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A Bayesian Belief Network Modelling Process for Systemic Supply Chain Risk

by

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Abstract

To effectively manage risk in supply chains, it is important to understand the interrelationships between risk events that might affect the flow of material, products and information within the chain. Typical supply chain risk management tends to treat events as if they are independent and so fail to capture the systemic nature of supply chain risks.

This thesis addresses this shortcoming by developing a quantitative modelling process to support systemic supply chain risk analysis. Bayesian Belief Network (BBN) models are able to capture both the aleatory and epistemic uncertainties associated with supply chains and to represent probabilistic dependency relationships. A visual modelling process, grounded in the theory of BBN and the decision context of supply chain risk management, is developed to capture the knowledge and probability judgements of relevant stakeholders. An experiment has been conducted to evaluate alternative approaches to structuring a BBN model for supply risk. It is found that building causal maps provides a good basis for translating stakeholder cause-effect knowledge about the supply chain risks into a formal graphical probability model, which underpins the BBN. The modelling process has been evaluated through a longitudinal case for the hospital medicine supply of NHS Greater Glasgow & Clyde. A BBN model has been developed in collaboration with relevant stakeholders who have expertise in all or part of the medicine supply chain. The perceptions of these stakeholders about the modelling process and results generated have been formally gathered and analysed. The BBN model of the medicine supply chain has provided insight into risks not captured by conventional risk management methods and supported deeper understanding of risk through exploration of modelling scenarios. Analysis of stakeholder evaluation of the modelling process provided valuable insights into the operationalization of BBN modelling for supply risk and has informed the final modelling process developed through this research.

Contents

List of Figures

List of Tables

List of Abbreviations

AHP	Analytical Hierarchy Process
BBN	Bayesian Belief Network
CDC	Centralised Distribution Centre
CM	Causal Map
CPT	Conditional Probability Table
DAG	Directed Acyclic Graph
DBN	Dynamic Bayesian Network
DES	Discrete Event Simulation
ET	Event Tree
FMEA	Failure Modes and Effect Analysis
FMECA	Failure Mode and Effect Criticality Analysis
FT	Fault Tree
GG&C	Greater Glasgow and Clyde
ID	Identification number
IPS	Individual Patient Supply
MCDA	Multi-criteria Decision Analysis
MMyM	Making the Most of Your Medicine
NHS	National Health Service
PDC	Pharmacy Distribution Centre (aka CDC)
PN	Petri Net
PT	Probability Table
RR	Risk Register
RRM	Risk Register Map
SC	Supply Chain
SCM	Supply Chain Management
SCRM	Supply Chain Risk Management
SD	System Dynamics
SN	Supply Network
SRI	Stanford Research Institute

Chapter 1 Introduction

Analysis is a key element of risk management (Wu et al., 2006). In a supply chain context there is a need to model systemic risks arising as a result of dependencies between adverse events if effective supply risk management decisions are to be supported. This chapter introduces key concepts and definitions relevant to supply chain risk for the development of models to support risk analysis. By identifying the important challenges from the literature, we scope the objectives of the research study and outline the structure of the thesis.

1.1 On the Nature of Supply Chains and their Management

A Supply Chain (SC) is the flow of goods or services, information, money from original supply sources to the end customers (Harland, 2001; Lamming et al., 2000). The general components of a SC are the actors, resources, and activities (Harland, 1996), where an actor can be connected to other actors via resources and activities. Actors have knowledge to control resources and perform activities.

The flow of resources either forward or backward from one to another actor can take place as a result of different activities. For example, Figure 1-1 shows that an original supply source can flow the material to supplier, transform to products and supply via different agents to the end customer. The resources that can flow forward consist of materials, products, services, and some information, but other information, and money, can flow in a backward direction. The resources can move from original supply sources to supplier, to manufacturer, to customer, and then to the end customer. On the other hand, a reverse SC may involve the return or exchange activities: the direction of resources in such cases will be the opposite of the regular forward SC flow.

A company, or organisation or agent, can be a member of different chains even playing different roles in each. For example, a company can be a supplier when its product is sold as a component to other manufacturers or the same company can sell directly to end customers. Therefore particular companies can determine their role in a SC by considering their relationships with their stakeholders for particular products. In addition, within each phase of the integrated SC are operational activities such as sourcing, purchasing, planning so there are SCs relevant to the operations (Waller, 2003).

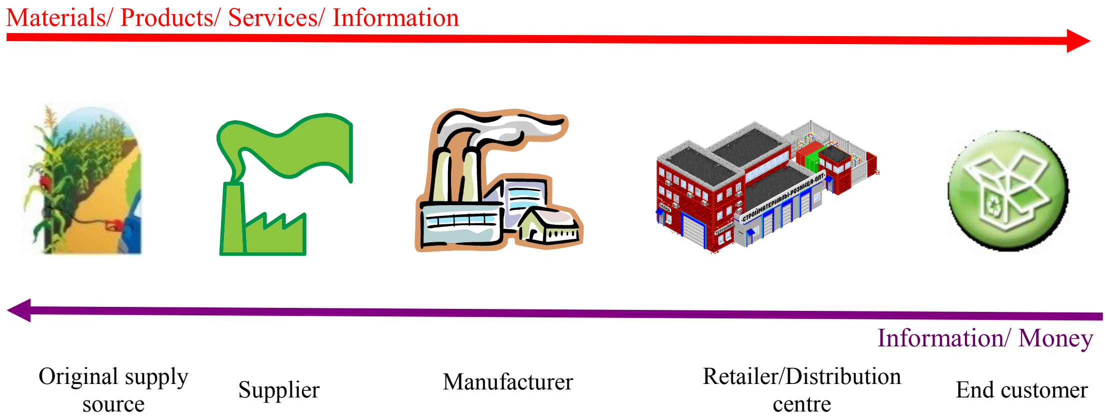


Figure 1-1 Generic supply chain

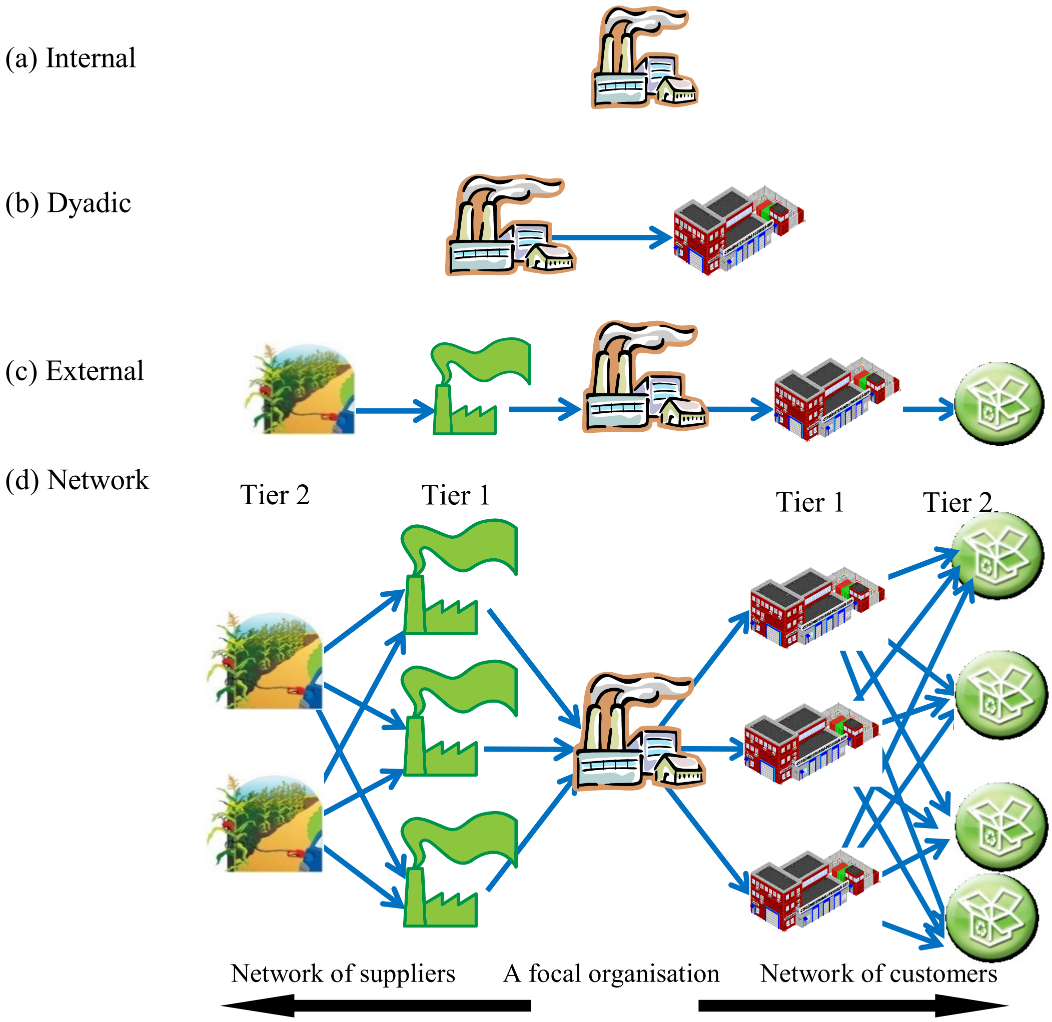
1.1.1 Classification of supply chain structures

The usual classifications of SC are physical, financial, informational, relational, and innovation SCs (e.g. Cavinato, 2004; Ritchie and Brindley, 2007a). However, SC have also been categorised by, for example, the level of the Supply Network (SN) (e.g. Bi and Lin, 2009; Harland, 2001; Mills et al., 2004), by number of stages and tiers in a SC (e.g. Capar et al., 2004; Neureuther and Kenyon, 2008), the characteristics of the relationships (e.g. Grandori and Soda, 1995; Hayes et al., 2005; Hinterhuber and Levin, 1994; MacCarthy and Jayarathne, 2013; Nassimbeni, 1998; Rosenfeld, 1996), the characteristics of product type (e.g. Faisal et al., 2006a; Fisher, 1997; Lamming et al., 2000; Wong et al., 2006). Appendix A presents a summary of the SC classifications reported in the literature.

The distinction between inter- and intra-organisational supply chain management and the SC structure scope has been categorised by Harland (1996) and Bi and Lin (2009). An intra-organisational SC refers to the case where there is a single management level for the chain. While in a so-called inter-organisational SC, leadership is carried out either by a *focal company* (point of reference in the defined SC) or a steering committee. When a company wants to manage risk in their own SC, the geographical boundary of the SC should be defined by considering the scope of management.

Figure 1-2 shows four types of SC relationships. *Internal relationships* are inbound relationships that do not link actors to their stakeholders, such as relationships within a plant, in a warehouse. *Dyadic relationships* are relationships between (only) two organisations, for example a focal company and a customer, or a focal company and a supplier etc. *External* *relationships* are relationships between actors in the chain but they do not consider the number of layers. *Network relationships* form a network of a focal company that links it to its customers and suppliers in different layers and tiers under the some resources or activities.

Typically, a SC has different tiers but each tier has only one actor. In contrast a SN is a set of SCs (Lamming et al., 2000) or multiple SCs (Mills et al., 2004) so may involve lateral links in different tiers with each tier possessing relationships between at least two actors, reverse loops and two way exchanges. While a SC might focus on the linear flow of materials and information, according to (Harland, 2001), a SN also includes a broad strategic view of management of the supply network.



Source: Adapted from Bi and Lin, 2009; Harland, 1996

Figure 1-2 General network relationship in supply chain management

1.1.2 Supply chain management decision making levels

Decision making associated with a SC may be associated with the goal of fulfilling customer demand and improving competitiveness for either the SC as a whole or for a single company within the SC (i.e. including stakeholders); see (Stadtler, 2005). Levels of decision making in Supply Chain Management (SCM) need to be clearly defined in order to identify the objectives relevant for SC planning. Typically, there are three levels in SC planning or decision making: strategic, tactical and operational. The differences between the three levels can be shown by comparing them under the headings: objectives (PRAM, 2004); time period (Chong and Brown, 2000; Shapiro, 2007); level of detail (Graham and Jones, 1988; Lee et al., 2002); nature of analysis (Graham and Jones, 1988) and decision problems (Van Landeghem and Vanmaele, 2002; Lee et al., 2002) which are summarised in Table 1-1.

Sometimes 'high level' is said to represent the strategic level and 'low or lower level' to represent tactical or operational levels. However, all decision making from operational to strategic level is relevant: strategic planning, for example, will impact the operational level (Zsidisin and Ritchie, 2008) and, according to (Cox, 2009) we might expect risks to be associated between different levels of decision-making.

Table 1-1 Summarised hierarchical levels of decision making in SC

Objective	Strategic	Tactical	Operational
Objective	Strategic objective	Functional objectives	Procurement objectives
Time period	Long-term/roughly 3 years or longer	Medium-term/1 to 3 years	Short-term/12 months or less
Level of detail	Simple detailed & high precision	Normal detailed & mostly high precision	Very detailed & low precision
Nature of analysis	Quantitative (Tightly defined definition)	Largely quantitative (Defined definition)	Largely qualitative (Loosely defined definition)
Typical decision problem	SC design business planning	Sales & operations planning	Master production scheduling plant scheduling
Example of decision problem	Define SC design (e.g. lean, agile etc.), location of distribution centre, plants	Volumes per product family, target levels of stock	Production volume and timing per product item, transportation orders, purchase orders, detailed capacity usage per shift

1.1.3 Distinguishing between projects and processes in supply chain management

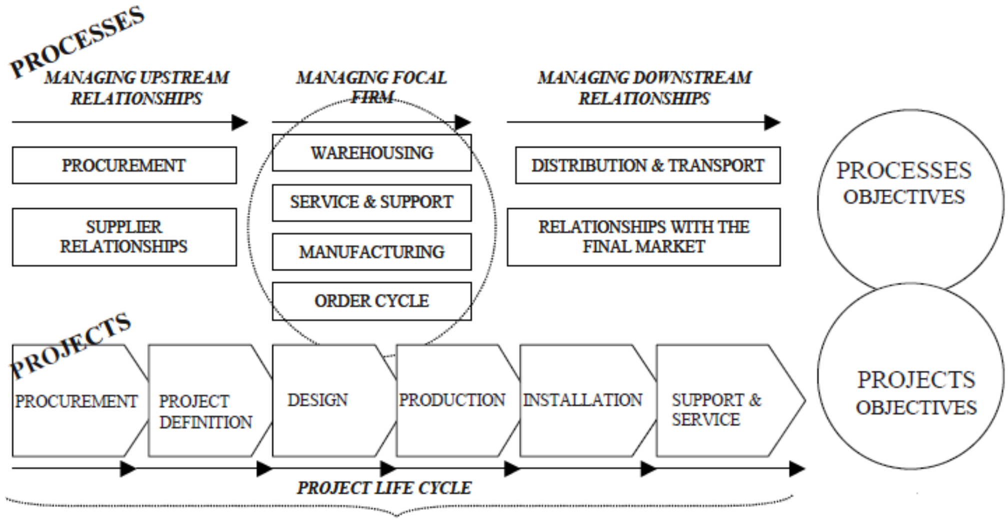
When considering SCM decisions it is also worth distinguishing between a SC project and a SC process. A project is considered to "*have starting points and finishing points*" (Edwards and Bowen, 2005, p. 30) and "*needs to deliver the project on time in budget and to scope*" (Morris and Pinto, 2007, p. x) whereas a process is "*an approach for converting inputs into* *outputs. It is the way in which all the resources of an organisation are used in a reliable, repeatable and consistent way to achieve its goals"* (Zairi, 1997, p. 64). According to the general definition given by ISO 10006, *"projects are unique processes"* (Gaudenzi, 2008, p. 68).

The typical activities of a SC project and process are explained by Gaudenzi (2008) as shown in Figure 1-3 and their characteristics are compared and summarised in Table 1-2. Naturally, a project aims to meet the requirements at the end of the project under limited resources and has to do with creating a new outcome (Rosenau and Githens, 2005) and it is not routine work (Young, 2003). On the other hand, process is routine work and potentially continuous and is needed to reach the SC goal such as becoming lean or agile (Gaudenzi, 2008). Therefore 'project' involves more strategic activities (Rosenau and Githens, 2005) while 'process' involves more operational level tasks.

Table 1-2 Differences between SC project and SC process

	Criteria	SC Project	SC Process
1	Nature	Temporary and new outcome	Continuous and day-to-day or routine work
2	Level of study	More strategic level	More operational level
3	Goal and matrix of management	Time, cost and customer expectation Well managed as a phase approach	SC goal (e.g. traditional, lean, agile, leagile)
4	Objective	Specific purpose Define objectives and outcomes in a progression, throughout their life cycle	Are oriented towards a set of objectives
5	Flexibility/consistency	More flexible by using a phase approach (more dynamic)	Less flexible (less dynamic)
6	Uniqueness	Unique	Not unique
7	Complexity	More complex	Less complex
8	Unknown	Many unknowns	Fewer unknowns

Moreover, projects define objectives and outcomes in a progression (Gaudenzi, 2008), throughout their life cycle, while processes – and their internal and sequential activities – are oriented towards a fixed set of objectives. Therefore a 'project' is more flexible; progress can be revised in a phased approach or it can accommodate change dynamically, while a 'process' is less flexible and less dynamic. A 'project' can relate to the creative or novel, so a project is unique and more complex than a process. Furthermore a project can provide opportunities to learn new skills since participants can have the temporary management roles during the life of the project (Young, 2003). SC projects can involve a high level of unknown factors and state of knowledge uncertainty (Khodakarami et al., 2007). There are many unknowns within a project to do with the work itself, people skills and external influence (Young, 2003). On the other hand, SC processes tend to be associated with fewer unknowns. Since their characteristics are different, they may not use the same approach to represent those activities.



Source: Gaudenzi, 2008

Figure 1-3 Difference between project and process in a SC context

1.1.4 Vulnerabilities in supply chains

Each SC will be aligned with its own goal. For example, a SC might be designed to be low cost but another SC designed to offer fast response to demand. There are four framing types reported to differentiate between common SC goals: traditional, lean, agile and 'leagile' (Faisal et al., 2006b). It is possible for suitable SC goals to be matched with different product types, as suggested by Lamming et al. (2000). For example, they suggested that lean SCs can fit with functional products but agile SCs are suitable with innovative products. Furthermore Faisal et al. (2006a) suggested that traditional SCs and lean SCs will tend to be suitable SC strategies for functional products with low risk alleviation competency, but agile SCs will be suited to innovative products with high risk alleviation competency. On the other hand, leagile SCs can be matched to innovative products with moderate risk alleviation. Although articulating the SC goal will help an organisation to define its strategy to achieve that goal, Faisal et al. (2006b) also point out that particular types of SCs are also vulnerable in different ways. For example, consider the following situations.

1. *A traditional SC* is designed to flow materials or products at the lowest purchasing cost. Since the traditional SC will have multiple partners and short-term contracts to maintain the lowest purchasing cost by reserving level of stock, they cannot cope with a variety of demands. When there are disruptions, they can gain products or materials from other sources but at higher cost.
2. *A lean SC* focuses on reducing waste, including time. Lean SC is suitable when product demand is stable so that stocks can be set up with low inventory levels and can depend on outsourcing. The impact of disruption would be very high and the network is vulnerable to any disruption in the SC.
3. *An agile SC* focuses on dealing with uncertain demand and customers' satisfaction, so an agile SC highlights on downstream SC (network of customer). Agile SCs aim to respond to demands in real time with high speed and flexibility, so it can be very vulnerable but in a limited time period.
4. *A leagile* SC is a combination of lean and agile SC. It focuses both upstream by using lean before decoupling point and downstream by using agile after decoupling point so it aims to manage cost effectiveness (with suppliers) and high service levels (to customers). Leagile SC is a mix of lean and agile SC so its vulnerability is somewhere between the two.

There is no perfect frame for a SC since there exists the potential for vulnerabilities in whatever type is adopted. Let us explore such vulnerabilities further by examining the sources and types of risks in SCs.

1.2 Supply Chain Risks

There is no consensus definition of SC risk and there exists multiple SC risk classifications reported within the literature – see, for example, Sodhi and Tang (2012), Zsidisin and Ritchie (2008) among others. In this section we explore what is meant by risk, before describing the sources of supply risk by drawing on the concepts discussed in the existing literature and considering the nature of dependencies between supply risk events.

1.2.1 The nature of risk in a supply chain

Risk is a word derived from the early Italian word 'risicare', which means 'to dare' (Khan and Burnes, 2007). Initially risk was studied in mathematics in a gambling perspective, and the results have been implemented widely in different fields. However, the meaning of 'risk' has been interpreted differently over time by different perceptions in different fields.

SC risk is defined in various ways in the literature. Words such as uncertainty, disturbance, disruption and nervousness are used interchangeably (Barroso et al., 2008; Khan and Burnes, 2007; Ritchie and Brindley, 2007a). But different scholars use them slightly differently.

The definition of 'risk' used in this research is the one given by the Royal Society. That is: *"The probability that a particular adverse event occurs during a stated period of time, or results from a particular challenge"* (The Royal Society, 1992, p. 2).

In other words, the components of risk are the probability and result/consequence/severity of events. Since an adverse event can happen or not, it will be described by *uncertainty* (see Section 2.2.1) and can be represented by probability. Furthermore, once an adverse event has occurred, it can generate uncertain levels of effects.

1.2.2 Sources of supply chain risk

A range of types of SC risk have been classified and expressed in SC risk taxonomies (e.g. Wagner and Bode, 2008; Wu et al., 2006). Many scholars have formed such taxonomies by collecting data, such as experts' experiences (Chopra and Sodhi, 2004; Simchi-Levi et al., 2008), surveys (Hillman, 2006), interviewing managers or other staff (Barroso et al., 2008), or literature reviews (Harland et al., 2003; Wu et al., 2006). Other risk classifications are developed to support studies that focus on particular risks, such as risks from suppliers (Levary, 2007; Treleven and Schweikhart, 1988), or risks from strategic alliances (Das and Teng, 2001a, 2001b), or risks in process (Haimes, 1991; Smallman, 1996).

A classification of possible sources of risks is proposed that relates to the scope and SC structure (see Section 1.1.1) by considering the relationships among agents, or stakeholders, from a focal organisation perspective. External environment, demand-side uncertainty, supply-side uncertainty and vulnerabilities in own organisations (see Figure 1-4) are classified as the four main risk sources. The external environment source indicates adverse events which cannot be controlled because they are mainly generated from the environment. Demand-side and supply-side uncertainty are generated by the focal organisation's partners or stakeholders in the given SC. The vulnerability in SC is known to be the problem of management (see Section 1.1.4) because some management strategies can reduce some adverse events but yet also stimulate other adverse events during policy implementation. Sources and subcategories of risks are summarised in Figure 1-4 and Figure 1-5.

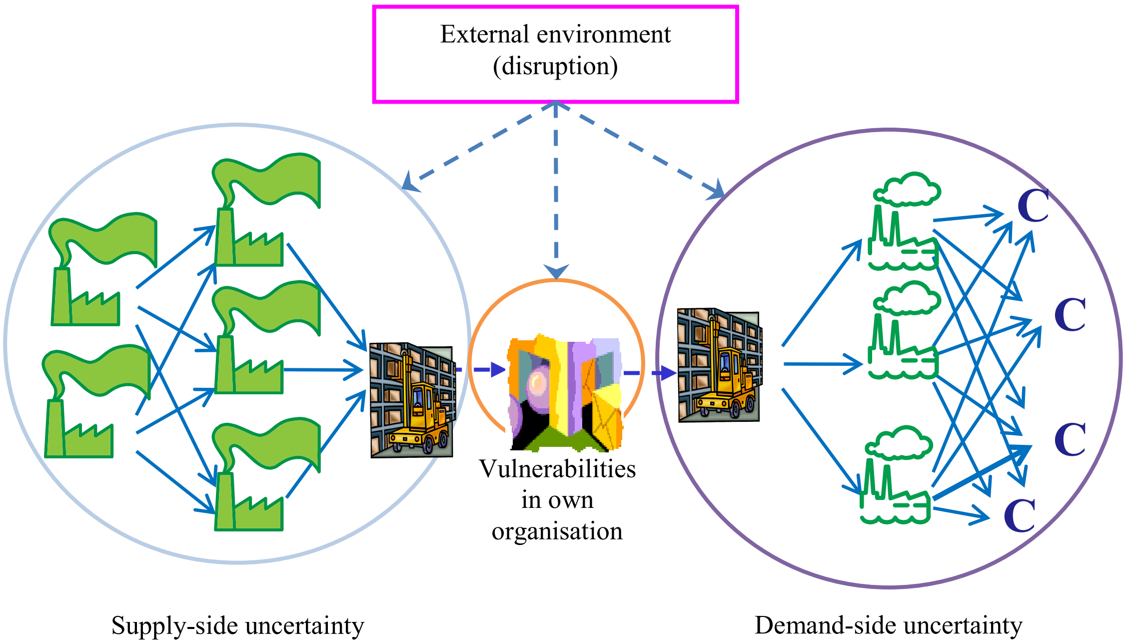


Figure 1-4 Sources of risks in SCs from the perspective of a focal organisation

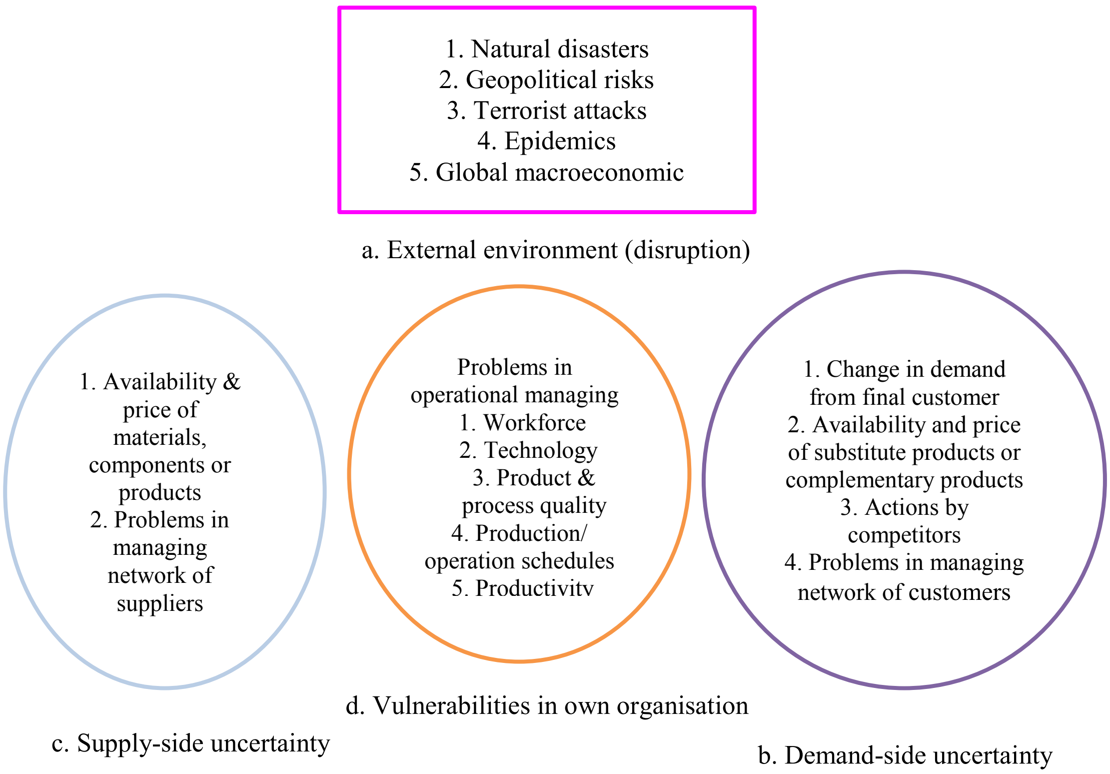


Figure 1-5 Overview of four main risk sources in SC

1.2.2.1 External environment (disruption)

External sources of risk disruption occur outside the SC. They are difficult to control and once they happen, they can generate a huge impact on the SC as whole. Such a risk factor could disrupt the SC from operational level to strategic level. Therefore the SC risk classification in literature always includes disruption by external environment as a part of risk categories. In this thesis, the disruption of external environment is defined as:

1. Natural disasters such as fire, earthquakes, flooding, hurricane, or tsunami
2. Geopolitical risks such as new regulation, legal regulations, taxonomy rule, or political issues
3. Terrorist attacks such as terrorist activities or man-made disasters
4. Epidemics such as Bird flu, SARS virus, or foot and mouth disease
5. Global macroeconomic factors such as inflation, movement in exchange rates, economic crises, or volatile fuel.

