and what the recovery time to the situation before the hazard.

To predict the fulfilment rate, the performances of different SC members have been considered. The performances of SC members that can lead to predicting the fulfilment rate in stores are the 3PLs, ferries, suppliers and DCs (Table 7-1). Some variables such as the status of supply, as can be noticed in Table 7-1, reflect the complementary nature of the performances of two or more SC members. For example, the status of supply from Ontario reflects the complementary character of the performance of suppliers from Ontario and the performance of 3PLs in delivering the available supply from Ontario suppliers to a DC.

Table 7-1: Factors to indicate the consequences of initiating events

Factors	**Description**
Ferries performance	The performance of the ferries in moving the food between ports.
Supplier performance	The performance of suppliers from a particular location that can affect the performance of a DC.
Third Party Logistics performance	The performance of trucks used to ship food.
Distribution centre performance	The ability of DC to fulfil the orders based on their inbound supply and stock.
Stores fulfilment rate	It shows the consequences of risk propagation across SC on the ability of stores to meet their demand.
The status of supply from a location	It is a complementary nature variable to represent the state of supply to DC based on the performance of suppliers and 3PLs.
The percentage of moved food	It is a complementary variable to represent the status of food movement between the ports considering the performance of DC (B), 3PLs and ferries performance

7.5.2 Hazards and Vulnerabilities Identification

Newfoundland is located in one of the hurricane paths in North America as has been stated above. The hurricane can occur at any point of time with very low probability. However, its occurrence has devastating consequences on the SCs from and to Newfoundland. If a hurricane hits Newfoundland, the nodes of the non-perishables food SC likely to be affected will be those who are downstream members. For example, those with responsibility for food distribution in Newfoundland and operating the critical infrastructure that is essential for food transportation (Port-aux-Basques and 3PLs). Regarding chickens SC, the majority of its nodes are located in Newfoundland. The hurricane is likely to affect all of them. Therefore, the hurricane has been considered to be the main hazard scenario that the resilience of SCs should be examined against its occurrence.

In contrast to hurricane scenario, the supply chains are exposed to some high probability hazards that they can face in day-to-day operations. Table 7-2 shows the identified hazards that high probability to occur. The hazards that hit the ferries and port operations (critical infrastructure) are the primary concern of the company. Any delay in their service might lead to disruption in the supply of DC (B) and, consequently, affects the stores supply. An example of the problem has been stated during the interview "we had an incident where the weather shut things down, and a ferry was being serviced, so they did not have the capacity to increase the volume of traffic. They have no backup plan for when breakdowns occur. When they get back up and running, they have capacity issues, and less capacity to move freight as tourists or personal vehicles take priority".

The 3PLs operations between different members in SC are also affected by the storms. "Sometimes because of the weather I cannot supply, sometimes there are problems with boats. Sometimes the trucks are full". In Newfoundland beyond the storms, there is a Wreckhouse area on Trans Canada[3], which prevents operations of 3PLs within the island. It has been stated "Wreckhouse area of south-west NL when there are wind warnings and the truck tips. Trans Canada can shut down for some periods due to high winds. Shutdown usually happens about once a week".

Table 7-2: The identified high probability hazards for non-perishable food SC

Hazard	**Description**
Storms	It describes the storms that affect the performance of 3PLs.
Ferries breakdown	It represents the breakdown of one ferry or more which influences the capacity of the ferries company in moving the food in the port.
Wreckhouse winds	It is a strong wind affects the movement in Newfoundland highway.
Borders status	It represents the status of the borders and how it affects the movement of supply from the USA.

The non-perishable food SC has many sources of vulnerabilities that might lead in conjunction with hazard sources to severe consequences. The identified vulnerabilities are shown in Table 7-3. The geographical location of SC members with a centralised

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[3] Trans Canada is a main highway in Canada with link all Canadian provinces and cities.

distribution centres and critical infrastructure has a visible impact on the type of hazards that the non-perishable food SC counters and the consequences of event occurrence.

Table 7-3: The identified vulnerabilities for non-perishable food SC

Vulnerability	**Description**
SC geographical dimension	The location of different SC members increases their exposure to the hazards. The members that they are located in Newfoundland such as DC (B) are more likely to hit by hurricanes due to their location on a hurricane path.
Centralised distribution centres	They are sources of vulnerabilities, any hazards that can impact them can drive a significant disruption in SC.
Critical infrastructure	The ports and the ferries company operations are the only single route to move the goods from and to Newfoundland.

The chickens SC has mainly same identified hazards with non-perishables. However, the vulnerabilities sources can be greater due to that the majority of SC members are centralised in the same location in Newfoundland such as the packer, the feed mill, etc. As same as the non-perishables food SC, the chickens supply goes to a centralised DC (C) through the ports that represent a critical infrastructure for this case. The main consequence of the adverse event for this case is the inability of the stores to fulfil their demand for the fresh chickens in the stores.

7.5.3 Cause –Effect Within and Cross Time Intervals

The model within time interval causalities are understandable from the natural dependency in the SC structure and where the hazard hits. For example, the DC performance is dependent on the status of the supply from different locations. These dependencies are recognised through the known structure of the SC and from the identified variables that represent the SC system. Where the hazard hits is linked to the identification process of hazards. For example, it is known through the interviews that all 3PLs can expose to the storms that lead to deteriorating their performance. The relationships between the storms and 3PLs performances represent a clear cause-effect relationship (i.e. the storms disrupt the operations of 3PLs). Similarly, the hurricane as a hazard scenario can affect the ferries performance and the variables that represent the SC system in Newfoundland.

Figure 7-7 and Figure 7-8 show the validated qualitative DBNs structures for the non-perishable food and chickens SC respectively. This map is the output of interviews and so represents the decision makers understanding of variables that lead to comprehending the resilience of considering SCs. The ovals represent the uncertain variables, and the lines show the relationship, where the arrow head represents the effect. For example, in Figure 7-7 the status of the US border will influence the performance of the 3PLs company transporting food from the US to Canada. Another example is the performance of DC (A). This DC performance is affected by the performance of food suppliers in the USA and Canada as well as by the third party logistics company performance that transports supplies to the distribution centre. If a storm occurs and influences the performances of 3PLs, then the consequences will propagate to affect the ability of DC to process the orders. There will also be knock-on effects downstream in the SC. This would be represented by a shortfall in the measured fulfilment rate against its target to meet demand. Similarly for the chickens SC, the consequences of adverse events propagate through the SC and impact the ability of the chickens SC to meet its demand.

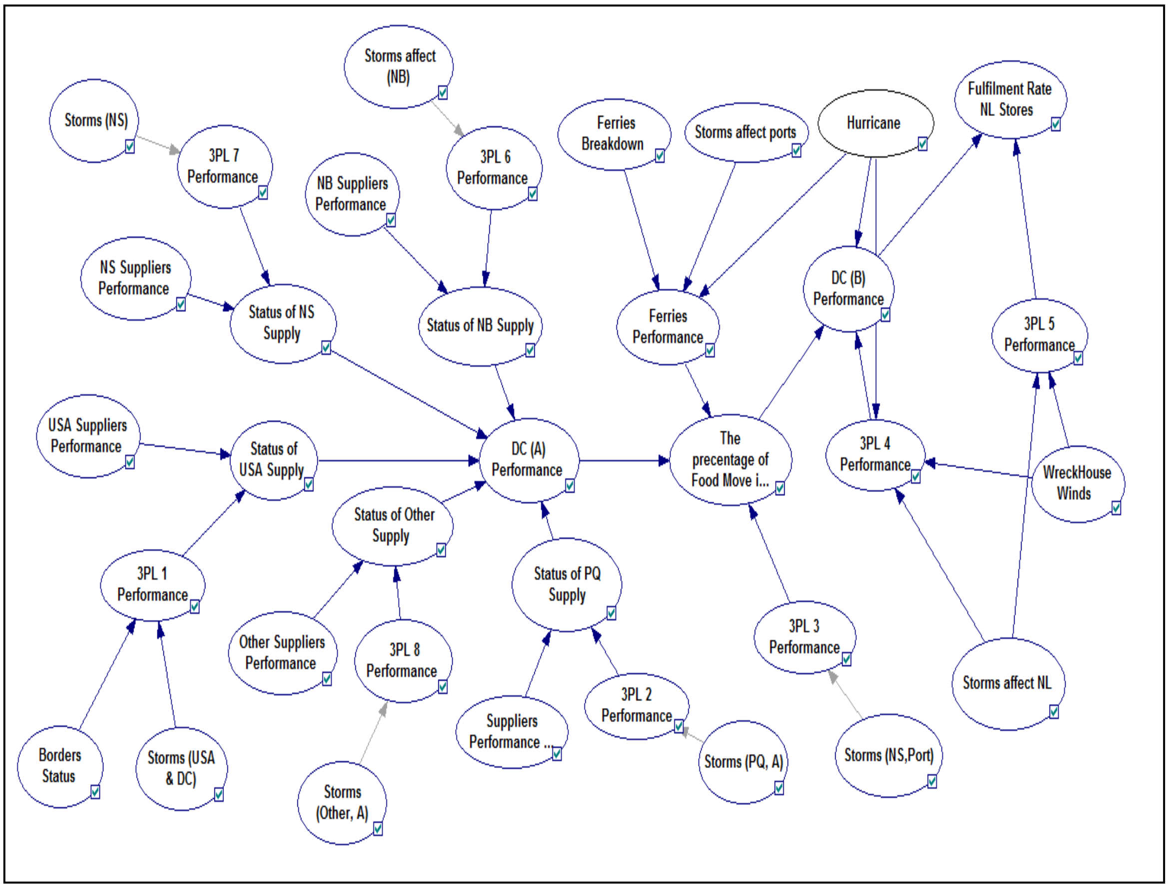


Figure 7-7: The structure of DBN for non-perishable food SC resilience

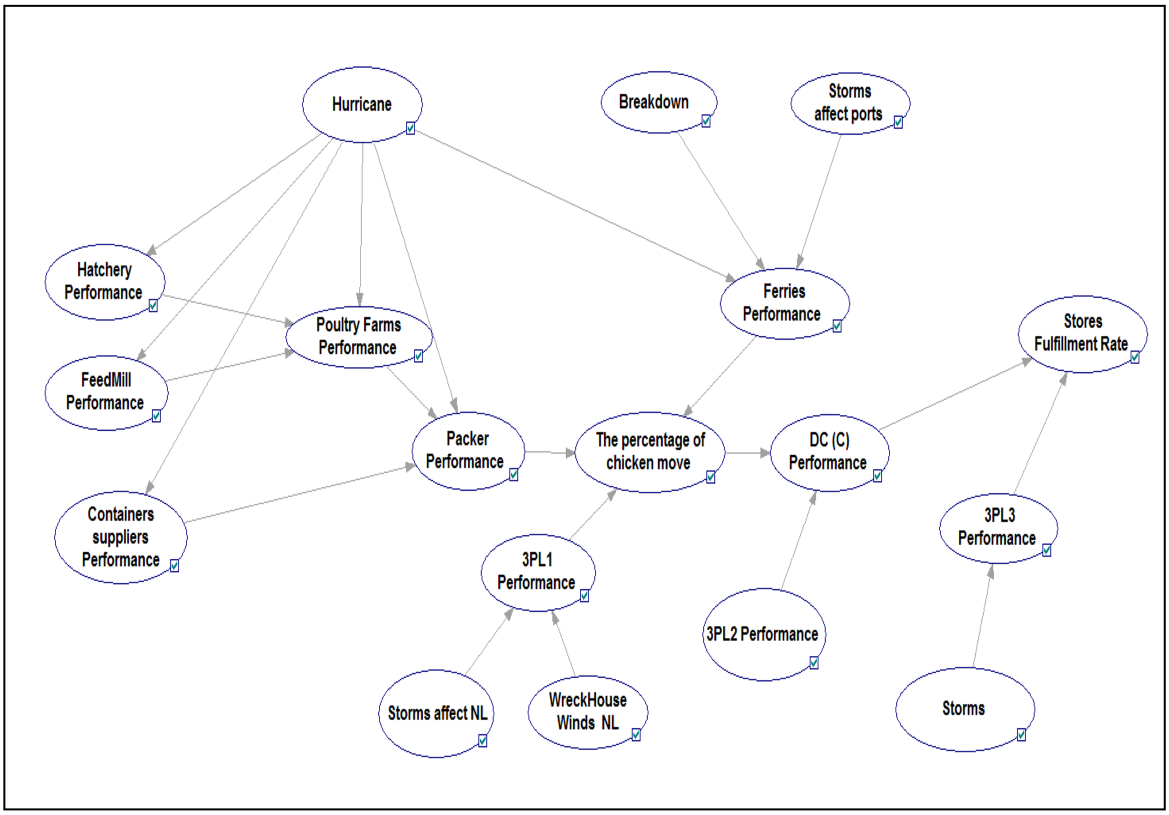


Figure 7-8: The structure of DBN for chickens SC resilience

The second stage involved identifying the variables that have causality through the time intervals. In this case, the variables that represent the SC members' performances have been named to be affected by its self-state. The reason is that the state of fulfilment rate depends on the performances of SC members. To understand the recovery of the SC to its fulfilment rate before the hazard, the recovery of these variables through time should be considered if the hurricane has occurred. Therefore, all these variables have causalities through the time. In the other hand, the hurricane as a scenario is assumed to occur at a particular point in the time and distribute the system. Therefore, it will appear only in a time interval. In contrast, the high probability hazards such as the storms can occur at each time interval. Figure 7-9 shows the DBN for non-perishable food SC. The loops denote the dynamic causalities.

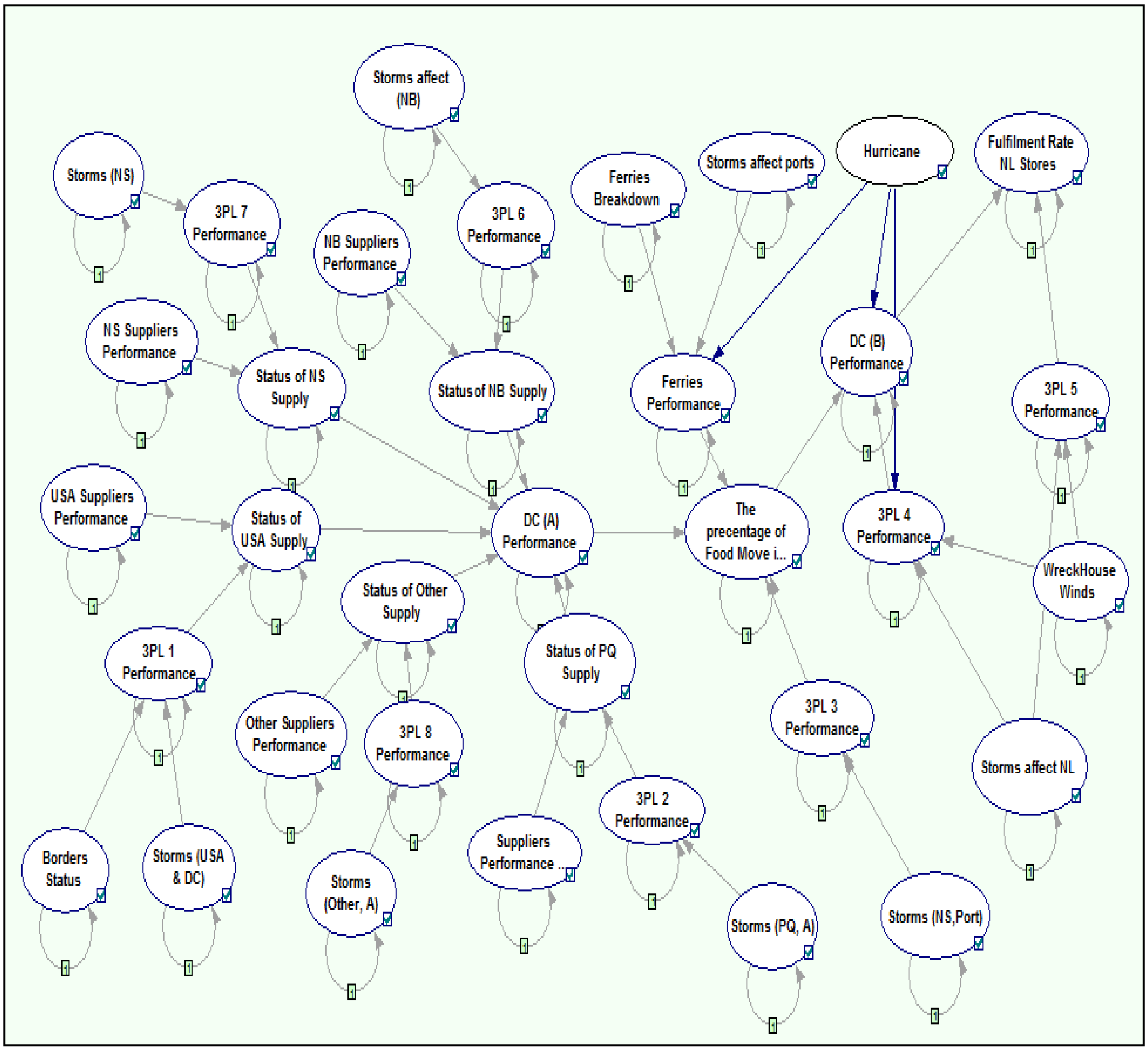


Figure 7-9: The actual DBN model for non-perishable food SC

7.5.4 Quantifying DBN of Non-perishable Food SC

7.5.5 Time Space

The main target across the SCs is to maintain the ability to fulfil 95% or more from their weekly orders. The weekly time frame seems to be a reasonable time interval to represent the capability to maintain and recovery to the same distribution of the fulfilment rate. It is supported by how the retailer calculates the performance of their SC members. See (Appendix D.2, Page 264) and (Appendix D.3, Page 264). However, this does not mean that DBN is intended to support operational decisions in SC such as how much I should ship and when. The supporting of real-time decision is neither an aim of such modelling approach nor a purpose for understanding and building SC resilience as I stated for the previous. As can be noticed, I consider the uncertainty distribution of weekly performances during few years.

7.5.6 Describing the Variables States

Variables in this model are continuous and discrete. The variables that explained SC system performances are continuous variables. The discrete variables in the model are the variables that show the hazards. For example, the storms can occur or not. In this case, the dynamic algorithm Neil *et al.* (2007) has not been used for discretizing the continuous variables due to a high number of the states that result from this discretization. The available data about some variables show that variables ranges are tight (10%). The dynamic discretization can show more than 20 states for this range. From a practical point of view, the retailer is keen to understand how SCs is meeting its target or above. Many discretized states for the area below or above this objective will not add more to their information. Instead of the dynamic algorithm I use a non-uniform static discretization. This is through:

- Understanding the distributions of continuous variables,
- Identify the areas with high density and discretize it more,
- Merge the areas that have low density,

- Finally, the discretization can be verified and validated with decision makers to ensure that the discretized states captured what they aim to know about the variable.

Figure 7-10 shows the performance distribution of DC (B) between 2007 and 2013 as an illustration for the continuous variables discretization in the model. The performance range is between 87% and 98.5%. They have been grouped into three mutually exclusive and exhaustive categories based on the above method. These are S1: <=87% to <92%, S2: 92% to <95% and S3: => 95%. Similarly, other continuous variables have been discretized. However, for variables that can be affected by a hurricane, additional states have been added with zero chances to enable the analysis based on the occurrence of a hurricane.

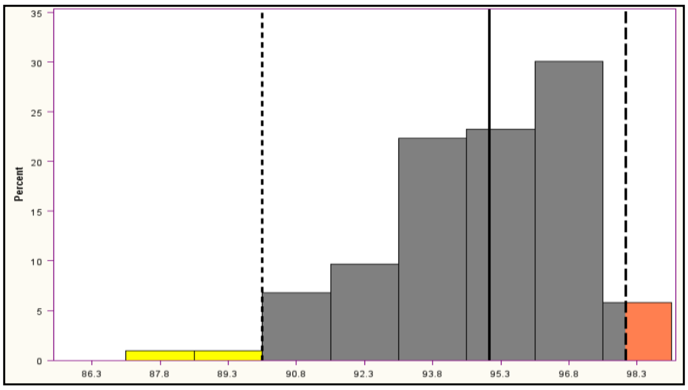


Figure 7-10 : Performance distribution of DC (B)

The retailer does not collect data for the ferries performance. The transportation manager has been asked to describe the ferries performance states. He has reported the following states to describe the weekly performance of ferries in shipping what the retailer is expecting them to ship.

Table 7-4: Ferries company performance states

Ferries company performance	S_1	S_2	S_3	S_4
	0% ->25%	25%->35%	35%- 50	>50%

The food moving between ports, the status of the supply, the performances of the DCs nodes are complementary nodes. Their states are prone to the lowest state of their parents. For example, if a supplier can fulfil 100 % of their orders but the 3PLs company can move only 83% from the orders to a DC. The status of the supply to a DC will be 83% although the supplier can fulfil the total number of orders.

The states of remaining discrete variables in the model are shown in Table 7-5. Ferries breakdown has four states. It denotes the breakdown of 0, 1,...,4 of the ferries. The storms and hurricane are assumed to be binary variables with two states.