1.2.2.2 Demand-side uncertainty

Focal organisations can be influenced by adverse events from their customer networks, not only from customers who they have to try to satisfy, but also from their competitors in the networks, who can generate adverse events that affect them. Therefore they have to manage their demand-side uncertainty properly. In the systemic perspective the source of risks from the demand-side uncertainty are classified in this thesis in four categories:

1. *Change in demand from final customers* can be caused by promotion, seasoning, fashioning etc. This is a known cause of the bullwhip effect. Key buyers are the main influence the demand of a product so their decisions can directly affect the focal organisation. Some organisations mitigate this uncertainty by putting in place contracts. Demand forecasting is the key tool for an organisation to manage customer demands but the accuracy of demand forecasting is challenge especially for a new product in a new market. There are many uncertainties leading to uncertain demands which will directly affect the success of the product in the market, the main profit target for any business.
2. *Availability and price of substitute products or complementary products* is a special kind of risk for innovative products because those products have short life cycle and high product variety. When the technology changes, the organisation will produce a new products, therefore no longer producing the previous products. This uncertainty can generate direct effects to customers rather than to a focal organisation itself.

3. *Actions by competitors* are important since they share the same market: actions of existing competitors or potential new competitors can affect a focal organisation in the long term. In addition, vulnerability of intellectual property rights is important in a SC vertically integrated by outsourcing. Once an organisation cannot protect its intellectual property, competitors can gain advantage in the market by competing with lower prices and subsequent increased demand. In some countries, such as China, suppliers who were originally outsourced go on to produce unauthorised product by using the identical design and material of the original owner's intellectual property.
4. *Problems in managing network of customers* are caused by the focal organisation itself. Typical issues are:
    a. *Inventories of finished goods* can represent the capacity of a focal organisation to cope with uncertain demands: however, levels of inventory are determined by balancing between cost and flexibility. The way to manage inventories is to improve inventory control, which is related to information management. Some companies manage to use make-to-order in order to reduce risks from inventories of finished goods. However, this may not suitable for some functional products.
    b. *Facilities* are the main resources used by the focal organisation to supply finished goods to their customers, such as carriers, staff, boxes etc. If facilities are not available, this can slow down the process and can lead to delay in supply.
    c. *Transportation or logistics* is a key factor in SC. Poor management of transportation can lead to transportation disruption and delivery delay. It can be a key measure of SC performance directly linking to customer satisfaction. Managing transportation issues such as time scheduling, size or mode of carriers are widely studied.
    d. *Coordination* can be seen as formal or informal relationships or hard or soft networks (Rosenfeld, 1996) and it is one strategy that can be employed to reduce uncertainty (Kull and Closs, 2008) with customers. The coordination of sales and demand fulfilment is one risk reduction strategy (Faisal et al., 2006a). Coordination can also link to relationship disruption and strategic risks.

1.2.2.3 Supply-side uncertainty

An organisation may try to reduce costs by reducing stock or by outsourcing. Key suppliers may react to policy changes that affect the supply availability at an agreed price such as wholesale price contracts (more detail in Cachon, 2004). Supply risks or inventory risk have been identified in the literatures (Kull and Closs, 2008; Zsidisin, 2003) and the supply-side uncertainty is summarised in this thesis as:

1. *Availability and price of materials, components or products* is very important to a focal organisation. The price of materials in the market can be increasing, which may be caused by a lack of materials in the markets. Some sources of supply disruptions can be explained as below:
    a. *Underperformance of suppliers* can be measured in a variety of ways and it is always found with supplier selection studies; therefore underperformance of suppliers can be taken to be not supplying materials at *"the right quantity, at the right time, to the agreed quality and at the agreed price"* (Ritchie and Brindley, 2007a, p. 1402). A focal organisation may not want to take a risk by dealing with suppliers who have not been proved capable beforehand since they may lack of knowledge of products. However, sometimes a focal organisation is willing to take risks because of lower costs.
    b. *Actions by key suppliers* are crucial to the focal organisation when there are few suppliers available or a lower number of qualified suppliers. When the key suppliers, especially single-source suppliers, take any actions this can affect the focal organisation dramatically. For example, if the key suppliers increase the price of materials or components, it can increase the cost of the product considerably.
    c. *Breakdowns in supply partnership* can be a cause of the unsecured information. If a partner becomes a competitor, this can lead to crucial effects on the organisation that can be substantial in long term (see *Actions by competitors)*. Generally a focal organisation is in a partnership with their key suppliers in order to develop responsiveness, flexibility and low-cost/low-volume manufacturing (Faisal et al., 2006a). They can gain advantages in long-term co-operation by win-win thinking. Furthermore, 'partnership' is claimed as an effective tool for managing risks (Ponomarov and Holcomb, 2009; Sinha et al., 2004).
    d. *Technological change* is the main reason to switch to another supplier who can fit better to newer technologies in a changing market (Harland, 1996). Wagner

and Bode (2008) mention that if suppliers cannot adapt to the new technology of product changes, this may have detrimental effect on cost. Changing suppliers is not easy and can lead to some other risks, but it is necessary in the competitive market, especially for innovative products. Fast technological change will mean that the inventory buffer is no longer an appropriate strategy (Helo, 2000) so it can lead to the risks of unavailability.

2. *Problems in managing network of suppliers* are similar to the risks in managing a network of customers but relates to Inventories of components and materials, Facilities, Transportation and Coordination. Inventory policies such as just-in-time or material requirement planning can also lead to different types of adverse events (Wong et al., 2006).

1.2.2.4 Vulnerabilities in own organisation

Another source of in-house risks is called vulnerabilities in own organisation, which can be classified into five categories.

1. *Problems in managing workforce*: can occur during labour turnover. Narasimhan (2009) clarifies this: the cause and effect of managing a workforce to increase production volume with unreasonable assignments can lead to dissatisfaction and labour turnover which leads to lost skills and knowledge. Some intangible factors such as workforce goodwill or creativity and talent are also be classified as loss in the risk concept (Mitchell, 1995). Although the organisation can outsource activities in order to mitigate the problems of managing a workforce, the organisation may then be faced with some other risks such as security of intellectual property, product quality control.

2. *Problems in managing technology*: can be caused by technology change which aims to add more value, to reduce cost of the product or to reduce lead time of production or operation in order to gain advantage from competitors by product differentiation in the market (Ritchie and Brindley, 2007b; Zsidisin et al., 2000). However, the focal organisation has to deal with unpredictabilities arising from its inability to forecast accurately the results of implementing a new technology. It was found that 'delisting un-performing suppliers' can lead to technological risk because the remaining suppliers can pool together, which leads to reliance (Khan and Burnes, 2007). Furthermore new technology increases the costs of investment and can lead to production disruption if the knowledge to use those technologies properly is

lacking. Technology is a double-edged sword in that it seems to be good but it can be a source of disruption of the processing process; however, it is necessary for business survival.

3. *Problems in managing product and process quality*: can affect operational performance. The quality of the end products is subject to the management process. Quality management is the foundation of new product development (Gidel et al., 2005) and it can be a part of quality control in a regular process. Good quality of materials is also an important factor in producing a good quality product and time saving (Salvador et al., 2001). The disruption that is caused by poor product quality can directly affect the customers. Customers might not accept unqualified products: as a result the focal organisation will need to reproduce, and may be discredited and lose reputation.

4. *Problems in managing production/operation schedules*: are key concerns to the success of the project (Luu et al., 2009) and the success of production and distribution in the SC process (Fernández et al., 2012). Disruption of production schedules can lead to production delay. When a focal organisation does not have a flexible plan to buffer changes in demand from final customers, perhaps arising from demand forecasting errors or actions by key customers, such disruption can affect the demand-side network. Furthermore, when the schedule changes, it can lead to unexpected costs (Van Landeghem and Vanmaele, 2002). Therefore a focal organisation should have decision support system to deal with the variations and disruptions related to rescheduling (Viswanadham et al., 2008).

5. *Problems in managing productivity*: can cover different adverse events. The process of transforming input into output using available resources such as machines/equipment, energy etc. or production policies such as make-to-stock, make-to-order etc. can face different adverse events (for more explanation see Wong et al., 2006). In addition, the non-availability of materials and equipment is the main constraint which can stop the producing activities. For example, a machine broken down or a delay in material delivery: without a back-up plan these events can generate negative effects. Production planning and inventory control aim to maximise profit and minimise cost and uncertainty under limitation of production capacity. In order to cope with those adverse event, the concept of flexibility of production (Chan, 2003; Hallikas et al., 2002) or postponement technique (Tang, 2006) is recommended.

Appendix B shows how the proposed SC risk classification discussed above compare with the existing risk source classifications reported in the SC risk literature in terms of coverage of risk sources and types of events.

1.2.3 Relationships between risk events affecting supply chains

Consideration of s*ystemic risk* implies moving from independent events to systematic events (Renn and Klinke, 2004). The general definition of systemic is *"formal affecting the whole of something"* (Summers, 2003, p. 1685), therefore to understand the effect as the whole, the *inter-relation* or *interaction* is key to distinguishing systemic risk. The nature of s*ystemic risk* has been recognised in, for example, the sphere of finance and in technology risk as well as in project risk management (Ackermann et al., 2007; Williams, 2000) and human health and safety (Renn and Klinke, 2004). More recently, the notion of systemic risk has been introduced to a SC context (Neiger et al., 2009) since the flow of materials or products not only has interactions between activities, but it can also stimulate related adverse events affecting the SC.

There is clear evidence to show that the interactions between risk events are key in managing SC risk for the following reasons. Firstly, when there are disruptions in any part of the SC, this can stimulate adverse effects to agents in the chain. For example, disruption can directly influence operational tasks such as producing finished goods, supplying products to the markets or providing service to customers (Jüttner, 2005). Secondly, an adverse event can generate causal effects. For example, if demand forecasting is inaccurate, this can result in the provided safety stock being unavailable, leading to stock out and having no product to fulfil orders (Brun et al., 2006). Thirdly, some risk mitigation strategies can be implemented to reduce some risks but at the same time they can increase other risks. For example, a company may decide to add inventory to reduce risk delay risk, disruption risk, procurement risk, and capability risk, but this can force inventory risk to increase greatly. The interaction between mitigating strategies and different types of risks are explained very clearly by Chopra and Sodhi (2004).

There appears to be no formal definition of systemic risk in a SC context; therefore, the following definition is proposed:

The systemic risk associated with a SC is the risk that (the system represented by) the SC will fail to fulfil its primary purpose – which is to supply the right product to the right customer in the right location at the right time – because of a possibly complex set of interacting adverse events occurring simultaneously or in quick succession.

The interrelationships between supply risks are important to understand and to capture if effective decision making is to be supported for Supply Chain Risk Management.

1.2.4 The role of risk analysis in supply chain risk management

Supply Chain Risk Management (SCRM) is beginning to establish itself, and the literature in this area is growing rapidly (e.g. Sodhi and Tang, 2012). SCRM aims to manage risk proactively to seek advantages of competitiveness through becoming leaner or more agile by changing the profile of risk rather than reacting to risk (Zsidisin and Ritchie, 2008). For example a typical reactive mode is to provide high stock to reduce the impact of SC disruption on a business. There is no consensus of the definition of SCRM since its scope is rarely defined (Sodhi and Tang, 2012).

Earlier we discussed that decision making might be considered at the operational, tactical and strategic levels (see Section 1.1.2) but we now add another dimension called 'scope of management' (see Section 1.1.1); see Figure 1-6.

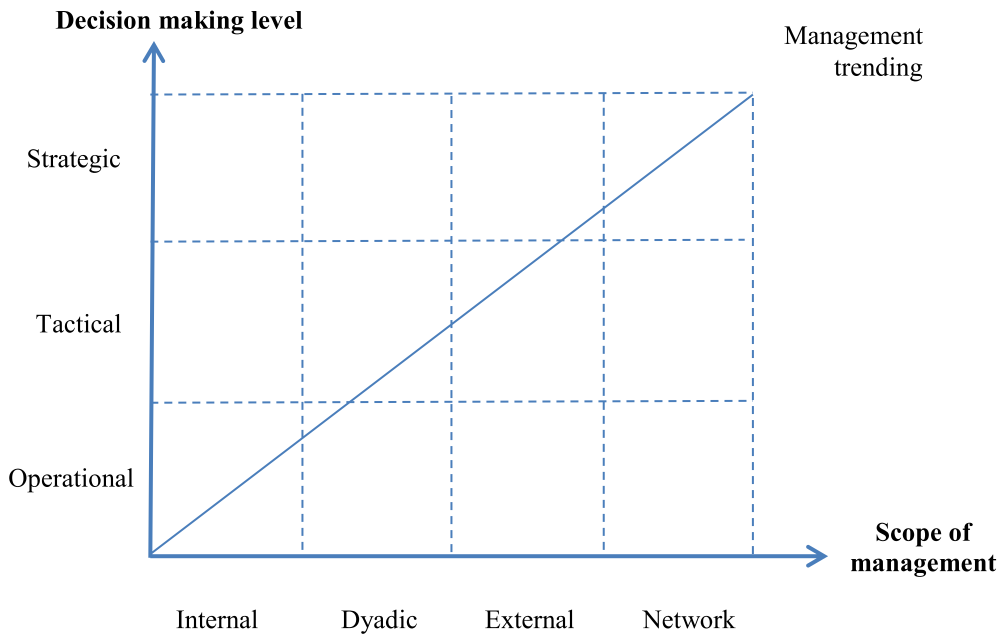
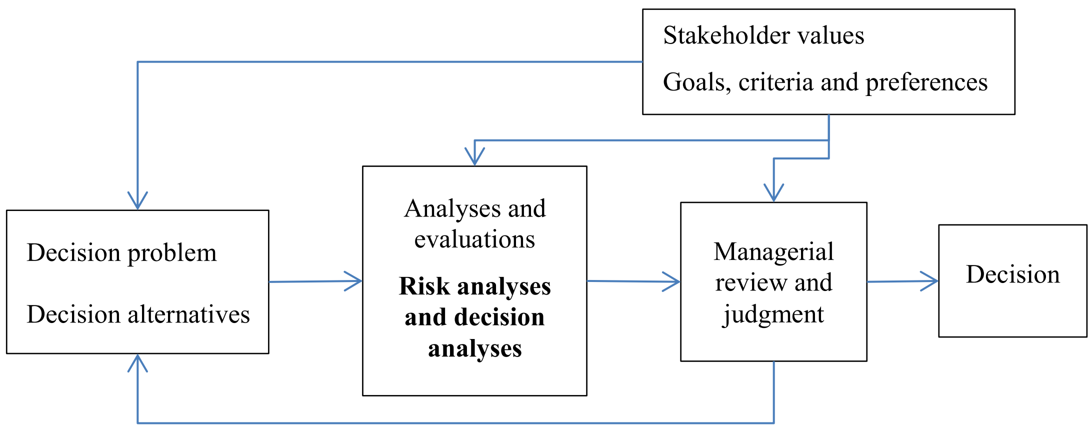


Figure 1-6 Level and scope of management as dimensions of SCRM

Since organisations aim to improve their SC by working across organisational boundaries by looking for collaboration at different levels (Ayers, 2010), the 'scope of management' dimension in SC risk appears important. If decision making for SC risk is internal to the organisation then, for example, risk management teams in each organisation unit are defined as the hierarchical managing levels, so they require to review risks with their team and to develop their own risk records for monitoring purpose. Generally when the decision making is defined in wider scope, decision maker can specify the decision scope at a higher level to reduce the demand of required details (Kobbacy et al., 2006).

Typically (e.g. Faisal et al., 2006a; Hallikas et al., 2004; Khan and Burnes, 2007; Trkman and McCormack, 2009) SCRM appears to be implemented in three or four basic stages: risk identification; risk estimation (or risk assessment); risk evaluation (or mitigation); and risk monitoring (or risk response). The combination of risk identification and estimation is collectively labelled as risk analysis (IRM, 2002). Risk analysis is relevant directly to SCM because outcomes from risk analysis should support the decision making required to manage and mitigate risks. Risk analysis is therefore considered as an essential stage of SCRM (Wu et al., 2006). This research will focus on developing a modelling process to support risk analysis rather than the entire process of SCRM.

A general framework for risk analysis as a decision making process is explained by Aven (2012) and reproduced in Figure 1-7. Basically in any decision problem the goals, criteria and preference are formulated by choosing from set of decision alternatives. The boundary conditions include stakeholder values to formulate goal and criteria etc. that can influence what decision alternatives are selected. After the decision alternatives are set, they need a tool to support analysis and evaluation. *Risk analysis* can provide the prediction of the outcome for particular alternatives by implementing the uncertainty assessment. This analysis can be used to provide basic decision support information and value for the process of managerial review by linking to the specified goal, criteria and preferences before making a decision.



Source: Aven, 2012

Figure 1-7 General process of risk analysis as a decision making process

1.3 Challenges in Analysing and Managing Supply Chain Risk

We now examine the main challenges which emerge and build upon our discussions in Section 1.1 and Section1.2 in order to inform the direction of our research study.

Challenge 1: SCs are increasingly complex

"When dealing with a network of interrelationships within the typical SC, the risk is associated with the entire chain itself. Potentially, all members within a network will be exposed to the risks although the direct impact maybe ameliorated or modified by the actions taken by others in the chain" (Ritchie and Brindley, 2007b, p. 310).

The SC is becoming more and more complex (Basu et al., 2008; Harland et al., 2003; Khan et al., 2008; Oehmen et al., 2009), through linking to many different tiers of suppliers and customers (Hwarng et al., 2005) and increased levels of interaction with one another in more global sourcing (Choi and Krause, 2006; Hendricks and Singhal, 2005a; Kumar et al., 2009). Outsourcing activities to the low cost countries, global SC, e-business, and product/service complexity are also identified as main causes of increased complexity (Harland et al., 2003). Therefore proactive SCRM should consider monitoring stakeholders either upstream or downstream (Zsidisin and Ritchie, 2008). Unfortunately, most current SC risk researchers scope their studies on individual risks such as supply risk (e.g. Levary, 2007; Wu and Knott, 2006; Zsidisin, 2003; Zsidisin et al., 2000, 2004) or demand risk (e.g. Chen and Seshadri, 2006; Sodhi, 2005) independently rather than representing their interaction from a systemic risk perspective. Furthermore, they scope their studies on dyadic relationships, or either customer or supplier network. Therefore some scholars (e.g. Faisal et al., 2006b; Hallikas et al., 2004) have suggested considering the risk analysis in SC or SN rather than scoping only within an organisation.

Challenge 2: Interconnected risks in SC are systemic

"Managing SC risks is difficult because individual risks are often interconnected" (Chopra and Sodhi, 2004, p. 54).

It is clear that risks in SCs are interconnected (Chopra and Sodhi, 2004; Faisal et al., 2006b; Ritchie and Brindley, 2007b; Zsidisin and Ritchie, 2008), as discussed in Section 1.2.3. The systemic risk concept implies that adverse events should be examined at more aggregate and integrated levels than in conventional risk assessment. *"A holistic and systemic concept of risk must expand the scope of risk assessment beyond its two classic components: extent of damage and probability of occurrence"* (Renn and Klinke, 2004, p. S41). The investigation of systemic risk should be an investigation of the relationship of risks rather than the usual basic risk estimation of cause and consequence (Renn and Klinke, 2004). Managing risks individually without considering the systemic risk perspective can cope with local optimal risks but it will face problems related to inconsistency (Tuncel and Alpan, 2010) and lead to inefficient risk management. Therefore SCRM requires to be more focused on risk interrelationships (see also Zsidisin and Ritchie, 2008).

Challenge 3: Need for effective models and methods for systemic risk analysis

According to the experience of a well-known researcher (Wu et al., 2007), the study of disruption analysis in SC is '*relatively untouched'*.

The Risk Register (RR) approach has been used in SCRM (Khan et al., 2008; Zsidisin and Ragatz, 2003) and was originally developed in the field of financial risks. A RR is a straightforward method of recording information about potential risk events from, for example, suitably qualified experienced people. Because a RR provides a formal record system (example of RR will be shown in Appendix C.4), knowledge of risks will not be lost by staff turnover (Edwards and Bowen, 2005). Therefore a RR can be considered useful for risk control and monitoring, requiring little experience (PRAM, 2004) to support risk management. However, a RR typically captures or identifies independent risk events and, therefore, does not easily support evaluation of any interrelationships between risks and the systemic structure (Ackermann et al., 2007; Fenton and Neil, 2012; Isaac and Navon, 2009; Williams et al., 1997). Typically a RR uses a risk matrix (see example in Figure 1-8) to show risks quantified on a 5-point scale for the probability and consequence of an event. For example, the risk matrix can categorise risk items by different colours and then a decision can be made to mitigate high levels of risk (represented by red) as the priority. However, reducing individual risks in the top right corner (red area) to green area does not guarantee that the overall risk will reduce, since risks are actually dependent (Fenton and Neil, 2012). A major effect can occur when more than one adverse event happen at the same time (Ackermann et al., 2007) but again a RR cannot capture this effect on the system (Fenton and Neil, 2012).

Cox (2009) has also identified further drawbacks of a risk matrix. He believes that it is unsupportive of the resource allocation to make a decision about selecting an appropriate mitigating action. The ambiguity between the input (probability and impact score) defined in the risk matrix and the resulting output of the risk rating requires subjective interpretations, since risk rating numbers are calculated from the product of probability and impact rating number. Although the meanings of particular rating numbers are defined, they can provide only rough estimates, and it is difficult to explain the direct meaning of those numbers rather than using them for comparison. Additionally the categories of risk rating can be assigned incorrectly, which can lead to prioritising risks incorrectly and taking poor decisions.

			Probability				
			Remote/ rare	**Unusual/ Unlikely**	**Possible**	**Probable/ Likely**	**Almost Certain**
		Score	**1**	**2**	**3**	**4**	**5**
Impact	**Catastrophic/ Extreme**	**5**	5	10	15	20	25
	Major	**4**	4	8	12	16	20
	Moderate	**3**	3	6	9	12	15
	Minor	**2**	2	4	6	8	10
	Negligible	**1**	1	2	3	4	5

Key:	HIGH
	MEDIUM
	LOW

Figure 1-8 Example of risk matrix implementation to structure risk register

Studies in SC performance measurement have also developed SC diagnostic tools, such as Quick scan (Naim et al., 2002), the diagnostic tool (Foggin et al., 2004), SCOR (Supply Chain Council, 2012) and other techniques summarised by Foggin et al. (2007). However, these techniques are mainly checklist tools and cannot capture uncertainty associated with risk events. Some techniques have been developed to capture uncertainty by selecting the level of probability (e.g. rating 1–4), such as network risk assessment tool (Hallikas et al., 2002), but they are still unable to capture interrelationship between risk items.

For all the reasons provided above, studying systemic risks is different from using available risk analysis tools currently used in a SC context, since systemic risks need a model to capture their relationships. There is a need to develop a modelling process to support identification and representation of systemic risks to support appropriate risk estimation for useful SCRM.

Three challenges of implementing SCRM effectively can indicate the research goal for this research; see Figure 1-9.

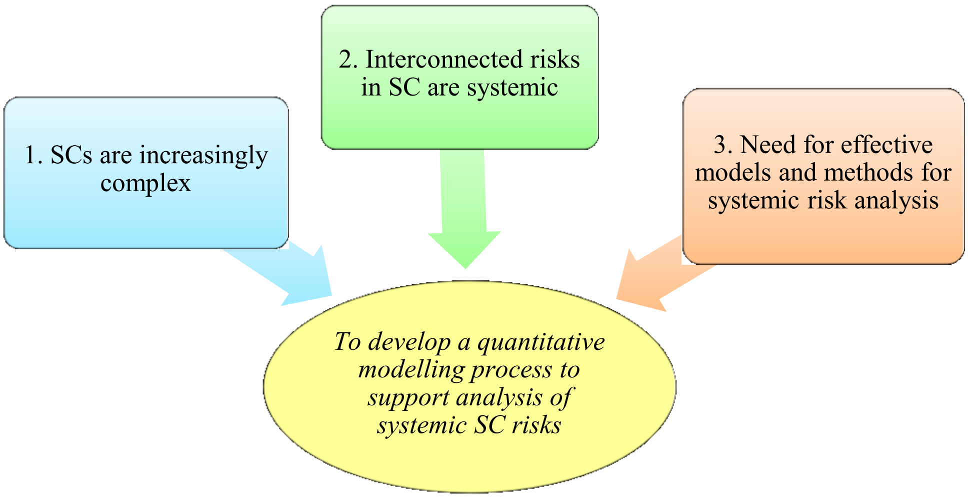


Figure 1-9 Research goal identification

1.4 Research Aim, Objectives and Thesis Structure

The overarching goal of this research is to develop a quantitative modelling process to support analysis of systemic SC risks.

Specifically, our objectives are:

1. To make an informed selection of a suitable model class to capture systemic SC risks;
2. To develop a theoretically grounded process for modelling SC risks, using the selected model class in the form of a Bayesian belief network;
3. To compare methods for identifying SC risks and structuring their dependencies in the form of a Bayesian belief network; and
4. To assess the feasibility of using a Bayesian belief network modelling process to analyse systemic SC risks within a real organisational context.

Figure 1-10 shows an overview of how the objectives relate to each other and so contribute to the overarching goal, and includes an indication of the research design associated with each objective.

The research has been conducted in three main phases, namely:

1. The first phase relates to the examination of candidate models for systemic SC risks (e.g. Failure Modes and Effect Analysis, Fault Tree and Event Tree, Discrete Event Simulation, System Dynamics, Petri Net and Bayesian Belief Network) and comparing their different characteristics. Bayesian Belief Network (BBN) is proposed as the suitable model for this research.
2. The second phase develops a process to construct the BBN from relevant expert knowledge of the SC to support risk analysis. The process was grounded in the principles reported in the literature and refined through the results from an experiment with part-time and full-time postgraduate supply chain management students. The outcome of this phase is a *primary BBN SC risk modelling process.*
3. The last phase of research involves an empirical case study where the primary BBN SC risk modelling process was implemented within a medicine SC for NHS Greater Glasgow and Clyde. By working with the organisational participants, the modelling process was evaluated and revised.

The outcome from this research is to propose a BBN SC risk modelling process which can be used to support risk analysis. Details of the research conducted and results are explained in ten chapters. Figure 1-11 presents an overview of the chapters within this thesis.

Goal: *To develop a quantitative modelling process to support analysis of systemic SC risks*

Objectives	1. To make an informed selection of a suitable model class to capture systemic SC risks	2. To develop a theoretically grounded process for modelling SC risks using a Bayesian belief network	3. To compare methods for identifying SC risks and structuring their dependencies in the form of a Bayesian belief network	4. To assess the feasibility of using a Bayesian belief network modelling process to analyse systemic SC risks within a real organisational context
Process	Phase I: Critical review of candidate model classes	Phase II-1: Literature review	Phase II-2: Experimental study	Phase III: Empirical case study
Outcomes	Proposing a suitable model class (in practical criteria) to support risk analysis in SC context	Proposing a *primary BBN SC risk modelling process*	a. Suggesting the suitable technique for structure the initial map b. Exploring the technical issues and recommendations for structuring qualitative BBN in the real organisations	a. Demonstrating the outcomes from implementing the BBN SC risk modelling process b. Evaluating the feasibility of the BBN SC risk modelling process
Chapter	Chapter 2	Chapter 3, Chapter 5	Chapter 4	Chapter 6 – Chapter 8

Anticipated research outcome: *The proposed BBN SC risk modelling process* (Chapter 9)

Figure 1-10 Overview of research goal, objectives, research process, outcomes, relevant thesis chapters and anticipated research outcome

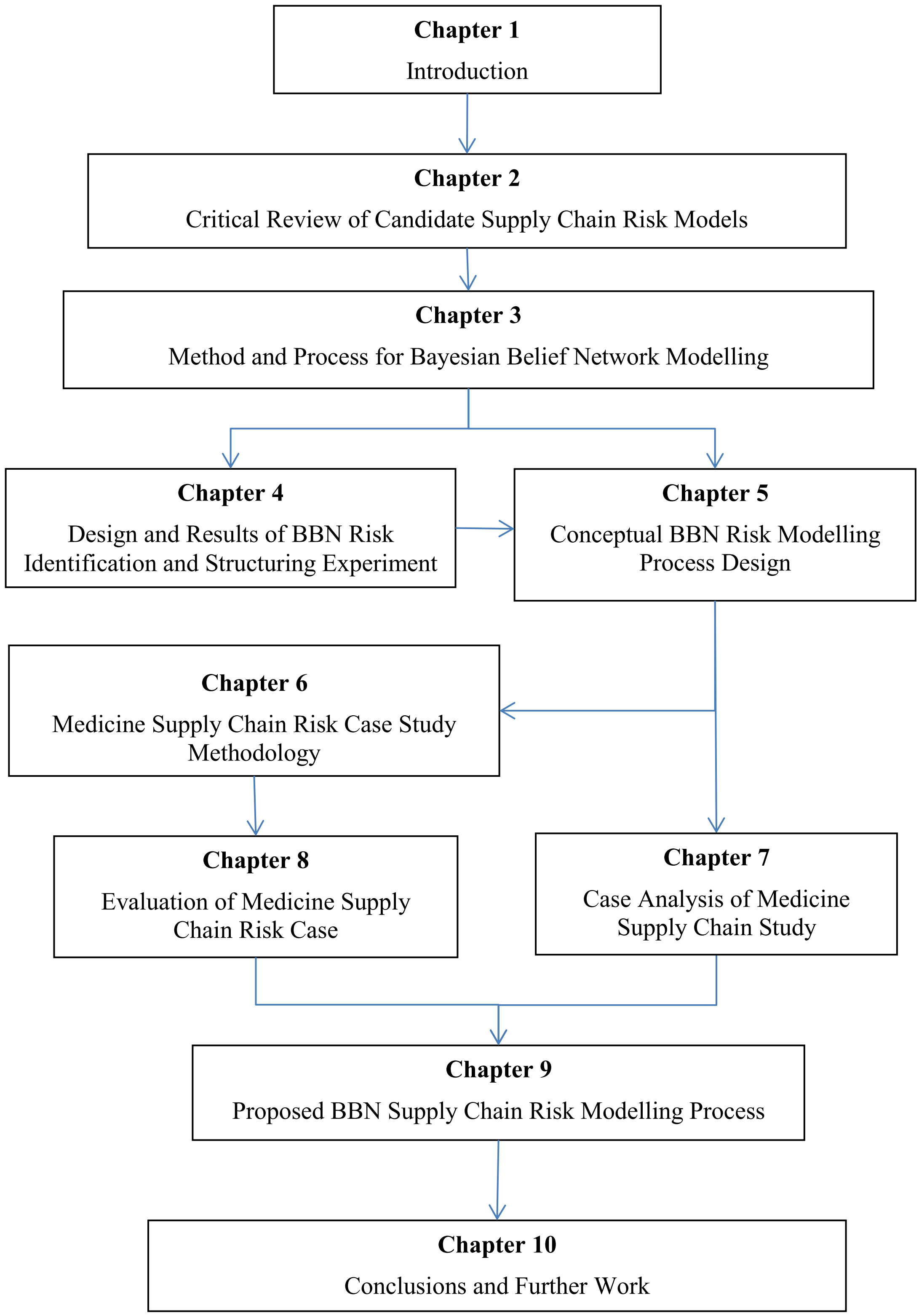


Figure 1-11 Structure of thesis

Chapter 2 Critical Review of Candidate Supply Chain Risk Models

The systemic risk associated with a SC is the risk that (the system represented by) the SC will fail to fulfil its primary purpose – which is to supply the right product to the right customer in the right location at the right time – because of a possibly complex set of interacting adverse events occurring simultaneously or in quick succession (Definition of SC systemic risk for this research; Section 1.2.3).

This chapter provides a critical review of candidate models for capturing systemic risks to support SC risk analysis which is the first objective of this research.

2.1 Process to Select Suitable Model

A model is an external and explicit representation of part of reality as seen by the people who wish to use that model to understand, to change, to manage and to control that part of reality (Pidd, 2003, p. 12).

Models have been applied in many disciplines in order to help understand the reality; they can be used as devices to help in making suitable decisions in problem solving or to allow guidance of better beliefs (Mitchell, 1993). Generally Management Science and Operational Research can use a model to represent (and simplify) some aspects of the reality in order to serve a purpose (Pidd, 2003; Williams, 2008). Therefore different models have been developed because there is no generic model that can be best in every situation (Riddalls et al., 2000). Although different basic models in risk analysis are summarised in literature – such as quantitative guide of risk analysis (Vose, 2008) – there is lack of comparison of model ability to capture systemic risks to support SC risk analysis.

Elements of reality and specific purpose can inform the process of selecting a suitable model for this research; see Figure 2-1. By considering the nature of risks within complex SC (Challenge 1 of SCRM, in Section 1.3) and the interaction among adverse events (Challenge

2 of SCRM, in Section 1.3), a number of candidate models to represent SC risk are identified then assessed in relation to criteria representing the SC risk analysis context.

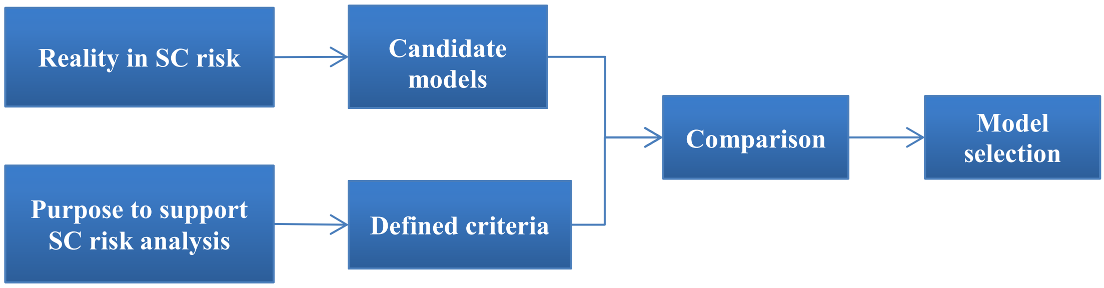


Figure 2-1 Mechanics of model selection

2.2 Representing the Reality of Supply Chain Risk Problems

First we examine the uncertain and temporal nature of the supply chain risk problem.

2.2.1 Uncertainty in supply chains

Uncertainty can be classified as aleatory or epistemic (Bedford and Cooke, 2001). Different types of uncertainty relate to SC risk and some scholars (O'Hagan and Oakley, 2004) claim that classifying uncertainty is useful since it can support the selection of a suitable model.

Aleatory is a Latin word which means 'dice' (Williams, 2000). Aleatory uncertainty is the natural variability in the system shown by the stochastic nature of the events; therefore aleatory uncertainty can be quantified by measurement, statistical estimation, and expert knowledge (Bedford and Cooke, 2001). In other words, aleatory uncertainty can come from natural and unpredictable variation in the system (Hora, 1996). Therefore it is not possible to decrease the level of uncertainty (once it is specified) by learning to gain more information. In a SC context, aleatory uncertainty might relate to, for example, the random variation in the number of order fulfilments.

Epistemic uncertainty is uncertainty due to 'imperfect knowledge' (O'Hagan and Oakley, 2004) or 'lack of complete knowledge' (Bedford and Cooke, 2001; Oakley, 2010; Williams, 2000) so this type of uncertainty can be reduced by obtaining more information (Bedford et al., 2006; O'Hagan and Oakley, 2004). Therefore epistemic probability can be related to measure of belief and can be quantified or characterised, mainly by expert knowledge (Parry, 1996), subjectively. In a SC context, epistemic uncertainty might relate to, for example, the state of knowledge about the political or environmental conditions in a particular geographical region in which a supplier is sourcing raw material. Typically epistemic uncertainties can be learnt and become aleatory uncertainties later on. For example, Williams

(2000) explained this using the project risk register as an example; generally it will contain epistemic uncertainties for a new project and once users learn that they are common they become aleatory uncertainties and a decision can be made as to whether to include them into the current version of risk register.

2.2.2 Degree of problem reality represented by models

The process of transforming from the exact reality to a model depends on the perceptions of those involved in attempting to understand and experience reality (Pidd, 2009). Therefore, the same reality can be presented by different models. Generally a model can present a simpler, more concrete and fully defined picture than actual reality (Pidd, 2009). There are two general types of characteristics used to classify model: these can be understood by considering two general questions:

Does the problem domain or model relate to a quantity which is subject to variation due to chance (i.e. stochastic or deterministic)?

Does the problem domain or model change in time (i.e. dynamic or static)?

The discussion of how the SC risk problems can be represented by different models will be based on these two questions.

Deterministic and stochastic are terms used to classify problems or models by considering the characteristics of uncertainty elements. *Deterministic* is defined when all variables in the model are known and specified. It means the model can generate the same outputs from the same inputs. On the other hand, in a *stochastic* environment the model can use probability theory to represent uncertainty. When at least one variable in the model involves an element subject to variation due to chance, the model can categorised as stochastic (Basu et al., 2008) and the element can be called a *random variable*. The main purpose of a risk model is to calculate, for example, a probability of an event occurrence or the degree of an impact of that event and so support risk analysis (see Section 1.2.1). However, risk can be represented by either deterministic or stochastic models.

If there is a relevant sequence of choices to be decided and the outcome of the choice depends on the previous taken choice (Mitchell, 1993), time can be incorporated into the explanation of the process as a dynamic model. On the other hand, when the situation or nature of the problem does not change with time, a static model can be implemented. SC problems can be viewed as dynamic, which means that the nature of a problem changes during the SC process or project, and therefore the model can include variables that change with time, showing sequences of the process as a dynamic model (Mangan et al., 2008). For example, SCs can be considered as processes generating dynamic discrete events occurring as, for example, lack of material flow from one supplier can spread adverse effects through the whole chain through time. In this perception the complex interaction of systems can be modelled by the representing the time of various discrete events (Viswanadham and Raghavan, 2000).

However, the applications of a dynamic model require modelling techniques that allow time to be the main element and this can lead to difficulties of resource availability during the modelling process. Mitchell (1993) advises modellers to make a trade-off between the complexity and computational difficulties (of dynamic models) and the feasibility or simplification of the model choices. Therefore the dynamics of SC can be captured as a sequence of static models as snapshots during a period of time as a technique to represent a dynamic problem (Marquez et al., 2010; Weber and Jouffe, 2006); see Figure 2-2.

A regular SC process can be dynamic in character; but it is mainly executing routine work so it can reach a relatively stable state of the process, called a *steady state* for a specific period of time which is less dynamic. *"The steady states result from continuous balancing of managerial control inputs of both a planned and a regulative nature regarding perturbation influences from the environment"* (Ivanov and Sokolov, 2010, p. 77). Maintaining the steady state for a specific period of time can help to manage a SC (Chandra and Grabis, 2007; Ivanov and Sokolov, 2010). Once the steady state is taken into account, the dynamic problem in a SC process at the stable state can be modelled by a static model. Especially in risk analysis which might be undertaken at key points in a SC project or process, there is not necessarily the need to capture risk in real time, the evaluation of the system can be used as a static approach to reduce required effort when implementing time factor into the model.

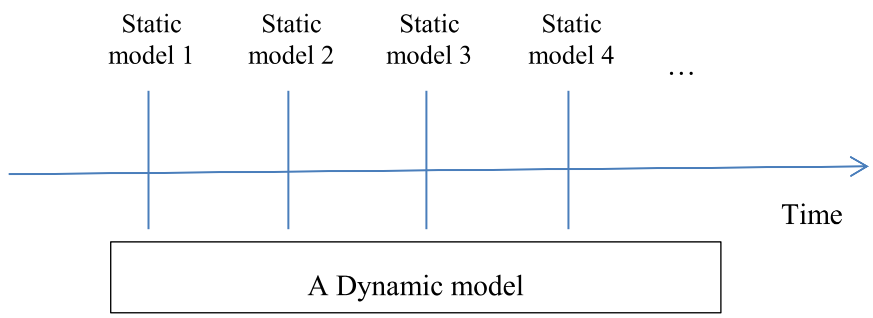


Figure 2-2 Representation of dynamic problem represented by multiple static models

2.3 Candidate Models and their Characteristics

The potential models which can represent uncertainty by capturing interrelationship in complex SC can be narrowed down to six models. Failure Modes and Effects Analysis or Failure Mode and Effect Criticality Analysis (FMEA/FMECA) and Fault Tree and Event Tree analysis (FT/ET) are well established in the technical risk analysis field (Epstein and Rauzy, 2005; Siu, 1994) while Discrete Event Simulation (DES) and System Dynamics (SD) are well-known models in SC study (Angerhfer and Angelides, 2000; Tako and Robinson, 2012). Recently, the applications of Petri Net (PN), Bayesian Belief Networks (BBN) in SC are increasing (Pai et al., 2003; Tuncel and Alpan, 2010).

The general characteristics of this sets of models is summarised in Table 2-1. The suitable level of model implementation and practical use is also explained in Table 2-2.

Table 2-1 Summary candidate model characteristics

	Static	**Dynamic**
Deterministic	-	SD
Stochastic	FT/ET FMEA/FMECA PN BBN	DES

Table 2-2 Summary the applications of candidate models in SC risk study

Modelling approach	Level of study/decision making	Practical use in SC risk study	Previous research in SC risk
Failure Modes and Effects Analysis (FMEA)	Operational details to high strategic level	Basic techniques for risk analysis Provide framework to mitigate risk	Omera et al. (2008) Mingxiao et al. (2011) Renn and Klinke (2004) Tuncel and Alpan (2010) Welborn (2007) Kumar et al. (2009)
Fault Tree (FT) and Event Tree (ET)	Operational detail	Basic techniques for risk analysis Represents system failure and sequences of system failure Represent the logical relationship by Boolean algebra	The Chartered Quality Institute (CQI) (2010) Norrman and Jansson (2004) Geum et al. (2009)
Discrete Event Simulation (DES)	Short-to-medium term operational or tactical level of decision making	Shows the effects of managerial interventions or risk mitigating actions on system performance	Saad and Kadirkamanathan (2006) Kull and Closs (2008) Persson and Araldi (2009)
System Dynamics (SD)	Focus on all level from the longer-term strategic level to short term operational level of decision making	Shows the effects of managerial interventions on system performance Can be used to model the dynamic effects of complex model Can include feedback loops on system performance	Chan and Chan (2006) Helo (2000) Wilson (2007) Thongrattana and Robertson (2008) Oehmen et al. (2009) An and Ramachandran (2007)
Bayesian Belief Network (BBN)	All levels of decision making	Can show both causes and effects of SC disruptions Can capture uncertainty	Pai et al. (2003) Neil et al. (2005) Kao et al. (2005) Chin et al. (2009) Lee et al. (2009) Deleris and Erhun (2011) Basu et al. (2008) Lockamy and McCormack (2010, 2012a) Fernández et al. (2010) Liu (2013)
Petri Net (PN)	Operational or tactical level	Can represent the physical and non-physical elements of uncertainty which can affect SC performance	Wu et al. (2007) Rossi et al. (2005) Tuncel and Alpan (2010) Zegordi and Davarzani (2012)

Source: Adjusted from Leerojanaprapa et al., 2011

2.3.1 Failure Mode and Effect Analysis

FMECA is an extension of FMEA to quantify risk as some function of event occurrence probability and impact with FMEA being the qualitative exploration of possible failure models and their causes for the system of interest. FMEA/FMECA is a static and stochastic method because it represents the probability of occurrence of an event over a specified time horizon (stochastic) but it does not capture the effects of time (i.e. static). FMEA/FMECA is simple and straightforward process so is widely used in industry, especially during product or process development, to evaluate the level of associated risk (IEC60300-3-1, 2003). Furthermore FMEA/FMECA can be used at different levels, from operational to strategic, or from component to system level (Cassanelli et al., 2006). The criteria of fault or failure of the supply system can be established in FMEA by combining input from and getting agreement in, for example, a group workshop; see example in Table 2-3.

Table 2-3 Example of FMEA

Process step	Key process input	Potential failure mode	Potential failure effects	Severity to customer	Potential causes	Frequency of occurrence	Control
What is the key process step?	What is the key process input?	How does the key input fail?	What are the output/effects of the failure?	How severe is the effect to the customer? E.g. 1-10	What causes input to go wrong?	How often does the failure occur?	What controls exist to prevent failure?
…							

Source: Kumar et al., 2009

Generally FMEA/FMECA can show cause and effect relationships but only allows for independency and does not capture complex dependencies between events. Since risk events or potential failure modes are identified independently, it cannot show interactions between them and cannot evaluate the level of system failure when a set of risks happens at the same time (Bedford et al., 2006). Therefore it will miss the interdependencies of risk events (Edwards and Bowen, 2005).

The main applications of FMEA/FMECA had been used in risk assessment to support risk management (Khan et al., 2008). The application of FMEA is a basic method which is suggested in risk analysis (IEC(60300-3-1), 2003; IRM, 2002; Tixier et al., 2002) and it has been implemented in such as device risk assessment (Mingxiao et al., 2011) and safety assessment (Renn and Klinke, 2004) etc. The example of implementing FMECA in the general SC process was shown implicitly by Tuncel and Alpan (2010). Welborn (2007) suggested process to assess outsourcing risks by FMEA while Kumar et al. (2009) used the model to examine counterfeit drugs in SC.

2.3.2 Fault Tree and Event Tree

Fault Tree and Event Tree (FT/ET) are a well-known methodology in technical risk and reliability assessment (Siu, 1994) and established within the set of risk analysis techniques

(Vose, 2008). Only conventional FT/ET will be discussed in this chapter, specifically the stochastic (Langseth and Portinale, 2007) and static approach (Siu, 1994). Although there are many studies on how to improve FT/ET (see reference in Cojazzi, 1996), such as extending it to dynamic situations (e.g. Dynamic event tree analysis method (Cojazzi, 1996) or Dynamic Fault Tree (Andrews, 2009)), they are not considered for the initial phase of model comparison in this thesis.

A FT is structured from some defined top event and the tree drills down to the cause events while ET is structured from a failure mode (top event of FT) and then considers possible consequences: combining both methods can show the cause-consequence analysis. Generally FT/ET is used in examining the detail of elementary events (Weber et al., 2012) and problems at an operational level of study, by defining different types of events. FT can accommodate failures with more than one cause by employing Boolean algebra gates (e.g. OR gate or AND gate) and can link probability assessments with physical structure (Bedford et al., 2006). Furthermore FT has the ability to convert the logical model to corresponding measures (IEC60300-3-1, 2003).

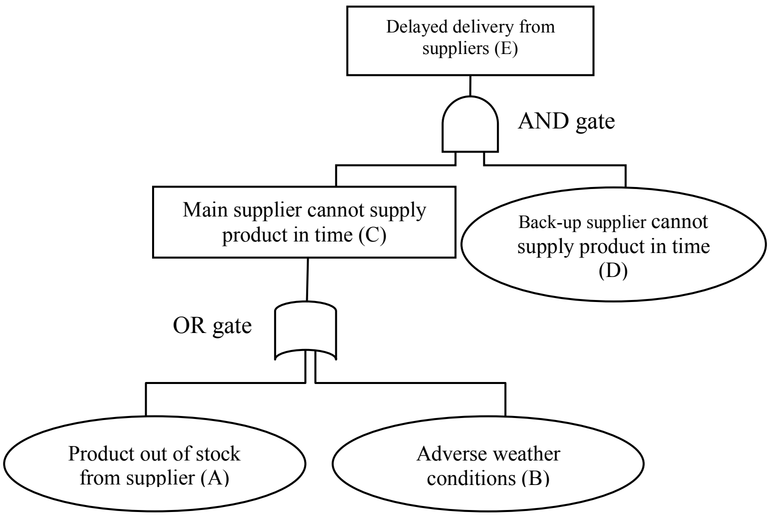


Figure 2-3 Example of Fault Tree

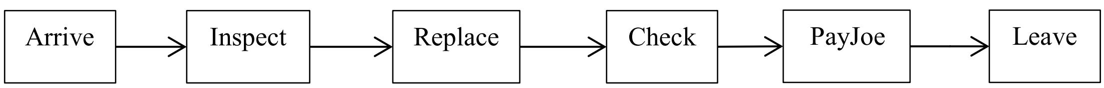
An example of FT considers the problem of when ‘Delayed delivery from supplier (E)’ is the top event. This can demonstrate a simple example in SC risk. The contributory cause events at all levels, called basic events, are identified and linked by logical gates; see Figure 2-3. ‘Main supplier cannot supply product in time (C)’ is OR gate linked to the basic events of ‘Product out of stock from supplier’ (A) and ‘Adverse weather conditions’ (B). Therefore the probability of the main supplier cannot supply product is $q_C = 1 - ((1 - q_A) * (1 - q_B))$, where q_i is probability of failure of variable or event i^{th}. Next, 'Delayed delivery from supplier (E)' is AND gate linked between 'Main supplier cannot supply product in time (C)' and 'Back-up supplier cannot supply product in time (D)' happening as the same time so probability of 'Delayed delivery from suppliers (E)' can be calculated as $q_E = q_C * q_D$.

FT/ET is a technique suggested to provide SCRM (e.g. Chartered Quality Institute (2010) guideline). It is a common technique used in the research of the cause of accidental events in SC (Norrman and Jansson, 2004).

2.3.3 Discrete Event Simulation

Discrete Event Simulation (DES) aims to simulate stochastic behaviour by keeping track of upcoming events when time moves to the time at which the next event will occur, in an event-based process. It is suitable to apply with Monte Carlo simulation to find the answer to how various system parameters affect system performance without changing the real system (Riddalls et al., 2000). DES aims to simulate the system by considering discrete entities (Pidd, 2003). It allows the modeller to define computable forms to define how entities can change the state and to capture the changes for all elements in any time, known as the dynamic property.

In general DES can be modelled as entities and activities. Entities represent tangible components in the system. The entities can simulate behaviour by moving through the system as dynamic or they can be static to represent resource, so DES can be used to define a process which is the sequence of activities. Entities can occupy states (which are discrete) for a period of time and each entity can occupy only one state a time. The time that an entity spends in a state may be defined by a stochastic variable represented by probability distribution. Therefore DES is suitable for modelling at the operational/tactical level (Tako and Robinson, 2009). The applications of DES in SC are related to high numbers of dynamic entities (Longo and Mirabelli, 2008). A simple example of Joe's exhaust parlour provided by Pidd (2003) shows the simple tasks and their links by arrows which can apply with DES by following the sequences of task as in Figure 2-4. If a car arrives for inspection, it then follows the process task until finish checking and pay Joe before leaving is the final task.



Source: Pidd, 2003

Figure 2-4 Example process of Joe's exhaust parlour

Application of DES in a SC context can relate to a manufacturing process, logistics and transportation, inventory (Saad and Kadirkamanathan, 2006) etc. Risks in those parts of the SC can be modelled by changing parameter values to generate the threat events that can disturb the SC system and then simulate them repeatedly unit the program reaches the *steady state*; it then calculates the SC key performances to compare the impacts with the regular situation, called scenario analysis. In addition it allows the model to dynamically change in SC more realistically and it can also model multiple disturbances (Saad and Kadirkamanathan, 2006). DES is suitable for analysing demand and supply risk in SC (Reiner, 2005) since DES is able to simulate the complexity of the flow of material and information in SC. Furthermore it shows uncertainty and complexity in the SC (Persson and Araldi, 2009). However, it cannot deal with psychological factors and it requires live accurate data from SC system operations.

The applications of DES and SD in SC and logistics have been combined (e.g. Reiner, 2005) and compared (Tako and Robinson, 2012) but not in the SC risk context. Furthermore DES is a well-known model in SC and it has been combined with Supply Chain Operation Reference (SCOR) to develop a new simulation tool box which can capture dynamic effects, such as the 'bullwhip' effect (Persson and Araldi, 2009) or to develop SCM techniques or methods (e.g. Longo and Mirabelli, 2008). Saad and Kadirkamanathan (2006) summarised the application of DES from their review of areas such as SC strategic decision, production planning, resource allocation, distribution and transportation planning. However, there are far fewer DES applications in SC risk. For example, Saad and Kadirkamanathan (2006) investigated the effect of policy on disturbance and effect of disturbance on the system by DES. Kull and Closs (2008) used DES to examine the SC risk issue within the second tier supply failures, by focusing on impact.

2.3.4 System Dynamics

Dynamic SC structure was introduced by Forrester (1961) who developed a continuous time mathematical model of the dynamic production and distribution process (Kamath and Roy, 2007) and most definitions of SDs refer to his work in Industrial Dynamics book (Forrester, 1961). SD is a deterministic replication method (Williams, 2008) and it is developed from the continuous time differential equation (Riddalls et al., 2000). In addition, SD has been proved to apply from the strategic to operational level (Helo, 2000). There are three characteristics of SDs: feedback loops, simulation and mental models (Lane, 2000). The basic concept of SDs is based on two pairs of ideas: resources & information and levels &

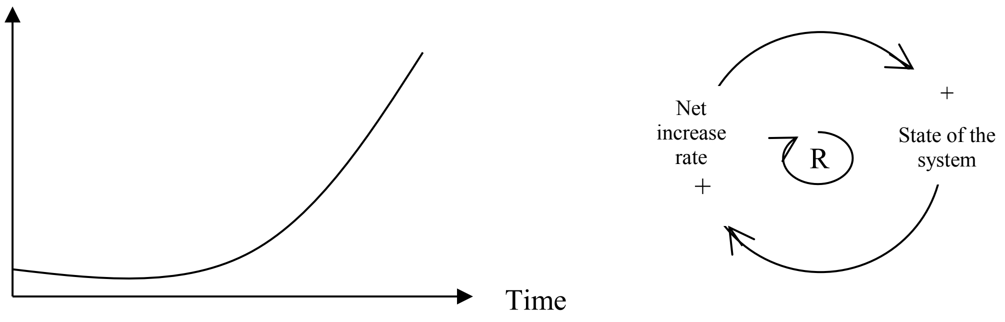
rates (Pidd, 2003), so SDs can be applied in SC study by combining both physical flow and information flow together as a feedback loop in the same model and representing those relationships as *causal loop diagrams* or *stock and flow diagrams*.