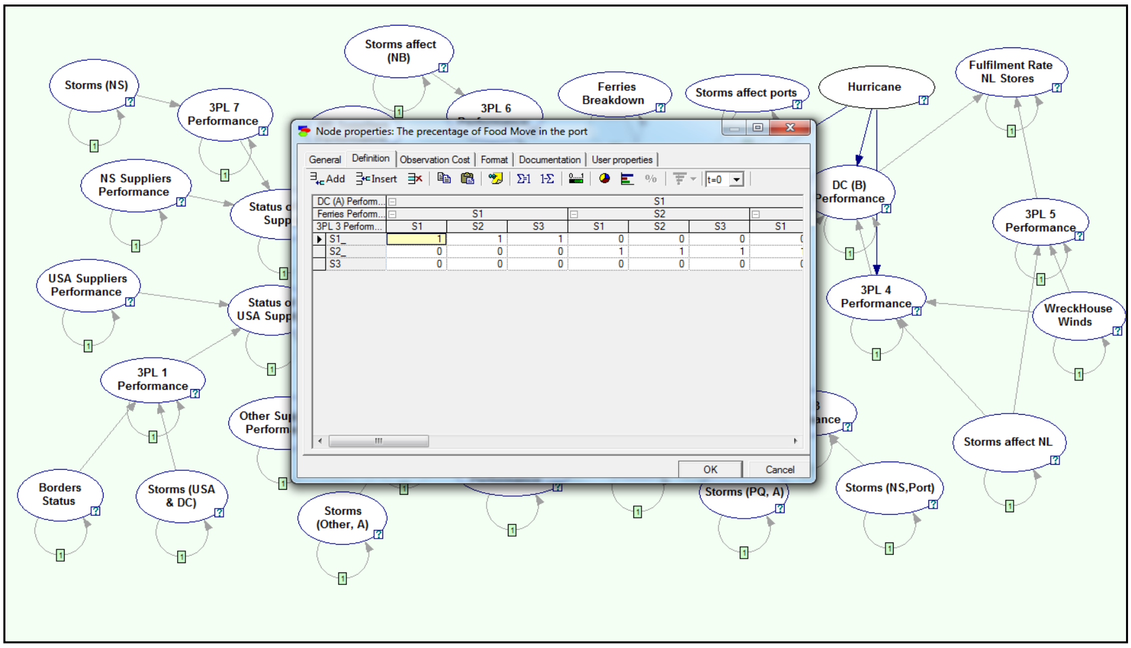
Table 7-5: The states of discrete variables in the model

Variable	**States**
Ferries breakdown	S_1 there is no ferry out of order. S_2: there is one ferry out of order. S_3: two ferries are out of order. S_4: three ferries are out of order. S_5: all four ferries are out of order.
Storms	True: there is a storm affects the performance of 3PLs or the ferries within one week. False: There is no storm affects the performance within one week.
Hurricane	True: there is a hurricane. False: There is no hurricane.

7.5.7 Assign Probabilities and Mathematical Relationships

The variables that represent the system in the first time interval are either parent variable such as the suppliers' performances or child node such as the variables that represent the DC performances. The parent nodes probabilities distributions are known from the data, which has been provided and used to describe the states of these variables through the discretization task. The child node variables that represent the SC system have complementary nature as I have stated above. In DBN, this complementary nature is quantified through the using of Boolean logic where 0 [1] denotes off [on] setting.

Figure 7-11 and Figure 7-12 shows the Boolean logic setting for the percentages of food moving between ports for time T0 and time T1.



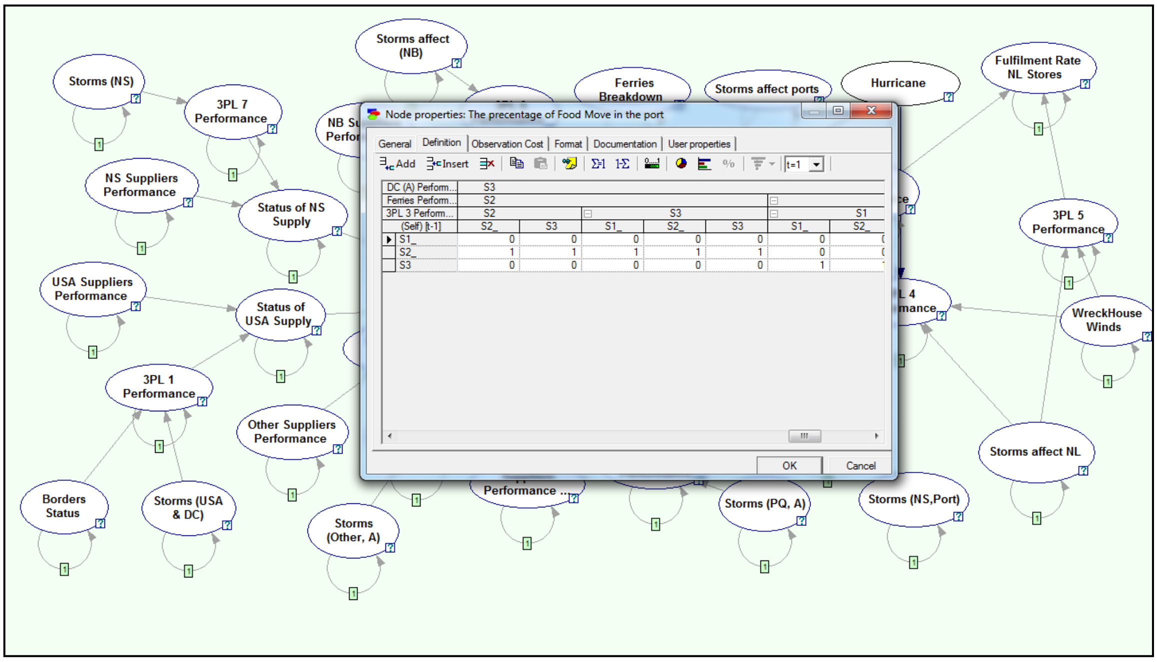
Node properties: The precentage of Food Move in the port

t=0

DC (A) Perform...	S1						
Ferries Perform...	S1			S2			
3PL 3 Perform...	S1	S2	S3	S1	S2	S3	S1
S1_	1	1	1	0	0	0	
S2_	0	0	0	1	1	1	
S3	0	0	0	0	0	0	

Figure 7-11: The conditional probability table example based on Boolean logic for T0

As can been noticed, the main difference between the conditional probability tables in Figure 7-11 and Figure 7-12 is that in the conditional probability table for T1 also depends on its state in the previous time interval. For variables that are affected by the hurricane, these feedback loops have a significant impact in understanding the recovery at the node level and consequently the recovery at the SC level. For example, if the ferries company has been affected by the hurricane the assumption is that their performance will be improved by 5% from its previous week state. It will, consequently, change the percentage of food that move between ports weekly.



Node properties: The precentage of Food Move in the port

DC (A) Perform...	S3						
Ferries Perform...	S2					⊟	
3PL 3 Perform...	S2		⊟ S3			⊟	S1
(Self) [t-1]	S2_	S3	S1_	S2_	S3	S1_	S2_
S1_	0	0	0	0	0	0	
S2_	1	1	1	1	1	0	
S3	0	0	0	0	0	1	

Figure 7-12: The conditional probability table example based on Boolean logic for T1

The variables that represent the hazards that might affect the performances of SC members such as the probability of storms to happen within a week between October and April was reasonably easy estimation for transportation manager who gives 0.5 for a storm to occur. If the storm occurs, the performance of the affected member will be in its lowest state. In the same hand, the probabilities of ferries breakdown have been assumed as 0.9 for Ferries breakdown to be in S1 and then 0.05, 0.03, 0.01, 0.01 for S2, S3, S4, S5 respectively to denote the low chance of all ferries to be out of order.

7.6 Resilience Analysis

The resilience analysis as has been explored in Chapter 2 has two stages. The first one is to understand the base behaviour of SC. Then, this behaviour will be investigated when a concerned hazard scenario is assumed to occur (resilience prediction). It is to scrutinise how the current SCs decision characteristics can maintain the same distribution of demand fulfilment in the stores and the recovery to this distribution.

7.6.1 SC Base Behaviour

Figure 7-13 shows the base behaviour at node and SC level. There is an uncertain stationary behaviour across the SC after the first time interval.

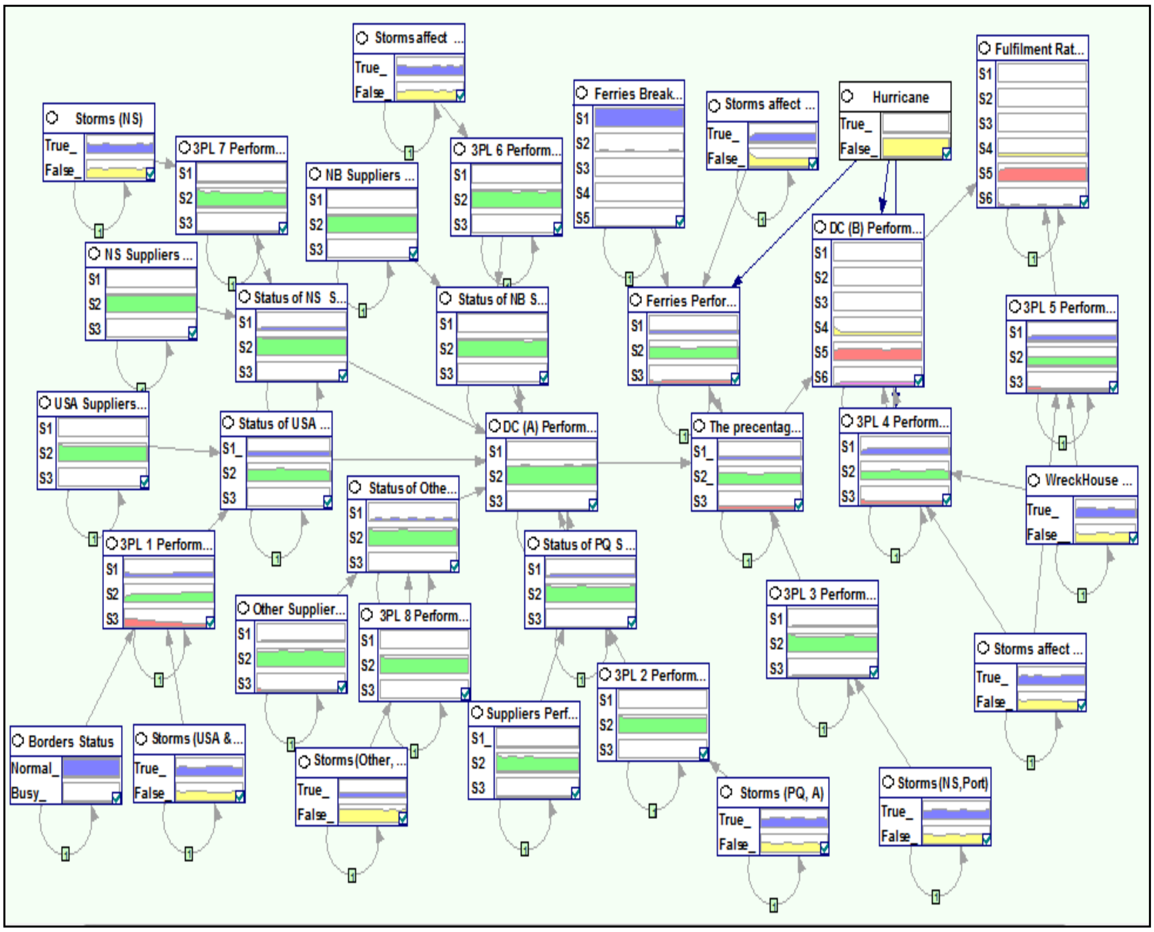


Figure 7-13: The base behaviour non-perishables food SC and its members

Figure 7-14 and Figure 7-15 are sample outputs of DBN for multiple weeks, which are labelled T1, T2 and so on. DBN produces almost same stationary uncertain behaviour after T1. Thus, extra time intervals will not add any value to the analysis if there are no adjustments in the model parameters through the time. The uncertain stationary behaviour is expected due to homogenous causalities and parameters through the time.

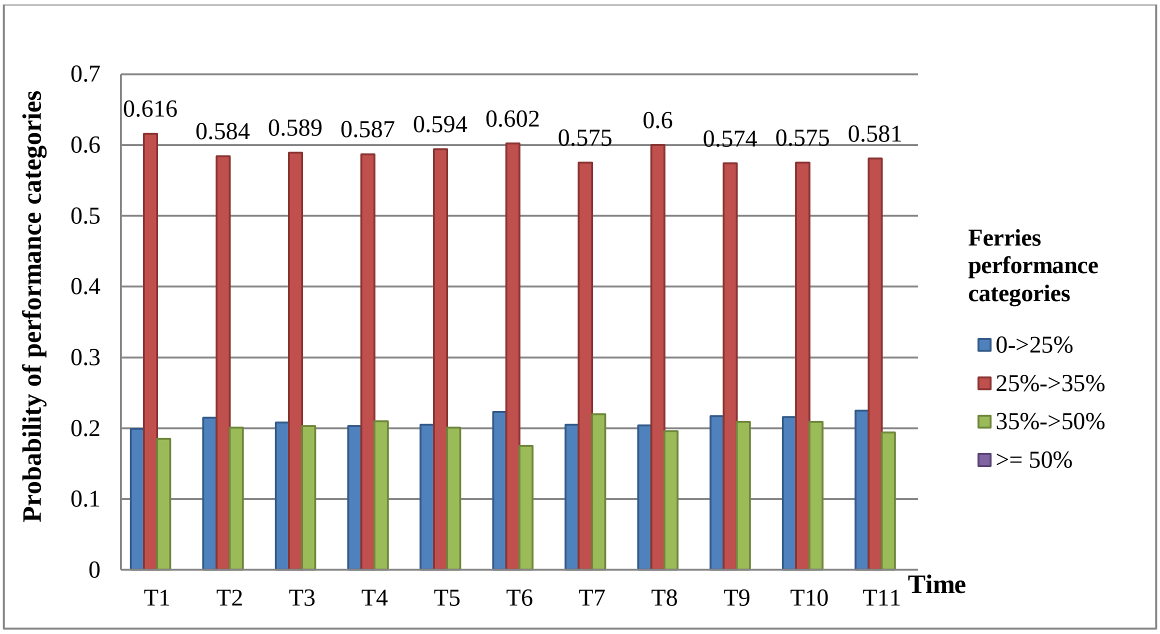


Figure 7-14: Ferries performances states (DBN output)

As can be seen, the base behaviour of Ferries (Figure 7-14) is consistent through the time. From 57% to 60% of the time, they can move around a third of company required goods. Although this variable is a child node in the model, it captures the expectation of transportation manager about the ferries company performance. The transportation manager state that there is a tendency that the ferries company performance to be between 25% to >35%. The latter point will be considered for validation purpose of the DBN prediction.

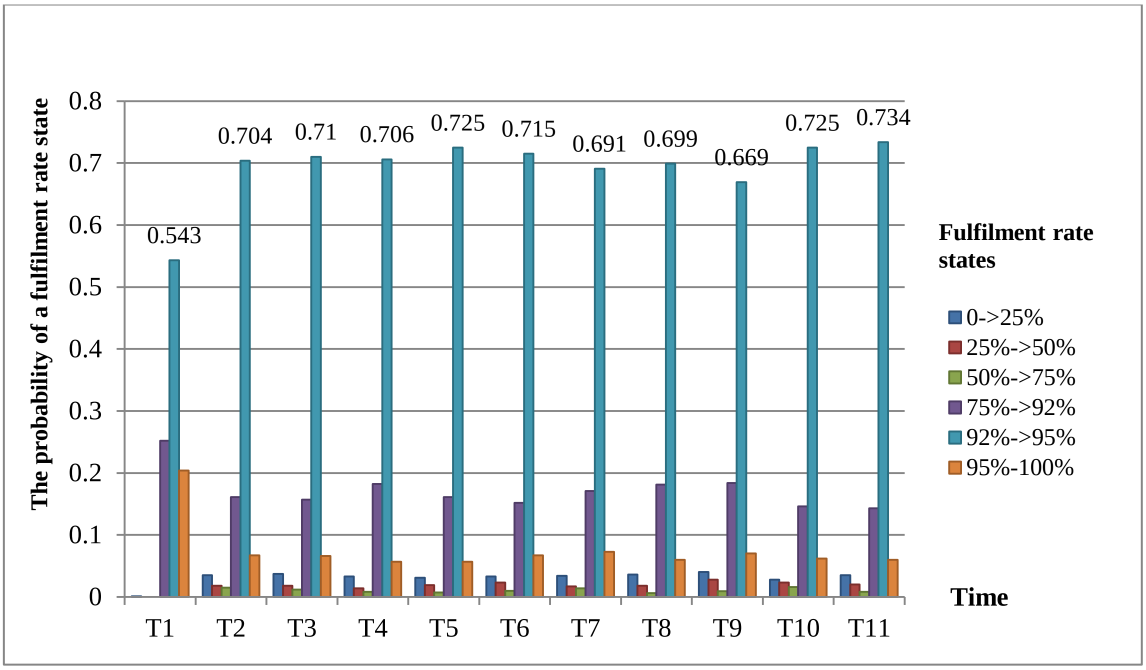


Figure 7-15: The non-perishable food fulfilment rate states in Newfoundland stores (DBN output)

Likewise, if the end point of the supply chain has been studied, the Newfoundland stores, their performance shows an uncertain stationary behaviour during the time (Figure 7-15). There is about 70% chance that they will be able to fulfil 92->95% of their supply. However, this means from the company perspective that the opportunity to meet their stated target is only about 6%. The prediction of DBN, in this case, is consistent the expectation about the behaviour of SC. Recall Figure 7-10 where the majority of the observations for DC (B) is below 95%. The fulfilment rate in the stores is directly influenced by the performance of DC (B) considering the conditional independence property of other variables in the SC.

7.6.2 Resilience Prediction Based on a Hurricane Scenario

The behaviour of non-perishables food supply chain in reaction to hurricane occurrence is shown in Figure 7-16. The influence of hurricane on non-perishables food SC would be observed for an extended period until the company figures out what actions can work to recover from the situation. It is because the company does not have currently a plan to maintain the resilience of the SCs. Similarly for the chickens SC, the company will lose their ability to fulfil the demand for an extended period. The contrasting nature of the two examples SCs shows different effects. For example, the hurricane is likely to influence other retailers (the company and their competitors) in Newfoundland. So, Newfoundland will be affected by a loss of supply for non-perishable food products, but the mainland will not be significantly harmed by the loss of supply for fresh chickens because other competitors can cover at least part from the missing supply.

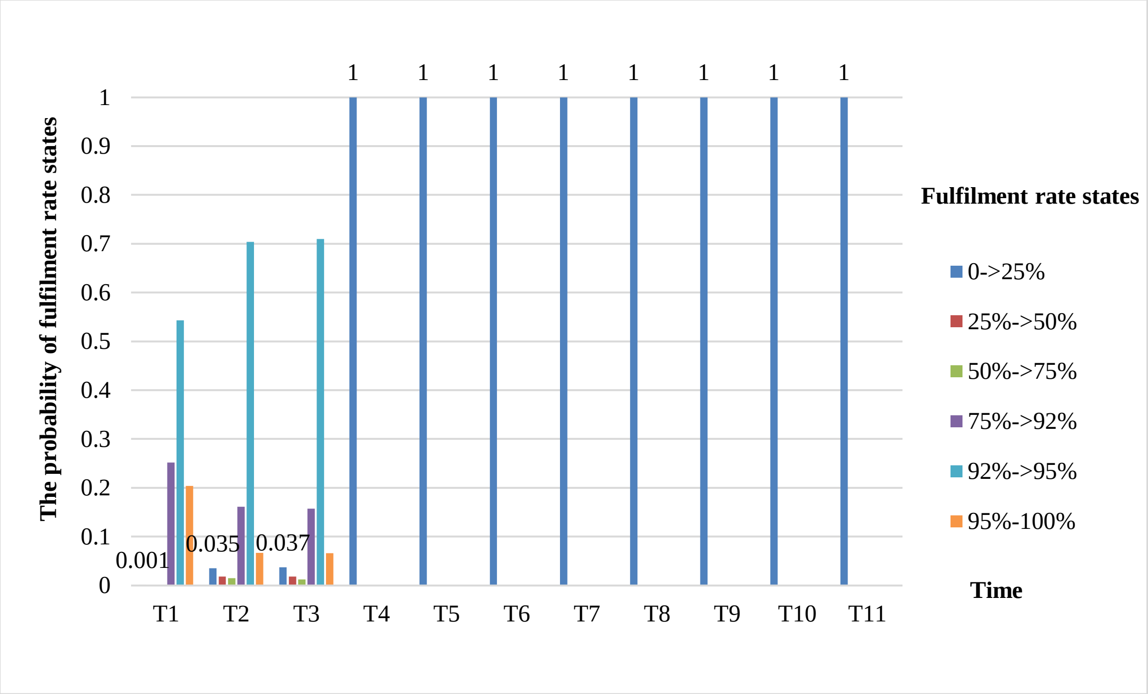


Figure 7-16: The expected fulfilment rate states based on the current supply chain design

Figure 7-17 displays another scenario where the retailer can have proactive plans for non-perishables SC such as air shipment to stores, quick recovery for DC (B). This is beside the actions of the government to rectify the affected infrastructure. The conditional probability tables, in this case, needs to be modified to reflect the consequence of actions on the recovery of the SC with taking into account the state of a variable in a previous time interval. The hurricane is assumed to occur at week 4. Immediately the fulfilment rate drops to 0 % but in week five it moves to 25% to > 50% class and not to zero. It is due to the assumed supply via air shipments. The other mitigating actions such as recovery of critical infrastructure and DC (B), then, start to take effect. The supply chain needs almost five weeks to overcome the impact of the hurricane on this case.

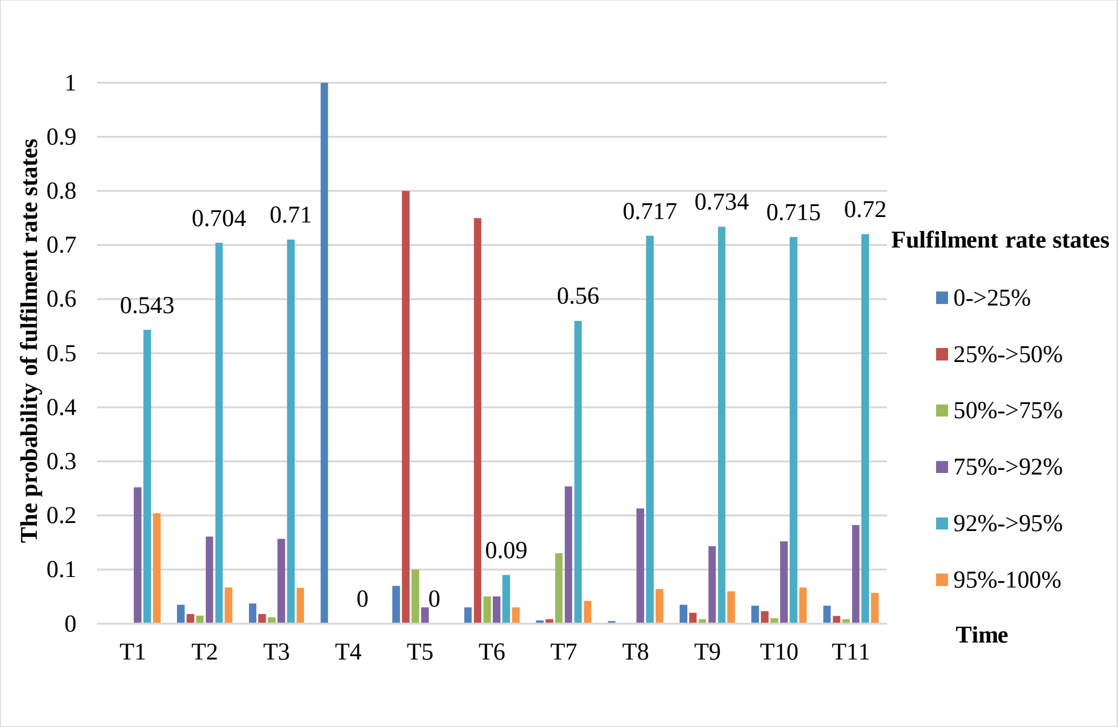


Figure 7-17: The expected fulfilment rate states with assumed mitigation actions

7.6.3 Resilience Triangles and Economic Loss

Recall Figure 7-13, Figure 7-14, Figure 7-15, it can be noticed that there is no one total quality state as the one has been revealed by Bruneau, *et al.* (2003), Bruneau and Reinhorn (2007) for infrastructure. All mentioned figures show the uncertain behaviour at a node and a network level. It means that there is no total quality state for the supply chain as in the previous cases. Instead, there are many states with their probabilities to happen through the time are varied. For instance, the probability of fulfilment rate to be between "92% and > 95% " is 0.7 before the occurrence of a hurricane. It shows that there is 70% chance that SC is able or have the resources to meet "92% to > 95%" from its demand. This chance changed to be 0 during the occurrence of the hurricane. Then, after five weeks the SC recovers back to its normal level before the occurrence of the hurricane.

One way of capturing the resilience triangle for this case can be through the check of the probabilities (chances) for the discretized states through the time (Figure 7-18.). In this way, the vertical axis will show the probabilities for a particular state through the time instead of the total quality. Apparently, it illustrates the ability of the supply chain or one of its nodes to maintain the probability of a desirable state and the recovery time to this ability.

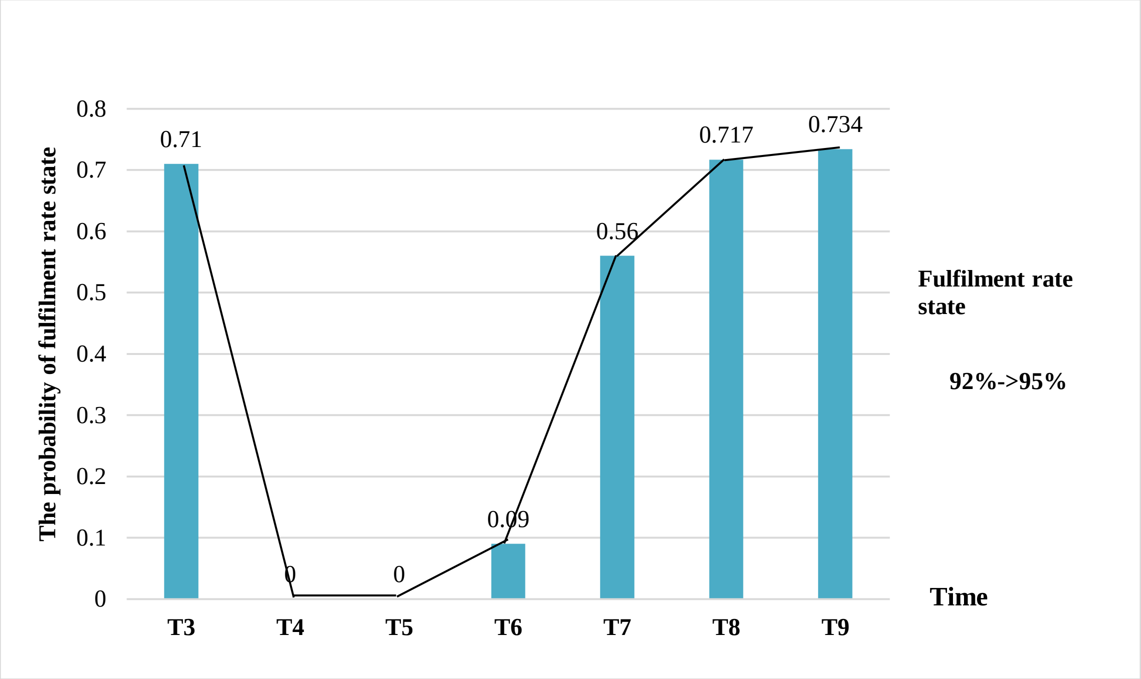


Figure 7-18: The probabilities change for fulfilment rate (state: 92% -.95%) as indication of the resilience triangle

The economic loss, in this case, has no practical meaning due to the use of fulfilment rate and not the actual flow. For example, if the planned fulfilment rate was 95% and the actual was 93%, there will be a 2% difference in the fulfilment rate. Consider the meaning of the fulfilment rate in this case as the percentage of the satisfied demand to the number of units has needed. The 2% difference can be 100 units or can be 3000. It raises a question about the meaning of such resilience index in terms of SC. I can argue the fulfilment rates can be used only as an indicator of the SC ability to maintain them and the time to recover. The economic and financial loss might be better understood actual material flow to represent the SC system as I have seen in the last two chapters.

7.7 Building Confidence in Case Study and the Model Results

The internal validity has been achieved through collecting data from:

1. Interviewing transportation manager, purchasing manager and three vice president from the board
2. Access to the company service level reports
3. Access to the company hard datasets
4. Collect secondary data from the Environment Canada and the ferries company websites

These data sources have played a collective role to understand the hazards and to populate the model.

7.7.1 Model Validation for Non-Perishable SC

The validation of the model to this case study has focused on ensuring that the DBN satisfies the conditional independence property, gather feedback on the model structure, check if the model produces a realistic behaviour and conduct the sensitivity analysis.

The satisfying of the conditional independence has been ensured by the modeller through the analysis of the interviews and the data from the company documents. Recall Figure 7-9 that dispenses the DBN structure. As can been noticed, the third party logistics performances and storms have appeared several times in the model structure as different variables. The reason behind this presentation is that performance of 3PLs in shipping the materials between two nodes can be affected by a particular geographical zone, although the same company owns all trucks. Their performances have been judged with the regard to a particular route. Likewise, the storms have been viewed from a particular road perspective. A storm can hit a particular geographical zone and not others.

To validate that I have captured a correct model structure, the interviewees have been placed in the centre of the modelling process. The model variables have described to them (decision makers) to confirm that they understand why different nodes described the performances of 3PLs. I have asked their feedback about that the model structure. The interviewees have removed from non-perishable food SC model one variable that represents the DC (C) performance and all variables that have casual relation with this variable.

The model behaviour has been validated through ensuring that the model produces a realistic behaviour which is according to Chong and Brown (2000) a sign of the model usefulness. Recall Figure 7-14 and Figure 7-15. The base behaviour of the model has been compared with the available datasets about the fulfilment rate in the stores as the end point of the SC. Similarly, the other variables that have available datasets such as the DCs' performances have been checked against its available data. For some model variables that there is no data about them such as the ferries performance, the transportation manager has been asked to comment on the behaviour of the ferries company. However, this behaviour cannot be further validated due to lack of data and communication with the ferries company.

The sensitivity analysis to extreme values has been examined. Figure 7-19 shows variables that have a high influence on the fulfilment rate by a red colour. The results indicate how the uncertainties propagate in the model to impact the fulfilment rate. For example, the status of supply from the USA have a high influence on the fulfilment rate in NL stores. Such results show the tight connection in the SC performance. The consequences of an adverse event hit the supply in the USA (a node level) can lead to an inability to meet customer demand at NL (SC Level). From these results, it can be said that there is a clear sign that the current characteristics of SC are not able to absorb the consequences of the adverse events. This point will explore further to inspect how the impact of level of integration can be understood through the model (Section 7.7.2.2.1).

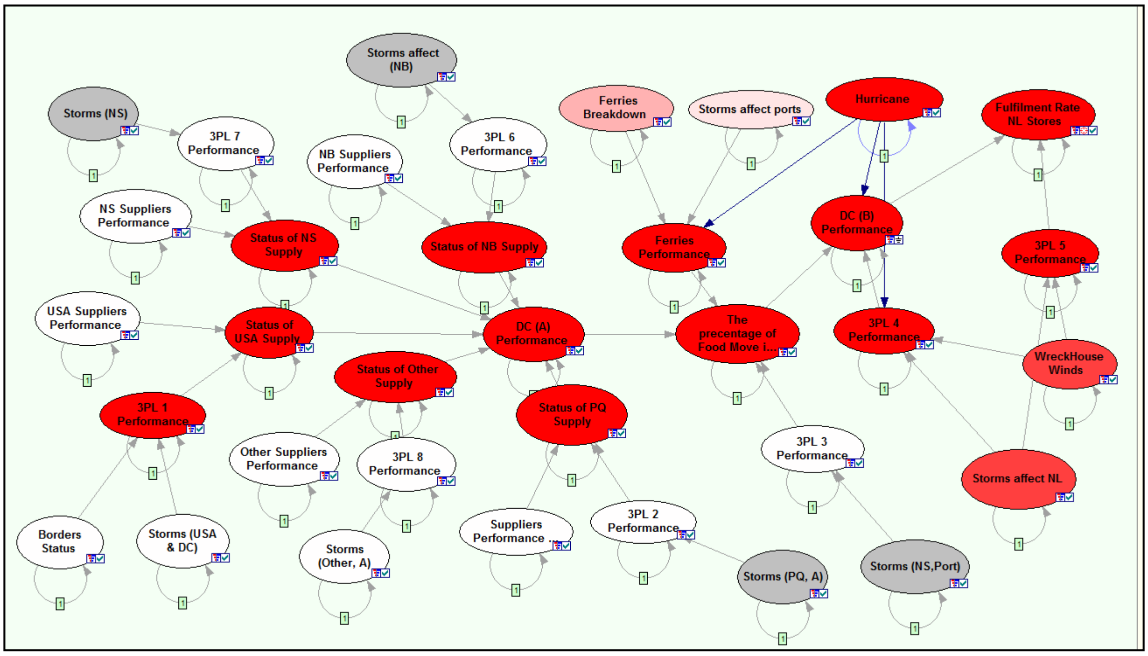


Figure 7-19: Sensitivity analysis results

7.7.2 Model Usefulness Based on Food SCs Characteristics

To draw some observations about the usefulness of the model to understand SC resilience I will discuss how the model capture the resilience and how the model process reveal the impact of some SC characteristics on the resilience analysis.

7.7.2.1 Capturing SC Resilience in Conjunction with SC Decisions Characteristics

DBN has captured the ability of non-perishable food SC to react and how long it needs to recover based on the understanding of the current base behaviour. The process to build the model for this case reveals that the fulfilment rate of the demand is the main index to understand the ability of the SC to react and recover. While Jüttner *et al.* (2003a) argue that the supply chain risk is the possibility and effect of mismatch between the demand and supply, for this case the consequences of event occurrence are the inability to meet demand. It results in not only financial implications but also affects the public food availability at the macro level.

On the other hand, the model process for chickens SC has identified the vulnerabilities, hazards and the causalities in the SC system. However, I could not quantify the model due to a different time length of how a node performance in supplying what they should supply can be assessed. For example, the poultry farms and hatchery performance cannot be assessed by weekly performance matrix that the company used because they usually supply all the chickens which are at a particular age to the packer. Similarly, for the packer, which provides the entire ready chickens that, they have to the DC (C). Therefore, there is no role the information at this stage can play to capture the reaction of SC members to the orders. This problem can be common in all extended integrated SCs due to different lead times at each tier of the network. Therefore, the main learning point from this case is to focus on the material flow to quantify the model due to the more flexible time space specification. The latter feedback has been considered as a pillar for the tubes and spare parts SCs modelling.

7.7.2.2 Food SC Characteristics and the Resilience Modelling

7.7.2.2.1 SC Integration and Visibility

The non-perishable food SC has a low integration level with a limited span as well. The limited integration span has an apparent effect on the visibility to and collaboration with other members of SC. It has limited the identified known structure of SC to only direct suppliers. It also impacts the identification of the vulnerabilities and hazards. Consequently, they affect the scope of the model and source of data to quantify the model. For example, I had to consider the retailer opinion in the performance of ferries due to inability to find out the ferry company views (the ferries company has been contacted several times with no reply from their side). Although Garvey *et al.* (2015); Kim *et al.* (2015) models' prerequisite is to identify the whole SC structure for analysing the risk and resilience, the current cases show that such visibility needs high vertical integration level. Also for Garvey *et al.* (2015) work the dealing with full SC structure can make BBN computationally intractable due to the complexity in eliciting BBN, quantifying its relations and running the inference. The inability of identifying the whole SC structure does not necessarily mean a paralysation to its power to produce a realistic output as I discussed in the validation section.

On the other hand, the little visibility about the hazards that might other members face could lead to significant consequences on the retailer ability to meet the demand in NL stores. As has been shown in the sensitivity analysis results, the current SC design can lead to the propagation of consequences through the SC despite the low level of integration. So, the low integration level does not mean small dependency in the SC. The dependency can be related to other factors such as the number of suppliers for the same product and if a SC member is critical or not. The output of DBN modelling shows that dependency between SC members can be still high and lead to snowball effect despite the low integration level. Thus, the focus to understand the resilience for non-perishable food SC is not only through how intensive is the degree of integration that mentioned by Jüttner *et al.* (2003b); Świerczek (2013) but also the impact of this integration on the dependency in the network.

This above relationship also should drive the discussion about the conventional value of the collaboration that has been adopted by Christopher and Peck (2004); Christopher and Peck (2003); Pettit (2008); Pettit *et al.* (2013); Pettit *et al.* (2010); Simchi-Levi (2010); Waters (2007). Although such collaboration might lead to identifying some hazards and avoid overreaction, it can also increase the dependencies in the SC and might lead to snowball consequences. It can be confirmed by the observations from the chickens SC where the collaboration level is at the highest level due to the fully-integrated structure. The fully-integrated structure steers that the retailer depends heavily on its chickens SC members. Thus, any disruption in the chickens SC could be more severe on the retailer ability to meet demand. It also affects them if there is extra supply because they need to freeze the chickens. It emphasises again on that the consideration should be devoted to the degree of dependency between SC members that the high collaboration level can create and what its consequences.

In a summary of this case study, while the integration level impacts the scope of DBN due to the visibility level, the DBN helps to recognise the dependency in the SC. The latter can be a factor to evaluate how the level of integration and collaboration absorbs or amplifies the consequences of hazard occurrence and the recovery from that consequences.

7.7.2.2.2 SC Operating System

In addition to the clear impact of the push and pull operating system on the level of the slack in the SC that has been discussed in chapter 1, this case study shows the impact of the operating system on forming DBN. The controlled pull operating system for non-perishable food SC assists in identifying a consistent time unit for the DBN intervals. These consistent intervals are based on the uniform performance matrix that the retail used for the non-perishable food SC. However, the push system regarding the production cycle of chickens SC means that once the chickens flow is scheduled, they cannot be modified. The latter has raised a problem about the suitable time interval to represent the base behaviour of the chickens supply chain.

The performance of chickens poultry, hatchery and mills cannot be represented by the defined performance matrix of the company. The defined matrix is built using weekly intervals, whereas the chickens' production cycles fluctuate. The production cycles members performances cannot also be represented by the percentage of the number of units they can provide to the number of orders. The role of information is negligible in this case. Therefore, the weekly performance matrix is unrealistic for upstream activities of the chickens SC whereas this matrix is still valid for the 3PLs, ferries and DCs. This problem is reflected by an inability to quantify DBN for the chickens SC based on the identified hazards, vulnerabilities and the factors to understand the consequences. The lesson from this case is to shape the DBN around the actual uncertain material flow. Thus, at any time interval, we would be able to understand the distribution of materials from upstream members and the distribution of how many units the 3PLs can deliver at the same interval. The latter observation calls for more data to be calculated in this case study which I was not able to do because of the timeline of the case. However, I have been able to do it for other cases as we have seen in the previous two chapters.

7.7.2.2.3 SC Structural Configuration

As it has been pointed out, the knowing structure of SC has aided in identifying the hazards and vulnerabilities in SC. In addition to that, the understanding of SC structure and the relationships between the SC members have played two other significant roles from a resilience modelling perspective. These are the identification of causalities in DBN and building the conditional probabilities tables. The causalities have been identified through the recognition of dependencies in SC structure. For example, the multiple dyadic relationships between DC (A) and its suppliers and the 3PLs are indicators that the performances of these suppliers and 3PLs are causes of the realisation of a particular DC (A) performance. Similarly, for the performance of DC (B) is related to the food that moves from the port and the performance of 3PLs that deliver the food from the port to the DC (B). Regarding building conditional probabilities tables, the investigation about the SC members whether they are complementary or alternative illuminates the idea of using Boolean logic in the conditional probabilities tables that reduce the burden of eliciting these tables for the expert. The complementary nodes type, for this case, indicates that the state of a child node in the model tends to take the lower state of its parent.

7.8 Key Insights and Concluding Remarks

Overall, the application of DBN for the food supply chains resilience in Atlantic Canada considers identifying different hazards sources that might have an impact on the chickens and non-perishable food SC based on their structure. It is a similar approach to the way Garvey *et al.* (2015), Kim *et al.* (2015) have theoretically built their models around, although this case study had conducted two years before the publication of these papers. The framing of DBN for this case has mainly based on variables that represent each the performance of each SC members in the known structure of SC. I have shown through this case study that there is impeded difficulty in identifying the structure of the SC from the source to shape the model as it has been argued by Garvey *et al.* (2015). In addition, the full SC structure can make BBN/DBN computationally intractable due to complexity in quantifying its relations and run the inference. Therefore, the uncertainty modelling should focus more on variables that can show the system behaviour and the known structure can be used to understand some dependency issues as in the tubes case where the supply from each supplier have to be presented individually to understand their business continuity impact on the system. Table 7-6 and Table 7-7 exemplify some key insights that have been gained in terms of the influence of SC characteristics on the resilience and DBN process.

Table 7-6: Key insights on the impact of food SCs characteristics on its resilience

Factor	Insights
Intensity of integration and the dependency	The dependency between SC members is high and leads to snowball effect due to the use of one supplier per good.
Operating system	Low level of slack, so the reaction of the SC is based on the ability to obtain food on time.
Visibility and span of integration	a) The non-perishable food SC has a limited integration span. This has an apparent effect on the visibility to and collaboration with other members of SC. It has limited the identified known structure of SC and the identification of the hazards and vulnerabilities, b) Chickens SC is fully integrated that leads to identifying the SC from source.
SC structural configuration	The presence of infrastructure led to a single point to move the goods.

Table 7-7: Key insights on the lessons learned about DBNs modelling process for food SCs

Factor	Insights
DBN scope	The focus on the structural representation of the model leads to include all supplies locations and transportation routes.
Qualitative structure	The multiple dyadic relationships between DC and its suppliers and the 3PLs are indicators that the performances of these suppliers and 3PLs are causes of the realisation of a particular DC performance.
Quantification	a) The controlled pull operating system for non-perishable food SC assists in identifying a consistent time unit for the DBN intervals. These consistent intervals are based on the uniform performance matrix that the retail used for the non-perishable food SC, b) The complementary nature of the supply and transportation process help to use the Boolean Logic for shaping the conditional probabilities distributions, c) The push system regarding the production cycle of chickens SC means that once the chickens flow is scheduled, they cannot be modified. The latter has raised a problem about the suitable time interval to represent the base behaviour of the chickens supply chain (The role of information is negligible in this case), d) The inability to quantify the model for chickens SC due to different time intervals.
Discretization	Heuristic discretization has been used for continuous variables due to the interest of decision makers in particular states. The dynamic discretization can show more than 20 states for a very tight range of variables (10%).
DBN Output representation	I focus on the change of probabilities of particular fulfilment rate states in order to understand resilience.