Causal loop diagrams are flexible and useful in modelling the feedback structure of systems in cause and effect domains. The diagram comprises a set of connected nodes and the relation between each node is represented by arrows from independent variable to dependent variable. Each link shows a positive (+) or negative (-) symbol to indicate the relationship between those nodes. The diagrams are a useful start in capturing the mental models; however, it is never perfect and it may change. The dynamic behaviour of the system can be presented by feedback loops such as 'state→action→state'. An example of feedback loop for growth or positive feedback is shown in Figure 2-5.

Stock and flow diagrams underline the physical structure and track the flow of material, money, and information. SC as represented as stock and flow diagram is shown in Figure 2-6.

A simple equation to show the dependency of the flow in the stock (adjusted from Pidd, 2003) is:

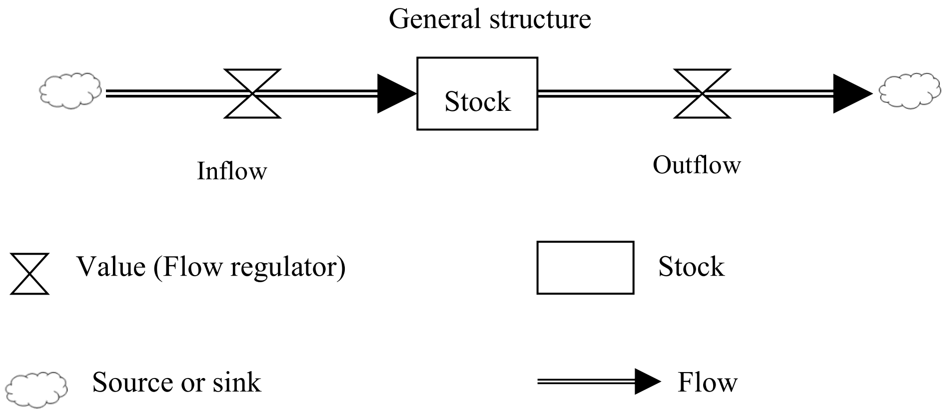
*Level (Current stock) = Level (Previous stock) + Interval * (Inflow rate – Outflow rate)*



(a) Growth mode (b) Positive feedback

Source: Sterman, 2000

Figure 2-5 Example of causal loop diagram



Source: Sterman, 2000

Figure 2-6 Stock and flow diagramming notation

There are many applications of SD related to SC. Examples are disruption and delay in project context (Howick, 2003; Williams et al., 2003), evaluating the effect on SC performance (Ovalle and Marquez, 2003; Reiner, 2005), displaying impact of change to the system on customer satisfaction (Reiner, 2005), and identifying critical information flow of the SC for short-life cycle products by feedback loop (Kamath and Roy, 2007). Furthermore, many mathematical models in SC analysis are usually evaluated by SD perspective (Riddalls et al., 2000).

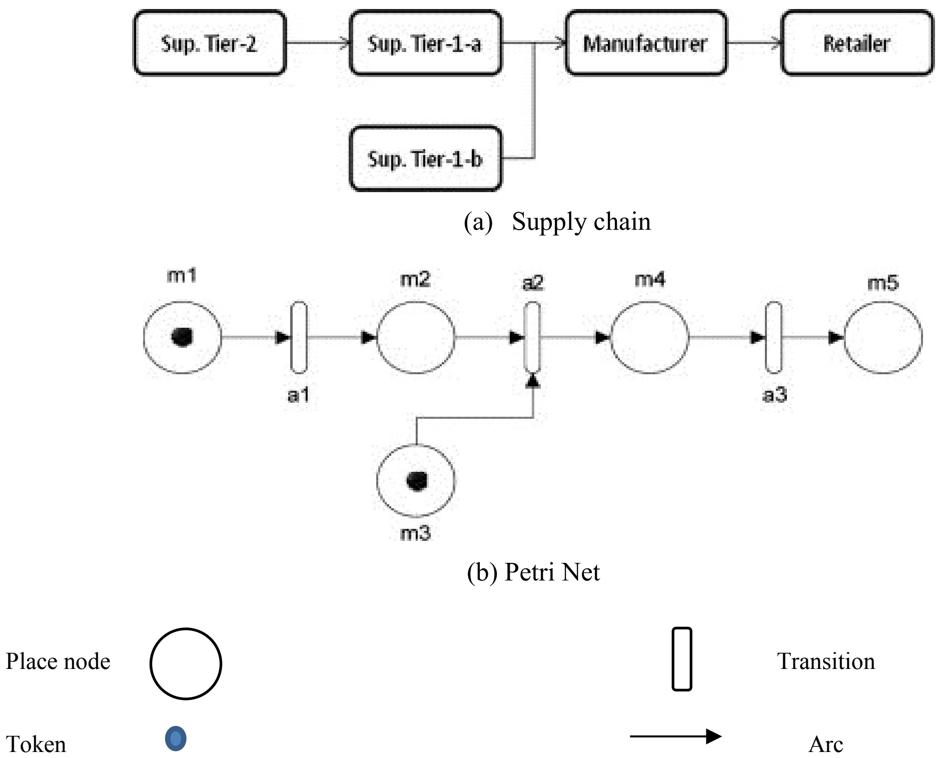
SD can be developed as a part of systemic-oriented SCRM to capture the dynamic of risk development in SC (Oehmen et al., 2009). Moreover, SD has been used to evaluate the effect of uncertainty in both demand and supply uncertainty on the system performance (Chan and Chan, 2006) or to show uncertainty on demand side, such as effect on rice supply caused by a rough year on SC rice performance (Thongrattana and Robertson, 2008), or demand risk on the delay and uncertainty in PC manufacturing SC (An and Ramachandran, 2005). It was also used to evaluate the effects of unpredictable market changes on production control (Helo, 2000) and the effects of transportation disruption on SC performance (Wilson, 2007). These application reviews clearly show that SD is suitable for predicting disruption effects in SC.

2.3.5 Petri Net

Petri Net (PN) is a relatively recent advanced technique based on a Monte Carlo approach and there has been considerable theoretical development to extend PN to dynamic problems. However, we consider only conventional PN, which is static and stochastic (IEC60300-3-1, 2003). A PN is a mathematical graphic which can represent a model via *place node*, *transition* and *directed arcs* as input and output from node to another node (Wu et al., 2007). *Place nodes* are shown as circles and represent the condition of the system. *Transitions* are shown as bar symbols and represent events that can alter conditions (i.e. change one condition to another one). *Arcs* are shown as arrows to connect between place and transitions and represent the links between the conditions and events.

The dynamic of a PN is presented by the movement of the token – the dot in the graph. It is possible to identify state equations mathematically. A place can have several arcs to link to or from transitions so they need to be combined or weighted or multiplicity (Andrews, 2009). The process is complex and is not explained in detail in this thesis, but a simple example from Zegordi and Davarzani (2012) will show the principles.

Example: A SC is defined by Figure 2-7 (a) consisting of supplier tier-2 and tier-1-b which are abroad where the manufacturer and supplier tier-1-a are in the same country. The SC can be transformed to Figure 2-7 (b) to show the disruption at m_1 place node and m_3 from political risks. Furthermore the problem from supplier tier-2 causes the supplier tier-1-a suffers disruption from bankruptcy. The transition a_2 can show the disruptions from both sources.



Source: Zegordi and Davarzani, 2012

Figure 2-7 Example of Petri Net and notation

A PN is claimed as to be a suitable model for complex SC networks (Viswanadham and Raghavan, 2000). For example, a PN has been used to compare two inventory policies of make-to-stock and assemble-to-order on carried cost and delayed deliveries cost (Viswanadham and Raghavan, 2000) or to compare the SC conflict by single and integrated conflicts (Blackhurst et al., 2008).

The applications of PN in SC risks have been investigated. Wu et al. (2007) claim that there is no PN research on disruption in SC so they used PN to develop a new method called Disruption Analysis (Wu et al., 2007; Zegordi and Davarzani, 2012). In addition PN was used to analyse and assess operational risks in SC (Rossi et al., 2005). Finally PN was used to analyse SC network with various risks and perform performance evaluation to define uncertainty in the system (Tuncel and Alpan, 2010).

2.3.6 Bayesian Belief Networks

A Bayesian belief network (BBN) is a type of graphical model whose elements are chance nodes and arcs which represent dependencies between nodes. A BBN is a directed graph developed from a mathematical structure and a BBN can combine a finite set of *nodes* together with a set of *arrows* (directed arcs) between nodes. A node represents a random variable (or group of random variables) and an arrow from one node to another represents probabilistic influence. The BBN model will be explained and a simple example provided in Section 3.1. A conventional BBN is a stochastic and static model because the model has been developed to deal with random variables that are either discrete or continuous (Fan and Yu, 2004) and does not change over time. More recent developments have extended simple BBN to represent time dynamics. These are called Dynamic Bayesian Networks (DBN). However, DBN is not selected for this research since it requires a lot of input and it would be difficult to implement given the large number of risks relevant to the many stakeholders in SC for this research.

BBN has been applied in SC recently especially in the area of SC risks. Pai et al. (2003) were the first group of researchers who applied BBN in a SC risk context (Lockamy, 2012) and research in this area is increasing. Trucco and Leva (2012) have proposed BBN as a method to model operational risks and they provided the list of literature for BBN operational risk application. Pai et al. (2003) proposed BBN mode to assess business risks (from the external environment) and evaluate safeguards to secure the SC. Furthermore BBN was used to evaluate supplier risk profile (Lockamy and McCormack, 2010, 2012) and SC risk (Liu, 2013) by defining levels of criteria. The middle level of BBN also has been implemented. Kao et al. (2005) developed DBN from cause and effect diagrams in engineer assemblies provided by Naim et al. (2002). Chin et al. (2009) developed a project risk network during new product development. BBN can be implemented in a SC project, aiming to measure cost and time so the model is implemented at the lower level of events. Lee et al. (2009) applied BBN to risk management in a large engineering project within the shop building industry by focusing on budgets and time schedules that were exceeded. BBN can also be developed at the more detailed event level. Fernández et al. (2010) implemented BBN for monitoring event in SC while Deleris and Erhun (2011) and Basu et al. (2008) developed a framework to support SC risk assessment by capturing the cause events to the performance measures defined by time and cost.

2.4 Purposes of Supply Chain Risk Models

"Management scientist needs different tools for different purposes" (Williams, 2008, p. 83).

In a Supply Chain Management (SCM) context Beamon (1999), Chandra and Grabis (2007) and Ivanov and Sokolov (2010), for example, say that the general purpose of modelling is to provide a basis: *to replicate or forecast the system behaviour (Simulation), to infer attribute of a system, to find the optimum (Optimisation).* However, such purpose categories for SCM are too general in relation to a risk problem. Therefore we examine the specific purposes of SC risk analysis to specify criteria for model selection for this research.

Sodhi and Tang (2012) identify expected outcomes from risk assessment which is the last process for risk analysis in SC risk (risk identification and risk assessment) so they can be used to define the expectations to be supported by risk model as:

> *To understand the nature of threats and other risks to help counter these better,*
>
> *To support risk measures for informing their stakeholders,*
>
> *To help management focus on specific areas* and
>
> *To support allocation of risk management efforts and budget to different risk mitigations such as to answer the question of who should make such an investment (organisation, its suppliers or its customers) in SC.*

Therefore the selected model should be able to provide the outcomes which can fulfil the defined purposes of the SC risk analysis. As the explanation of mechanics of model selection (see Figure 2-1), purpose of model to support SC risk analysis can be interpreted to define critical criteria for selecting the model and it will be explained in Figure 2-8.

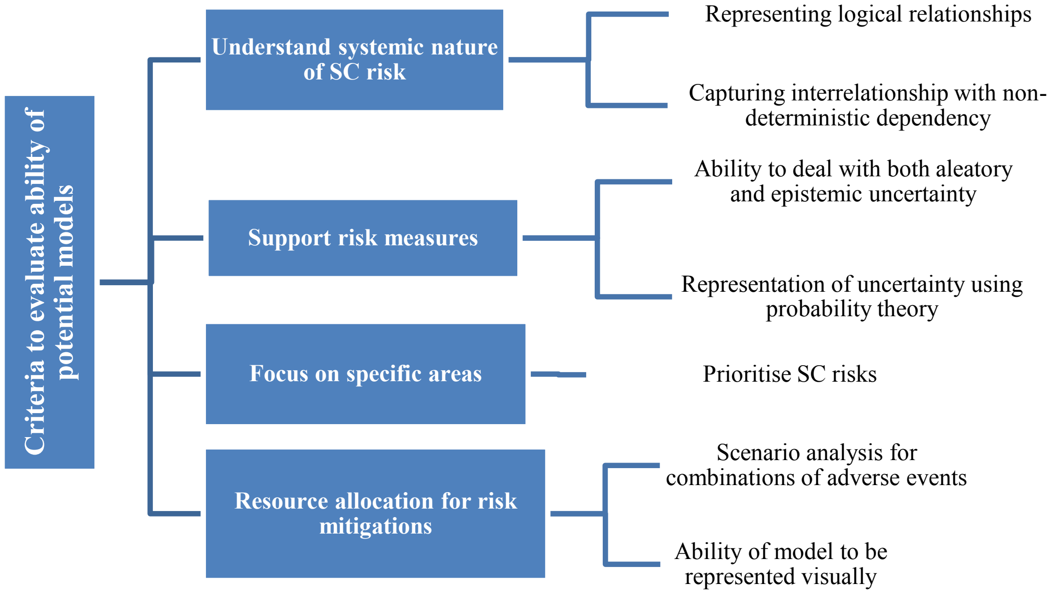


Figure 2-8 Criteria model selection for SC risk to support SC risk analysis

2.4.1 Understand systemic nature of supply chain risk

The nature of systemic risk is the main interest of this research (Challenge 2 of SCRM, see Section 1.3). Therefore suitable methods to represent SC risks and the ability to capture systemic relationships by particular models are considered.

2.4.1.1 Representing logical relationships

The causal relationships might be represented at different degrees of abstraction from a direct actual ‘physical’ representation through to an abstraction at a more ‘logical’ level (Nilsen and Aven, 2003). In this research we want a degree of abstraction since a logical model is simplification so modellers do not necessarily consider all possible causal mechanisms. The logical model can be used in a complex system by trading-off the complexity and level of required details in the models. Accordingly the challenge in SCRM is that SC becomes more complicated (Section 1.3) and is involved with a variety of risks from different sources (Section 1.2.2). The logical model can provide a convenient reduction of the analysis efforts which is necessary for modelling risks in SC scope. Although a physical relationship can provide more accuracy but logical relationship is sufficient in the risk analysis which aims to prioritise specific areas (by comparison) to allocate resources rather than focusing on estimator accuracy.

2.4.1.2 Capturing interrelationship with non-deterministic dependency

Since interrelationships represents the nature of systemic risks, models should be able to capture the interrelationship via ability to capture dependency. *Dependency* can be represented by variables and links to represent relationships. The dependency between variables by using a link represents the probability, impact, confidence, knowledge of business logic etc. (Li and Chandra, 2007).

However, models can capture dependency in different ways. The level of dependency between a pair of events or variables can be classified as *independence*, *dependence* and *complete dependence* (Bedford and Cooke, 2001). When two events are *independent,* they do not have a relationship or when an event happens, it will not influence the occurrence of another event. For example; there is no logical relationship or dependency between a customer buying a product from supermarket and human error in the process of delivering a product to the distribution centre, so these events are defined as independent.

If there is a dependent relationship between a pair of events then the outcome of an event can relate to another event outcome. If their relationship is one of *complete dependence*, the level of dependency is totally related (Bedford and Cooke, 2001). For example when the chance of a product being out of stock from manufacturer A is 0.2, the chance of the manufacturer A not being able to supply the product to their customers is also equal to 0.2. On the other hand, if the relationship between a pair of events may not be completely dependent, the level of dependency can be assigned explicitly by two approaches. One is *deterministic dependence* and another is *non-deterministic dependence*.

The deterministic dependence, called 'known actual outcome' of the (input) event, describes the cause of an event that happens in a way that cannot be changed. Therefore it will return the same result of output from the same set of input (Lane, 2000) since the relation is fixed from known inputs. For example, when the chance of 'supplier not being able to supply material to a manufacturer on time' is 0.2, the chance of 'manufacturer not being able to produce its product' is defined by the function combining the chance of 'unable to be supplied from supplier (0.2)' and 'machine broken down (0.005)', i.e. 0.2×0.005. If a 30% of chance of 'unable to be supplied from supplier' can make 'manufacturer not being able to produce its product' then the resulting chance that the manufacturer cannot produce is 0.2×0.3.

On the other hand *non-deterministic dependence*, called 'unknown actual outcome', will show the different outcomes from the same set of input values. The outcome is not always observed since its relationship may include random variables in relation function or relationship can be specified without requiring formulation. For example, when the chance of ‘a supplier not being able to supply material to a manufacturer on time’ is 0.2 (input), the chance of ‘the manufacturer not being able to produce its product’ is equal to a function of the input number with a random variable. Therefore the outcome cannot be defined directly from input since random factors are included. For example, the chance the manufacturer cannot produce its product is defined by 0.2*X, when X is not a constant number. We summarise the types of dependency in Table 2-4.

Table 2-4 Summary types of dependency

Independence	Dependence		Complete dependence
No relation	**Non-deterministic** Unknown actual output from the (input) event e.g. DES, PN, BBN	**Deterministic** Known actual output from the (input) event e.g. FT, SD	**Completely deterministic** Output = Input

If a model can capture non-deterministic dependency, it can be simplified for other types of relation. Therefore model should be able to model non-deterministic dependency in order to cope with different types of complex relationships in SC risks.

2.4.2 Risk measures supported

Risk analysis should support SC risk measurement which can show the level of uncertainty in SC so the model should be able to capture both types of uncertainty using probability theory.

2.4.2.1 Ability to deal with both aleatory and epistemic uncertainty

Generally either aleatory or epistemic uncertainty (Section 2.2.1) can occur as risk events in SC. However, an imbalance between the number of aleatory and epistemic uncertainties involved in SC project and SC process can be observed and compared by considering the different characteristics of SC project and SC process as discussed in Section 1.1.3.

The nature of a project is unique and it can finish within a period of time so knowledge from one project will provide not much information for a later project. Since projects are confronting with opportunity to perceive the same adverse events from the same setting of unique characteristics, it involves uncertainties from lack of information of unique projects or unknown from incomplete knowledge (Rosenau and Githens, 2005). Therefore SC projects are more involved with epistemic rather than aleatory uncertainty.

On the other hand, SC process is day-to-day activity occurring repeatedly. Process will be involved less with unknown events since people will be familiar with their work by learning and gaining information from the repetitive nature of the work. In addition, the SC process is less flexible, not unique and less complex so it will be faced with a smaller number of unknown adverse events. Therefore, uncertainty in SC process or production would be more relevant to aleatory uncertainty than epistemic uncertainty. However, some threats outside the process, risk from the external environment (see Section 1.2.2), can affect the SC process; for example new regulations or new tax law can affect the cost of production, price, and demand of customers. Furthermore when the operational task involves a new task (such as buying products from a new supplier), some unknown will be involved (Khan and Burnes, 2007). In addition risk analysis in system failure should not only concern the failure rates of the components (aleatory uncertainty) but also other technical, human and organisation factors (Øien, 2001; Weber et al., 2012). Those factors of uncertainty are defined as lack of knowledge, epistemic uncertainty. Therefore the SC process modelling should be able to capture both aleatory uncertainty and epistemic uncertainty and the logical relationship allows to integrate those factors in the model (Weber et al., 2012).

2.4.2.2 Representation of uncertainty using probability theory

Probability can represent the level of uncertainty by the chance of occurrence. Probability can also represent inter-correlation between different adverse events to support normative decision making (Kjaerulff and Madsen, 2008). Furthermore rare and catastrophic events which are difficult to estimate from the empirical data are usually applied to assess in probabilistic risk assessment (Cox, 2009; Weber et al., 2012).

Simulation is a useful technique to represent impact of adverse events in a real, complex system and carry out controlled experiments (Melnyk et al., 2008) and it has been identified as a best practice for SC planning by SCOR (Supply Chain Council, 2012). However, simulation models may not fit well with risk assessment. Firstly, simulation is not suitable for representing rare events which can generate high impact, especially at the low probability tails (Siu, 1994; Vose, 2008). Secondly, calculating combinations of effects which are dependent on a set of uncertainty variables (different input variables) is difficult to do: it needs a lot of efforts to carry out multi-simulation runs for individual inputs in order to gain the result of a single output (Williams, 2000). Finally the indirect advantage of using probability language in the risk model is unit consistency. Equations for simulation can be developed from different units of measurement used and the results of simulation are sensitive to the units applied in the equations and can lead to invalidity of the model results;

for example using 350 km or 200 miles in the same equation will come out with different results (Finlay, 1988). Using probability language is less complex and less confusing since probability has no 'unit' to be applied so it will not be a source of mistakes.

2.4.3 Focus on specific areas

There are a lot of possible risks that can be identified but only specific areas should be focused in management under limited resources. Therefore the model should support risk prioritisation.

Prioritise SC risks

SC risk is a function of probability and impact (see definition of risk in Section 1.2.1). Those two components are essential and can be used to support making a decision to reduce either probability or impact, called reducing probability (preventive[1]) and/or reducing the impact (interceptive[2]) (Khan and Burnes, 2007; The Royal Society, 1992; Viswanadham et al., 2008). Therefore risk analysis should help to prioritise possible risks in SC by considering both chance and impact of those adverse events to help management focus on the specific areas of adverse events. For example some adverse events can occur with high chance but if it does not affect the main focus of the SC they may not be prioritised in the high rank.

2.4.4 Resource allocation for risk mitigations

Outcomes from risk analysis can help to define possible mitigating options by considering the allocation of risk management efforts which is defined by the final purpose of risk analysis.

2.4.4.1 Scenario analysis for combinations of adverse events

SC risk analysis can support the allocation of resources in risk mitigating actions from different stakeholders by demonstration of the scenario analysis. What-if scenario is a recommendation for managers to implement in SCRM since there are many risks and many risk mitigating approaches can be applied (Chopra and Sodhi, 2004) and option of action can

---

[1] Preventive approach seeks to reduce the likelihood of occurrence of an undesirable deviation or disruption through the design of a robust chain (Viswanadham et al., 2008, p. 209).

[2] Interceptive approach attempts to contain the loss by active intervention subsequent to the consequence of the event (Viswanadham et al., 2008, p. 209).

be identified from adding of the models. Furthermore referring to the definition of systemic risks in SC (Section 1.2.3), risk events can occur simultaneously and can cause SC disruption so the model should not only demonstrate scenario analysis but also show scenario by combining of adverse events or fault variables.

2.4.4.2 Ability of model to be represented visually

The modelling scope of SC can involve different stakeholders, so the risk analysis should support the communication and negotiation between stakeholders. Hence, modelling visual display is important in order to provide a visual result and can effectively support identifying stakeholders who should take responsibility of investment to mitigate those substantial risk events.

2.5 Comparison of Candidate Models against Modelling Criteria

Although the six models are selected as candidate models to support SC risk analysis by their ability to capture interrelationship between risk events or elements in Section 2.3. They can also be compared through specific criteria to select suitable models to support SC risk analysis, as shown in Table 2-5.

Table 2-5 Criteria to evaluate potential models to support risk analysis

Models	FMEA/ FMECA	FT/ET	DES	SD	PN	BBN
1. Representing logical relationships	No	*Logical*	Physical	Physical	Physical	*Logical*
2. Capturing interrelationship with non-deterministic dependency	No (Independent)	Deterministic	*Non-Deterministic*	Deterministic	*Non-Deterministic*	*Non-Deterministic*
3. Ability to deal with both aleatory and epistemic uncertainty	Epistemic	*Both*	Aleatory	*Both*	*Both**	*Both*
4. Representation of uncertainty using probability theory	*Yes*	*Yes*	No	No	No	*Yes*
5. Prioritise SC risks	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
6. Scenario analysis for combinations of adverse events	*Yes* (no combination)	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
7. Ability of model to be represented visually	No	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*

* But less suitable for epistemic uncertainty

1. *Representing logical relationships*

FMEA/FMECA cannot show interrelationship between failures so it cannot represent either physical or logical relationships. SD, DES and PN can categorise as physical model since they represent failure of the system by functions which are based on replicating behaviours or activities by physical model. On the other hand, FT/ET and BBN are logical model which represent the function by considering adverse events of system barrier.

2. *Capturing interrelationship with non-deterministic dependency*

FMEA/FMECA cannot show interrelationship between failures so the FMEA/FMECA is not sufficient to model systemic risks in this study.

FT and SD can capture deterministic dependence. FT can capture the deterministic dependency from basic event to top event. The relationships from basic event to the top event are defined via OR gates or AND gates assigned to the deterministic formulation of basic events (see example of calculation in Section 2.3.2). Therefore the actual outcome from the top event (output) can be known if the chance of occurrence of basic events is defined (input). SD can capture dependency by using deterministic equations of previous levels and rates of flow at the current time, without random factors being involved (see formulation in Section 2.3.4).

On the other hand, DES, PN and BBN are able to capture non-deterministic dependence. DES and PN represent the relations of activities or tasks in the system via the links which can be defined by functions of random variables. DES can show relationships between entities and the outcome of the entity, using arrow points to define functions. Entity is known in a state and an entity takes time to change a state; this called an activity. For example, an entity can operate if it is free so, it can be involved with random variables such as service time of each entities or customer time arrival. When a customer arrives at a clinic (known input), he or she cannot start consulting with the doctor if there are previous customers with the doctor (unknown output). Alternatively PN can transform input nodes to output nodes via transitions, determined by different transition rules involving random variables (Murata, 1989). The BBN can capture relationships by defining levels of uncertain relationships in CPTs by probability numbers (see example of defining CPTs in Figure 3-6) rather than by defining a mathematical equation. If only probabilities of the root cause or parent variables are defined, the probability of the top event cannot be obtained automatically, as it can in FT unless the CPTs of the intermediate variables are quantified. Therefore BBN can capture dependency as non-deterministic relationship (Røed et al., 2009) rather than deterministic relationship.

3. Ability to deal with both aleatory and epistemic uncertainty

The DES model can represent process tasks by stochastic variables which mostly can capture aleatory uncertainty by probability distributions to represent the aleatory uncertainty in the stable physical system. It is recommended that FMEA/FMECA is used to identify failures in early product and process development (IEC60300-3-1, 2003) and in establishing the criteria for faults and failures (Edwards and Bowen, 2005). Therefore it is mainly able to capture epistemic uncertainty.

On the other hand FT/ET, SD, PN and BBN are able to model either aleatory or epistemic uncertainty. SD can use stock-flow in simulation which can duplicate the known system and SD can implement causal loop diagrams (Angerhfer and Angelides, 2000) to capture mental models or the behavior of human as well as technical systems (Siu, 1994). Therefore SDs allow not only hard or objective effect or historical data but also soft or subjective effect to be considered in developing a model and estimating parameters (Angerhfer and Angelides, 2000; Howick and Eden, 2001; Sterman, 2001; Williams, 2000). FT can also model either a concrete or a novel system, including human aspects (Weber et al., 2012). FT transforms the physical system to a logical graph which can show the minimum set of basic events leading to a top event (Geum et al., 2009), so uncertainty in the system can be learnt and known. In the novel design system, there may be a lot of ‘unknown’ potential occurrences or adverse events in the system (Angerhfer and Angelides, 2000; IEC60300-3-1, 2003). PN is a suitable technique for performance dependability analysis and system novelty (IEC60300-3-1, 2003) but Wu et al. (2007) argue that the traditional PN may not be suitable for capturing the abstraction which can make a model lose information required to develop a good PN model. Finally, BBN can represent the epistemic uncertainty (Garbolinoa and Taroni, 2002) and can also deal with aleatory uncertainty because it can incorporate expert judgements to contribute qualitative estimation in risk assessment as well as empirical data (Kallepalli, 2004; Neil et al., 2005; Pai, 2004); this means it can be used with incomplete evidence (Neil et al., 2005).

4. Representation of uncertainty using probability theory

As well as presenting interrelationships differently, models are able to represent different formats. Outcomes of models can be classified in two formats: probabilistic and non-probabilistic. Of the six potential models only BBN and FT/ET models (Bedford and Cooke, 2001; Fernández et al., 2012) can present probability. Besides the probability language, some decision makers may be interested in evaluating the effectiveness of different mitigating strategies or scenarios (Sodhi and Tang, 2012), or evaluating the impacts on SC goal by setting the occurrence of the disturbance events, policies or SC redesign etc. in risk analysis and showing the outcome of those elements for the system as a whole (Hallikas et al., 2004). Therefore they would develop a model to replicate the behaviour of the system by using simulation (such as SD, DES or PN).

5. *Prioritise SC risks*

All candidate models can support risk prioritisation by considering both probability and impact although the representation of the probability and impact of risk events can be captured differently by different models, see Section 2.3.

6. *Scenario analysis for combinations of adverse events*

All candidate models can provide scenario analysis but some of them can present combining multiple failures to explain interrelationship between events or variables. Simulation methods can set scenarios by defining different parameters and then compare between outcomes from simulation experiments (PRAM, 2004) therefore SD, DES and PN can regularly perform scenario analysis by setting multiple variables as the same time. FT can also perform scenario analysis by diagnosis from the providing information of higher level of failure (Iverson, 1992). BBN can provide scenario analysis (Pai, 2004) and it can support risk diagnostic or prognostic analysis by posterior probabilities (Andrews, 2009). FMEA can provide scenario analysis but it cannot show the combination of faults (IEC60300-3-1, 2003) as other candidate models can perform.

7. *Ability of model to be represented visually*

The visual version of a model is important for facilitating communication when the model involves different stakeholders or clients. Generally apart from FMEA, candidate models are capable of being shown in visual form by supporting of specific software.

2.6 Concluding Comments on Choice of BBN as SC Risk Model

The suitable model to support SC risk analysis for this study needs to satisfy a set of criteria defined in Section 2.4. BBN is the highest ranked so BBN is selected for the further development of the modelling BBN process to support risk analysis in SC process. In summary, although BBN can provide the outcome of risk prioritisation along with scenario analysis as other candidate models, BBN is dominant over others in additional defined criteria. BBN can perform scenario analysis either predictions or diagnostics (Weber et al., 2012) by setting combination of simultaneous occurrence of a number of risk events. BBN can represent systemic risks in a SC process by ability to capture either aleatory or epistemic uncertainty since BBN can model different types of uncertainty: operational failure (e.g. McNaught and Chan, 2011; Neil et al., 2008), human error (e.g. Kim and Seong, 2006; Kim et al., 2006) or combining system related factors with human organisation factors (e.g. Ren et al., 2008; Trucco et al., 2008) etc. Next BBN can capture complex relationship via non-deterministic dependence (i.e. be able to capture complex relation between risks or adverse events) and it is also able to capture the less complex relations. This is an advantage of BBN over FT (Langseth and Portinale, 2007). Furthermore BBN can support measure of SC risks by representing via probability language which is defined as the nature of risk assessment (Williams, 2000). Moreover BBN represents logical relationships so it can simplify the complex demands of modelling inputs and deal with number of adverse events including rare and high impact events such as using BBN to analyse human fatality risk in building fires (Hanea and Ale, 2009). Finally the model visual display which can show the link of adverse events from different stakeholders since BBN can deal with great numbers of variables (Weber et al., 2012). Hence BBN can be used to support risk communication between stakeholders once they want to decide for mitigating risks with their stakeholders.

The possibility of developing a model in practice; the cost of the modelling software should be considered. BBN can be supported by GeNIe (The Decision Systems Laboratory, 2013) which is a free software tool and it is available to anybody to use the model, see Section 3.2.3. Furthermore the BBN also allow the translation of other models into a BBN such as transforming FMEA to BBN (e.g. Lee, 2001) or Transforming FT to BBN (e.g. Bobbio et al., 2001; Lampis and Andrews, 2009). If those models are available in a company, they can be used as supportive techniques by transforming to BBN for future improvement.

BBN can capture risks and interrelationships by simply using snapshots of the model during a specific of time (see Section 2.2.2). Therefore the assumption of using a static model to capture the dynamic SC process does not mean that the reality of risk in SC process is misrepresented; indeed, this can reduce the resources and efforts needed for using a dynamic model. However, if the simple case to represent risks in the SC process is feasible in practice, the static BBN could potentially develop as a series of static models in different time slices to represent the dynamics SC system (i.e. DBN), (Kao et al., 2005; Kjaerulff and Madsen, 2008) which can define for future study.

Chapter 3 Method and Process for Bayesian Belief Network Modelling

Bayesian belief network (BBN) modelling, also called Bayesian network (BN) modelling, was first reported as a method for studying inference by Dempster in the 1970s and Shachter in the 1980s (Kjaerulff and Madsen, 2008). Generally, BBN is a visual map linking variables by one-way arrows (qualitative BBN). It can also act as a probabilistic graphical model since it can represent the uncertainty of causal relationships by probability language (quantitative BBN). Inference uncertainty using Bayes' theorem provides useful outcomes that support risk analysis. This thesis first demonstrates the applications of BBN with uncertainty in SC, to give a basic understanding of the BBN method, before going on to develop BBN as a modelling process. Therefore this chapter will explain a theoretically grounded process for modelling SC risk using a BBN which is the second objective of this research.

3.1 BBN Basic Concepts and Theoretical Underpinning

The basic concepts of BBN will be explained using examples in the risk context of SC in this section.

3.1.1 Representing dependency – qualitative BBN

Let us consider how BBN can represent dependency by examining Example 3.1.

Example 3-1 If a supplier cannot supply the product then the product will be out of stock in a focal organisation.

There are two main events:

1. A supplier cannot supply the product (Cause event)
2. The product is out of stock (Effect event).

The causal chain can be identified by a graphical causality as shown in Figure 3-1.

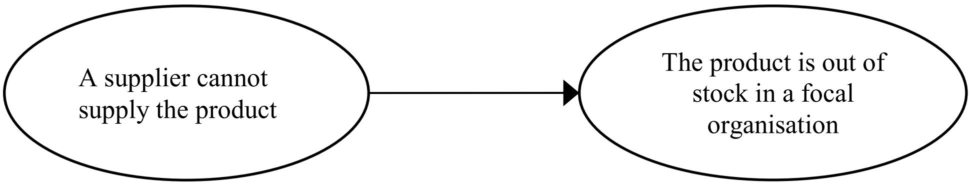


Figure 3-1 Simple example of graphical causality

More generally, a pair relationship can be explained by a causal sentence as: 'If cause event then effect event', representing the causality. The causal statement is able to transform to the graphical model by using an arrow pointing from cause to effect.

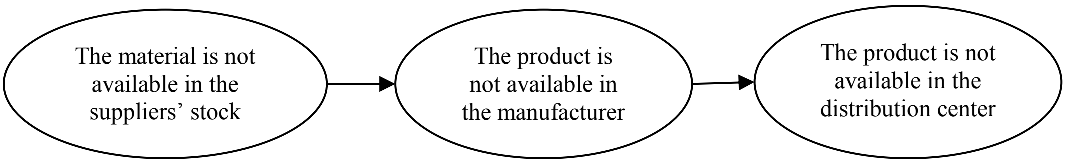
This simple visual graph can also be used to show the concepts of BBN. A random variable is shown as an oval and an arrow shows a causal influential link (Bedford and Cooke, 2001) or probabilistic influence (Neil et al., 2005). If there is an arrow pointing from variable *X* to variable *Y*, BBN (Kjaerulff and Madsen, 2008) defines 'The product is out of stock in a focal organisation' as a *child* or a *descendant* of 'A supplier cannot supply the product' while 'A supplier cannot supply the product' is an *ancestor* of 'The product is out of stock in a focal organisation'. Additionally a variable with no parents is called a *root cause variable* and a variable that has no child is called a *top variable* or *top event*. The top event can represent the event of interest of a BBN model.

3.1.2 Satisfying the conditional independence property

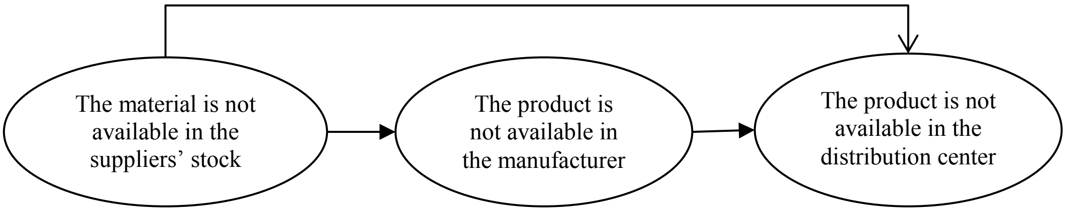
When the BBN becomes more complex, the conditional independence that is the basic property for a BBN means that it is vital for the BBN structure to get the variable ordering right. Why we need to use arrows to represent conditional independence is explained in Example 3-2.

Example 3-2 If material from a supplier is not available this means the manufacturer's product is unavailable since they cannot produce: this extends the causal chain to three variables as a series of causal relations. The finished product will not be available in the distribution centre, as shown by Figure 3-2 (a). Some hold to the theory that the material not being available in the supplier's stock is an additional cause link to the product unavailability in the distribution centre, as shown in Figure 3-2 (b).

If we already know that the product is not available in the manufacturer, then knowing that there has been an out of stock product in the distribution centre will not tell us any new information about the status of the material in the supplier's stock. If we had not observed the product (un)availability in the manufacturer, then knowing that there has been the unavailable product in the distribution centre will increase the belief that the product is not available in the manufacturer, which in turn will tell us something about the availability of the material in the supplier's stock. Therefore, by considering the conditional independence, we see that the link from unavailable material from the supplier's stock is necessary. The conditional independence property can be satisfied by the structure shown in Figure 3-2 (a). The link from 'The material is not available in the supplier stock' to 'The product is not available in the distribution centre' is unnecessary and should not be included in the BBN.



(a) First option



(b) Second option

Figure 3-2 Alterative structures for the simple causal relationship example of three variables

The structure of BBN expresses the conditional independence required to satisfy the Markov property and to simplify the Bayes' theory via the *Chain rule* (Taroni, 2006); see also Section 3.1.6.1. Furthermore the relation between conditional independence and BBN structure can explain how the BBN works (Korb and Nicholson, 2004). Considering the conditional independence helps to develop the optimal compact BBN while the dense network is unable to represent the causal dependencies explicitly (Korb and Nicholson, 2004).

The concepts of *independent* and *conditional independent* property can be distinguished by the following definitions:

> "A variable X is *independent* of another variable Y with respect to a probability distribution P if $P(X|Y) = P(X)$" (Kjaerulff and Madsen, 2008, pp. 54–55).

"A variable X is *conditionally independent* of Y given Z (with respect to a probability distribution P) if $P(X|Y,Z) = P(X|Z)$" (Kjaerulff and Madsen, 2008, p. 55).

Conditional independence can be explained via three types of connections in BBN (Korb and Nicholson, 2004) and it can be used in the SC risk context.

In general, there are three main types of causal relationship which are able to represent conditional independence: causal chains, common causes and common effects.

1. *Causal chains (serial connections)*: You believe that *A* is relevant to *C*, that *C* is relevant to *E*, and that *A* and *E* are conditionally independent given *C* (see Figure 3–3).

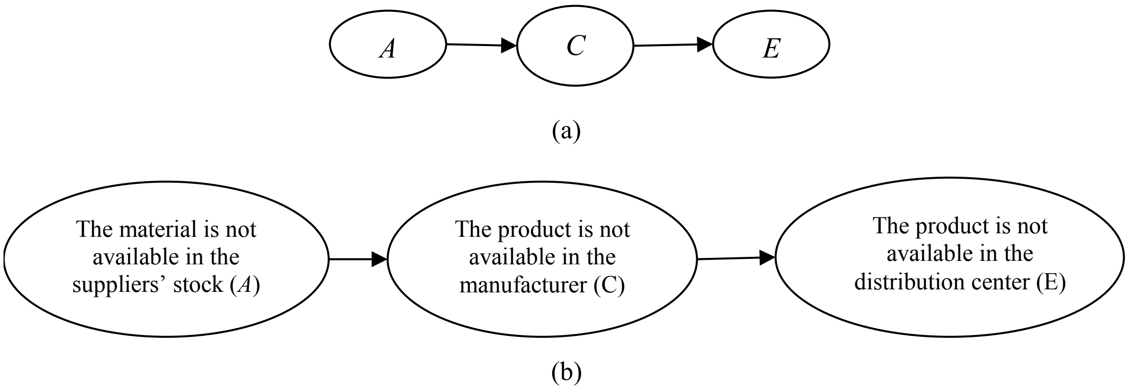


Figure 3-3 A causal chain relationship

If the state of *C* is known, then additional knowledge about the state of *E* does not change the belief about the possible states of *A* (and vice versa). If the state of *C* is not known, then knowledge of the state of *E* provides information about the possible states of *A* (and vice versa). This is what is shown in Example 3–2.

2. *Common causes (diverging connections)*: You believe that *Z* is a common cause of both *X* and *Y* so that *X* and *Y* are conditionally independent given *Z*.

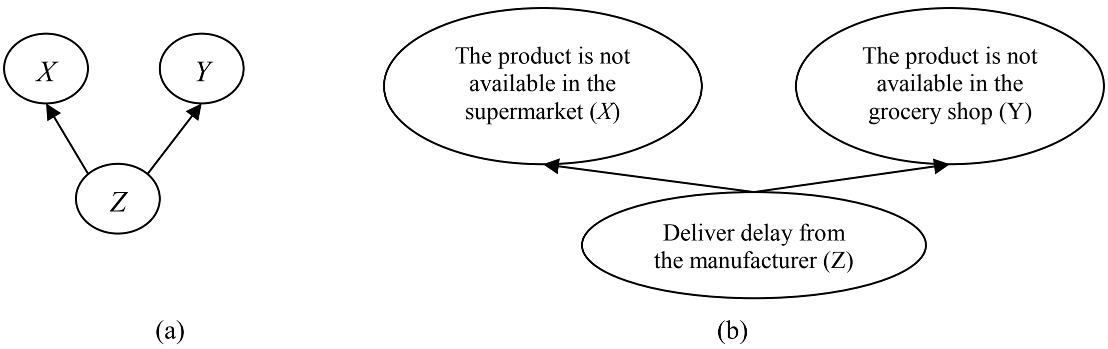


Figure 3-4 A common cause relationship

If the state of *Z* is known, then knowledge also of the state of *X* does not change the belief about the possible states of *Y* (and vice versa). For example, if it is known that delivery from the manufacturer is delayed then knowledge that the product is available in the supermarket gives us no extra clue as to the status of the product in the grocery shop.

If the state of *Z* is not known, then knowledge also of the state of *X* provides information about the possible states of *Y* (and vice versa). For example, if we do not know whether delivery from the manufacture is delayed or not, then the knowledge that the product is available in the supermarket (or not) will give us more belief in the product status in the grocery shop.

3. *Common effects (converging connections)*: A converging connection is an appropriate graphical model whenever it is believed that *A* and *B* are both relevant for *C*, *A* is not relevant for *B*, but they become relevant if the state of *C* is known (which is opposite to the previous two types of connection).

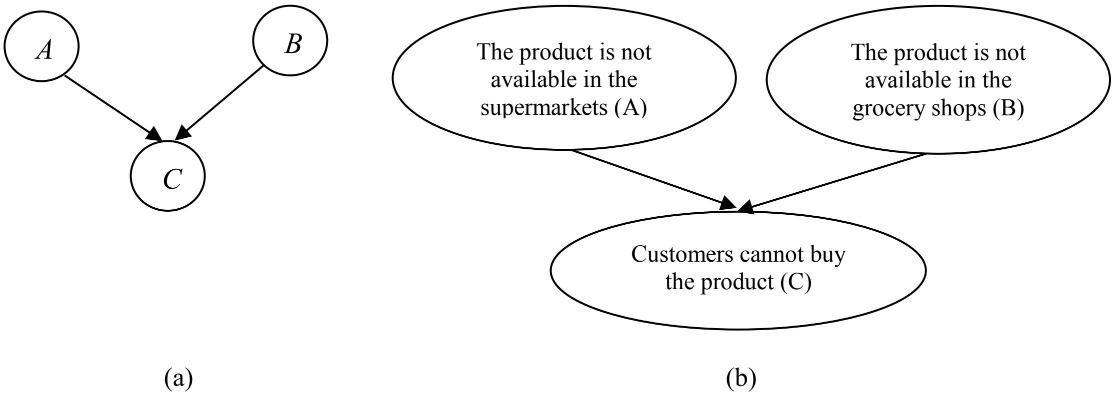


Figure 3-5 A common effect relationship

If the state of *C* is known, then knowledge of the state of *A* provides information about the possible states of *B* (and vice versa). For example, if we know that a customer cannot buy the product, then the information that the product is not available in the supermarket will make us more ready to believe that the product is not available in the grocery shops.

If the state of *C* is not known, then knowledge of the state of *A* provides no information about the possible state of *B* (and vice versa): the flow of information is blocked if the state of the middle variable is unknown. For example, when we know nothing about customers, then information on whether the product is available in the supermarkets will not tell us anything about the availability of the product in the grocery shops.

3.1.3 Defining variable state

After the causal statement is depicted by graphical causality, particular events can be transformed into the state format of BBN. The variable in BBN has to be defined at state level to represent all possible variable domains since it is uncertain that all variables can be present all the time.

According to Example 3-1, ‘A supplier cannot supply the product’ can be transformed to a variable in BBN but it should also identify the set of states to show all possible variable domains. Since sometimes a supplier can supply the product at the agreed time but occasionally cannot, the possible domains of ‘A supplier cannot supply the product’ variable can be defined as ‘Can’ or ‘Cannot’: two simple states, called Boolean values.

Furthermore a set of states is finite for discrete variables of *mutually exclusive* states and *exhaustive* states (Korb and Nicholson, 2004). Mutually exclusive states means only one state can happen at a time. Exhaustive states means all defined states cover all possible events which can occur in particular domain. For example, each time dealing is made for a supplier to deliver a product, a focal organisation can observe that either the supplier can or cannot supply the product (*mutually exclusive states)* and ‘Can’ and ‘Cannot’ cover all possible occurrences of supplying the product (e*xhaustive events)*. On the other hand, if the variable includes the delivery of set of products from a supplier, the state of the variable can be define as ‘Completed’, ‘Partial’, or ‘Not at all’; this can follow the *mutually exclusive states* and *exhaustive event* properties (rather than using the simple ‘Can’ and ‘Cannot’ states). Identifying states in more detail can provide richer information; however, the definition of particular states should be very clear and should also support the analysis of the required outcomes. Preparing the variable in the state format is important since it will then be possible to quantify the chance of individual states.

3.1.4 Quantifying uncertainties – quantitative BBN

Probability can represent the chances of individual states of a variable. The level of possibility ranges between 0 to1 to represent probability of occurrence in particular states for individual variables.

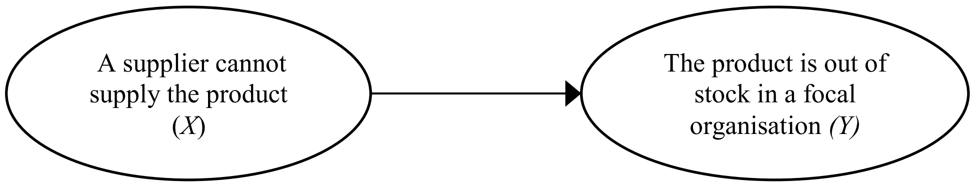
Example 3-3 Referring to Example 3-1, ‘A supplier cannot supply the product’ is a root cause variable and the probability that a supplier cannot supply a product can be quantified by using what proportion ‘A supplier cannot supply the product’ is of total delivery time. If the relative frequency of ‘A supplier cannot supply the product’ is 0.1, this means normal supply, $P(X = x)$, is 0.9 (i.e. 1 – 0.1). This is a simplified example, supposing that ‘product out of stock' is the only defined cause of 'supplier cannot supply a product'. However, it is uncertain that every time the supplier cannot supply the product, the product in a focal company will be out of stock: safety stock should be in place and if new supply can be obtained before the safety stock runs out, the product will still be available. It may be found, for example, that if the supplier cannot supply the product then it will be out of stock 40 times in 100, or:

$$P(Y = y|X = x) = P(Y = \text{Out of stock}\,|X = \text{Cannot}) = 0.4\,.$$

This demonstrates **reasoning under uncertainty**. Since for 40 per cent of the time the product can be out of the focal organisation stock (when they cannot get supply from the supplier), this means that there is a 60 per cent chance that they still have the product available in stock before they get supply from their supplier again. If the product is supplied normally then the focal organisation can observe that they can face some other problems in their own operation to make the product out of stock, say, 5 times in 100:

$$P(Y = y|X = x) = P(Y = \text{Out of stock}\,|X = \text{Can}) = 0.05\,.$$

The quantification of those two variables will be shown in Figure 3-6.



PT

A supplier cannot supply a product (*X*)	
Cannot	0.1
Can	0.9
Total	1.0

CPT

The product is out of stock (*Y*)	A supplier cannot supply a product (*X*)	
	Cannot	Can
Out of stock	0.4	0.05
Available	0.6	0.95
Total	1.0	1.0

Note: The numbers in the table sum to 1

Figure 3-6 BBN example of Probability Table (PT) and Conditional Probability Table (CPT)

In general, variables can be explained by *root cause variables* and *effect variables,* which can be quantified via a Probability Table (PT) and/or a Conditional Probability Table (CPT).

If X is a root cause variable, there is no variable link into it so it is independent from and therefore not conditional on other variables. The probability of root cause variable X being in state x, $P(X = x)$, is quantified in a Probability Table (PT).

If Y is an effect variable as child variable (because it always has parent variable(s) linked to it), it is conditional on other variables. Therefore the probability of occurrence of an effect variable depends on its causes. The probability of an effect variable being in a given state can be determined by the known states of parent variable(s), $P(Y = y|X = x)$, and is quantified in a Conditional Probability Table (CPT). There are two special cases. If the cause event occurs, it can influence the effect event in such a way that it is certain to happen (probability = 1) or is certain not to happen (probability = 0); this is called the certainty factor which can represent *completely deterministic relationship* (Section 2.4.1.2).

3.1.5 Using BBN inference to answer supply chain risk analysis questions – reasoning under uncertainty

Input probabilities will be propagated under BBN concepts to provide outcomes from inference process of BBNs. To support SC risk analysis, outcomes from the model are defined based on user demand. From the managerial point of view as defined as Section 2.4 given by Sodhi and Tang (2012), using the BBN model should provide outcomes to support risk measures, to help management focus on specific areas and to support allocation of risk management efforts and budget with their stakeholders. Those three purposes can be served by the answers to three questions.

1. What is the chance of a particular adverse event occurring?
2. What are the main risks that cause supply failure?
3. What is the impact of (combination of) uncertain events on supply through the chain?

3.1.5.1 What is the chance of a particular adverse event occurring?

Example 3-4 Using Example 3–3, the current probability of 'A supplier cannot supply the product' of 0.1, $P(X = Cannot) = 0.1$ is the input probability in PT for a cause variable. On the other hand, the chance of the product being out of stock in a focal organisation (for an effect variable) cannot be indicated directly from probability numbers in the CPT: it requires inference by BBN theory by using probability numbers from both PT and CPT (see Figure

3-6). Therefore the chance (*Y*) that the product is out of stock in a focal organisation can be calculated as 0.05*0.9 + 0.4*0.1 = 0.085, as can be seen by Figure 3-7.

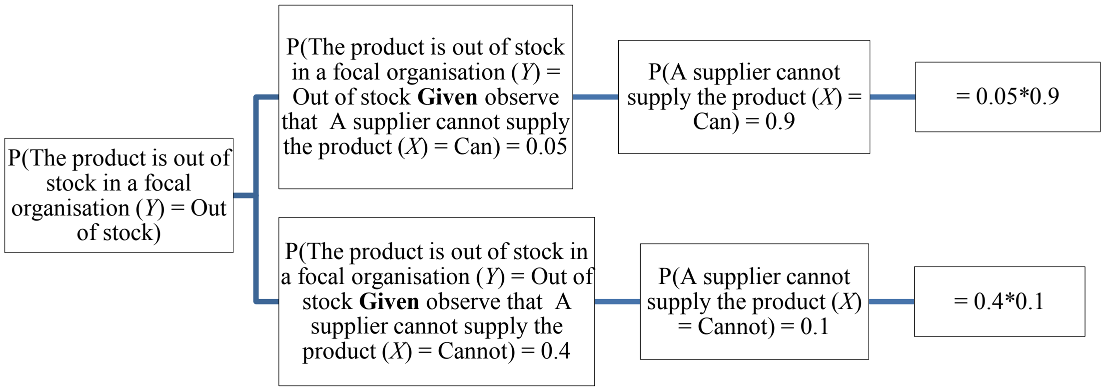


Figure 3-7 Calculating the chance (*Y*) that a product is out of stock in a focal organisation

The detailed equations for this calculation are:

$$\begin{aligned} P(Y = \text{Out of stock}) &= \sum_x P(Y = \text{Out of stock} | X) P(X) \\ &= P(Y = \text{Out of stock} | X = \text{Can}) * P(X = \text{Can}) \\ &\quad + P(Y = \text{Out of stock} | X = \text{Cannot}) * P(X = \text{Cannot}) \\ &= 0.05 * 0.9 + 0.4 * 0.1 = 0.045 + 0.04 = 0.085 \end{aligned}$$

Probability of the product available in a focal organisation stock is:

$$P(Y = \text{Available}) = 1 - P(Y = \text{Out of stock}) = 1 - 0.085 = 0.915$$

In general, the *marginal probability* of a variable (either root cause or effect variable) is the probability of occurrence for each variable in particular states. In this thesis, it will be called the *current probability* of particular adverse events to show the likelihood of a variable which represents an adverse event occurring. If a variable is a root cause variable, the marginal probability is equal to the input probability from PT. If it is a descendent variable or effect variable, the marginal probability is not directly input and will be calculated by eq. (3-1).

The simple example is given by showing the relationship of two variables where X is a cause of Y, see Figure 3-8.