8 Cross-Case Analysis

8.1 Introduction

This chapter is mainly devoted to drawing cross-case analysis between the previous four case studies to deepening the understanding of the issues that have been raised in each case study. The cross-case analysis will focus on the four main points that have been mentioned in Chapter 4 (i.e. DBN role in informing SC resilience analysis, lessones about DBN process to analyse SC resilience, the impact of SCs characteristics on SCs resilience, Terminology refinement).

8.2 The Role of DBN in Informing the Resilience Analysis

During the previous three chapters, the ability of DBN to support the analysis of the resilience based on different problems have been explored. I have illustrated how DBNs can be considered to evaluate the suppliers based on their business continuity, managing spare parts uncertainties based on an interdependent view to support After-Sales agreement and maintaining the food supply in Atlantic in the presence of infrastructure operations problem. The shaping of DBNs for these problems have taken into account how their SC characteristics affect their resilience and how they contribute to the model construction. Table 8-1 revisits the factors that have shown in Table 3-1. I have indicated in Table 3-1 some factors about how complexity theory models contribute to the resilience analysis. While the latter models assume the visibility to the whole system, DBNs are more focus in supporting the analysis of SC resilience to a particular problem that the focal firm is countering. It means that the boundaries of DBNs are attached to the ability to obtain knowledge about the situation from different sources (data, expert, etc.). It is with taking into account the characteristics of SC and how these characteristics affect the resilience analysis. Although some complexity theory models can provide a simple standard way in understanding some SC resilience index, this would be at the cost of losing some important factors. The complexity theory models do not consider the variation in the material flows based on the information and the ordering strategy, the uncertainty around the flow and the uncertainty around the impact of the hazards occurrence and its early warning factors. It also does not consider supporting particular decisions to enhance the resilience.

Table 8-1: Factors that can help to evaluate the role of DBN in informing the resilience analysis based on the case studies outputs

Factor	**DBN**	**Models that consider SC as a complex system**
Deal with interdependencies (Dependency level)	It shows the dependencies between two variables through the conditional probabilities distribution.	It illustrates the dependencies by understanding the ratio of the output of the member to the input of other members.
Understanding the impact of SC structure	The structure of SC can be taken into consideration using DBN through the introduction of variables that represent the different SC members and their links to others. However, It suggests the more members, the more complex is the model. It is due to more burden in generating the conditional probability tables and joint distributions.	This provides a less complex way to deal with structure through a direct computation. So end to end SC can be modelled.
Show the impact of some decision rules in triggering the flow (operating system)	It provides an uncertain view of the material flow, so the role of information and decisions in triggering the material flow can be considered through the uncertain non-deterministic relationships.	A deterministic view of the material flow, so the information plays no role across the time intervals.
Deal with the uncertainty	The flow of the material from each member are represented by distributions as well the impact of adverse events on the material flow.	No
Understanding the recovery	Understand the recovery curve and time through the output of the model, so there is no need for prior assumptions.	Deal with Recovery functions, so there should be assumptions about the time to recover and how the recovery curve are going to be.
Decisions support tool	DBN explores the analysis of resilience to a particular problem and support decisions about this problem.	A standard way that does not intend to study the specific issue from a decision maker perspective.
Time unit specification	In both models, it stems from how the outputs of SC are understood before the adverse events (daily, weekly, monthly). However, in the use of complex system models to the economy is also stem from the time to recovery, which must be specified in advance to use the recovery functions. It is not realistic to consider the time unit monthly while the total time to recover can be one week or two.	
Factors that contribute to hazard scenario	Early warning factors can be used to understand the hazard scenario probability of occurrence.	No consideration of such factor.
The impact of adverse events	It considers through the uncertain epistemic relationships between the hazard states and the output of the affected member.	It considers the deterministic value about the initial impact of adverse events occurrence on the output of the affected SC members and the type of the recovery function (k_i^t).

The latter issues are tackled using DBN. On the other hand, I have shown in chapter 7 that the analysis of an extended type of SCs with many members based on a structural view of the network can lead to a complex DBN. It is why in Atlantic Canada case study some variables that collectively represent the performance of different suppliers from one location (e.g. the status of supply) have introduced.

8.3 Lessons Learned about DBN Process to Analyse the SCs Resilience Considering their Characteristics

In this section, I explore the process to build DBN based on the cross-case analysis and how this process is influenced by the SC characteristics, the selection of time element and discretization methods.

8.3.1 DBN Scope

The clear defined scope of DBN, as has been mentioned in chapter 3, is imperative due to the burden of the data collection and elicitation of the model. During within case analysis, it should have been explicit that the DBN scope is influenced by the concerned SC problem that the resilience needs to be analysed against it, the identified SC structure and the visibility to this structure.

The concerned SC problem affects the boundary of the DBN due to the interest of case study holder in figuring out their impacts on the processes of SC and the ability to maintain base behaviour of SC. It directs DBN scope to SC members and variables that contribute to understanding the propagations and consequences of this problem. For example, in tubes SC, the chief concern is to evaluate the business continuity of the suppliers in the market and the resilience of tubes SC to that. This problem has led that there is no need to include variables that represent the transportation in the model. In contrast, in the Atlantic Canada SCs, the performances of 3PLs have been vital to recognise the base behaviour of SCs and how the hazard scenario affects the SC. In the pipe coating case study, the lumpy demand of the spare parts has led to including the internal processes of the focal firm to understand the base behaviour of the SCs and how the flood might affect this behaviour with consideration to the capacities of the single point of the supply.

The scope of DBN is also controlled by the identified structure of the SC and the visibility to this structure. The visibility and the extended identification of SC structure could lead to better identifications of some variables that can trigger the problem or understand its consequences. For example, in tubes SC, the ability to collect data about the suppliers' facilities locations ensured that the focal firm understands the impact of an environmental hazard on the supplier business continuity. Similarly, the visibility to some financial indicators draws a direction about the ability to contain these variables within the model scope. However, the raw material suppliers of the first tier suppliers have not been identified. Their identification could have given a better estimation of the business continuity of the suppliers because it leads to learning the dependency between the suppliers and their raw material suppliers. In the other hand, the identified structure of the non-perishable food includes many stages from the suppliers to the store as sink node from the downstream. While the identification of many stages of SC leads to a better understanding of the effect of the hazards and the dependencies in the SC, the complexity of the supply chain structure has steered to a higher burden in the quantification of the DBN. The modeller using DBN should be aware of the impact of the SC complexity when the scope of DBN is to be declared. Therefore, the structure method that Garvey *et al.* (2015) propose to build the BBN to analyse SC risk should be revisited because of two main reasons. First one, the difficulty in identifying the whole SC structure from a practical point of view. Secondly, the quantification of BBN will be cumbersome.

8.3.2 DBN Qualitative Structure

The DBN qualitative structure is concerned about the identification of variables and the relationships between them in a way that assist in understanding the SC resilience against a particular problem. While the determination of the variables and the relationships between them vary from the use of the expert and the data in the literature of DBN and BBN (Chapter 3), the construction of DBN to understand SC resilience can stem partially from SC system and structure. Then, the qualitative structure can be completed through identifying where the hazards can hit and the validating of model structure. Figure 8-1 explain the factors that affect the structure building of DBNs to understand SC resilience.

The known structure of the SC represents explicit relationships between the supply chain members. The causalities within DBN can be defined based on these relationships. For example, in the Atlantic Canada SCs, the understanding of the SCs structure have guided the structure of DBN to understand the base behaviour of the SCs through considering the dependency between a DC performance, for example, and the performances of the supply chain members that feed this DC. The structure of the tubes SC assists in identifying the supply sources of the inventory and lead to consider the supply from these suppliers in the model structure. The internal structure of SCs in the pipe coating case has served to comprehend the causalities between the demand for spare parts and the production from a process. It also shows the common suppliers for some specialised spare parts.

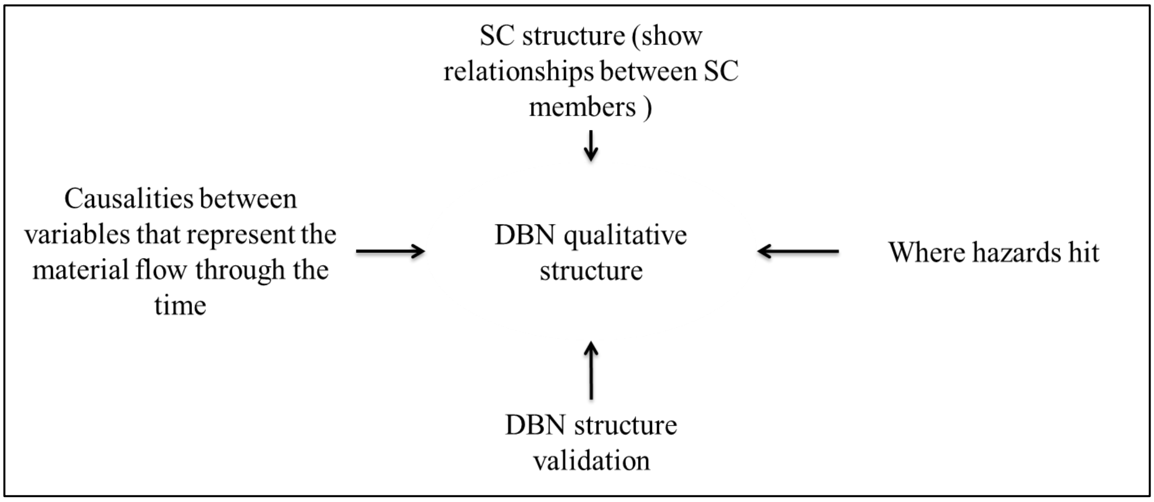


Figure 8-1: Factors that assist in forming the qualitative structure of DBN for SC resilience

Likewise, the variables that represent the flow of the material in the SC have helped in structuring DBN to understand the resilience of a SC. In tubes and pipe coating spare parts SCs, these variables revolve around the supply from the suppliers, the inventory level, the remaining inventory, the replenishment quantity and the demand. These variables have intuitive causalities between them. While the supplies feed in the inventory level, the demand leads to a reduction in this level. Then, the remaining inventory level at each stage affects the level of inventory in the next time interval. The replenishment quantity is influenced by the remaining inventory level and triggers the supply in the next time interval.

Once the relationships between the above variables have been considered "within and across the time intervals" in a way that aids to predict the SC resilience to a particular problem, the DBN structure can be validated through ensuring the conditional independence and feedback from the participants as I discussed in each case study separately.

8.3.3 Time Element Description

The depiction of time element is an intrinsic property to build DBNs as has been mentioned in chapter 3. However, the current literature in DBN as can be noticed in (Ghahramani, 2001; Mihajlovic, Petkovic, 2001; Oliver, Horvitz, 2005) more focus on learning DBN from the datasets where there is no guidance about how the time element can be defined. Through the case studies for this research, it emerges that three factors should be taken into consideration to understand the time-space in the model. These are the time intervals, the time window and the interaction time point. The time intervals are for variables that contribute to understanding the behaviour of SC before and after the hazard scenario occurrence. The time window is of the early warning factors that help to understand the chance of hazard scenario to occur. The interaction time point shows when the hazard scenario hits the SC system to comprehend the resilience. Figure 8-2 visualise the relationships related to the time description of DBNs.

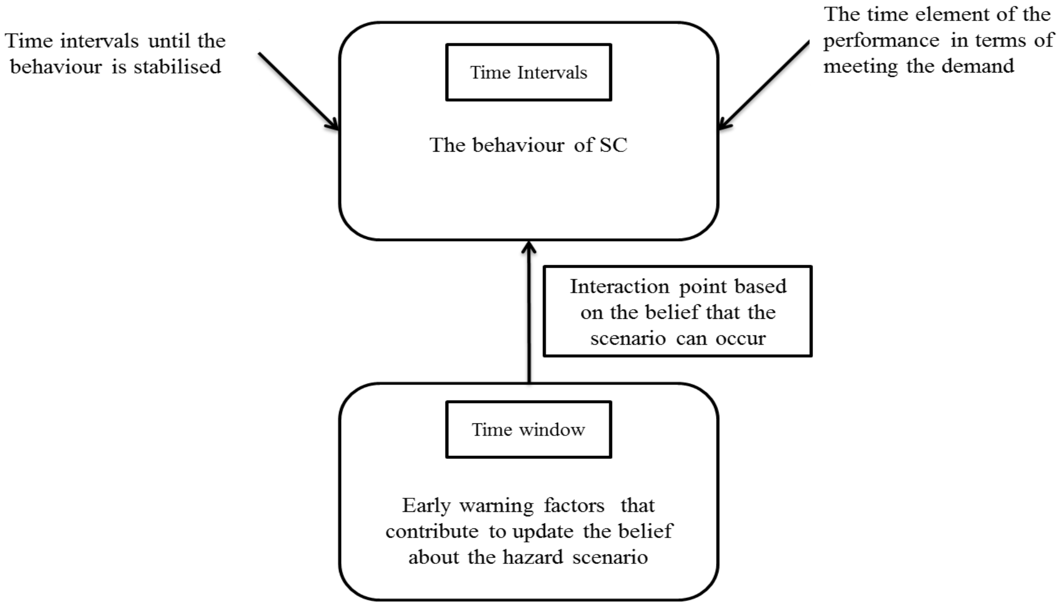


Figure 8-2: Factors that influence DBN time element to understand SC resilience

The time intervals to represent the behaviour of SC before and after the hazard occurrence has stemmed from the time space that the focal firm uses to understand their performances in meeting the demand and the time to recovery. In Atlantic Canada non-perishable food SC, the performance in meeting the demand has been considered based on weekly time intervals. Therefore, weekly time intervals have been used to understand the resilience of the SC in maintaining their base behaviour and the recovery to this behaviour. Likewise, one month time intervals have been employed to represent the dynamicity in tubes SC due to the firm concern about their shortages chance within one month time. However, for pipe coating spare parts SCs, the definition of the time intervals have considered with relation to the production due to the influence shortages on the downtime of the processes.

The other point about the time intervals is that the number of time intervals should be considered to understand the behaviour of SC before and after the adverse event occurrence. To answer this question, we should ponder what the model is going to represent and if there might be a change of the model parameters through the time. In the first case when there are no variations in the model parameters through the time, the model will produce almost stationary uncertain behaviour after the second time interval as we have seen for the conducted case studies. Thus, extra time intervals will not add any value to the analysis of the SC behaviour. Similarly, for the case when the SC response is examined against a hazard scenario. The main aim is to investigate the number of intervals that the SC takes to recover to its uncertain stationary behaviour. The number of time intervals is determined by the recovery to the base state before the event occurrence. While in Atlantic Canada case study, it takes up to five weeks for the behaviour to stabilise, in tubes and spare parts SCs case studies the behaviour has taken almost two months to bounce back to its steady state.

In an exceptional case when the dependencies over the time change (nonhomogeneous DBN), the model parameters need to be adjusted over the time. For example, an adverse event hits a supplier in a particular week with the secondary suppliers need two weeks lead time to make the supply available for the company. It means that DBN parameters need to be modified after two weeks from the occurrence of the event to show the influence of new supply in enhancing the resilience.

The interaction between the hazard scenario and the variables that contribute to understanding the base behaviour of the SC occurs at one point of the time as has been seen during within case analysis. Then, the consequences of the event are analysed to recognise the ability of SC to react and how long it takes to recover based on some predetermined strategies. However, in tubes SC, there has been a need to deal with factors that help to understand and updated the chance of a hazard scenario occurrence. Recall the discussion of the time framing for DBN to the tubes SC. The introduction of these factors creates a dilemma about the difference between the time intervals that represent the behaviour of SC and the sensible time window to capture the chance of the hazard scenario. However, this dilemma has been clarified through pondering the role of these factors as early warning factors that help to update the chance about the hazard. Then, the decision maker can shape his belief in the possibility of adverse events initiated by the hazard scenario. The early warning factors can also be updated by the obtained data about their values as we have seen for the financial indicators and environmental hazards in case of tubes SC.

8.3.4 Variables States Description

While the description of discrete variables has been related to their meanings in the case study context such as the storms states etc., the description of continuous variables states are connected to the type of discretization that has been used. Figure 8-3 illustrates a tree of how modeller might describe the states of the variables based on the types of variables that they have. In the dynamic discretization, the continuous distribution is approximated by many states that lead to an inability to explain these states individually. Therefore, the summary statistics can be used to understand their distribution. In contrast, the uniform and heuristic discretization can lead to a focus on a small number of individual states. For instance, in Atlantic Canada case study there have been three states of the performances where one of them represents the target of the focal firm.

The dynamic discretization methods have many advantages comparing with static discretization as have been shown during the case studied and from the pieces of evidence gained from the literature (Neil *et al.*, 2012; Neil, Marquez, 2012; Zhou *et al.*, 2014; Zhu, Collette, 2015). The use of dynamic discretization for the tubes and pipe coating spare parts has dealt directly with numeric distributions that are inevitable in the SC to represent the material flow. It also drives to run the mathematical operations between these distributions with no need to consider predefined states and then describe these states in a meaningful way for the case study. However, as has been shown in tubes and spare parts SCs case study; the dynamic discretization might result in a big number of states to represent the distribution. The vast number of states is unavoidable to approximate the distribution of a variable to reduce the information loss. This big number of states is not a burden if the mathematical relationships to produce the conditional probability distributions for child nodes are known or obtainable as in the tubes and spare part SCs.

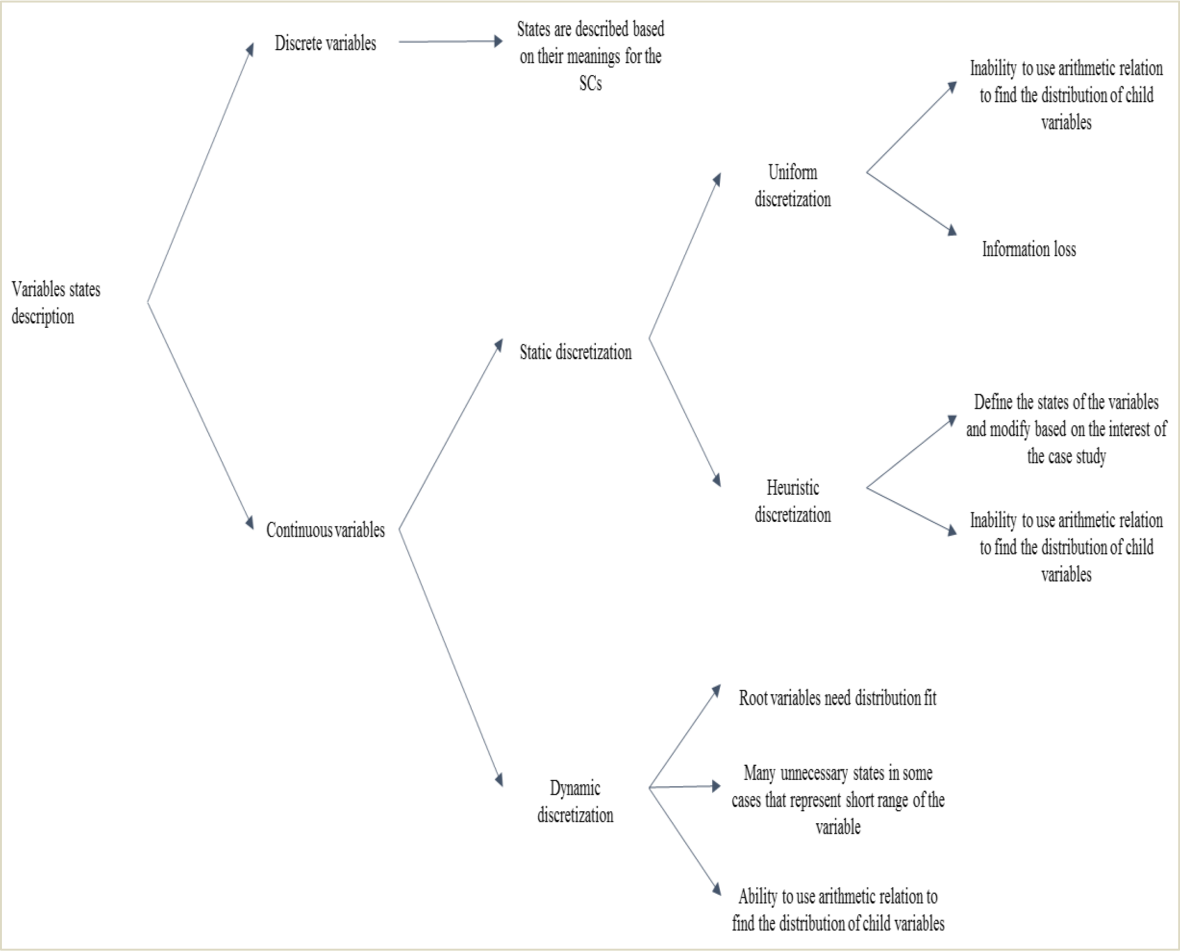


Figure 8-3: A tree to show the choices to describe variables states to understand SC resilience

The fundamental challenge is when the discretized continuous variable is a parent of a node and the mathematical relation to obtaining the conditional probability distribution for the child node is unknown. In this case, a manual elicitation for the conditional probability tables is needed. It means that hundreds of conditional probabilities need to be elicited. The elicitation of that number of probability can be practically prohibitive. For example, in Atlantic Canada case study the conditional probabilities tables have been inserted manually based on the complementary nodes logic between the variables. This task could have been exploded if the continuous variables have been dynamically discretised.