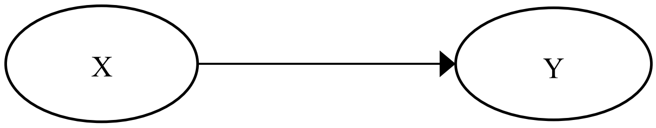


Figure 3-8 BBN representation of a pair relation

The chance of an effect variable Y occurring can be calculated by eq. (3-1).

$$P(Y) = \sum_{x} P(Y|X)P(X) \tag{3-1}$$

Marginal probability has been used to estimate and evaluate network risks to compare suppliers (Lockamy and McCormack, 2010; Lockamy, 2012), and to calculate risk factors (Pai et al., 2003).

3.1.5.2 What are the main risks that cause supply failure?

Example 3-5 Referring to Example 3-3, if we observe that the product is out of stock in a focal organisation, how likely this is caused by a supplier not being able to supply the product?

The *adjusted probability* that a supplier cannot supply the product (*X*) when it is observed that 'The product is out of stock in a focal organisation' (*Y*) is:

$$P(X = \text{Cannot}|Y = \text{Out of stock}) = \frac{P(Y = \text{Out of stock}|X = \text{Cannot})P(X = \text{Cannot})}{P(Y = \text{Out of stock})}$$

$P(X)$, the *prior probability,* and the conditional probability distribution $P(Y|X)$ were specified in Example 3-3 as inputs into the model by PT and CPT along with the marginal probability of $Y = \mathit{Out\ of\ stock}$, Example 3-4.

Therefore:

$$P(X = \text{Cannot}|Y = \text{Out of stock}) = \frac{P(Y = \text{Out of stock}|X = \text{Cannot})P(X = \text{Cannot})}{P(Y = \text{Out of stock})}$$

$$= \frac{0.4(0.1)}{0.085} = 0.4706$$

Therefore when we observe that the product is out of stock in a focal organisation, the belief that the supplier cannot supply the product is adjusted to 0.4706, an increase from 0.1 as has been defined for the current probability. The ratio between the adjusted probability and current probability represents the effect impact for individual adverse event on the top event is called the *Normalised Likelihood (NL)* as will be explained in Section 3.1.6.2. If more than one cause variable is defined *NL* will be used to compare them, to identify the main risks that cause supply chain failure (top event).

In general*, marginal posterior probability* represents the probability of each variable being in a particular state when the set of evidence variables have been observed by specifying observed states. In this thesis, marginal posterior probability will be known as the *adjusted probability* of an adverse event after knowing the specific state of the set of evidence variables, since the adjusted probability of particular events can be calculated by setting any other observed variable. However, to identify the main risks that cause supply failure, the adjusted probability of particular cause events should be defined by using diagnosis from setting the top event.

Consider the simple example of two variables where X is a cause of Y, and Y is also a top event (Figure 3-8). Then the marginal posterior probability of X given the evidence of Y can be calculated by eq. (3-2).

$$P(X|Y) = \frac{P(Y|X)P(X)}{P(Y)} \tag{3-2}$$

3.1.5.3 What is the impact of (combination of) uncertain events on supply through the chain?

The adjusted probability can also be used to compare different scenarios of adverse events or combinations of adverse events, defined as a set of observed variable; see Section 3.1.5.2.

Therefore when the adjusted probability is to be calculated, a set of evidence variable(s) should be identified by setting of scenarios.

When $\boldsymbol{\varepsilon}$ is defined as set of evidence variables and X is defined as a focus variable, the marginal posterior probability of X can be calculated as:

$$P(X|\varepsilon) = \frac{P(X,\varepsilon)}{P(\varepsilon)} \tag{3-3}$$

The posterior probability can be calculated by Bayes' theorem, developed by Thomas Bayes (1772 - 1761). In general form this is:

$$P(X|\varepsilon) = \frac{P(\varepsilon|X|)P(X)}{P(\varepsilon)} \tag{3-4}$$

Because of the complicated nature of the manual calculations for a complex network, we cannot show the example calculations here. This is the main reason for using GeNIe software to support analysis. However, the extended analysis method for complex network will be explained conceptually in the next section.

3.1.6 Extended analysis method for more complex networks

3.1.6.1 Current and adjusted probability

In general a BBN is much more complex, combining many more variables and arrows than the examples seen so far. The *joint probability distribution* becomes very complex and the marginal probability and marginal posterior probability become difficult to calculate manually. The process of applying conditional independence in BBN can be explained by the four-variable network shown in Example 3-6 (which will be used for explanation of conceptual modelling framework in Section 5.1).

Example 3-6 BBN inference from a four-variable network can be shown as in Figure 3-9.

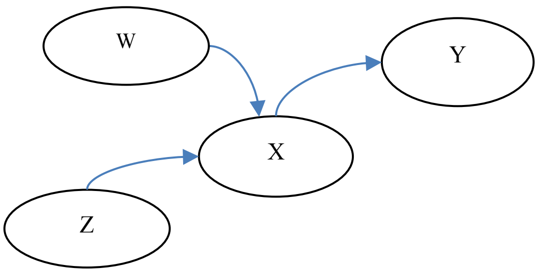


Figure 3-9 Example network of four-variables

In general, a network of *n* variables is a sequence of directed graphs from $X_i \longrightarrow X_{i+1}$ for $i = 1, 2, 3, \dots, n\text{-}1$ where there is no cycle in the network structure, which is called a Directed Acyclic Graph (DAG). Therefore the multiplication law or *Chain rule* or Markov property allows decomposing a joint probability with *n* variables as a product of conditional distribution as:

$$P(X_1,\dots,X_n) = \prod_{i=1}^{n} P(X_i|X_1,\dots,X_{i-1}) \tag{3-5}$$

In Example 3-6, the top variable Y is a sequence of directed graphs of W, X, Z with no cycle. According to the *Chain rule* (see eq. (3-5)), joint probability of W, X, Y, Z is:

$$\begin{aligned} P(W,X,Y,Z) &= P(Y|W,X,Z)P(X|W,Z)P(W|Z)P(Z) \\ &= P(Y|W,X,Z)P(X|W,Z)P(W)P(Z) \end{aligned}$$

Therefore the set of conditional variables can combine with the set of parent variables of the focus variable and other variables which are non-descendent variables (by following the sequence of directed graph).

For example, consider the set of conditional variables of $P(Y|W,X,Z)$, which is W, X, Z. It is found that only X is the parent of Y while W, Z are non-descendent variables.

Therefore, using eq. (3-5) we can obtain:

$$P(X_1,...,X_n) = \left[\prod_{i=1}^{n} P(X_i \,|\, \boldsymbol{PA}(X_i), \boldsymbol{Non\_Descendent}(X_i))\right] \quad (3\text{-}6)$$

Where $P(X_1,...,X_n)$ is the joint probability distribution, $\mathbf{PA}(X_i)$ is the set of the parent variables of variable X_i, and $\mathbf{Non\_Descendent}(X_i)$ is set of all variables in DAG other than $X_i, \mathbf{PA}(X_i)$ and $\mathbf{Descendent}(X_i)$

The next property of BBN, conditional independence, is introduced to simplify eq. (3-6). X_i is *conditionally independent* from the set of $\mathbf{Non\_Descendent}(X_i)$ given the set $\mathbf{PA}(X_i)$ of the parents of X_i. Therefore eq. (3-6) can reduce the complexity of the conditional variables by including only set $\mathbf{PA}(X_i)$ of the parents of X_i:

$$P(X_1,...,X_n) = \prod_{i=1}^{n} P(X_i|\mathbf{PA}(X_i)) \quad (3\text{-}7)$$

Bearing in mind conditional independence – see eq. (3.7) – the joint probability can gain calculating advantages by reducing the complexity of the condition:

$$P(W,X,Y,Z) = P(Y|X)P(X|W,Z)P(W)P(Z)$$

The marginal probability can also be calculated from the joint probability distribution via eq. 3-7. The joint probability can be used for calculating marginal probability or marginal posterior probability.

For example, the marginal posterior probability of variable X given that a particular value of variable Y is observed, $P(X|Y)$, was defined by eq. (3-2) as:

$$P(X|Y) = \frac{P(X,Y)}{P(Y)}$$

where $$P(X,Y) = \sum_{W}\sum_{Z} P(W,X,Y,Z)$$

$$P(Y) = \sum_{X}\sum_{W}\sum_{Z} P(W,X,Y,Z)$$

Since the example of a 4-variable network requires a considerable amount of input, the manual calculation of this example will not be shown in detail here. However, standard examples of BBN calculations have been shown in the literature (Kjaerulff and Madsen, 2008; Lauritzen and Spiegelhalter, 1988).

The burden of BBN inference in a complex network is solved by advanced algorithms and software packages in academic or commercial organisations that have been developed to support the application of large and complex BBN. GeNIe software was selected to support model construction and provide risk analysis outcomes in this research, see Section 3.2.3.

3.1.6.2 Normalised likelihood (NL): Ratio of adjusted probability and current probability

NL is a sensitivity analysis method (Kjaerulff and Madsen, 2008). Diagnostic reasoning from the top event *(Y)*to individual cause variables (ε) is implemented by calculating marginal posterior probabilities, $P(\boldsymbol{\varepsilon}|Y)$.

$$NL = \frac{P(\boldsymbol{\varepsilon}|Y)}{P(\boldsymbol{\varepsilon})} = \frac{P(Y,\boldsymbol{\varepsilon})/P(Y)}{P(\boldsymbol{\varepsilon})} = \frac{P(Y,\boldsymbol{\varepsilon})/P(\boldsymbol{\varepsilon})}{P(Y)} = \frac{P(Y|\boldsymbol{\varepsilon})}{P(Y)} \qquad \text{(3-8)}$$

When we consider only single cause variable (ε), eq. (3-8) can be used to measure the impact of each variable (ε) on the top event *(Y)*, a comparison can be made with the current probability (without observing the top event), $P(\varepsilon)$. The impact of particular events on the top event can be measured by the ratio of marginal posterior probability (with observed evidence), $P(\varepsilon|Y)$, and marginal prior probability (without observed evidence), $P(\varepsilon)$. In other words, it is equal to the ratio of adjusted probability (given a focus variable is observed) and the current probability of a general variable.

3.2 Issues of Concern in the BBN Modelling Process

With respect to the definition of necessary basic concepts, issues of concern to the BBN modelling process arise in two areas: problem structuring and model validation.

3.2.1 Issues in problem structuring – differentiating BBN model structure from qualitative maps by using four criteria

According to BBN basic concepts (see Section 3.1) and a proposed procedure suggested by Nadkarni and Shenoy (2001), four criteria are of concern for BBN structuring.

1. *Conditional independence*

Conditional independence is required when implementing BBN inference (eq. (3-6) - (3.7)), to help control the structure of the BBN which is different from other qualitative maps.

The process for checking conditional independence of the BBN structure can be applied: for the explanation of three types of causal relationship see Section 3.1.2.

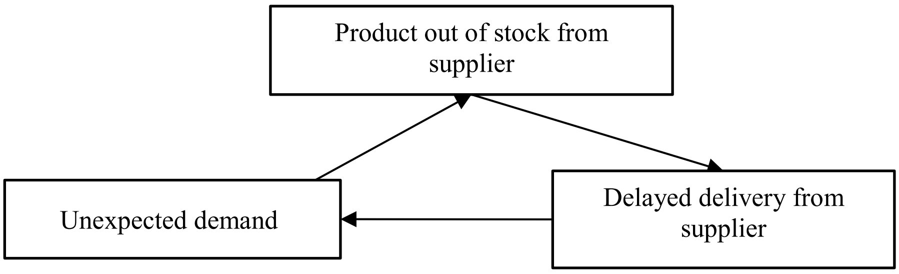
2. *Loops must be eliminated, or two-way arrows adjusted to one-way arrows*

The BBN map must present only links between variables without a *cycle connection*; see Section 3.1.6.1. A *cycle* is said to exist if a variable is an ancestor, and also descendant of itself and a graph is connected if there exists at least one path between every pair of variables. Therefore, there are no loops or feedback loops in the BBN.

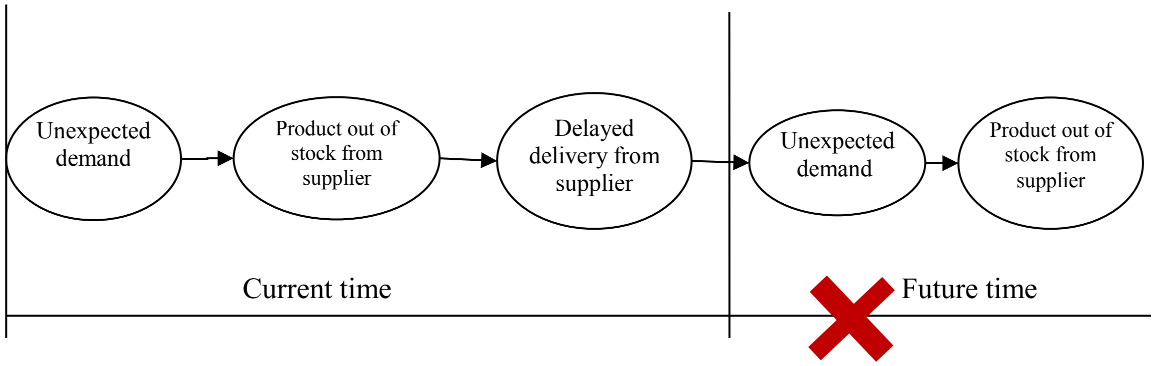
The feedback loop can be thought of as describing the dynamic relations between variables over time so part of the loop will be contained in the current time frame and some of links will be associated with the future time frame. This involvement with the time element is outside the scope of the static BBN.

For example, when the focal company cannot get the product from supplier, they may worry that it might happen again and want to increase safety stock level. This can stimulate unexpected demand for the supplier and lead to the product being out of stock from supplier, a loop of reasoning as shown as Figure 3-10 (a).

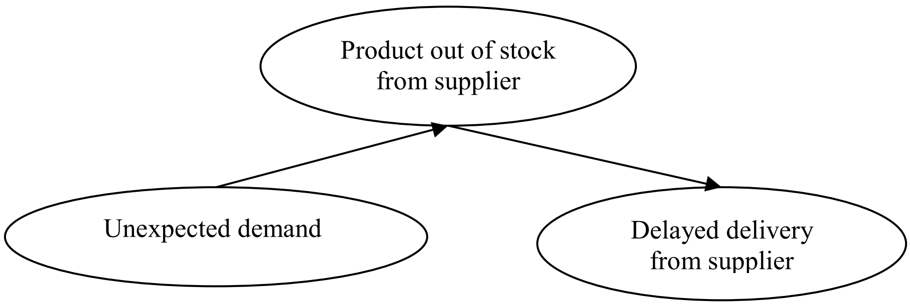
To eliminate loops the reasoning process can be classified into two time slices (see Section 2.2.2), current and future. The model can only take into account the current time frame since the static BBN cannot include the effect of time. Relating this to the supplier stock example, the effect of supplier inability to deliver on time stimulating unexpected demand cannot be captured with the model; see Figure 3-10 (b). The loop can be eliminated by deleting the link 'Delayed delivery from suppliers' to 'Unexpected demand'; see Figure 3-10 (c).



(a) Example of causal loop



(b) Flow of reasoning over time

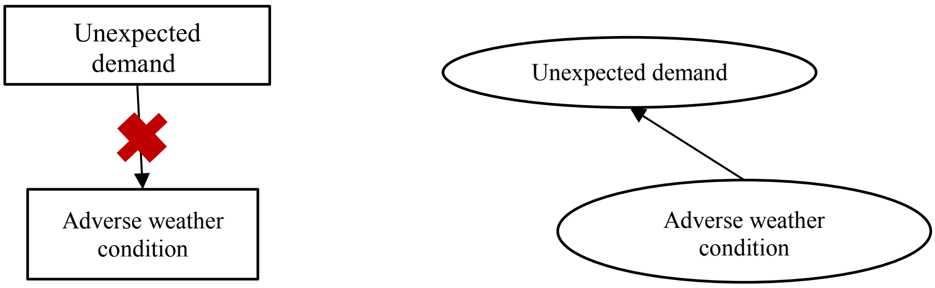


(c) A part of Adjusted BBN map (after delete inapplicable link)

Figure 3-10 Eliminate loops by disaggregating variables over time

3. The direction of links is from cause to effect

Cause-consequence or cause-effect is the main relationship for qualitative BBN structuring in this research although some other relationships can also be modelled by BBN (see Appendix E). The direction of arrows in BBN can be used to determine inference formulation and can lead to the reasoning analysis, so structure of the model should link only from cause to effect (deductive reasoning). There should be no mixing with opposite direction links, from effect to cause (abductive reasoning).



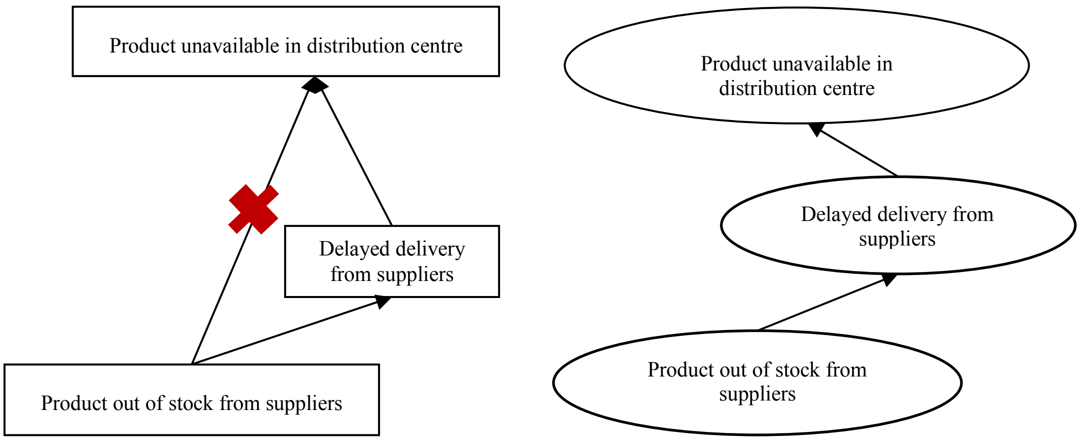
(a) Abductive reasoning (b) Deductive reasoning

Figure 3-11 Distinguish between abductive reasoning and deductive reasoning

For example, the direction of arrow which links from 'Unexpected demand' to 'Adverse weather condition', Figure 3-11 (a), employs a reasoning direction of effect to cause. Since the adverse weather could be the cause of increasing unexpected demand (such as some medicines), the reverse arrow should be replaced, see Figure 3-11 (b). To put it another way, clearly unexpected demand cannot cause adverse weather conditions, so this is not a deductive reasoning.

4. *Including only direct relationships*

Distinguishing direct and indirect cause-effect relations can help to reduce the number of less relevant variables and indirect links. The effect of 'Product out of stock in supplier stock' could be that the product is unavailable in distribution centre stock and its availability is delayed or it might mean the product is unable to be supplied on time from the supplier. When the supplier cannot supply product on time or delivery is delayed, this can also make the product unavailable in distribution centre stock; see Figure 3-12 (a). Once the supplier is out of stock this can directly lead to the supplier not being able to supply the product on time, which in turn can be a cause of the product being unavailable in the distribution centre. But the effect from 'Product out of stock in supplier stock' will not directly link to the unavailability in distribution centre if 'Delayed delivery from supplier' is in the map; see Figure 3-12 (b).



(a) Direct and indirect links (b) Only direct links

Figure 3-12 Consider only direct relationships

3.2.2 Issues in model validity

It should be possible to validate a developed model; however, there is no agreement on the questions of 'what is a valid model?' or 'what is the way to validate model?' (Dery et al., 1993). Different approaches can be implemented for validation but cost and time constraints of the research make any of them difficult to undertake (Borenstein, 1998). As in modelling BBN for risk in SC the truth value under the modelling assumptions will not be easy to access or may not available, the validation methods for modelling **with unknown true value** in the literature on Decision Support Systems and Management Science/Operational Research are reviewed in this section.

Model verification and validation, as explained in the literature, are not the same.

> **Verification:** 'Is the model built right?'
>
> Verification aims to test whether the model can follow the right process (Finlay, 1988; Finlay et al., 1988) to ensure the quality of the model. Therefore it is a debugging process when the model is constructed by using an algorithm (Laskey and Mahoney, 2000). Although verification is not the main concern of this study since the BBN model can be constructed by available software called GeNIe software (The Decision Systems Laboratory, 2013), checking for some common modelling errors, such as making sure the variable states are exhaustive and exclusive (see Section 3.1.1), should be carried out (Korb and Nicholson, 2004).

Validation: 'Is the right model built?'

Validation can be evaluated whether or not the model provides an appropriate representation of the real world (Finlay et al., 1988; Watson and Buede, 1994). Validation means knowing whether the right answer or the truth value is known. Although the recorded data are generally kept to show the SC performance, this may not include the same underlying modelling assumptions, or they may not link the data for whole SC. Even once data are recorded in the required format, some rare risk events are difficult to observe in reality, and more data are needed (McCarl, 1984), so more time is required to collect real data. In addition, the BBN model for this research aims to support SC risk analysis which intends to improve understanding of SC risk rather than provide accurate risk predictions. Therefore the process of validation may not require investing in a lot of resources. This is why validation can and should be performed under the assumption that grounded truth data currently are not available.

*The term **appropriate** has been used rather than **right** or **truth** since with models for managerial decision making the search is for usability, and usability is based on user's view point and the context in which he find himself* (Finlay, 1988, p. 176).

According to the literature, one widely implemented method is 'face validity' (e.g. Borenstein, 1998; Houben, 2010). When the truth value is unavailable, knowledgeable people are asked if the model and/or its behaviour are reasonable (Sargent, 2005). This is known as validation model with experts' feedback (Borenstein, 1998) or validation by assumption (McCarl, 1984). Face validity is the most commonly used method in BBN (Pitchforth and Mengersen, 2013) to achieve the consistency between the modellers' and users' perceptions in a timely and cost-effective way (Borenstein, 1998). A summary of the criteria for validation from literature (Houben, 2010; Korb and Nicholson, 2004) is given in Table 3-1. The suggested criteria are mainly implemented by the face validity method which is more subjective, and the criteria will be taken into the design of BBN modelling process, but they can be assigned in different stages.

Consistency checking is mainly implemented by the modeller, while clarity and definition of variable and relation checking of the model structure is validated by experts. The model analysis outcome also is validated by showing sensitivity analysis and scenario analysis to experts and asking for their perceptions.

Table 3-1 BBN model validation criteria when the truth value is unknown

Related process	Criteria
Model structure by expert panel	**1. Clarity test** Do all variables and their states have a clear operational meaning to all stakeholders? **2. Variable definitions and relation checking** Are they named usefully? Are state values appropriately named? Are all relevant variables (under the modelling scope and assumption) included?
Process to achieve different perceptions by modeller	**3. Consistency checking** Are the state dimensions (e.g. a week, in a month etc.) and state units (orders, products, units etc.) across different eliciting questions consistent? Are all state values useful or can some be combined?
Model analysis outcome by expert panel	**4. Model robustness (Sensitivity analysis)** Are the sensitivity analysis results acceptable for experts? Or are the ranges of concerned variables specified in the map? (Include or exclude some variables) **5. Model behave appropriately (Scenario analysis)** Are experts comfortable with the results of the scenario testing?

Source: Adapted from Houben, 2010; Korb and Nicholson, 2004

3.2.2.1 Sensitivity analysis

Sensitivity analysis aims to evaluate how best to use a model (Korb and Nicholson, 2004). It can show how sensitive the network is when the values of probabilities input into the system are changed. When sensitivity analysis is used for validation, experts are asked to adjust the parameters to bring the behaviour of the model within the scope of the experts' belief (Laskey, 1995). There are two kinds of sensitivity analysis: evidence sensitivity analysis and parameter sensitivity analysis.

Evidence sensitivity analysis is commonly applied since it is the simpler of the two methods. Main effect analysis (Houben, 2010) tries to answer the question: *'What are the minimum and maximum beliefs produced by observing a variable?'* (Kjaerulff and Madsen, 2008). The analysis can be carried out by systematically changing the input variables one by one to observe the output variables. Alternatively, if the combination of input variables is changed systemically, the interaction of the input variables can be observed from the output variables, and this is known as interaction sensitivity analysis.

Parameter sensitivity analysis is used to check the correctness of the model by showing whether more precise parameter estimation (subjective probabilities) will be more useful. It can vary a parameter at a time to examine the effects on a focus variable when the other variables are fixed. The behaviour of the model cannot be validated from all possible combination of evidence variables, especially in a complex network, so some researchers use design of experiments (Houben, 2010) or sampling of evidence variable combinations (Laskey and Mahoney, 2000) or sensitivity functions (Bednarski et al., 2004; Coupé and Gaag, 2002; Kjaerulff and Madsen, 2008).

However, parameter sensitivity analysis is very time-consuming, especially in the large BBN for SC risk which is going to be developed. Additionally, the expectation from the BBN model in this context is to support risk analysis by using comparison and prioritisation to understand the vital risk rather than by requiring a high precision of parameter estimation. The parameter sensitivity analysis may beyond the scope of this modelling process.

3.2.2.2 Scenario analysis

Scenario analysis is a case-based evaluation used to show the behaviour of the model. Scenario analysis in BBN can use either component testing or whole-model testing (Korb and Nicholson, 2004). Basically a focus variable (or a few focus variables) is the main interest when it comes to observing the effects of different scenarios. The particular scenarios are defined by assigning specific states for scenario variables (as observed evidence variables) and then analysing the marginal posterior probabilities. Some set of scenarios for testing can be identified by the experts and group workshop discussion to enable feedback of what they would consider satisfactory in their judgement (Laskey and Mahoney, 2000). This analysis tends to show the reasoning flow from different directions. Apart from the validation purpose, scenario analysis is also used to support inference for SC risk analysis (Section 3.1.5.3).

3.2.3 Issues in calculation

The discussion in Section 3.1.6 shows that it is difficult to calculate the current and adjusted probability for a complex BBN manually. Therefore, BBN software has been developed which can make the application of BBN more practical: a list of software packages is available in Korb and Nicholson (2004). This research recommends GeNIe software (version 2.0) which was developed at the Decision Systems Laboratory, University of Pittsburgh and is available to general users since 1997 (The Decision Systems Laboratory, 2013). GeNIe is free software which we can be downloaded from http://genie.sis.pitt.edu/; so we do not need to be concerned about limitations on the model size, which is the main concern with using a trial version of some commercial software. Furthermore, GeNIe is versatile and user-friendly.

3.3 State-of-Art of Proposing BBN Modelling Process to Support Supply Chain Risk Analysis

3.3.1 Problem definition

We believe that implementing BBN to support risk analysis in SC is different from applying BBN in other domains for the following reasons.

1. *This thesis aims to contribute a generic BBN modelling process rather than a generic BBN model to support SC risk analysis.*

Recently, the number of studies of BBN applications in SC or SC risk has been increasing and the list of BBN applications in SC risk have been summarised in Section 2.3.6. However, most of these studies intend to contribute in terms of outcomes rather than in terms of developing the process of BBN to support risk analysis. Therefore, they provide less detail on the process of constructing those BBNs. Once these scholars aim to propose a generic outcome, they propose the high level BBN model structure such as loss evaluation (e.g. Fenton and Neil, 2001; Kallepalli, 2004; Pai et al., 2003) or evaluation of objectives from sub-objectives or sub-criteria (e.g. Liu, 2013; Lockamy and McCormack, 2010, 2012). We argue that those high-level models are less complex, so they cannot show the interaction of adverse events from different stakeholders in SC explicitly. Furthermore, particular organisations can be faced with different adverse events, so individuals involved in a specific SC should develop their own SC risk model in order to support risk analysis.