The other challenge is related to the nature of dynamic discretization which includes the use of simulation nodes to produce the distribution for a continuous variable and then discretized this distribution. These types of simulation nodes up to now do not support the discretization of actual data about the variables where they are available. For example, if data about a supply node is available the current dynamic algorithm does not support the discretization of these data directly. The data need to be fitted to an appropriate distribution, and then the parameters of the distribution can be used to generate the distribution again and discretise this distribution. This process might lead to losing some information. However, this problem occurs only for nodes that have no parents. For the nodes that have parents, this issue is not countered because their distributions are determined given their parents' distributions.

8.3.5 DBN Quantification

DBN quantification to capture SC resilience revolves around two concepts. The first one is the base behaviour of SC. The second one is the behaviour of SC when it is affected by adverse events. Both behaviours are associated with a task to validate them. Figure 8-4 shows a tree of different choices that can face modeller during the quantification of DBNs for SC resilience and the available ways to operationalise the model.

The realisation of SC base behaviour is significant to understand the ability of the network to react and recover as has been discussed in the literature and the case studies. Two groups of variables contribute to understanding the base behaviour of the SC have appeared through the case studies. These are the variables that represent the material flow and the variables that show the high probability hazards. The probability distributions of the latter types of variables depend on if the variable is static or dynamic through the time and the selected discretization methods. If the variable has been considered to be static through the time such as the demand for tubes, it means that its uncertainty distribution remains as it is through the time. The dynamic variables indicate that the variables states in the current time interval rely on the states of one or more variables in the previous time interval. For example, the inventory level and the supply depend on the remaining inventory level and replenishment quantity in the earlier time interval respectively. Consequently, the function to produce the conditional probabilities distribution/ the elicited probability tables should reflect this dynamic impact through the time.

The selection of discretization method leads to different quantification process for the continuous variables that represent the material flow or the performances of SC members. While the observations of the root variables are fitted to a distribution form in the dynamic discretization, the child nodes distributions are figured out by proper mathematical relationships to produce their conditional probability distributions. The mathematical relationships can be comprehended from the decisions rules about the inventory and the operating mode. The latter leads to figure out how the information such as rules about the amount of replenishment quantity and reordering can trigger the supply. In the other hand, the use of static discretization for the root continuous variables drives the need to estimate the probability for each state. For the child nodes, it requires either the conditional probability tables to be elicited or specifying based on the logic relationships, which stem from the structural configuration of the SC. For example, in Atlantic Canada case study the relationships to form the conditional probability tables have originated from the complementary nodes types in the SC. The heuristic discretization can be used in such cases. It means that instead of having uniform states that result from the static discretization, the states can be refined in a way that takes into consideration their meaning to decision makers. Recall the discretization of the financial indicators in tubes SC case and the discretization of performances variables in Atlantic Canada food SCs case. However, the reader should notice that selection of a discretization method is all the time driven by reducing the calculation and the elicitation burden with taking into account the mentioned advantages that Dynamic Discretization where there are known mathematical relationships between the continuous variables.

Regarding hazards, through the case studies, a distinction has been made between two types of hazards. These are hazards that add to understanding the base behaviour of the supply chain and the hazard scenario that disrupts this base behaviour of the SC. The hazards that contribute to the base behaviour of SC are essential to learning the uncertainty around this behaviour. These hazards can be called "high probability low impact" because the focal firm gets used to being exposed to these types of hazards such the tropical storms in the spare parts SCs. Therefore, the probabilities of these events should be studies in the same time interval that utilised to comprehend the flow of the materials /the performances of the SC members. On the other hand, the hazard scenarios usually have very low chance to occur whatever the time window to find this hazard chance. Their probabilities have a negligible effect on the base behaviour calculation.

However, these scenarios have high consequences once it occurs (low probability, high consequence hazards). The low probability high consequences hazards through the case studies have been called a hazard scenario. The main interest to consider them is to check the resilience of the SC against the adverse events can initiate from them. Therefore, their probabilities assumed to be one when the resilience is examined. However, in tubes SC, I designed an early warning model that can help to notify the focal firm about the increase the chance of hazard scenario to occur based on the pieces of evidence about the financial indicators and the environmental hazards.

The other consideration to quantify to understand the resilience to a hazard scenario is to examine the impact of some resilience enablers that can improve the SC ability to react and recover. The importance of these enablers from a quantification point of view is how they influence the conditional probabilities. To reflect their influence in DBN, four main inquiries can be made. These are what available resilience enablers in SC are, when these enablers can start to take effect, where the influence of these enablers will be manifested and how the probabilities distributions should be changed. For example, the ability to reallocate the orders in tubes SC has been stemmed from the capacities of suppliers B and C. The conditional probabilities tables of these two nodes in the model have been changed by the percentage of orders that they can fulfil once the supplier A has gone out of the market. This ability to meet the orders differs based on the time intervals as have been shown in the case study. This different ability leads to taking into consideration how the conditional probabilities distributions evolve through the time. In pipe coating spare parts SC, the limitations on flexible capacity have been taken as a constraint on the distribution of the supply post the hazard scenario occurrence.

Once the model has been quantified and run to capture the base behaviour and the resilience, the validation of these behaviours can be monitored. The validation of the base behaviour as can be noticed in the case studies have been ensured either through the consistency with the available dataset or through how the decision maker has described the current situation in the SC.

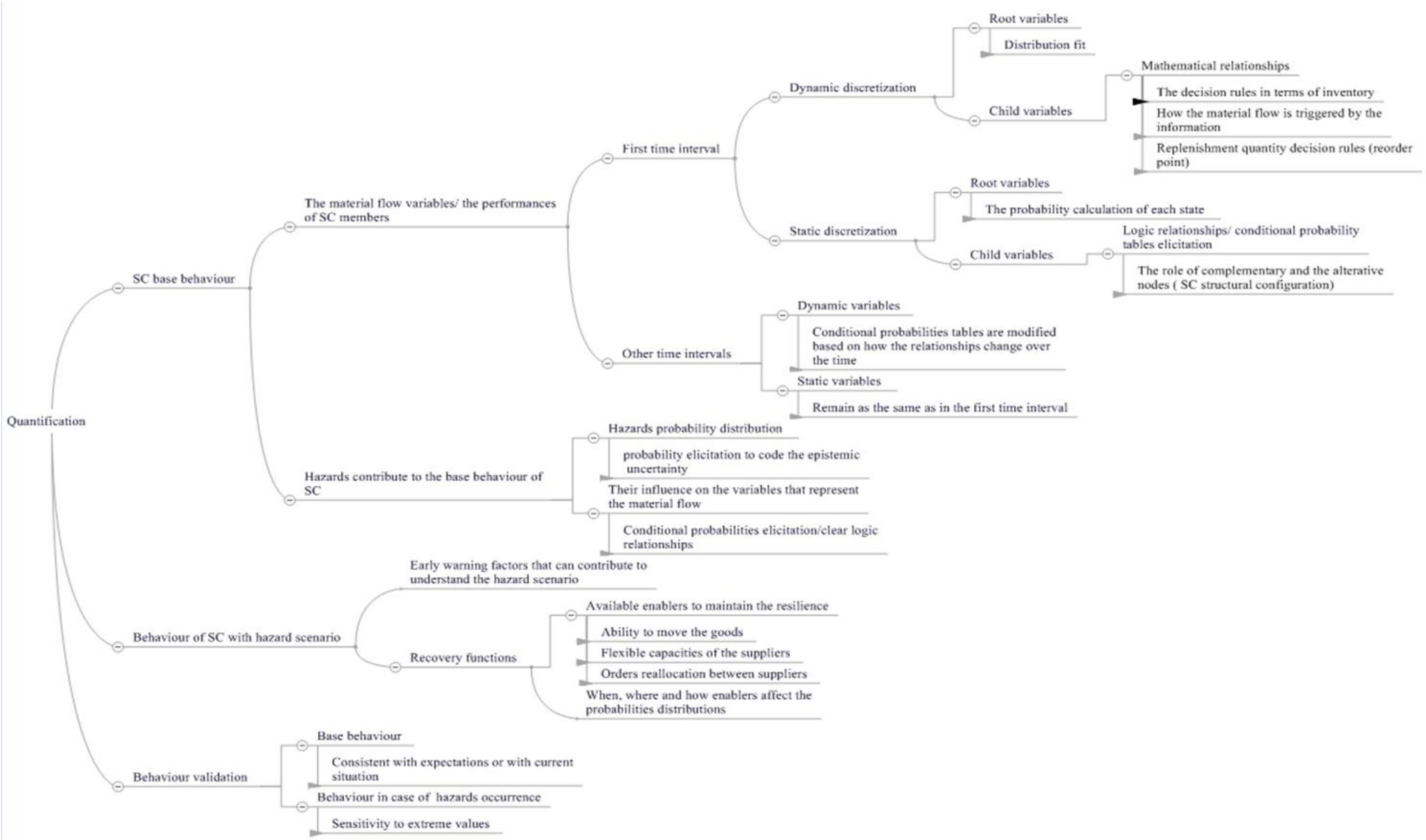


Figure 8-4: A tree of choices for DBN quantification to understand SC resilience

For instance, in spare parts SCs; the model show that there is a high chance of the company to have a very high inventory of spare parts and low demand. The latter is consistent with the description of the SC manager to the current behaviour of the SC. On the other hand, during and post hazard scenario behaviour can be validated by ensuring the sensitivity of the model to extreme values and ensure that the DBN is producing a realistic behaviour based on these extreme values as have been shown within case analysis.

8.3.6 DBN Outputs Representation through Resilience Triangles

Resilience triangles and economic loss have been used as a concept to represent the output of DBN and comprehend SC resilience concerning the case study problem. However, the latter measures are deterministic measures due to its use in the literature with complexity theory models. It is different from the outputs of DBN. As have been seen through the case studies, these outputs represented by a probability distribution. DBN uncertain outputs differ also based on the types of discretization that have been considered. In static discretization as in Atlantic Canada case study, there are a limit number of states that represent the probability distribution of the fulfilment rate in the store. On the other hand, the dynamic discretization has led to many states that approximate the continuous probability distribution (Recall the outputs of DBNs for the conducted case studies).

One way that has been used to capture the resilience triangle and the economic loss for uncertain DBN outputs is to focus on one or more of outputs states that can give an indication of the SC performance in meeting the demand. For example, in tubes SC and spare parts SCs, the shortages state have been the focus due to the interest of SC management in maintaining a little chance for the shortages. The resilience triangles for the latter cases have been captured through understanding the change in the probabilities of occurrence for the shortages state through the time. In this way, the vertical axis has shown the different probabilities for the state through the time intervals (horizontal axis). The latter indicates the ability of the SC to maintain the likelihood of a desirable state to occur and the recovery to this state.

The other way which can be examined based on the case is to explore the changes in the value of some statistics such as the mean, median, percentiles of DBN outputs through the time. For example, the values of the median can be checked through the time before and after the hazard occurrence until this value goes back to its usual or better level. In tubes SC and pipe coating case, I considered how the expected economic loss distribution (i.e. the expected shortages and unprocessed pipes distribution) can be represented through the boxplots and the recovery to the distributions before the hazard occurrence. The latter can be associated with financial loss distribution to find the cost of inability to meet the demand.

8.4 From SC Characteristics to SC Resilience

Table 8-2 show a summary of case studies that have been discussed in the previous three chapters. This section explores the impact of the studied SC characteristics and resilience enablers on SCs resilience.

Table 8-2: Summary of the case studies main attributes

	Tubes SC (UK)	**Pipes coating spare parts SCs (Malaysia)**	**Atlantic Canada food SCs**	
			Non-perishable food supply chain	**Chickens supply chain**
Problem to affect the resilience	Supplier evaluation based on their business continuity	Spare parts lumpy demand and uncertain supply	Critical infrastructure operations in extreme weather conditions	
Resilience index	The shortages	The chance of plant to be down due to spare parts shortages	The weekly fulfilment rates of demand during winter time	
Level of integration	The upstream activities for suppliers are highly vertically integrated. However, for the distributor, there is business relation	There is no integration (internally and externally). However, part of the supply is secure by 'After-Sales care policy'.	A business relation with suppliers and vertical integration starts from DCs to stores	A high level of a vertical integration with exception of feed and containers suppliers
Decisions explored to improve the resilience	Orders reallocation strategy	After-Sales agreement	The influence of Air shipment, Infrastructure and facilities recovery preparedness	The effect of infrastructure and facilities recovery preparedness

8.4.1 SC Integration and Its Resilience

The fully non-integrated relationship between SCs members does not seem to lessen consequences of events initiated by hazards that hit other SC members. In contrast, the focal firms in these case studies are so sensitive to the hazards that affect their SC members. Recall the output of DBN for the non-perishable food and tubes SCs. These SCs have a low integration level with their SC members. However, the focal firm is sensitive to the occurrence of an adverse event at a node level. Similarly, the ability of focal firms in the previous cases to react and recover is also so attached to the recovery of the affected nodes or the ability of non-affected nodes to provide the missing capacity of the affected nodes as in tubes case. The case studies outputs show that the main reason for a focal firm to be highly impacted by hazards at member level when there is a low integration level is the high dependency level of the focal company process on their SCs members' resources. For example in tubes SC, supplier A supplies 77% of the focal firm needs to fulfil their demand. In pipe coating specialised spare parts, one supplier supplies 100% from the needs of spare parts. Therefore, the level of dependency on the resources of a SC member can be considered to figure out the influence of the integration level. The focal decision could be to have very low integration with its SC members but the dependency on their resources can be so high as in tubes and specialised spare parts due to natural of the industry. Figure 8-5 shows how the above relationships have been analysed to shape the propositions about the level of integration. The question mark between the level of integration and the dependency level means that I need to figure out the level of dependency created by the level of integration. This is in order to understand the impact of level of integration on the resilience of SC.

This high dependency can be emerged from the single source of the supply (pipe coating case study), one supplier with high capacity to fulfil the demand of focal firm (tubes SC) and the critical infrastructure (Atlantic Canada food). The high dependency between the supply chain members has led to that the ability of the SCs to absorb the consequences of an adverse event at a node level and recover from these consequences are greatly related to the ability to create resources through flexible supply sources and means to move the goods. While in tubes SC, this ability to create flexible resources is embodied in the capability to reallocate orders between the other suppliers, in Atlantic Canada and pipe coating cases there is a limited ability to create flexible routes or supply sources. The latter is due to the criticality of the affected SC members (single route, single supply point). Therefore, the less ability of the focal firm to decouple its processes from other SC members through creating flexible resources would lead that consequences of the adverse event to be amplified and the firm will be less resilient in meeting their targets regardless of the integration level. The above discussion has directed the following proposition:

Proposition 1: The impact of integration level on amplifying or absorbing the consequences of adverse events in SC is determined by a) the level of dependency that is created by the integration intensity, and b) the ability of the focal firm to isolate itself by creating enough resources from other members in the SC or outside the SC.

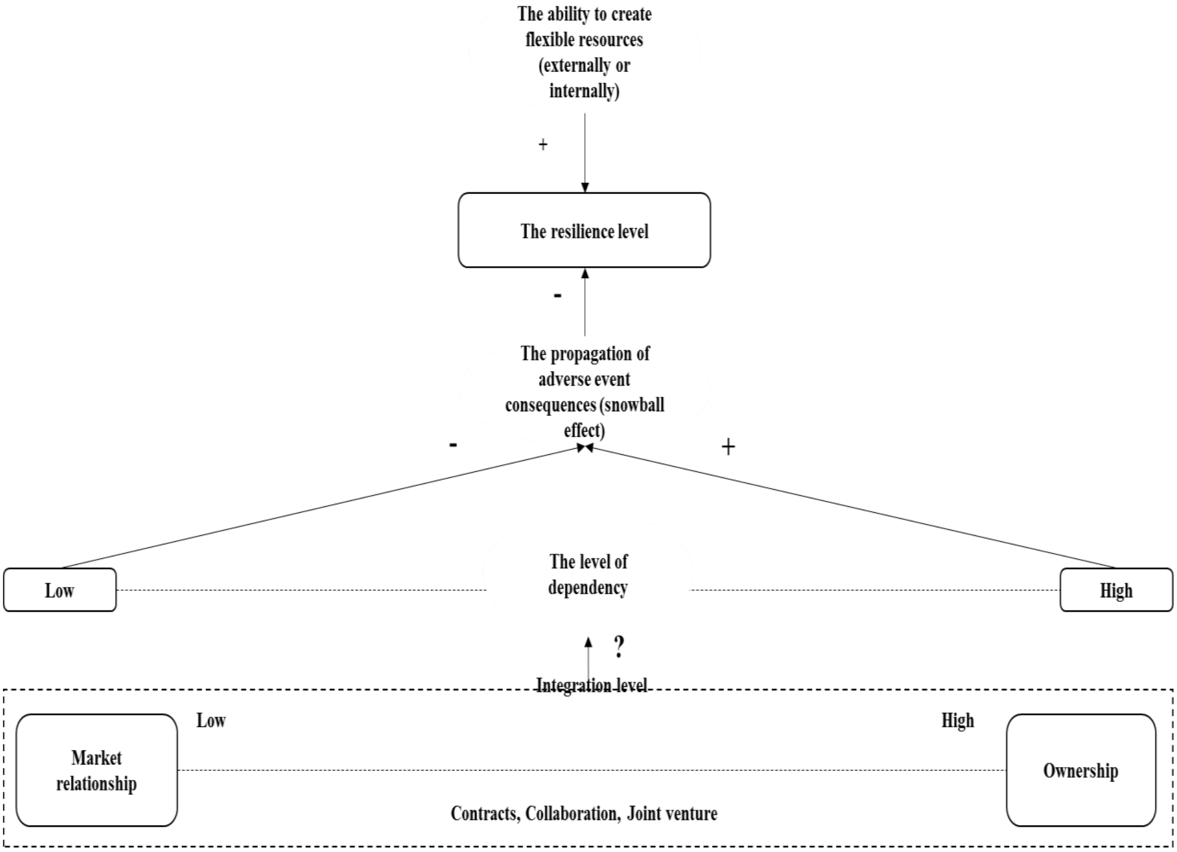


Figure 8-5: A visual analysis of relationships between the level of integration and the SC resilience

The above proposition means that the focal firm should seek to a level of integration that maintains a low dependency on other SC members where the same material is sourcing and flowing by a number of SC members. In another case, if the level of dependency is high due to lower cost; better quality etc. a level of capability to secure enough flow of resources should be maintained from secondary sources. Jüttner *et al.* (2003a); Peck (2005); Świerczek (2014) recognise that there is an association between the level of integration and the snowball effect in the SC. However, in this research, I propose that the determinant of integration forms influence is: 1) the level of dependency between the SC members that integration level creates, 2) the ability of the focal firm to isolate itself through creating flexible resources for sourcing and flowing of the material.

8.4.2 SC Structural Configuration and Its Resilience

The identified SCs structures have led to highlight many issues that can show the vulnerabilities of SCs and contribute to the understanding of their resilience. The single/multiple points for supply and flow, complementary/alternative SC members, geographical location of the SC members and geographical location of the focal firm have appeared to be significant to build DBN to understand the SC resilience. Figure 8-6 shows the analysis of relations between the SC structural configurations and its resilience.

The analysis of SC resilience through DBN demonstrate the importance of considering the concept of alternative and complementary supply and flow points. It refers to the real redundancies and flexibility in the SC structure. In tubes SC, the failure of the big supplier, is likely to have severe consequences on the focal firm ability to fulfil their demand, although the structure seems to be redundant as five suppliers supply same tubes. However, the capacities of the suppliers tend to be complementary. Likewise, the complementary types of supply in non-perishable food leads that the performance of a DC (A) is dependent on the performance of all suppliers and 3PLs that move the food from one location to the DC. In the latter case the performances of the suppliers and 3PLs from one location are complementary as well as the statuses of supplies from all locations are complementary.

The SC with multiple supply and flow points that they are alternative in terms of the capacity and the material types tend to be more resilient due to inherent flexibility and the high level of redundancies. However, the resilience of SC structure with single supply/flow or complementary supply and flow nodes is dependent on where the hazards hits and the ability to create resources to recover. For example, the resilience of tubes SC is mainly based on their capacity to source their orders from other suppliers in the current SC. Similarly, the resilience of Atlantic Canada food SC is largely dependent on creating alternative means for the transportations such as the air shipment and the quick recovery of the infrastructure.

For pipe coating spare parts SCs, the hazards occurrence at the supply side means that the company should wait for the recovery of the affected members because of the lack of ability to create resources from other suppliers. Also in pipe coating case study, the vulnerability of the geographical location and lumpy internal processes of the focal firm leads that the only way to ensure the resilience of spare parts supply chains is to make sure that the manufacturers of spare parts can provide flexible capacities. However, this flexibility is always limited to a maximum point. The above discussion results in forming the below propositions:

Proposition 2: The SC with multiple alternative points to supply and move the goods are less vulnerable to hazards due to inherent flexible resources and means to move the goods.

Proposition 3: The resilience level of SC with complementary supply and flow points rely on the capability to create resources from the external members.

Proposition 4: The resilience of SC with a single inevitable point for sourcing or moving the goods is a) entirely dependent on the processes of that point and b) the flexible level of the capacity that the single inevitable point can make available when hazard hits the focal firm.