2. *This thesis aims to suggest a modelling method based purely on expert judgement.*

SCRM is a new aspect of SCM to manage risk proactively, as has already been explained in Section 1.2.4. Proactive management can involve changing the profile of any risks which can disrupt an entire SC. Therefore, risks can occur anywhere in the chain and we should not focus on a specific type of risks or scope the model for internal organisation rather than define the possible events in SC level of management (see Section 1.1.1 and Section 1.3). Risk analysis is a part of SCRM process and it can be supported by BBN, so the model should be able to cope with a complex network of many adverse events from different stakeholders.

Although BBN can be quantified from the historical risk performance and it is good for describing historical risk performance, it may not be sufficient for risk prediction to support proactive management. Furthermore, those recorded data can generally only cover aleatory uncertainty (see Section 2.2.1); on the other hand, situations involving epistemic uncertainty, such as human errors, rare events or organisation factors, are difficult to record accurately, and they also make it hard to implement Markov Chain Monte Carlo simulation.

Once we consider a complex network, there may be no historical data to link logical relationships as cause and effect between stakeholders at the operational level; in that case, the method of BBN developing from machine learning (e.g. data mining or neural network technique) is infeasible in this context. In practice, the only available data source for BBN modelling in this context to predictive risk assessment should be developed by based on the collection of expert knowledge (further supporting reasons to use expert knowledge are also provided in Section 3.4.3 (1)).

In the available literature on BBN modelling in SC risk, in which the model is not complex, modellers can retrieve recorded data or collect historical data for quantification of risks. Alternatively, some scholars (Lee et al., 2009) use a survey method to claim that the generic result of the model is represented by a population. However, modelling BBN in SC scope by linking with different stakeholders can make a model much more complex and it requires a lot of input data. Donaldson and Soberanis (2010) provide an approach and example of assumed data to quantify the model via operation of SC, but the feasibility to collect those data in a real organisation has not been demonstrated. Therefore, when they develop a complex BBN model in SC risk context with real case studies, scholars generally implement expert judgement with simulation techniques (e.g. Basu et al., 2008; Deleris and Erhun, 2011; Kao et al., 2005; Ravi and Singh, 2013; Uhart et al., 2012; Yuan et al., 2012) or design software agent based simulation model (e.g. Fernández et al., 2010, 2012; Ponnambalam et al., 2013; Weidl et al., 2005). None of these models used methods based on purely recorded data or applied expert knowledge in a manual fashion.

3. *The modelling process should be able to provide 'soft' benefits*

From a practitioners' point of view, the main existing SCRM tool, which is known as Risk Register, aims to communicate significant risks to the senior management team (Williams, 1993) and *"the risk registers becomes a bureaucratic procedure instead of being treated as a valuable exercise"* (Ackermann et al., 2007). Therefore, operational staff follow a rule to provide information for developing a Risk Register for their own organisations, but they may not perceive value from either the results or the process of developing their Risk Register. Developing a BBN model, on the other hand, can help operational staff to improve their understanding of risk events or to increase corporate experience in their SC. Those are the key 'soft' benefits of the modelling process, apart from 'hard' benefits gaining from the outcomes of risk management as suggested in Project Risk Analysis and Management

(PRAM, 2004). The 'soft' benefits which are related to people issues during the process are implicit, but they may be more essential to the success of the implementation of risk management (Bowers, 1994). Furthermore, we also believe that collecting data from expert judgement is able to stimulate the 'soft' benefits to the risk modelling team.

As a result, developing the BBN to support risk analysis in SC should be based on a step-by-step modelling process by eliciting knowledge from relevant SC experts (expert judgement) to provide reasonable outcomes; and this modelling process can also provide intellectual value for all participants in the risk modelling management team.

3.3.2 Insufficient available BBN modelling process to support SC risk modelling

In order to be sure that this thesis has advanced the state-of-the-art in BBN generally and in SC in particular, the BBN processes which have been proposed for either generic or specific applications in SC risks will be compared, and an explanation given as to why none of them can be completely applied in this research under identified requirements.

It has, in general, been difficult to find a step-by-step BBN process that was completed by using expert domains (Houben, 2010), not only from the emerging SC risk domain but also from the available modelling processes. The available BBN processes in literature are compared according to the three main stages of BBN modelling process: problem structuring, instantiation (quantification) and inference, as shown in Table 3-2.

Kjaerulff and Madsen (2008) have discussed in detail the essential processes needed to develop a BBN and have suggested the general possible modes or techniques that could be used to construct a BBN model. But it may be difficult for practitioners in SC risk to determine the proper techniques suitable in their context. Sigurdsson et al. (2001) suggested seven-stages to model a BBN in a reliability domain by expert judgement; but those researchers are developing the model with engineers and they do not explain the process in the context of SC Risk. Next, a detailed step-by-step process of using BBN based on with expert's knowledge is proposed by Houben (2010), by adaptation from Sigurdsson et al. (2001). But the process is designed for reliability management throughout a product development project and uses high-level variables. A BBN process is also used in the operating environment for fire management within a natural resource management agency by Smith et al. (2007). However, the abstract model (high level) is structured hierarchically from critical success factors from particular objectives, and the model structure is developed from the prior information rather than from knowledge of staff directly. Those processes are not concerned to include important characteristics of SC activity, nor do they handle complex interactions of a number of risks in an operational SC process.

Some scholars are concerned with procedures that are suitable for coping with a complex network. The 'safety and risk evaluation using Bayesian nets' (SERENE) project is a programme to develop process of using BBN in a safety and programmable electronic system and is concerned with the functional safety of a complex system (SERENE, 1999). Therefore, the process may be applicable in a SC complex system. Furthermore, the improvement of the communication with exerts is specified as one of the expected benefits by employing the process. However, the associated authors do not provide details of eliciting expert knowledge in either the problem structuring or the instantiation stage.

Nadkarni and Shenoy (2004) have explained step-by-step how to structure a BBN from a Causal Map (CM), which is a useful way to inform the process of collecting data from different stakeholders, which can then be combined into a large model. However, their process was defined to develop a model with only a single expert and it cannot show how to combine knowledge from more than one expert; also, they provide very little information on the qualification process.

More recently, suggestions for processes in specific SC risk contexts which include describing how the processes or resources combine into the model structure are presented by Basu et al. (2008) and Deleris and Erhun (2011). They use the BBN model to capture possible risk events in SC. However, they simulate probability numbers by defining a probability distribution. They do not purely use knowledge of experts to quantify the model manually so the process of eliciting experts' knowledge is not provided. Additionally, they do not intend to provide a useful process for stimulating participants' contributions (rather, they use simulations with commercial software such as that provided by IBM).

All in all, none of the afore-mentioned authors suggest a step-by-step practical procedure for linking the interrelationships of risk events between stakeholders at the operational level by solely using expert knowledge to develop a BBN for risk analysis in the SC context. Furthermore, none of these authors recommend particular BBN inference methods that are useful to support the specific purposes of SC risk analysis. Finally, they do not aim to propose a process that can provide the 'soft' benefits to the operational staff who are involved in a SC risk management team.

Table 3-2 Comparison of BBN modelling processes in the literature

Stages	Generic procedure	Generic procedure for expert judgement	Using BBN for reliability management	Abstract hierarchical model for operating environment	Safety and Risk Evaluation using Bayesian Nets (SERENE)	Bayesian causal maps (BCM)	SC risk for IBM	Risk assessment in SC
	(Kjaerulff and Madsen, 2008)	(Sigurdsson et al., 2001)	(Houben, 2010)	(Smith et al., 2007)	(SERENE, 1999)	(Nadkarni and Shenoy, 2004)	(Basu et al., 2008)	(Deleris and Erhun, 2011)
1. Problem structuring	1. Design of the network structure (identification of variables and (causal) relation among variables and verification of network structure)	1. Identify variables 2. Identify network structure	1. Gather data, based on diversity of information sources (interviews) 2. Perform open coding on the gathered data 3. Define the variables by defining the different possible states of variables (coding and direct conversation with experts) 4. Characterise the relationships between the different variables using the idioms (Appendix E) 5. Control number of conditional probabilities by using the definitional/synthesis idiom 6. Evaluate the BBN (leading to repetition of the first 5 steps)	1. Identify objectives for each adaptive management step 2. Identify critical success factors 3. Build draft influence diagrams 4. Review draft influence diagram (workshops) 5. Convert influence diagrams into BBN	1. List the key entities (products, process and resources) 2. Determine the key attributes of the entities that are relevant for the safety argument 3. Group together related attributes 4. Determine the appropriate idioms (Appendix E) that relate the attributes	1. Data elicitation 2. Derivation of causal maps by narrative a. Identify causal statements in the narrative b. Construct raw causal maps c. Design coding scheme d. Convert raw causal maps into coded causal maps 3. Modification of causal maps to construct Bayesian causal maps a. Conditional independencies b. Reasoning underlying the link between concepts c. Distinction between direct and indirect relations d. Eliminating circular relations	1. Identification of SC risk 1.1 Mapping the business process needed in order to procure parts, and assemble and deliver machines 1.2 Map the human, capital, and informational resources to indicate how they support components activities and decision 1.3 Interview key managers and engineers to identify key risk factor and root causes 1.4 Further integrated these influencing factors into the business process and resource maps to pinpoint the exact location and means by which disruptions propagate into SC	1. System definition and performance value (definition of system under consideration) 2. Risk identification (identify uncertainty events that disrupt SC)
2. Instantiation	2. Implementation of the network (converting the process of populating the CPTs and PTs) 3. Test of the network to check if it provides sensible outputs to a carefully selected set of input	3. Express as statistical variables 4. Specify conditional probability	7. Identify and define the conditional probability tables 8. Fill the conditional probability tables	6. Write questionnaires to capture data for BBN 7. Review questionnaires 8. Run questionnaires and populate BBN (same as survey)	5. Define the CPTs for each variable in each idiom 6. Apply the join operation to build the complete safety argument	4. Derivation of the parameters of Bayesian causal maps a. Identification of state space of each variable in the Bayesian causal map b. Derivation of the conditional probabilities associated with the variables in the map	2. Quantification of identified SC risks 2.1 The combined map of business process, resources and risk causes and factors become the basis of the BBN model 2.2 Once these quantities were identified, the map provided a structured template for gathering all the required data needed to populate the quantification model	3. Risk quantification (expert opinion and statistics using for simulation)
3. Inference	4. Analysis of the network is performed to pinpoint problematic aspects of the network revealed in the test phase	5. Enter evidence 6. Propagate 7. Interpret results	9. Evaluate the BBN (leading to repetition of the early steps)	–	7. Enter observations and make predictions with the safety argument template	–	2.3 Combined map of business processed provided a blueprint for a simulation model for computing the effect of disruptions and failures on SC performance	4. Risk management (simulation, boxplot, risk-curve, decision analysis)

3.4 Challenges in Implementing BBN to Support Risk Analysis in Supply Chain

The process of developing BBN is known to be as much an art as science, especially when constructed by expert knowledge (Druzdzel and Simon, 1993; Houben, 2010). Therefore the success of a BBN model implementation in this context depends on the process design. However, it has in general been difficult to find a BBN process that was completed by using expert domains (Houben, 2010). Most studies have to adjust their BBN protocol from one used in the professional community in general contexts to be suitable in their own contexts (Morgan and Henrion, 1990). The implication is that to support risk analysis in SC, BBN should be adjusted in the light of challenges from application contexts.

3.4.1 Ability to deal with complex supply chain risks and time issues – process should be efficient and not invasive

Well-calibrated and unbiased probability assessment techniques suffer from the problem of being very time consuming (Druzdzel and van der Gaag, 2000). For practical reasons, a compromise has to be reached between quality and limitation of resources. The fact that the process is time-consuming is a significant barrier to the success of the model development since *"the time of genuine experts is seriously limited and may be expensive"* (O'Hagan, 2005, p. 6). Furthermore the model is more complex and the process is more time consuming when the model to be developed is in the large scale typical of SC, involving multiple experts and different stakeholders. Therefore the BBN modelling for this study, which will be implemented with genuine experts, requires an effecient process.

3.4.2 Scoping the risk analysis

1. *Bounding of the SC scope*

Modelling risks in SC is broader than risk analysis within an organisation unit. Although the SC could be defined as long as the flow of product and information can be defined, by linking from one to another, resource is limited and the scope of the model should be determined and agreed with the problem owner. Guidelines on how to define the SC scope should be explained in the BBN modelling process.

2. *Identifying relevant stakeholders who understand the system within the SC scope*

The boundary of the SC should be defined by including the relevant stakeholders who can take a part in developing the model. Numbers of stakeholders can represent number of modelling team and efforts to be taken for collecting data. How to invite then and make them trust to share their adverse events with their stakeholders are the practical concerns.

3. Defining outcome measures

The BBN model is useful since it can provide a variety of analysis, but providing the modelling measures to support risk analysis is also a main challenge. This is why analysis to answer managerial questions in risk analysis is suggested, as shown in Section 3.1.5.

3.4.3 Thinking about possible future risk events and relationships

BBN is a qualitative and quantitative model and generally BBN can be structured and quantified by a data record and/or knowledge of experts (also known as expert judgement[3]).

1. Identifying and quantifying causal relationships in the SC process

Underpinning the SC process is the basic understanding of how to identify adverse events and the causal relationships. The problem structuring process for qualitative BBN should include the SC process since logical relationships can be influenced via linking of activities in the SC process.

Although some adverse events can be recorded in an organisation's SC activities, the data may not support quantification in the required format for CPT. For example, order fulfilment rate may be recorded but the data may not be categorised by all interested causes. Even though in operational SC there seems to be a lot of probabilistic information available from the recorded data about the simplest quantifying variable as the root cause variable representing the chance of an adverse event occurrence, generally it is not easy to provide the requested data (Walls and Quigley, 2001), or there are problems of missing values in the recorded data. Furthermore the general scope of risk management exists in an organisation unit rather than linking between stakeholders within the SC scope. Therefore the main input in developing a BBN model is defined by expert knowledge rather than by using recorded data either in model structuring or quantification.

Expert knowledge is not just a main source of data to develop a BBN model when there is no recorded data in the organisation, but also a process that can stimulate the involvement of experts who can improve their understanding of risks in the SC perspective by sharing perceptions between stakeholders (which will be explained further). However, the model structure and probability elicitation from expert knowledge can lead to heuristic biases which

[3] **Expert Judgement** is data given by an expert in response to a technical problem (Meyer and Booker, 2001).

need to be properly accounted for. Bias can corrupt the judgemental data (Hodge et al., 2001) because it can affect the real data which are elicited. Bias can used to explain psychological reasons why experts do not always provide the right data. Different types of bias are explained in the literature (Merkhofer, 1987; Meyer and Booker, 2001; O'Hagan et al., 2006; Renooij, 2001). However, biases can be controlled by implementing proper standard elicitation procedures with the real experts and the standard guidelines will be adjusted for designing the BBN modelling process in the context of this research.

2. *Dealing with rare events which can have major systemic consequences*

Some adverse events may rarely occur or have not occurred according to the company data records but if they occur, they will generate the major impact to the company. Therefore those adverse events which can be captured in probabilistic model; Section 2.4.2.2, should be included into the BBN model. Therefore the relevant knowledge is important source for the model quantification.

3. *Linking adverse events within the SC scope under the knowledge boundary of participants in individual organisation units*

One challenge of modelling risk in SC is the need to consider how to link them in the same network to show interrelation between adverse events sourced by different stakeholders who may have limited perceptions only in their own organisation. As a result, the conceptual modelling framework is suggested in the context of adverse events liking in SC, which will be explained in Section 5.1.

3.4.4 Modelling supply chain risk analysis at an appropriate level

1. *Ability to deal with the perceptions of experts who may have less experience in modelling: the process should be simple and transparent*

The BBN model is developed by SC operational experts from different stakeholder organisations so they may not have a lot of modelling experience or understand probability language. Furthermore, the expectation of the process is not just that data from expert knowledge is gathered, but also that communication of the experts or stakeholders is stimulated, thereby improving the understanding among stakeholders. Therefore it is important that the process is simple and transparent, to enable communication between stakeholders. This is a key factor for the success of the BBN model development in this study.

2. *Focusing on key SC uncertainties is challenging because of the tendency to think about every activity in an operational process*

SC process is not an independent process in the business. For example, in the medicine healthcare SC, the system for ensuring there is medicine to provide to inpatients is involved with other activities such as clinical therapy errors. However, it is outside the SC scope and it is necessary to limit the model by excluding some activities, for general limitation of using model to represent part of the reality.

3.5 Conclusion

The combination of BBN theory and BBN process in literature helps to identify the issues of concern to the design of the modelling process for this research. The challenges in implementing BBN to support risk analysis systemically in SC at the operational level to lie in adjusting the BBN standard process and selecting the proper modelling techniques for particular stages. A review of the literature including available techniques is required to fulfil the challenges of BBN modelling in this context, as will be explained in Chapter 5. Since implementing BBN in a SC risk context is a novel application in a new field which involves operational multidisciplinary experts, suitable techniques should be carefully considered, especially as the perceptions of participants. The problem structuring is very significant to the success of the modelling process as it is the first stage where participants are involved, and the ownership of the model needs to be developed in a way that represents their beliefs. Therefore an experiment with MSc supply chain students is implemented to explore the mode of structuring the BBN, by considering participant perceptions and then taking observations during the experiment. This is explained in the next chapter.

Chapter 4 Design and Results of BBN Risk Identification and Structuring Experiment

Risk modelling by BBN in the context of SC risk should be structured by experts who have knowledge of the problem domain: so a method to help the expert to think through possible adverse events and their relationships is required. Modelling the true belief of an expert not only represents the reality of risks in SC but also stimulates confidence in and ownership of the BBN model. The model is therefore able to keep experts willing to participate until the sequential BBN SC risk process is finished. Furthermore the literature has shown that outcomes from the model developed from BBN inference are more sensitive to qualitative structure than to quantitative probability numbers (Darwiche and Goldszmidt, 1994; Nadkarni and Shenoy, 2001). Therefore the quality of the BBN structure directly impacts on the quality of the model outcomes and participant confidence of implementing the model.

The 'suitable' method of model structuring aims to build a bridge between expert knowledge on the problem domain and the BBN structure. One of the main challenges in this research, that aims to model risks by BBN in the SC operational process, is the difficulty of representing perceptions of SC operational experts who may have less experience in modelling; see Section 3.4.4. Potential techniques to capture perception of the interactions between adverse events are reviewed either in cognitive science or BBN modelling. However, there is a little research on the qualitative BBN structuring process (Bedford et al., 2006, n.d.; Fischhoff, 1989), although none of it has made a comparison of different manual problem-structuring techniques in a practical perspective. There are a number of studies in cognitive science to show how humans develop their causal learning of causal structure (Sloman et al., 2009; Steyvers et al., 2003; Waldmann and Martignon, 1998). However, they do not involve SC people, do not focus on the practical aspects and do not link to the process of transforming to BBN format. Consequently, a strong influence on this study was the plan to experiment with SC subjects in the control environment to compare potential techniques to serve the third research objective (see Section 1.4). In reality it is very difficult to run experiments with SC experts in organisations that are under time and resource constraints, particularly as the manual BBN construction can be a labour-intensive task (Kjaerulff and Madsen, 2008). Therefore an experiment was designed and conducted with MSc supply chain students as participants rather than the real SC experts.

The anticipated result of the experiment is to be able select suitable techniques from a range of potential techniques discussed in Section 4.7 and to provide suggestions for implementing BBN problem structuring within the real industry environment (Section 4.8).

4.1 Rationale for Conducting the Experiment

4.1.1 Rationale for selecting the experiment

Experiment can provide a mechanism for systematically comparing possible ways for capturing and structuring domain (SC) experts' thinking. It can also provide an opportunity to make careful observations of the practical problems of structuring the BBN in the field setting in a controlled environment (Druckman, 2005). Furthermore it allows a trial of the potential BBN model structuring methods for a setting similar to the real practice. This research experiment also implemented classical experimental design to ensure that all groups are equivalent, by assigning experimental units randomly with potential techniques. This increases the confidence in explanations of relationships between potential techniques and outcomes (Druckman, 2005) because the differences between participants are controlled (Orr, 1999).

4.1.2 Methods for aiding the comparison of experts thinking

In general SC operational experts regularly carry out their routine work and perceive uncertainty of adverse events. However, they may not have been required to record those adverse events, so their knowledge of them is undocumented. A method is required to help them explain their thinking about and capture their perceptions of adverse events.

The standard risk identification methods and techniques in regular risk management literature (e.g. Edwards and Bowen, 2005; Rosenau and Githens, 2005) are reviewed. There are three potential methods for aiding expert thinking: Causal Map (CM), Fault Tree (FT) and Risk Register Map (RRM).

1. CM can support expert thinking about a cause and effect relationship by following the direction of an arrow. It can also deal with the complexity of various risks and the range of different knowledge people have because it is understandable and accessible by natural language (Williams, 2000; Williams et al., 1997). Additionally

it has been used to detemine causal value and has been combined with some analysis techniques including BBN (Nadkarni and Shenoy, 2004).

2. FT can provide a common approach for thinking through a system failure. It has been used to transform the flow of the system between components (Iverson, 1992), similar to the product flow of SC but much wider in scope. FT has also been used to structure BBN by Bobbio et al. (2001) and Lampis and Andrews (2009).
3. RRM was initially developed from a Risk Register (RR), an approach that exists in general organisations. The RR can provide historic available knowledge as a starting point to help think through the all possible future adverse events and then invent a new method for this research to define their relationships, and the result is known as RRM.

These three techniques, CM, FT, RRM, are identified to develop particular activities for further comparison in the experiment.

4.2 Overview of Planning for Experiment

The experiment is designed by setting two sequential tasks for individuals; three initial methods are provided and then a particular method is assigned to two groups of students randomly (six groups in total) to work through, by discussing within their team. The way that students learn and apply new techniques mimics the activity of structuring the BBN with real experts. The experiment is controlled by using the design of activities as the input for students to practice on. Furthermore the evaluation of the activities is designed to collect data to be used in two parts of planning for the experiment, as explained in this section and summarised in Figure 4-1.

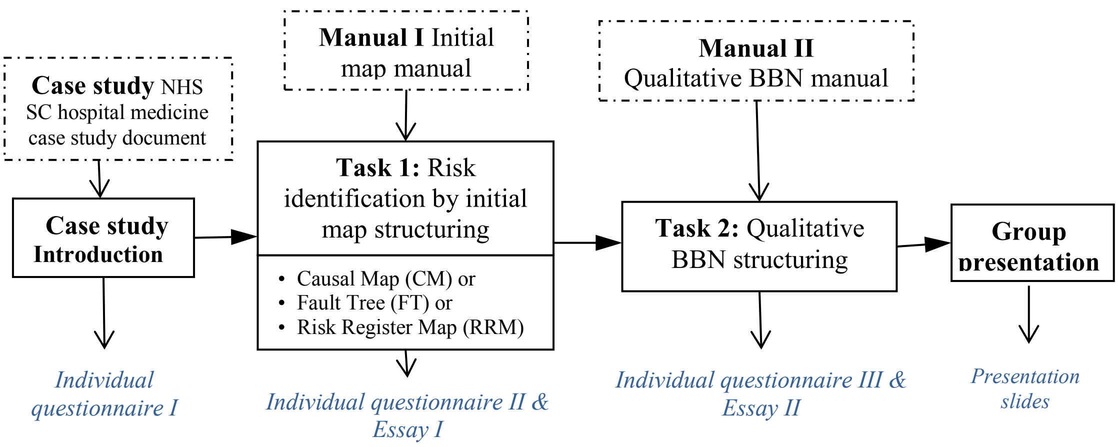


Figure 4-1 Design of experiment to compare the initial techniques of model structuring

4.2.1 Planning for experimental activities

As noted before, CM, FT, and RRM are selected for their ability to support experts for thinking through possible adverse events before transforming to qualitative BBN. There are two main relevant activities designed for this experiment. The first activity is to structure CM, FT, or RRM: this will be called the initial map structuring activity for task 1 as those three methods are the initial states for developing to qualitative BBN, which will be defined as the activity of task 2. The structures of all initial maps are based on the same case study. After both tasks are done, participants are expected to have completed an initial map and qualitative BBN and will be asked to present them to the class.

The experiment is embedded in class activity so needs to be conducted during the module of a course in a fixed time slot. Students can be assigned different initial methods but all groups have to engage each activity at the same time. Manuals of the two task activities are prepared for self-learning format rather than as a lecturing (by module leader) format. Manual I and Manual II are developed to support the two tasks. Details of the manuals and case study design will be explained in Section 4.3.2. Apart from the manuals, a workbook is also developed to provide the activity details week by week. Since the main information derived from the activities will be explained in this chapter, the workbook will not be shown in this thesis.

4.2.2 Planning for experimental evaluation

The experimental evaluation is designed to be an assessment by students' reflection on the main two task activities. Quantitative reflecting data is collected by questionnaires and qualitative reflecting data is collected by reflective essays. Three questionnaires is designed to support the evaluation of pre-post activities of Tasks 1 and 2; it will therefore not only allow an evaluation of the individual activities but also a comparison between activities. Each student is required to write two reflective essays for each task which they are allowed to write and submit after the end of the final week activities. The initial maps and qualitative BBNs which students have developed will also be collected for comparison. Additionally, the researcher observes the engagement of all groups in each activity during the experimental sessions. Details of evaluating data collection from the experiment will be explained in Section 4.3.3.1.

4.3 Experimental Protocol Design

The important protocol design of the experiment is shown in this section.

4.3.1 Selecting subjects

MSc students in the academic year 2011–12, who registered for the *Case Studies in Supply Chain Management* (MS970) module of the MSc programme in Supply Chain Management, were selected to represent real SC professional experts. The MS970 module aims to introduce students to as much as possible of the practical reality of analysing and, where possible, solving supply chain management problems in real life. To this end, students are given the opportunity to explore – through the use of case studies and relatively unstructured problems – situations where, for example, data may be ambiguous and hard to come by, it may be far from obvious which methods or models can be applied, and where managers will need to be convinced of the merits of any suggested solutions. The students concerned were taking the professional master's degree class to prepare them for professional work by introducing SC practical skills, SC frameworks and understanding issues in SC and were therefore considered to be suitable subjects to reflect on the activities of this experiment.

4.3.2 Design of experimental devices

The first device is the NHS medicine SC case study design, which will be provided to all students. The second device is Manual I – Initial map structuring, which was prepared in three versions for three methods of initial maps. Each version will be given to assigned groups. Lastly Manual II – Qualitative BBN structuring was developed in two versions based on the similar process. The experimental devices are the materials for the class activity and they were developed by the module leader and the researcher.

4.3.2.1 NHS medicine supply chain case study design

The case study document, NHS medicine SC, includes text and figures. It was developed from the past knowledge of the National Health Service Greater Glasgow and Clyde (NHS GG&C) hospital medicine SC. The case study document is constructed by using information from the report 'NHS Greater Glasgow and Clyde Acute Pharmacy Redesign Project November 2010' (Bennie et al., 2010) which had presented key findings of the hospital medicine supply after its redesign in 2010. The redesign changed the medicine supply system to a robotic pharmacy distribution system, installed with a newly built IT system and centrally located Centralised Distribution Centre (CDC). The roles of related stakeholders were combined and explained in the case study document, shown in Appendix C.1, and it was given to all students.