The network concept and its social analysis that have been suggested (Choi and Hong 2002, Kim, Choi *et al.* 2011) and (Kim, 2014) or supply network resilience, in particular, try to find out the critical nodes in the whole network. It is by finding out the number of links the inputs and outputs of each node. The latter does not focus on how a particular node geographical location, the complement and alternative supplies contribute to the criticality of the node. That why more detail modelling such as DBN can reveal such inherent characteristics and drive to a better understanding of the resilience.

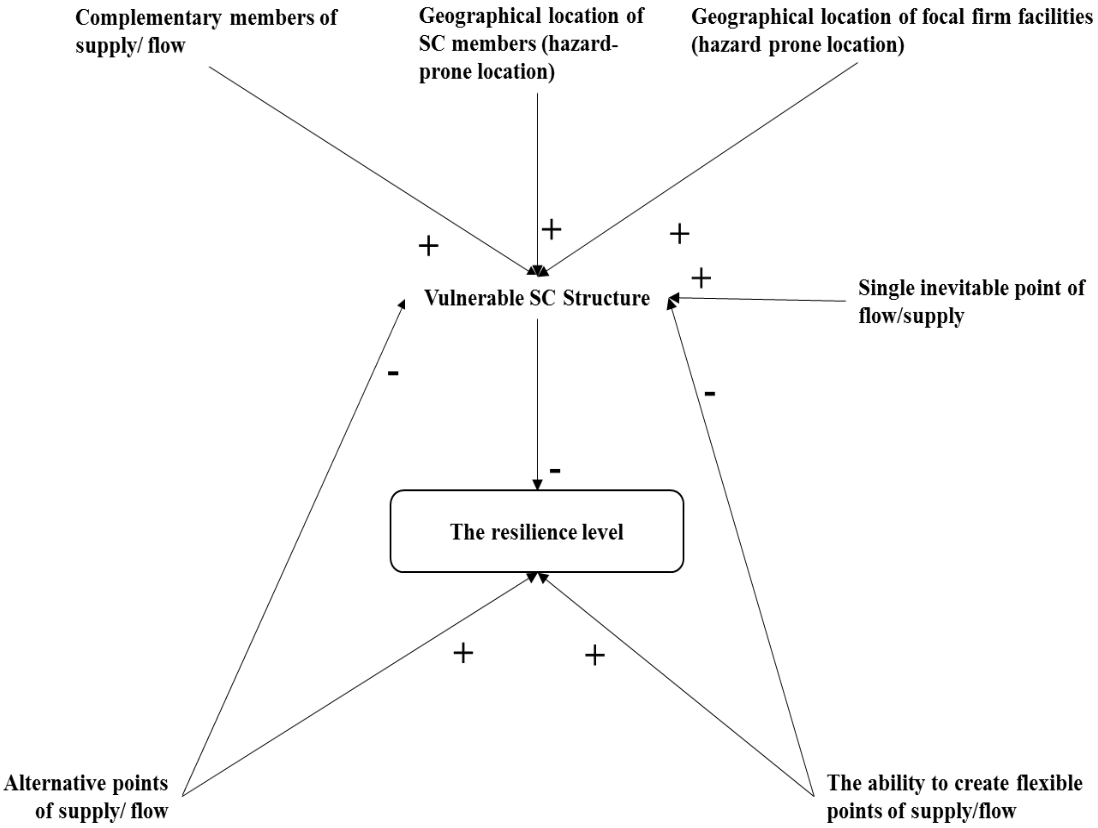


Figure 8-6: A visual analysis of relations between the structural configurations and the resilience level

8.4.3 SC Operating System and Its Resilience

While the type of operating system in demand cycle shows mainly the expectation of the customers whether to find the goods on the shelf or pull them with an acceptable lead time, the supply cycle operating system demonstrates the level of redundancy that the company is maintaining to decouple the demand and supply cycles. The latter also illustrates the role of the information in triggering the material flow in the SCs. Notice that I am considering the operating system only from my case studies perspective. Intuitively, the operating system is not limited to that it also is related how production is triggered as I have shown in chapter 3. The high level of redundancy in the inventory associated with push operating system of the supply cycle plays a role in enhancing the resilience. However; this role will be deteriorated if there are no strategies to source the supply from other places than the affect SC members. An exceptional case is that the focal firm or its warehouses in a hazard-prone area as in the pipe coating case study. In the latter situation, the inventory plays no role in maintaining the resilience of SCs as in pipe coating spare parts SCs because it is affected by the hazard. Formally, I can say that the redundant inventory associated with a push supply cycle for the focal firm provides an only interim ability to meet the demand if the supply side affected. This is agreed with the argument of Kim *et al.* (2015) who doubt the conventional role of the redundancies as an enabler to the SC resilience that has been argued by some authors such as (Sheffi and Rice 2005). However, Kim *et al*. (2015) focus on the redundancy in the structure rather than the redundancy in the inventory.

In the pull supply cycle, the focal firm naturally maintains a low redundant inventory level as in the case of non-perishable food SC. The inventory is only to keep them operating for a week at each stage. Therefore, the inventory does not play a significant role in improving the ability of the SC to react to hazards from the supply side. The low inventory level in case of pull supply operating system leads that their capability to react is conditional on the type of their demand cycle. If the demand cycle is a push cycle (the customers expect to find their goods on the shelf), It the demand will be missed if the goods are not on the shelf. If the pull supply cycle is associated with a pull demand cycle, then the demand can be lost once the lead time is longer than the acceptable one by the customers. Therefore, the resilience of pull supply cycle is evaluated by the ability to create resources in the acceptable lead time for the customers. Although Tang (2006), Spiegler *et al.* (2012) highlight the importance of SC operating system in risk study, the current literature in the SC resilience does not give detail about their influence in understanding the resilience of SC. In the current research, I show the role of operating systems in understanding the consequences of hazards occurrence through appreciating when the demand is considered to be missed and the effects of different operating systems on the redundancies level of the inventory.

Another reason to why the operating system to be considered is to comprehend the role of information in triggering the flow of the material on the supply side and the ability to adjust this flow based on the hazard occurrence in the demand side. For example, in the chickens SC, this information plays no role once that production of chickens has been organised. The material flow is not adjustable to the hazards that could occur on the demand side. However, the information about the inventory levels in tubes and spare parts SCs perform a role in shaping the flow on the supply side for the focal firm. This role of the operating system influences the DBN building as I have reported.

8.4.4 SC Visibility and Its Resilience

Recall the visibility definition as “the identity, location and status of entities transiting the supply chain, captured in timely messages about events, along with the planned and actual dates/times of these events” (Francis, 2008, Page 182). The consistent pieces of evidence from the case studies show that the visibility between SC members is related to the span of integration in the SC. Figure 8-7 displays of the analysis about how the visibility impacted by the span of integration and affect the planning that leads to a better resilience level. In the chickens SC, the extended span of integration leads to high level of data sharing and collaboration between the SC members. However, in other case studies; this visibility level is limited due to non-integrated nature of SC. The narrow span of integration or non-fully integrated level across SCs can be attributed to many reasons such as the extensive number of suppliers that the focal firm has (the non-perishable food SC), a member has many customers as the big suppliers of tubes SC and the ferry company in the Atlantic Canada food SCs.

The extended span of integration across the supply chain tiers breaks down the walls between supply chain members as in the chickens SC case. It would lead that more information can be obtained about the SC structure. The latter assists in identifying the vulnerabilities that the SC has and the hazards that SC member could face. It is beside the primary value of visibility in getting timely information about the SC members exposure to hazards and avoid the needless reactions that have been reported by many authors such as Jüttner and Maklan (2011), Christopher and Lee (2004). The better hazards and vulnerabilities identification in the SC will lead eventually to better planning for maintaining the resilience through identifying strategy to counter the consequences of the hazards occurrence or to mitigate the vulnerabilities in the SC to avoid the hazards. This discussion leads to propose the following:

Proposition 5: The extended span of the integration drives a better visibility in identifying the hazards and the vulnerabilities in the SC that leads to a better planning to maintain the resilience.

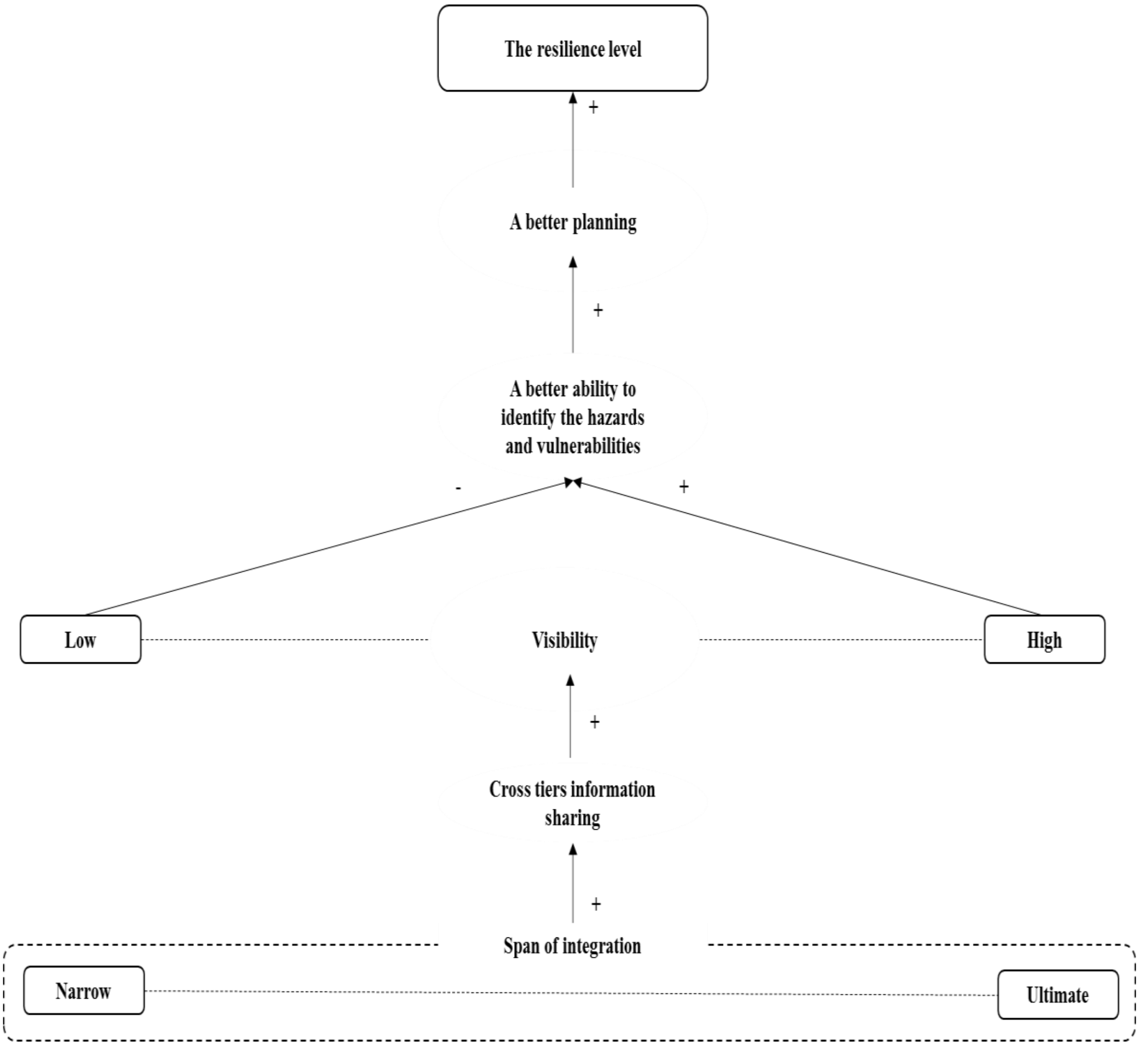


Figure 8-7: A visual analysis of relations between the visibility and better planning to maintain the resilience

Świerczek, (2014) has considered the impact of the span of integration on the transmission of the disruption between the SC members. Świerczek, (2014) concluded that the extended span of integration might cause a reduction in the snowball transmission of adverse consequences in the SC. Świerczek, (2014, Page: 100) argues that “the structure of supply chains rather absorbs the strength of disruptions propagated in the forward and backwards transmission in the material and information flow.” However, I propose that this absorption can be attributed to the improved level of visibility that might give room for members in the downstream or upstream to react to the hazards occurrence. This argument is supported by the argument of Jüttner and Maklan (2011), Christopher and Lee (2004) and other about the impact of visibility across SC in providing timely information for reaction to hazards occurrences.

If the visibility is hard to achieve between the SC members, there would be less ability to identify the hazards and vulnerabilities in the SC. However, this might be overcome partially through obtaining data from secondary data sources to understand the hazards that a SC member could face. For example, in tubes SC; the visibility to suppliers have been improved by using in-house financial company data and the secondary data from the suppliers’ websites.

The visibility issue can clearly distinguish the SC from any other network. In any other networks, the visibility across the span of the network can be achieved in a way that graph theory can be applied to understand the flow from the source to the sink as in (Kim, Chen *et al*. 2015). However, this view of the SC is not the situation for the conducted case studies for this research where there are many issues limited the visibility across the SCs.

8.5 Relationships between Vulnerabilities, Hazards, Consequences, Risk Mitigation and Resilience Enablers (Post Case Studies)

In chapter 2 I have discussed a framework that has been obtained from the literature about the relationships between the vulnerabilities, hazards, and consequences. In that theoretical framework, it has been argued that the combination of the hazard with vulnerability in the system can lead to an event with consequences. However, the cross-case study analysis shows that the vulnerabilities in the SC are the key to understanding the hazards that the SC can face. Then the occurrence of these hazards can lead to the adverse event with the consequences on the supply chain ability to achieve their goals/ maintaining their performance. Figure 8-8 illustrates some types of vulnerabilities that have been noticed in the case study SCs and the types of hazards that SCs can expose to them because of these vulnerabilities.

The geographical locations of the firm and its supplier members lead to identifying the type of environmental hazards that these members can face. In tubes SC some facilities location of suppliers are in a hazard-prone area where other are not. The focal firm in Malaysian pipe coating SC is in an area where there are chances to have tropical storms and floods that might destroy the inventory from spare parts. In Atlantic Canada case studies the facilities of the focal firm and critical infrastructure are located in a hurricane path. The other vulnerability that the supply chain can have is the high dependency on one supply chain member or single source of the supply and flow. This dependency has led the tubes and spare parts pipe coating SCs to be sensitive to the failure and the capacities of the supplier. Similarly, in the Atlantic Canada food SC the flow of goods in the SCs is so susceptible to the processes of the ferries Company and DCs. If the ferries company stops, then the movement of goods will be halt.

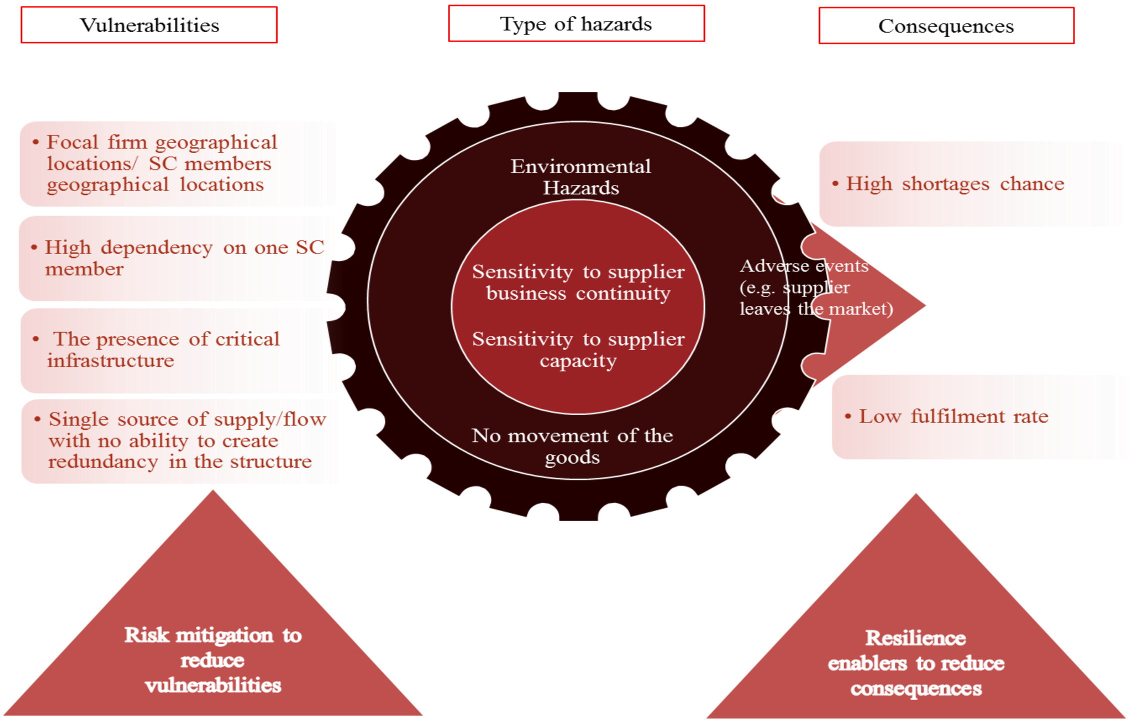


Figure 8-8: The relationships between vulnerabilities, hazards, consequences, risk mitigation, resilience enablers based on cross-case analysis

The occurrence of hazards leads to adverse events with consequences on the supply chain ability to meet their targets. In my cases, the consequences revolve around the ability to meet the demand despite the differences in the terminology. In the case of Atlantic Canada food SCs, the main concern is the fulfilment rate at the store. In tubes SC and spare parts SCs, the goal is to reduce the chance of shortages in meeting the demand. The inability to meet the demand in Atlantic Canada and tubes SCs lead to that the demand to will be missed. The latter will push towards financial consequences and customers dissatisfaction. On the other hand, the inability to meet the demand in spare parts pipe coating leads to the production disruption. However, the financial and customers dissatisfaction consequences, in this case, are related to the ability/inability of the pipe coating production processes to overcome the disruption consequences and meet the project's deadline.

The risk mitigation actions and the resilience enablers are two broad categories that can lead either to reduce the vulnerabilities of the SCs or to ease the consequences of adverse events. The risk mitigation actions have discussed in the literature as they aim to “reduce the risk” (Chapter 2). However, I propose in this research that these actions should seek to lessen the vulnerabilities in the SCs. The latter would lead to reducing the chance of hazards. For example, in tubes SC the lower dependency on one supplier can result in low sensitivity to the supplier business continuity state. Similarly, the selection of suppliers with facilities in low hazard prone areas can lead to better security of the supply. The actions to mitigate the risks are not available to the decision makers all the time. For example in Atlantic Canada case studies, the decision makers have no choice to use or not to use the ferries company. Similarly, in spare parts SCs, the location of the firm warehouse is attached to the industry type. Such cases are a venue to where the resilience enablers can contribute to ensuring the ability of the SC to face the events initiated by hazards with minimum impact on the focal firm ability to meet its goals.

8.6 Summary and Concluding Remarks

In this chapter, I have tried to build a bigger picture about the case studies observations based on a cross-case analysis. Four streams of findings have been expressed. These are the role of DBN in informing the resilience analysis based on different problems, the lessons learned about the process to build DBN to understand the SC resilience based on SCs inherent characteristics, the impact of SC characteristics on the resilience level and the reforming of the relationships between the terms that contribute to analysing the SC resilience.

I have illustrated how DBNs have been considered to evaluate the suppliers based on their business continuity, managing spare parts uncertainties based on the interdependent view to support After-Sales agreement and maintaining the food supply in Atlantic in the presence of infrastructure operations problem. I also have also shown the advantages and limitations of DBNs comparing with tools that consider SC as a complex system. The analysis of DBN outputs has shown the importance of considering the SC decisions characteristics to understand the SC resilience. The impact of level integration (the intensity of integration) on SC resilience can be understood from the level of dependency between the focal firm and the resources of the integrated SC part. For a high level of dependency, there is a high chance that the adverse consequences of hazards occurrence to be propagated and result in less ability to maintain the base behaviour. The span of integration can affect the visibility level which affects the capability to identify the hazards and their consequences. Consequently, it influences the planning for the occurrence of such hazards. The results of the analysis also show that operating system in SC is a key to understanding the level of redundancies. However, the impact of this redundancy differs based on the source of the hazards (supply side, focal firm, demand side). Also, the ability to create flexible resources has appeared to be a key determinant to understand the ability of the SC to recover.

While the DBN outputs and processes show benefits in analysing the resilience of SC considering their characteristics, the process to build and quantify the model have been influenced by SC characteristics, the selected discretization method and the time element description. The structural configuration has a distinct role in recognising the dependencies in SC that aid the building of the DBN qualitative structure and figuring out if there are logic relationships that can lead to building the conditional probability tables. The operating system shows what the triggers for the flow in the SC and the decisions rules regarding the replenishment. While the former has a clear impact on forming the causality in DBN, the latter and the former aid finding the mathematical relationships to create the conditional probability functions.

The decision about the selection of discretization method and the time interval length have impacted the way that the variables states are described and the quantification process. The static discretization has seen to increase the complexity of the quantification process due to inability to use numeric variables and relationships. On the other hand, the dynamic discretization would require specifying the distribution form and increase the burden of conditional probability distributions elicitation when there is no a clear mathematical relationship can be used to understand the joint probability distribution of a discrete and continuous variable. The output of the model varied also based on the selection of discretization method and the time interval length as has been discussed.

9 Conclusion

In this chapter, I reflect on the objectives of this research and how they have been met through this thesis. The limitations and implications of this research will also be addressed to shape directions for future research.

9.1 Research Objectives Recap:

The aim of this research has been to advance the quantitative analysis of SCs considering their characteristics. The objectives of this research have been demonstrated in Chapter 1 are:

1. To clarify the interrelations between terminologies that contribute to the SC quantitative resilience analysis
2. To empirically explore the role that DBNs play in informing the quantitative SC resilience analysis to different problems,
3. To report the key lessons around the process to employ DBNs to understand and support decisions about SC resilience based on the SC characteristics

In the following section, I will review these objectives and highlight the contribution to knowledge made by this research in respect of each one.

9.2 Key Contributions

9.2.1 Objective 1: To clarify the interrelations between terminologies that contribute to the SC quantitative resilience analysis

The development of a framework for resilience analysis has started by drawing guidance for the use of terminology from a resilience analysis perspective. This guidance is new in the area of supply chain resilience analysis as it considers how risk and uncertainties affect the SC resilience analysis. I established in Chapter 2 that the terminologies have been used loosely in the literature of SC resilience. This might have prevented the development of suitable quantitative resilience analysis models. In the light of generic risk management literature, a theoretical base to re-understand the terminologies in the SC resilience literature has been reached. I have illustrated how hazards, vulnerabilities and consequences can be defined and the importance of their identification to understand the resilience. This theoretical base has also assisted in critically re-classify and re-define the terminologies that have been discussed in the SC resilience literature. In Chapter 8 based on the cross-case study analysis for my probabilistic modelling approach output, this theoretical base has been advanced in a way that reflects the practical side of the resilience analysis. While in Chapter 2 I have shown that the combination of hazards and vulnerabilities lead to an event with consequences, in section 8.5 I have illustrated that vulnerabilities of SC are keys to understanding the hazards that they are facing. Then, the occurrence of adverse events can lead to the consequences on the SC ability to achieve their goals/ maintaining their performance. I have also noted that the risk mitigation actions should aim to reduce the vulnerabilities in SC, whereas the resilience enablers should enhance the ability to deal with consequences of adverse events.

The value of the above clarification of the terminologies and the suggested base to understand these terminologies is that the modellers can be clear on what their probabilistic analysis aim to. Is the aim of the model to show vulnerabilities in the SC, hazards, consequences, the resilience of the SC to specific hazards or can be all of them? It is despite the empirical value of identifying how the fulfilment rate and the shortages can be used to understand the resilience of the SC, which has not considered to date in the literature.

9.2.2 Objective 2: To empirically explore the role that DBNs play in informing the quantitative SC resilience analysis to different problems

In chapters 5, 6 and 7 DBNs have been applied to three various problems that affect the resilience of real SCs. I have shown through the latter three chapters, DBNs formulation to understand the SC resilience based on the evaluation of suppliers business continuity, interdependent view of spare parts management and food availability in the presence of critical infrastructure. Then, I have examined how DBNs outputs show the impact of some decisions in improving the resilience. The latter applications of DBNs are entirely new applications that aim to contribute not only to understand realistic problems that case studies face about their SCs resilience but also demonstrate a new way to solve existing problems in the literature in a probabilistic sense.

9.2.2.1 Dynamic Uncertain Analyse of SC Resilience to Different Problems

Based on ‘within case analysis’, it can be argued that DBNs can play three main roles in the SC resilience analysis. These are probabilistic predicting the resilience of SC against a particular problem, figure out the influence of SC distinctive characteristics on probabilistic resilience measures and support the decision making through examining the impact of some resilience enablers on the resilience level.

Tang (2006) argues that the supplier business continuity can be an important criterion for the supplier evaluation and selection. The issue of evaluating suppliers based on their business continuity has been stated as the primary concern of decision makers concerning tubes SC resilience. The current research offers a new perspective of how this business continuity can be understood and evaluated based on a new two main types of factors. These are the environmental hazards that can affect the facility locations of the suppliers and the financial stability of the suppliers. Regarding the financial stability, I have suggested the use of suppliers net worth changing rate and profit changing rates. The latter factors can give a clear indication if suppliers business is flourishing or declining. Then, I have shown through DBNs outputs how the business continuities can affect the current SC ability to meet its target and what role the inventory and expectation about flexible resources (SC characteristics) can play to enhance the resilience.

The spare parts SCs management is another problem that affected the pipe coating industry. It has been reported in the literature by Bacchetti and Saccani (2012); Braglia *et al.* (2004a); Deshpande *et al.* (2006); Everingham *et al.* (2008); Fleischmann *et al.* (2003); Hassan *et al.* (2012); Hishamuddin *et al.* (2012). The current literature makes separate attempts to manage these spare parts through the forecasting of their lumpy demand and classify them. The use of DBNs for this research shows a new interdependent view of spare parts management through the consideration of supply, inventory and internal processes uncertainties. In this view rather than focusing on demand fitting to a particular distribution as in the literature, I focus on the probabilistic interdependencies between supply, inventory and internal process to understand the ability of spare parts SCs to meet their demand and to recover if an adverse event occurs. Then, how After-Sales agreement can affect this resilience can be shown. Due to a massive number of spare parts, I find out through this research that these spare parts can be classified into two types from user's point of view. Firstly, the specialised spare parts that have particular specifications and quality and might be very hard to be obtained from suppliers other than the manufacturers of the machines. This latter increases their supply uncertainty. The other type is the non-specialised spare parts that can be acquired from several suppliers.

The third case study that I have applied DBNs to understand the food SCs resilience in Atlantic Canada. Food SCs are described to be very complicated SCs (Sarathy 2006). The extreme weather conditions and the presence of the critical infrastructure have led to many concerns about maintaining a high fulfilment rates in meeting the food demand in Atlantic Canada. Through this case study, I have shown how DBNs can assist probabilistically in predicting of the fulfilment rates and the influence of infrastructure on the food availability. Then, how the actions of government and company can support in maintaining the resilience to a hurricane occurrence have been illustrated. While the majority of food SC literature focus on the food safety concerns, the current case study provides a novel application of DBNs to understand the resilience in maintaining the food availability, especially if this affects the public as in the case of the food supply to Newfoundland Island.

9.2.2.2 A Probabilistic Mechanism to Understand the Impact of SC decisions Rules and Characteristics on the SC resilience

This research offers a novel view of Probabilistic Mechanism to understand the resilience based on supply chain decision rules and characteristics. This probabilistic mechanism consists of comprehending the supply chain characteristics and decision rules, modelling that using DBN, producing measures such as resilience triangles and economic loss to support the selection of resilience enablers.

Empirically the output of DBN research has shown how the level of integration, operating system, visibility can influence the SC resilience analysis. Five propositions have been generated in the light of the cross-case analysis to capture the role of these characteristics. I have shown that the impact of integration level on amplifying or absorbing the consequences of hazards occurrence in SCs is determined by the level of dependency and the ability of the focal firm to create enough resources from other members in the SC or outside the SC. It has been noted also that the high level of dependency can lead to snowball effects for the adverse events initiated by hazards.

The consideration of operating system prompts to recognise how analytically push and pull cycles can lead to a particular resilience level through understanding how the level of redundancy can provide only an interim ability to react if a hazard occurs at the supply side. Regarding the visibility, I explain that more visibility level can lead to a better planning due to the better ability to identify the vulnerabilities and hazards. However, I have shown that the visibility level is attached to the span of integration in the SC. The long span of integration improves the visibility level.

9.2.3 Objective 3: To report the key lessons around the process to employ DBNs to understand and support decisions about SC resilience based on the SC characteristics

DBNs as a modelling approach for reasoning under uncertainty through the time are still an area of the research that can be advanced at a theoretical and application side. To date, there are no attempts have considered their elicitation to supply chain problem. This research offers a unique attempt to shape a protocol that can control the building of DBNs to a probabilistic analysis of the SC resilience. This protocol mainly steam from characteristics of the SC, the selected discretization method and the specifying of the time element.

In this research, the role that the known SC structure can play to aid the building of DBN qualitative structure have been demonstrated. I have illustrated that some logic relationships that can be utilised in the model quantification stem from recognising the relationships between SC members in the structure. The known structure also can lead to identifying the vulnerabilities of SC and the hazard that might hit the SC. The operating model shows the decision rules regarding replenishment and inventory that support the quantification stage across the time intervals. The role of the visibility in scoping and populating DBNs also has been noted.

This research provides a novel empirical attempt in illustrating how the selection of discretization methods can impact the quantification process and the result of DBNs. The static discretization has been shown to increase the complexity of the quantification process due to inability to use numeric variables and relationships. It also has been clarified that despite the obvious advantages of dynamic discretization in using numerical distribution, it necessitates the distribution specification and escalate the burden of conditional probability distributions elicitation if there is no relationship can be deployed to comprehend the joint probability distribution.

Concerning the time element for DBNs, I have shown that the modeller should distinguish between the time intervals for the factors that contribute to understanding the behaviour of the SC and the time window for the early warning factors that contribute to recognising a hazard scenario chance. The attention to differences between the hazards that add to understanding the base behaviour of SC has been drawn, which appears at each time interval and the hazard scenario that hits the SC at a particular point in the time and disturb its uncertain base behaviour.

9.3 Research Issues and Future Work

9.3.1 At Case Study Level

The first limitation of this research at case level can be how the measured resilience can be reflected in a cost-benefit analysis for the decisions makers. Such concern has been addressed partially by considering the expected distributions of shortages and the expected unprocessed pipes respectively. However, the cost-benefit analysis needs a further research that studies what the focal firm can lose to the cost of decisions that can make. It means that the decisions process in each case study should consider. Then, a comparison between the investment levels to use different resilience enablers can be drawn. The resilience triangle can be employed in these cases by understanding how various dimensions of the triangle can imply different financial loss. The rules that can shape calculations of such cost-benefit analysis, the selection of resilience enabler and the contribution of resilience triangles to this study are worth further investigation due to their contribution in the decision-making process.

The visibility and the examination of the resilience based on the full structure of SC is an issue also for further study. My investigation shows that it could be difficult to obtain data about the detailed structure of the SC to use them in the model. Choi *et al.* (2001) argue for a structure investigation of the SC where the SC members are identified from the origin. They have been able to map a structure of three SCs in the automotive industry (Choi and Hong 2002, Kim *et al.* 2011). Suppliers of suppliers have been accessed to map the supply chains structure. However, such study took three years. The visibility to suppliers of suppliers needs an intensive arrangement with the suppliers of suppliers and so forth. The rules that can control this arrangement can have value at SC resilience level due to its impact on identifying the hazards that the company can face and lead to a better planning for resilience. This issue of visibility to whole SC and the identification of the hazards has been outlined by Garvey, *et al.* (2015). Garvey *et al.* (2015) insist that the use of their BBNs model to analyse the SC risk require the identification of full SC structure. In Atlantic Canada case study, I have tried a similar structural approach to building DBN. However, this has led to complex model despite the lack of the visibility to the whole network. The practicality of such way to build uncertainty modelling approach can be under further discussion.

The third issue of this research as in any other case studies research is the generalisation of the findings. Despite the fact that I have tried to capture a wide range of the supply chains characteristics through targeting extreme cases and compare the added values of DBNs to complexity theory modelling approach, the generated propositions are still attached to study SC. One way to drive this research further is to examine the generated propositions on a wider population using questionnaires. It might give an enhanced level of generalisation to the propositions. It can be done either by using a control population sample such as focusing on particular industry sector or it can be random population where different industry can be considered. It also can be attached to a precise geographical location such as the UK or it can be attracted by the global nature of supply chains.

9.3.2 Using DBNs for the Problems that have Implication with SC Resilience

In the within case study analysis, I have introduced three areas that appeared to have implication with the resilience analysis for this research. These areas are the food safety, the supplier selection and the forecasting of the spare parts demand.

The interconnection between the food safety and supply chain characteristics can be under further examination. The use of DBN to understand the interdependencies between the causes that can lead to contaminate the food can be a new area of DBNs applications considering its benefits in understanding the uncertainty through the time. The food safety is highly related to factors such as the storage time and shipment time. Thus, a modelling approach that captures the uncertainty through the time can become an appealing approach.

The supplier selection is a well-flourished area in the literature as it can be seen in chapter 6. However, the current methods of selecting suppliers do not take into account how the performance of suppliers can be re-evaluated probabilistically through the time. This area is worth for a further investigation. Despite my focus on evaluating the suppliers based on their business continuity, a DBN that takes into account operational factors such as quality and delivery can have a potential contribution to the area. It can help to support timely evaluation about the suppliers with taking into account the uncertainty.

The spare parts demand can be another vital issue where someone can speculate. In my case, I have focused on the user view of this issue. DBNs can be used to consider the problem from the buyer of spare parts. DBNs in such case can be utilised through the pondering of some causes that can contribute to the lumpy demand of spare parts for the buyer and update of the information about these causes through the time. It might aid latter the communication between the buyer and users at a strategic level.

9.3.3 Computational Improvement for DBNs Algorithms

The issues of this research at DBNs level can revolve around two main schemes. These are the comparison between the algorithms that can use to run the inference and the distribution fit using dynamic discretization algorithm.

This research has ignored the impact of using different algorithms in the calculation of DBNs. This point can be under an additional examination. The literature of DBNs lacks of the study that shows how the current algorithms to run DBNs can be improved and the impact of using different algorithms in the calculation. This literature is mainly focused on using the same algorithms that have been used for BBNs to run the inference in DBNs. It means that the increase of the time intervals will increase the model complexity because the algorithm deals with the variables in each time interval as a new set of variables. Therefore, the improvement of these algorithms through reducing this complexity in the calculation can be a platform for a new area of research.

In terms dynamic discretization, despite its benefits in accommodating the numerical distribution directly, it requires the use of parametric distributions with root variables that need to be fit to a particular distribution form. This point might imply information loss about some observations during the distribution fit process. The area of the future research can be an extension of the current algorithm of dynamic discretization to learn distribution from the available data. It will be at node level within the model. It means to insert the data within a node and, then, the discretized distribution can be found. The latter also can be extended to learn DBNs from datasets, although the latter is considered a different approach from my research. In this research, I consider the model to be structured from the qualitative data obtained from the case study. The use of some datasets in my research is only to shape some prior distributions as it has been stated through this research.

Appendices:

A. Entropy Mathematical Meaning

The Entropy-based method has been used a lot mathematically in the literature of discretization to find the suitable discretised intervals to represent the continuous variables with the smallest loss of the information as well as in Dynamic discretization. It has been used for univariate analysis and multivariate analysis. See (Frank, 2011). According to Cover and Thomas (1991), the entropy is a measure of unpredictability or information content. It measures the amount of information needed to describe a random variable. Consider the example of a poll on some political issue. Usually, such polls happen because the outcome of the poll is not already known. In other words, the outcome of the poll is relatively unpredictable, and performing the poll and learning the results gives some new information; these are just different ways of saying that the entropy of the poll results is large. Now, consider the case that the same poll is performed a second time shortly after the first poll. Since the result of the first poll is already known, the outcome of the second poll can be predicted well and the results should not contain much new information; in this case the entropy of the second poll results is small".

As can be seen, Figure A-1, if the entropy increases in relatively higher than the increase in the number of states (k partitions) that means we learn more and new significant information still obtained. We stop when we reach the knee of the concave function (H(X)) to maximise the information loss and make the computation tractable (Clarke, Barton, 2000). This exactly what control the number of states in Dynamic Discretization.

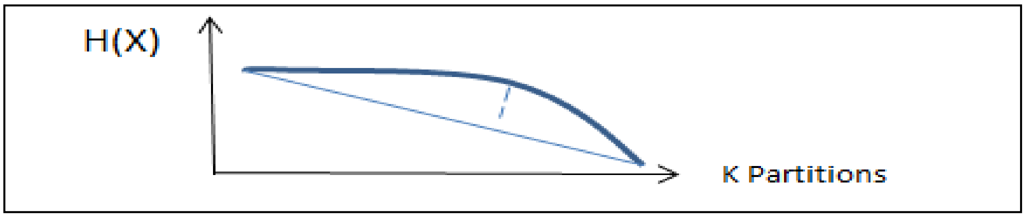


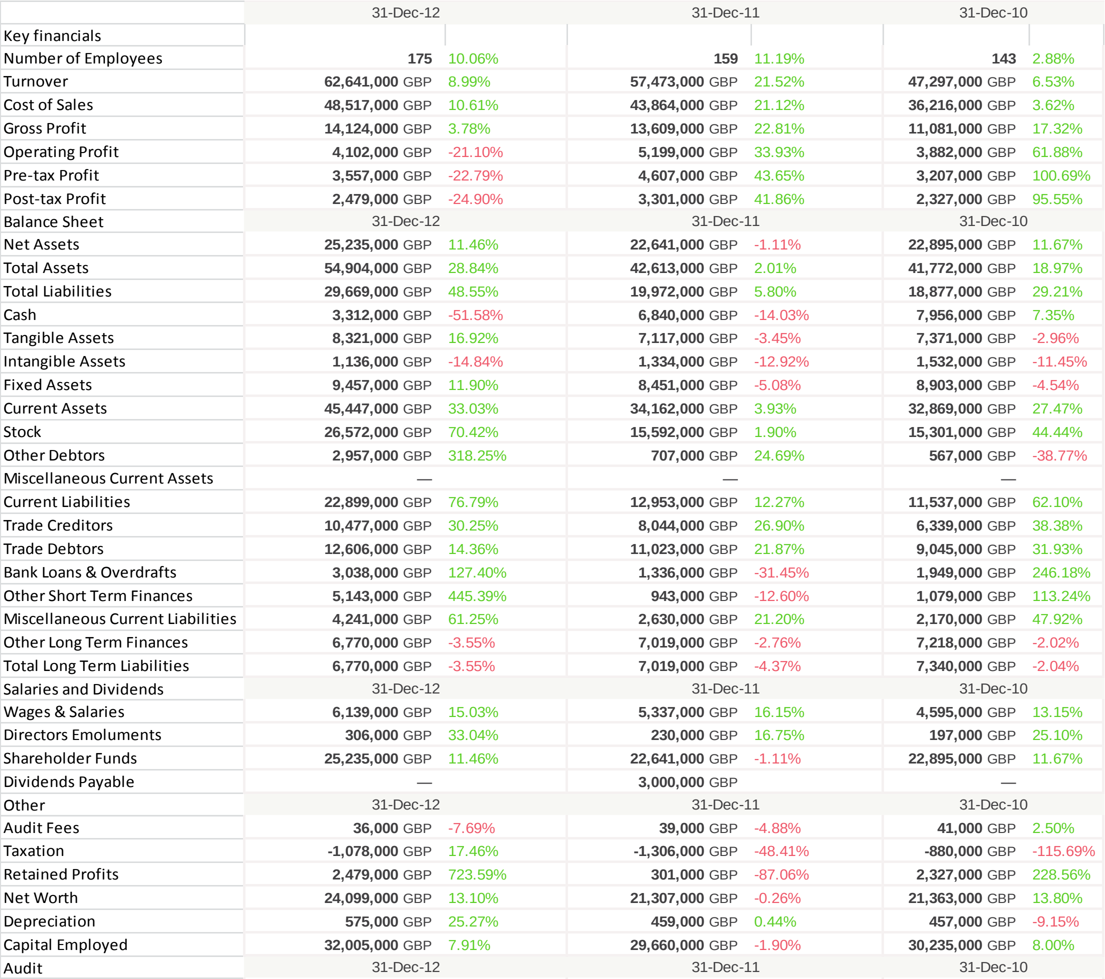
Figure A-1: The relation between the entropy and the number of partitions

B. Tubes SC Case: Interviews Questions and Data Examples

B.1 Semi-Structure Interview and Meetings Questions

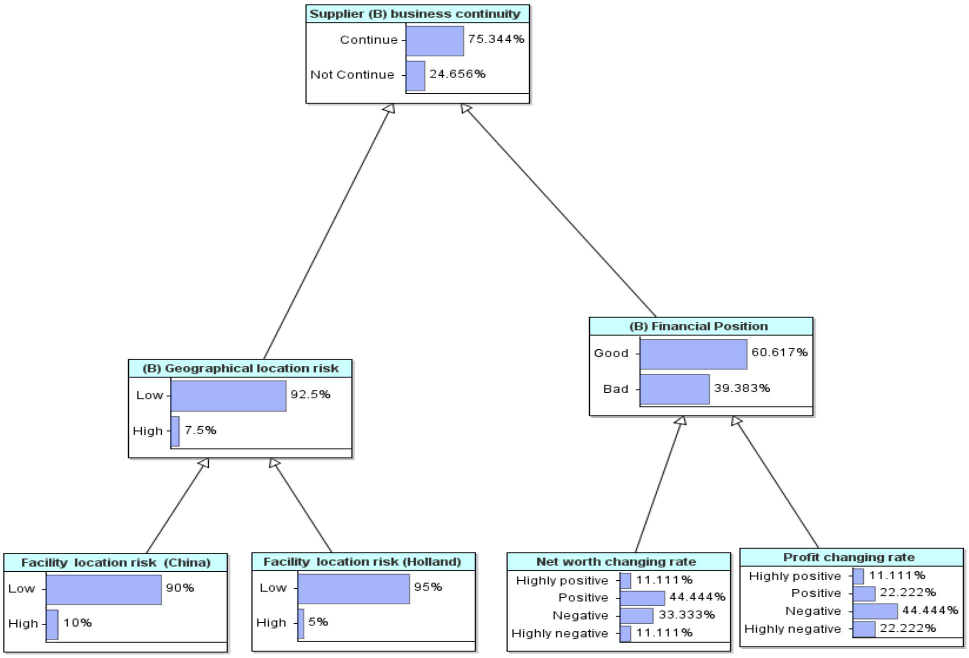
1. Could you please identify a product or group of products that they are strategically important to the company or you have concerns about the resilience of their supply chain?
2. What are the main suppliers for “tubes”? Where are they located?
3. Do you have any idea about the suppliers of your suppliers?
4. How do you order from your suppliers?
5. What are main risks events could affect your suppliers?
6. Where are the main warehouses for “tubes”?
7. What are main hazards concern you about tubes warehouses?
8. Could you please describe the transportation process and what are the means of transportation between warehouses and suppliers?
9. Where are the main consumption points for “tubes”?
10. Could you please describe the transportation process and what are the means of transportation between tubes warehouses and their consumption points (Hubs)?
11. What are the main hazards could affect transportation between suppliers and warehouses and warehouses and the consumption point?
12. What is the current strategy in assessing and managing the supply chain risks?

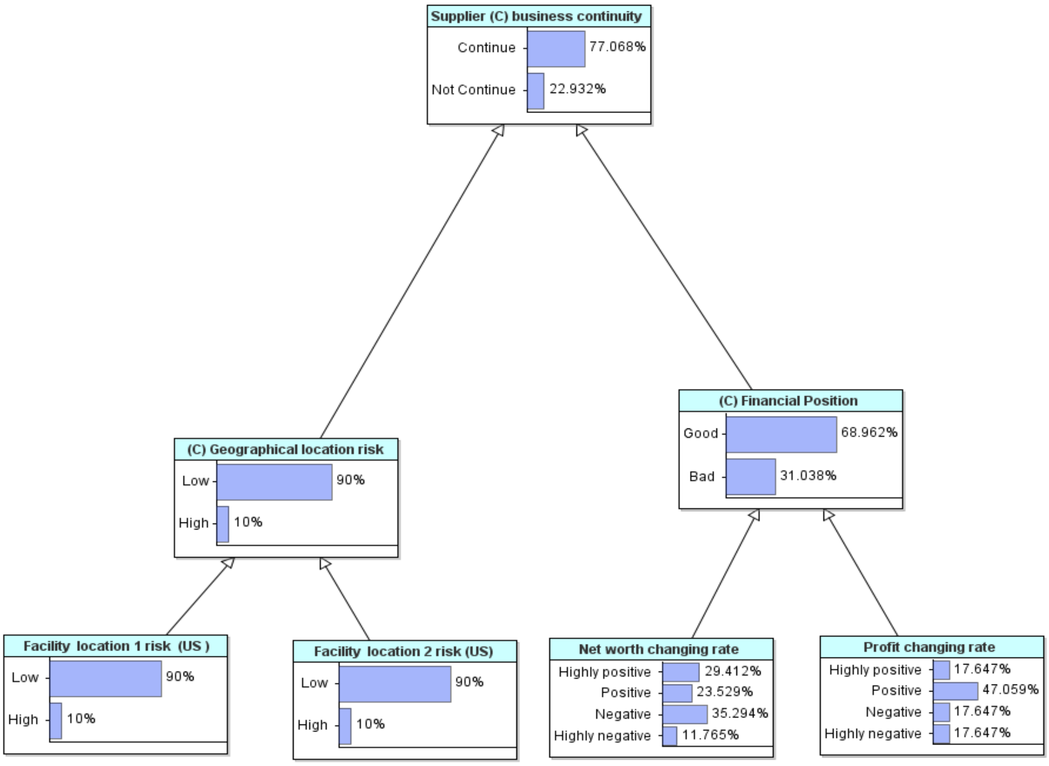
B.2. Sample of Financial Data for One Supplier

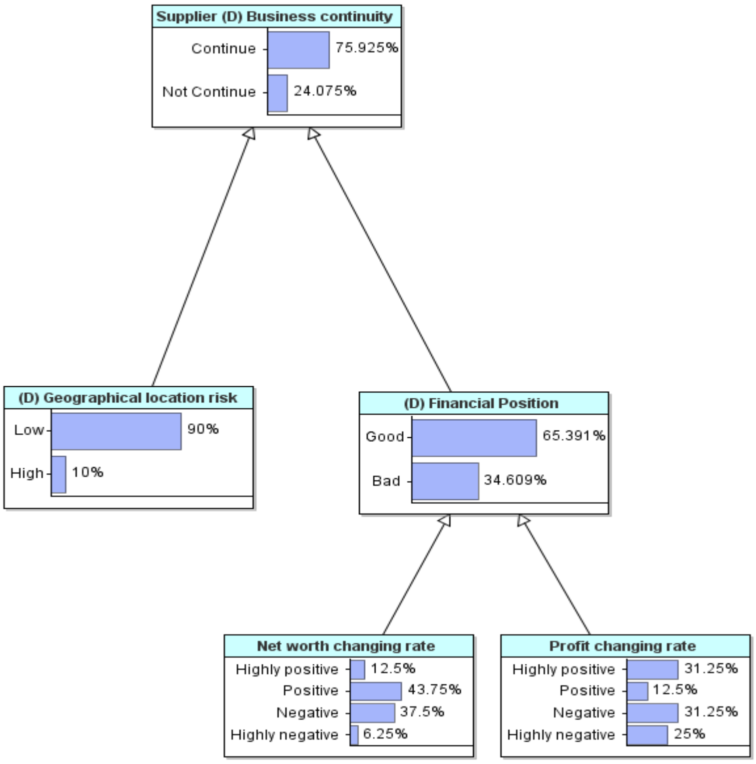


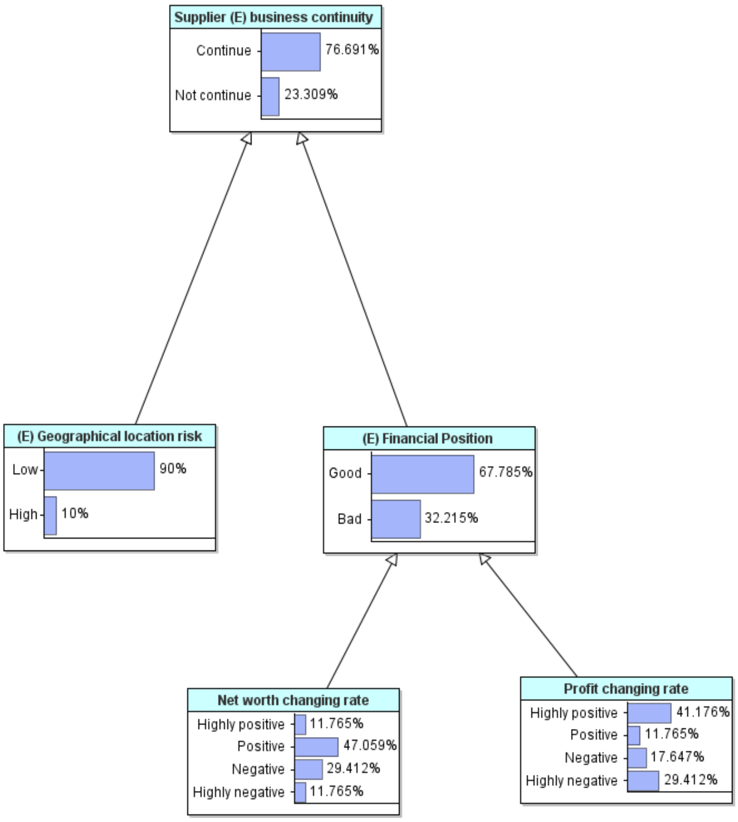
	31-Dec-12		31-Dec-11		31-Dec-10	
Key financials						
Number of Employees	**175**	10.06%	**159**	11.19%	**143**	2.88%
Turnover	**62,641,000** GBP	8.99%	**57,473,000** GBP	21.52%	**47,297,000** GBP	6.53%
Cost of Sales	**48,517,000** GBP	10.61%	**43,864,000** GBP	21.12%	**36,216,000** GBP	3.62%
Gross Profit	**14,124,000** GBP	3.78%	**13,609,000** GBP	22.81%	**11,081,000** GBP	17.32%
Operating Profit	**4,102,000** GBP	-21.10%	**5,199,000** GBP	33.93%	**3,882,000** GBP	61.88%
Pre-tax Profit	**3,557,000** GBP	-22.79%	**4,607,000** GBP	43.65%	**3,207,000** GBP	100.69%
Post-tax Profit	**2,479,000** GBP	-24.90%	**3,301,000** GBP	41.86%	**2,327,000** GBP	95.55%
Balance Sheet	31-Dec-12		31-Dec-11		31-Dec-10	
Net Assets	**25,235,000** GBP	11.46%	**22,641,000** GBP	-1.11%	**22,895,000** GBP	11.67%
Total Assets	**54,904,000** GBP	28.84%	**42,613,000** GBP	2.01%	**41,772,000** GBP	18.97%
Total Liabilities	**29,669,000** GBP	48.55%	**19,972,000** GBP	5.80%	**18,877,000** GBP	29.21%
Cash	**3,312,000** GBP	-51.58%	**6,840,000** GBP	-14.03%	**7,956,000** GBP	7.35%
Tangible Assets	**8,321,000** GBP	16.92%	**7,117,000** GBP	-3.45%	**7,371,000** GBP	-2.96%
Intangible Assets	**1,136,000** GBP	-14.84%	**1,334,000** GBP	-12.92%	**1,532,000** GBP	-11.45%
Fixed Assets	**9,457,000** GBP	11.90%	**8,451,000** GBP	-5.08%	**8,903,000** GBP	-4.54%
Current Assets	**45,447,000** GBP	33.03%	**34,162,000** GBP	3.93%	**32,869,000** GBP	27.47%
Stock	**26,572,000** GBP	70.42%	**15,592,000** GBP	1.90%	**15,301,000** GBP	44.44%
Other Debtors	**2,957,000** GBP	318.25%	**707,000** GBP	24.69%	**567,000** GBP	-38.77%
Miscellaneous Current Assets	—		—		—	
Current Liabilities	**22,899,000** GBP	76.79%	**12,953,000** GBP	12.27%	**11,537,000** GBP	62.10%
Trade Creditors	**10,477,000** GBP	30.25%	**8,044,000** GBP	26.90%	**6,339,000** GBP	38.38%
Trade Debtors	**12,606,000** GBP	14.36%	**11,023,000** GBP	21.87%	**9,045,000** GBP	31.93%
Bank Loans & Overdrafts	**3,038,000** GBP	127.40%	**1,336,000** GBP	-31.45%	**1,949,000** GBP	246.18%
Other Short Term Finances	**5,143,000** GBP	445.39%	**943,000** GBP	-12.60%	**1,079,000** GBP	113.24%
Miscellaneous Current Liabilities	**4,241,000** GBP	61.25%	**2,630,000** GBP	21.20%	**2,170,000** GBP	47.92%
Other Long Term Finances	**6,770,000** GBP	-3.55%	**7,019,000** GBP	-2.76%	**7,218,000** GBP	-2.02%
Total Long Term Liabilities	**6,770,000** GBP	-3.55%	**7,019,000** GBP	-4.37%	**7,340,000** GBP	-2.04%
Salaries and Dividends	31-Dec-12		31-Dec-11		31-Dec-10	
Wages & Salaries	**6,139,000** GBP	15.03%	**5,337,000** GBP	16.15%	**4,595,000** GBP	13.15%
Directors Emoluments	**306,000** GBP	33.04%	**230,000** GBP	16.75%	**197,000** GBP	25.10%
Shareholder Funds	**25,235,000** GBP	11.46%	**22,641,000** GBP	-1.11%	**22,895,000** GBP	11.67%
Dividends Payable	—		**3,000,000** GBP		—	
Other	31-Dec-12		31-Dec-11		31-Dec-10	
Audit Fees	**36,000** GBP	-7.69%	**39,000** GBP	-4.88%	**41,000** GBP	2.50%
Taxation	**-1,078,000** GBP	17.46%	**-1,306,000** GBP	-48.41%	**-880,000** GBP	-115.69%
Retained Profits	**2,479,000** GBP	723.59%	**301,000** GBP	-87.06%	**2,327,000** GBP	228.56%
Net Worth	**24,099,000** GBP	13.10%	**21,307,000** GBP	-0.26%	**21,363,000** GBP	13.80%
Depreciation	**575,000** GBP	25.27%	**459,000** GBP	0.44%	**457,000** GBP	-9.15%
Capital Employed	**32,005,000** GBP	7.91%	**29,660,000** GBP	-1.90%	**30,235,000** GBP	8.00%
Audit	31-Dec-12		31-Dec-11		31-Dec-10	

B.3. Suppliers Business Continuity Calculation






Supplier (D) Business continuity
Continue 75.925%
Not Continue 24.075%
(D) Geographical location risk
Low 90%
High 10%
(D) Financial Position
Good 65.391%
Bad 34.609%
Net worth changing rate
Highly positive 12.5%
Positive 43.75%
Negative 37.5%
Highly negative 6.25%
Profit changing rate
Highly positive 31.25%
Positive 12.5%
Negative 31.25%
Highly negative 25%


Supplier (E) business continuity
Continue 76.691%
Not continue 23.309%
(E) Geographical location risk
Low 90%
High 10%
(E) Financial Position
Good 67.785%
Bad 32.215%
Net worth changing rate
Highly positive 11.765%
Positive 47.059%
Negative 29.412%
Highly negative 11.765%
Profit changing rate
Highly positive 41.176%
Positive 11.765%
Negative 17.647%
Highly negative 29.412%

B.4 Tubes Specifications

1/4"ODx.036WT 316/316L	1/8"ODx.028WT	1.1/4"NB SCH40	1/2"ODx.095WT
1/4"ODx.048WT 316/316L	5/8"ODx.048WT	1.1/2"NB SCH40	5/8" OD.x.095"WT 316 TUBES
1/4"ODx.064WT 316/316L	5/8"ODx.064WT	2"NB SCH40	3/4"ODx.125WT
3/8"ODx.036WT 316/316L	3/4"ODx.109"WT	1/4"NB SCH80	1"ODx.036WT
3/8"ODx.048WT 316/316L	1"ODx.049WT	1/2"NB SCH80 SEAMLESS	1.1/4"OD x 0.134" 316SS TUBING
3/8"ODx.064WT 316/316L	3MMx.3MM	3/4"NB SCH80	1/4"ODx.065"WT 6MO A269
1/2"ODx.036WT 316/316L	8MMx1.5MM	1 NB SCH80	3/4"OD x .095" INCONEL TUBES
1/2 ODx.048WT 316/316L	15MMx1MM	1.1/2"NB SCH80	3/4"ODx.125"INCONEL625
1/2"ODx.064WT 316/316L	15MMx1.5MM	1/2"NB SCH160	3/4" OD X 0.156" INCONEL625
3/4"ODx.048WT 316/316L	15MM x 2MM	1.1/2"NB SCH160	3/8"ODx.083"SUPER DUPLEX
6MM ODx1MM WT 316/316L	18MMx1.5MM	1/4"ODx.035WT 6MO	5/8"ODx .083" SUPER DUPLEX
6MM ODx1.5MM WT 316/316L	18MMx2MM	1/2"ODx.065WT 6MO	12MM ODx1.5MM WT 316/316L
8MM ODx1MM WT 316/316L	20MMx1.5MM	GE TUBING	16MM ODx2MM WT 316/316L
10MM ODx1MM WT 316/316L	20MMX3MM	1/2"ODx.083WT 316/316L	1/16"ODx .016" 316SS
10MM ODx1.5MM WT 316/316L	22MMx2MM	3/4"ODx.064WT 316/316L	1/8"ODx.036WT
10MM ODx2MM WT 316/316L	28MMx2MM	3/4 ODx.083WT 316/316L	1/4"ODx.028WT
12MM ODx1MM WT 316/316L	35MMx2.0MM	1"ODx.083WT 316/316L	3/8"ODx.083WT

12MM ODx2MM WT 316/316L	38MMx2MM	6MM ODx2MM WT 316/316L	3/8"ODx.095WT 316L
16MM ODx1.5MM WT 316/316L	42MMx3MM	1/16"ODx.022WT	1/2"ODx.104WT
20MM ODx2MM WT 316/316L	1/4 NB SCH40	1/4"ODx.080WT	1/2"ODx.125WT
25MM ODx2MM WT 316/316L	1/2 NB SCH40	3/8"ODx.104WT	3/4"ODx.036WT
25MM ODx3MM WT 316/316L	1"NB SCH40	3/8"ODx.125WT	1"ODx.064WT
6MM x 1MM 400	10MMx1.5MM 400	1/2"ODx.083WT 400	1"ODx.104WT
6mmx1.5mm 6MO A269	12MMx1.5MM 400	1/2"ODx.049WT 904L	1"ODx.125WT
3/8"ODx.083"WT 6MO A269	12MMx2MM 400	38MMx4MM	25MMx2.5MM
6MM ODx1.5MM HASTELLOY TUBES	1/4"ODx.064WT 400	3/8"NB SCH 40	30MMx3MM
10MM ODx1.5MM HASTELLOY TUBES	3/8"ODx.064WT 400	6mmODx1mm WT 6MO	30MMx3MM
12MM X 1.5MM HASTELLOY TUBES	1/2"ODx.064WT 400	1/2"ODx.049WT 6MO A269	3/4"NB SCH40
1/2"ODx.065"INCONEL625	MS15-055 316/316L SS	1/2"ODx.095"INCONEL625	MS15-085 316/316L SS
5/8"OD X 0.083"INCONEL625	MS15-062 316/316L SS	1/16"OD x .010 ALLOY 600	MS15-097 316/316L SS
3/8" OD X 0.071" WT DUPLEX	MS15-065 316/316L SS	1/8"OD X 0.035" WT	MS15-095 316/316L SS
1/2"ODx 049 SUPER DUPLEX	MS15-254 316/316L SS	FT6MO916	MS15-098 316/316L SS
B20-203-316	MS15-251 316/316L SS	3/8"ODx.065"INC625	MS15-096 316/316L SS

1/2"NB SCH80 UNS 32760 PIPE	12262	3/8"ODx.083"INC625	MS15-099 316/316L GRADE SS
MS15-051 316/316L SS	MS15-092 316/316L SS	3/4"ODx.125"INC625	MS15-081 316/316L SS
MS15-150 316 SS	MS15-093 316/316L SS	12mmODx1.5mm WT 6MO	MS15-087 316/316L SS
3/8"ODx.065"INCONEL625	MS15-093 316/316L 2.5%MO	20mmODx2mm WT 6MO	MS15-083 316/316L SS
3/8"ODx.083"INCONEL625	MS15-090	25mmODx2mm WT 6MO	MS15-252 316/316L SS
1/2"ODx.083"WT 6MO A269	3/8"ODx.065WT 6MO	6mmx1mm 6MO A269	12mmx 1.5mm 6MO A269
1/4"ODx.065"INCONEL625	1/2"ODx.064"WT 6MO A269	10mmx1.5mm 6MO A269	12mm x 2mm 6MO A269

C. Spare Parts SCs: Sample of Semi- structure Interviews Questions:

1. Could you please tell me in general about the production process?
2. Could you please identify a SC or group of SCs that they are strategically important for your production process and you have concerns about them?
3. Regarding the spare parts are there one of some of them are so important? How do you classify them?
4. How do you decide that you need to order more from the spare parts?
5. What are the main suppliers of “spare parts”? Where are they located?

6. Could you please describe the transportation process and what are the means of transportation between warehouses and suppliers?
7. What is the current strategy in assessing and managing the supply chain risks?
8. What do you think the main hazards that could affect your suppliers? Transportations from suppliers to warehouses? Machinery? Transportations?

D. Atlantic Canada Case: Interviews Questions and Data Examples

D.1 Semi-Structure Interviews Questions

Initial discussion questions:

1. Could you please identify a supply chain that they are strategically important to the company or you have concerns about the resilience?
2. What are your main concerns about the identified supply chain?

First interview questions (An example about the chickens supply chain)

1. Could you please describe in general the chickens supply chain?
2. Who are the suppliers of the packer? What type of material does each of them supply? Where are they located?
3. What are the means of transportation between the packer and their suppliers?
4. What are main hazards could affect the suppliers of the packer?
5. Where does the company keep the chickens?
6. What are the means of transportation between the packer and the DC where the chickens are stored?
7. What are the main hazards could affect the distribution centre?
8. What are the main hazards could affect transportation between the Packer and the DC?
9. What is the current strategy in assessing and managing the risk?

Validation questions (After drawing the main structure of the network and the qualitative structure of DBN and showed them to the interviewee)

1. Do we correctly capture the chickens supply chain map from your point of view?

2. Does the model include the main factor that affects the resilience of the chickens supply chain?

D.2 Sample of Performance Data for DC (B) from 2011

Week	Performance
01/01/2011	94.21
08/01/2011	92.45
15/01/2011	93.07
22/01/2011	90.19
29/01/2011	92.54
05/02/2011	88.6
12/02/2011	92.01
19/02/2011	92.25
26/02/2011	92.22
05/03/2011	90.03
12/03/2011	91.79
19/03/2011	87.1
26/03/2011	92.9
02/04/2011	93.93
09/04/2011	95.51
16/04/2011	95.16
23/04/2011	94.3
30/04/2011	94.16
07/05/2011	95.52
14/05/2011	93.69
21/05/2011	94.74
28/05/2011	94.4
04/06/2011	93.7

D.3 Calculation Matrix for DC Performance

ordered	Available to ship	
782	781	
98	94	
3	3	
1737	1736	
82	81	
121	121	
2823	2816	
		99.8

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