4.3.2.2 Manual document design to support sequence of activities

CM, FT, and RRM are different in nature (see Table 4-1) so task 1 and task 2 activities can be conducted differently. Furthermore the different characteristics of those methods were used to design two manuals for supporting the two experimental tasks.

Table 4-1 Different characteristics of different initial map methods

Tasks	Method 1	Method 2	Method 3
I. Initial map structuring	Causal Map (CM)	Fault Tree (FT)	Risk Register Map (RRM)
Direction of structuring	Bottom-up	Top-down	Not identified
Special requirement	×	×	Require to structure RR before using to develop RRM
Provide top event	✓	✓	× (Determined during the process)
Arrows	Can link to more than one event (one to many)	Can link to only one event (one to one)	Can link to more than one event (one to many)
II. Qualitative BBN structuring	Construct the qualitative BBN from the assigned initial map		
Process of changing structure of the initial map to BBN	Change symbols straightforward	Different symbols and allow to link from the basic event to the multiple events	Change symbols straightforward
Define variable description document	Select five variables to define variable and state description		
Guideline to transform to a qualitative BBN	Check four criteria		

1. *Manual I (Initial map manual)*

Generally all three methods are implemented to structure cause to effect relationships which can be indicated by arrow directions. However, CM can be structured by defining the different causes and trying to link up to the effects, which is known as 'bottom-up'. On the other hand, FT can be structured by defining the top event and laddering down to the cause events: this is known as 'top-down'. RRM can be structured differently from either of these two methods, from the risk items indicated by a pairwise relationship matrix. Therefore RRM is structured by risk matrix rather than by defining the direction of relationships directly. Furthermore the design processes for CM and FT provide the top events before their maps are structured. However, the top event cannot be provided for RRM since the map is structured from the identified risk items from RR rather than identified directly at the beginning: in RRM it is necessary to structure the RR first.

The activities to develop three initial maps were developed for individual CM, FT, and RRM so there are three versions of manual I. The formats of the versions are similar and consist of an explanation of what an initial map is, icons and symbols, how to develop the initial map, suggestions, exercises, further reading and references. The process of developing initial maps is explained in Appendices C.2–C.4.

2. *Manual II (Qualitative BBN structuring manual)*

The second task activity, the main process of transforming from CM to qualitative BBN, has been defined by Nadkarni and Shenoy (2001, 2004) and this is also adapted for transforming FT and RRM to qualitative BBN. They suggest four criteria for checking the variable connections: by considering conditional independence, eliminating loop or adjusting two-way arrows to one-way arrows, checking that the direction of links are from cause to effect, and including only direct relationships and more explanation. These criteria are adjusted for the SC risk context and shown in Section 3.2.1. Criteria checking and variable/state defining are the main activities for task 2 provided in Manual II.

Since the visualising symbols of CM and RRM are similar but are different from FT, Manual II is developed into two versions. The manual consists of three main sections: an explanation of transforming symbols from initial map to BBN (this section only is different between the two versions), checking the BBN modelling assumptions by the four criteria, and defining variable and state descriptions (sample for five variables). Since both versions are similar in the main process, only one full version is shown in Appendix C.5 and extra section for FT will show in Appendix C.6 to avoid duplication.

4.3.3 Design of experimental evaluation

The protocol of experimental evaluation is designed by data collection and data analysis.

4.3.3.1 Methods of evaluating data collection for comparative experiment

Three questionnaires and two essays were designed to collect perceptions on the particular method assigned to individual students. Furthermore the observations during the experimental session were also recorded. Finally the presentation slides from particular groups were also collected to show different outcomes from particular groups.

1. *Questionnaires*

Questionnaire I was used to collect background knowledge of participants and two further questionnaires (Questionnaires II–III) were used to reflect on the initial maps (defined by different treatments) and the qualitative BBN by asking 13 similar questions developed by applying the 5-Likert scale to evaluate individual students' perception on the particular activities. The scale ranged from the low scale for the poor or unwilling characteristic to high score for good perceptions. Questions are classified into three areas: satisfaction of map outcome (Q2.1–Q2.6/Q3.1–Q3.6), difficulty of the process (Q2.7–Q2.10/Q3.7–Q3.10) and satisfaction of team learning (Q2.11–Q2.13/Q3.11–Q3.13); see Appendix D.

2. *Essay*

The use of essays rather than face-to-face interviews was selected to collect the reflections from individual students on particular techniques. This is because it may be difficult to arrange interviews of individual students by a researcher, and students may not reflect their real perceptions if face-to-face with a researcher. Two essays of 500 words each were assigned to students after each task (initial map structuring and qualitative BBN structuring).

Essay I (Initial map structuring),

1. How easy/difficult did you find it to build the map (exclude the brainstorming session)? (Process transparency, process clarity, effort spending to follow the process etc.)
2. How easy/difficult was it for the brainstorming session to identify risks? (Dealing with disagreement of the group, the domination with minority of the group etc.)
3. How do you compare the map with the original information of the case study? (Understand ability, usefulness, complexity, completeness, etc.)

Essay II (Qualitative BBN structuring),

1. How easy/difficult did you find the process of developing the BBN from CM/FT/RRM? (Explain and give an example)
2. How different are the BBN map and your initial map (task 1)?

3. *Presentation slides*

The initial map and qualitative BBN are the two main outcomes which students are asked to describe in their presentations. Although each group can have several versions of the map outcomes, the final version of both maps from their presentation slides are collected as data.

4. Observation

Observational notes were taken to record learning observations from the experiment, classified by groups (see example of observational note outline in Table 4-2). The researcher records important events using the outline for guidance. The observational information can be used with data from other sources in order to understand perceptions of students in-depth and provide recommendations for further implementation the BBN structure within the real industry.

Table 4-2 Observational note for lesson learning during experiment in task 1 – initial map structuring

Observational learning	CM-1	CM-2	FT-1	FT-2	RRM-1	RRM-2
Length of the session						
Can they finish task in time or not?						
Style of working						
How do they manage the brainstorming session? (Equal power, leading by somebody, dominated by minority etc.)						
Everyone's opinion is taken into consideration?						
Do they agree on the problem boundary? (Physical boundary, temporal boundary)						
Do they look to the other groups? (Sharing knowledge) How?						
How confident are the students to develop the initial map?						

4.3.3.2 Analysis methods for comparative experiment

Quantitative and qualitative data were collected and then analysed by a variety of methods to fulfil the main objectives of the experiment. The main analysis of both essays was conducted by content analysis and exploratory data analysis was used to analyse the questionnaires and to summarise the main characteristics of perceptions from students. Hypothesis testing was also implemented on top of those analysis.

1. Content analysis from essays

Reflective essays were analysed by categorising context and counting the number of comments provided by students and presented in group. This method is known as the categorical-content type (Lieblich et al., 1998; Silverman, 2006). The content from the essays can be analysed manually by following four steps as outlined below.

a. *Selection of the subtext* can be formed by following different questions in the essays (see questions in Section 4.3.3.1). This can help the researcher to define the area of the text to be analysed by subtext.

b. *Definitions of the content categories* are classified and predefined by framework. In the essays the content definition is categorised for particular essays as below.

Initial map (Essay I)

1. Satisfaction of initial map outcome
2. Difficulty of initial map structuring process
    - 2.1. Time consuming
    - 2.2. Difficulty from the process
    - 2.3. Difficulty from brainstorming process
3. Satisfaction of team learning

Qualitative BBN (Essay II)

1. Satisfaction of qualitative BBN map outcome
2. Process difficulty of transforming an initial map to the qualitative BBN
3. Difficulty of identifying variable and state description

c. *Sorting the context into the categories*: in the subtext, word sentences or group of sentences are categorised and assigned into relevant categories. Within particular categories, the numbers of positive or negative ideas are sorted and represented by groups.

The judgement of sorting the context in this research was repeated by the researcher three times, taking a couple of months off between each time, to ensure that the classification is reliable. The repeated classifications revealed only minor differences since the researcher was the observer in the experiment and the identified category was clearly expressed.

For example, subtext from essay I provided by students in group CM-1 are categorised as shown in Table 4-3. Two comments are counted for 'time consuming' during their initial map developing by two students (ID-2 and ID-24).

d. *Drawing conclusions from the results*: numbers of sentences can be counted in this phase to support frequency analysis. Analysis showed that some similar ideas were presented repeatedly in the same essay of a student. If an idea appeared more than twice it was counted a maximum of two times in each category.

Number of comments on particular themes can be counted to represent the opinions of a whole group. The frequency data can be used to compare and emphasise significant issues for each initial map, rather than be used quantitatively.

Table 4-3 Example of sorting the material into the defined categories by group CM-1

Categories	- (Negative comments)	+ (Positive comments)
1. Time consuming	2. The construction of the map itself is not very difficult but it was time consuming. 24. Even can be considered easy, but it just takes a lot of time to summarise everyone's opinion of risk possibility.	-
2.1 Difficult to identify risk events	6. It would have been difficult for them to identify a potential risk. 17. The difficulty of this is that we had to find out what is the particular risk could impact to the processes.	-
2.2 Difficult to identify relationship between risks	2. We divided the risk into 2 major causes and expand it again into 30 risks might appeared. It happened because there are so many risks that could happen and it seems the risks are correlated to each other and very hard to differentiate with each other.	6. A bunch of events appeared and it was very easy to link them using the Causal Map technique. Although the team was not familiar with the NHS procedure, the causal logic helped the team to address the sequence of these initial events.

2. *Exploratory data analysis for the compatibility of initial map and qualitative BBN*

Complexity in qualitative BBN corresponds to the density of connectivity and the number of parent variables, both of which increase the number of parameters required for CPTs (Korb and Nicholson, 2004). Therefore the qualitative BBN structure requires to be simplified from the structure of an initial map. The comparative complexity measurement of the initial map and the qualitative BBN is proposed by comparing the ratio of number of links to variables (Bryson et al., 2004; Korb and Nicholson, 2004) from different groups. However, there is no absolute right answer to the complex problems but rather a better or worse answer (IAS, 2009). The ratio between numbers of links and variables can represent the complexity of the maps but it cannot explain the quality of the map: it is just used for comparative purposes. For this study, if the ratios of the initial map and qualitative BBN are similar, this would explain the similarity or the compatibility of the qualitative BBN model and the initial maps.

3. *Statistical analysis from questionnaires*

The collected data from questionnaire are ranged numbers, between 1 and 5, and data were collected from limited numbers of participants in the experiment. Therefore non-parametric statistics is employed for the statistical hypothesis testing, calculated by SPSS software.

a. *Across treatments (among types of initial maps):* the Kruskal-Wallis test was carried out on the three independent samples across initial maps to determine whether at least one sample is different from other samples. The Kruskal-Wallis test is suitable for ratio scales (Druckman, 2005) and when fewer constraints are involved. Kruskal-Wallis will use the rank number for calculating the p-value which is approximated from the Chi-square distribution. When the p-value of Kruskal-Wallis is less than the significant level (alpha), the hypothesis of equal population medians (from three initial methods) will be rejected, and it can then be inferred that at least one median of a treatment is significantly different from the others. However, because the Kruskal-Wallis test cannot specify which initial map is different from the others, the extension of multiple comparisons by Mann-Whitney U test was implemented to test the difference between two treatments at a time. The U statistics is a formula of sum of rank of particular treatments. Since there are three treatments in the experiment, the Mann-Whitney U test will be repeated for three matching pairs to distinguish the treatment which is significantly different from others.

b. *Pre-post test (between initial map and qualitative BBN):* the Wilcoxon signed rank test is proposed for comparing two related samples or matched samples. Wilcoxon sign rank statistics can be calculated from rank of difference for particular pairs of data. In this experiment, questionnaires II and III (see Appendix D) are used to evaluate the pair perceptions of the initial map and qualitative BBN from the same students. The median difference between reflections on a criterion from questionnaire II and III can be tested by the Wilcoxon signed rank test, calculated by different levels of perceptions between the assigned initial map and qualitative BBN on individual criterion (question). If the p-value of the calculated Wilcoxon signed rank statistics is less than significant level (alpha), the median of difference is not zero which mean perceptions on both maps on the criterion are significantly different.

4.4 Operational Considerations for the Experimental Study

4.4.1 Pilot experiment and learning lessons

Before implementing all documents in the experiment, manuals were pre-tested for three hours on 14th December 2011 with PhD students of the Management Science Department, University of Strathclyde. Six students participated in the pilot experiment. Two students were assigned in a group to structure particular initial maps. The three main developed experiment devices (healthcare medicine SC case study document, Manual I and Manual II) were given to all students. The observations during the pilot experiments and questions or comments from pilot students were recorded and were taken into account to improve the materials and process for the real experiment. For example, they might have spent an hour to read the case study or they could have come up with a huge and complex map. Therefore the document of the case study was modified. Some of them used whiteboard and post-it notes, which are highly visible and so supported team discussion very well.

4.4.2 Challenges to be managed before conducting the experiment

Apart from all materials to be used as the experimental devices, there are other issues related to conducting the experiments with students that have to be managed.

4.4.2.1 Ethical approval for the experiment

The researcher was aware of the need to protect the experimental subjects, so an application was made to the departmental ethical committee, and was approved. There are no potential risks in taking part in the experiment since the class activities did not involve the use of confidential data. It was explained in the participant information sheet that participation in the experiment (by answering questionnaires, being observed during the class and allowing their essays to be analysed for research objectives anonymously) was work over and above their normal class activities. We also explained to participants that whether they agree to participate in this research (or not) would not affect any class assessments. Once they agreed to participate in the experiment, they were asked to sign the consent form.

4.4.2.2 Defining role and relationship of module leader and researcher

The module leader's role was to guide the class by implementing the manuals for team learning for task 1 and task 2. The module leader introduced and controlled the activities for any particular week. On the other hand, the researcher's role was to act as an observer and assistant to the module leader by helping to answer questions from students; but she did not take any responsibility for the assessment of the class, either from essays or group presentations. She just used those data for analysis to serve research purposes. The researcher distributed and collected the consent forms and ensured that the evaluation plan was followed.

4.5 Implementing the Experiment and the Response Rate

The experiment was operated with sequential activities in two-hour sessions once a week for four-weeks, running from 26th January 2012 to 16th February 2012. Students were allocated into six groups randomly, each group comprising 3–5 students, although three members were part-time students with a similar working background in the public sector and they were required to be in the same group. Pairs of two groups were assigned randomly with the initial maps (CM/FT/RRM) and those six groups will be called CM-1, CM-2, FT-1, FT-2, RRM-1 and RRM-2 respectively.

4.5.1 Implementing the designed experiment

During the first week the researcher and details of the experiment were introduced to the class before inviting them to participate in the experiment. The NHS hospital medicine SC case study detail and Manual I were then given to students for self-learning in the class. At the end of the first week, students were asked to practise a simple exercise of their assigned initial map with their group members to build their confidence with the new technique. At the end of the session, questionnaire I was given to students to ask about their experiences and evaluate their understanding of the case study document. In the second week, the activities were started by providing them with a brief instruction before asking them to develop their CM/FT/RRM by using Manual I. At the end of the session, questionnaire II was given to students to evaluate perceptions during the process to structure the initial map and they were asked to return it before starting the third week activity. Students were also asked to write reflective essay I for this task.

The third week was started by collecting questionnaire II before asking students to modify their own initial map to qualitative BBN by following Manual II with their group members. At the end of the session, students were given questionnaire III, which was used to evaluate the process of modifying from initial map to qualitative BBN (task 2), and they were reminded to write reflective essay II. The final week was the presentation week. All groups presented their initial map and qualitative BBN to the class. From their qualitative BBN, they were asked to suggest the mitigating actions to manage those risks and share their own experiences of their method with other groups who might be assigned with different methods. Students were asked to submit essays for task 1 and task 2 for the class assessment: these essays were also a main source of experimental data.

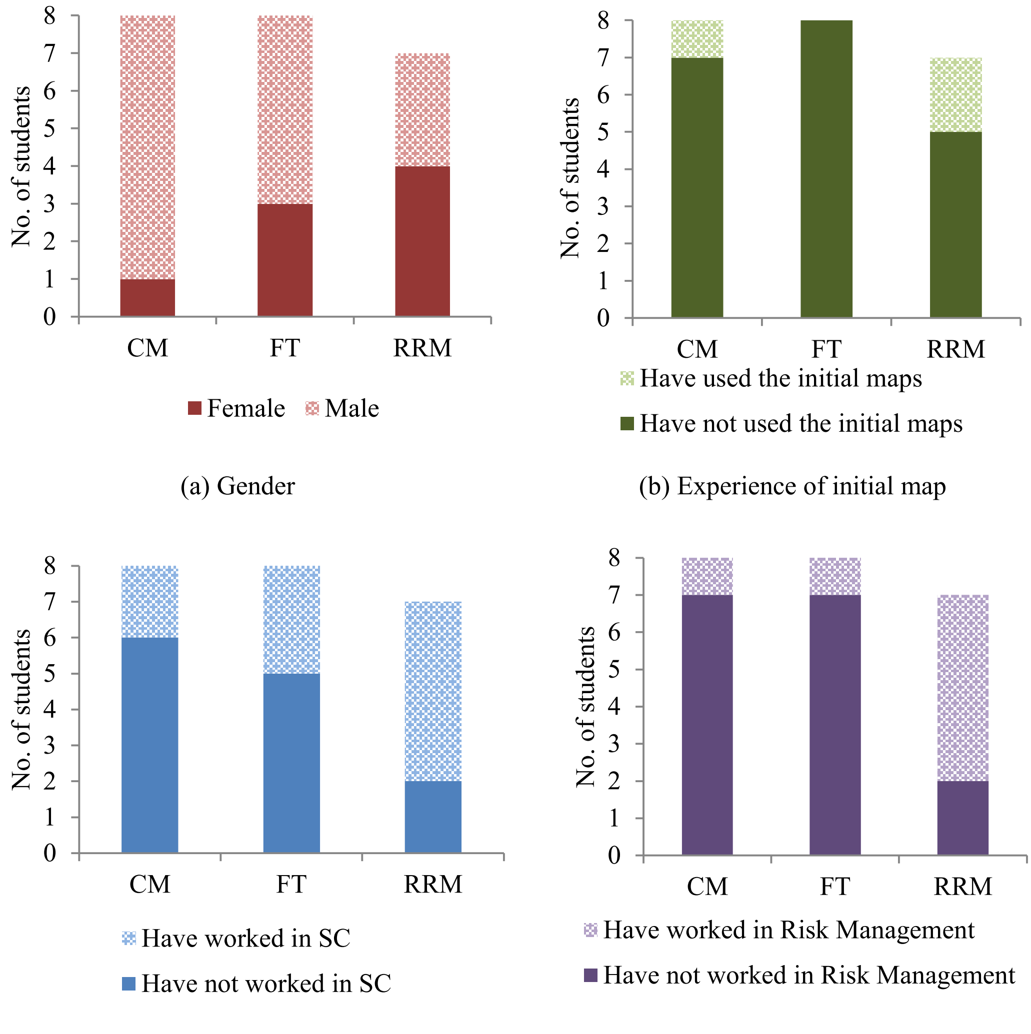
4.5.2 Response rate and participant characteristics

Two essays and three questionnaires (see Section 4.3.3.1) were employed to collect data. One student from group RRM-1 submitted only essay I. Each questionnaire was given to students after they finished each week's activities and was collected before starting the next activity, so that perceptions on particular activities were not contaminated by the following activities. If questionnaire II was not collected before the task 2 activity started, that student's questionnaire is shown as missing; see Table 4-4.

Table 4-4 Number of students and responses of particular groups

Assigned map type (Group)	No. of members	No. of Respondents				
		Essay I	Essay II	Questionnaire I	Questionnaire II	Questionnaire III
CM-1	5	5	5	5	5	5
CM-2	4	4	4	3	3	3
FT-1	4	4	4	4	4	4
FT-2	4	4	4	4	4	3
RRM-1	4	4	3	4	4	4
RRM-2	3	3	3	3	3	3
Total	**24**	**24**	**23**	**23**	**23**	**22**

The bar charts in Figure 4-2, compiled from questionnaire I, show a number of features. The majority in the class were male. The number of females who worked in developing RRM was greater than for any other method, while only one woman joined in the CM groups; see Figure 4-2 (a). Figure 4-2(b) shows that only one student who was assigned CM and two students who were assigned RRM implemented one of the initial techniques and RR was specified. Since RRM is developed for this experiment, this shows that all students do not have experience or prior knowledge for their assigned technique. In addition most students who were assigned to the development of RRM have experiences of working in SC and Risk Management before (5 of 7 students) – see Figure 4-2 (c) and Figure 4-2 (d) – since some of them were part-time students. Although most students who were allocated CM and FT had not worked in SC before, they took a SC management programme for at least one semester. Therefore they had been trained as SC professionals and can be representatives of SC people.



(a) Gender

(b) Experience of initial map

(c) Experience in Supply Chain (SC)

(d) Experience in Risk Management

Figure 4-2 Characteristics of participants in experiment

4.6 Experiment Results

The comparisons between initial maps aim to select a suitable initial map technique for structuring qualitative BBN with real SC people. The results from the experiment are analysed qualitatively or quantitatively from either within or between tasks, giving four aspects as outlined in Figure 4-3.

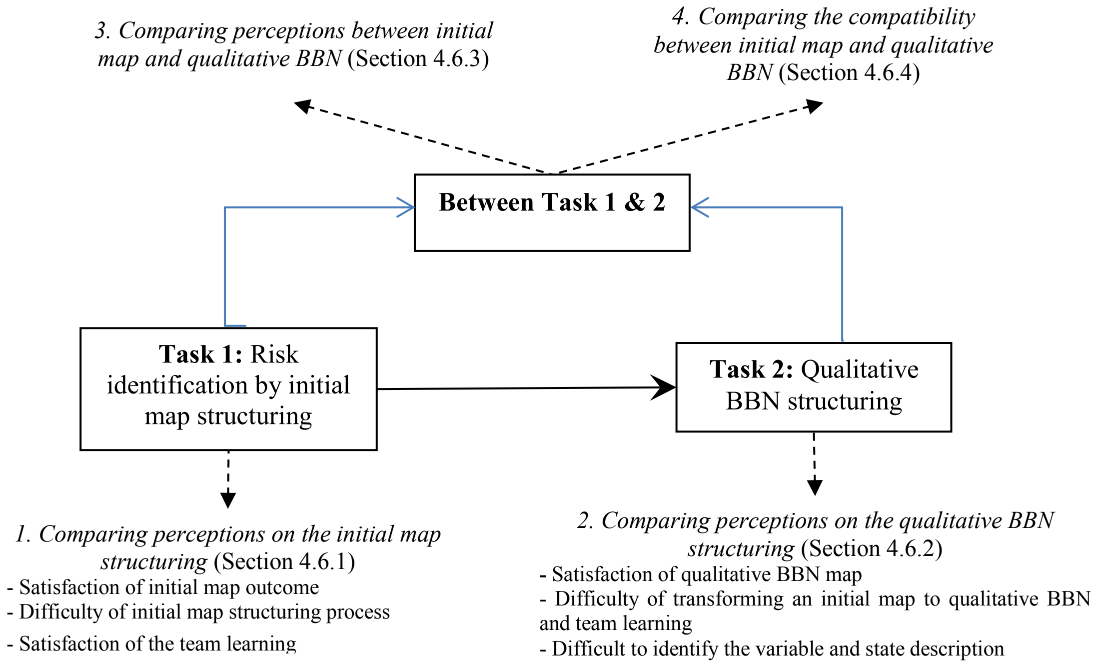


Figure 4-3 Summary of the four analysis aspects of the experimental activities

4.6.1 Comparing perceptions on the initial map structuring

In line with the initial map structuring task, results will be presented as an overview of three main criteria: satisfaction of initial map outcome, difficulty of the initial map structuring process and satisfaction of team learning. There was found to be no statistical difference in the overall perception, three main areas of map outcome process and team learning among CM, FT and RRM.

Table 4-5 Mean score of perceptions on overall and particular criteria for initial map structuring and p-value of Kruskal-Wallis tests

Criteria	Mean score: Questionnaire II (Initial map)				Kruskal-Wallis	
	CM	**FT**	**RRM**	**Total**	**Chi-Square**	**p-value**
Satisfaction of map outcome	**3.42**	3.24	2.95	3.22	2.98	0.23
Difficulty of the process	2.91	**3.00**	2.89	2.91	0.04	0.98
Satisfaction of team learning	3.88	3.95	**4.14**	3.99	0.54	0.76
Overall	**3.37**	**3.33**	**3.21**	**3.30**	**0.40**	**0.82**

Table 4-5 shows there is no statistically significant difference among perceptions of CM, FT and RRM on the overall or three specific areas at the 95% significance level. The highest mean score of overall perception and the perception of the map outcome is CM; the highest mean score of the perception on the process to develop is FT; and the highest mean score of the perception of team learning is provided by RRM.

Although there does not appear to be a significant difference in the overall perceptions of the three initial maps, it is still useful to examine sub-criteria from those three areas which are presented in Sections 4.6.1.1–4.6.1.3. The analysis will start from the statistical testing of students' perceptions, obtained from questionnaire II (see Appendix D), of types of initial maps. In addition numbers of comments from reflective essay I will be presented by bar chart. In some cases, an issue can be mentioned by few students but with a high level of concern. The number of comments and level of concern (which is evaluated by data from questionnaire II) are shown by scatter plot. For both graphs, the minus sign on the horizontal axis represents negative feedbacks and the frequency of comments is measured by the values on the left side of the vertical axis. Positive feedbacks are represented on the right side of the axis, and general frequency can be counted normally. Although two groups were assigned the same map, they may have perceived practical difficulties slightly differently, which is beyond the experimental process design. To understand students' perceptions, frequency of the mentioned issues are counted and represented by group rather than by type of initial maps.

4.6.1.1 Satisfaction of initial map outcome

The average scores of sub-criteria for satisfaction of initial map outcome (Q2.1–Q2.6) are categorised by three types of initial maps. Statistical hypothesis testing found that at least one types of initial map is perceived significantly differently on transparent and robust sub-criteria of the map outcome with 95% significance level; see Table 4-6. Transparent sub-criterion shows how well the initial map can communicate with other stakeholders to make them aware of the effects of risk events to the entire SC. On the other hand, the robustness sub-criterion can show how users who have not involved developing the initial model can understand all variables without missing interpretation.

It is found that students in the RRM groups provide the lowest score of both transparency and robustness while CM score the highest on both criteria. Next the difference between pairs of initial maps was tested by Mann-Whitney U test, for both transparent and robust criteria (see Table 4-7). This showed that students who use CM and FT do not have significantly different perceptions on transparency but they are significantly different from RRM. Furthermore it can be seen that CM scores better than FT and RRM on perceptions of robustness, at the 95% significance level.

Table 4-6 Mean score and p-value of Kruskal-Wallis test of perceptions on particular sub-criteria for satisfaction of the initial map outcome

Sub-criteria for the satisfaction of the initial map outcome	Mean				Kruskal-Wallis	
	CM	FT	RRM	Total	Chi-Square	p-value
Understanding risks from the initial map (Q2.1)	3.63	3.88	3.29	3.61	3.173	0.205
Transparency of the initial map (Q2.2)	***3.75***	***3.75***	*2.86*	*3.48*	*6.225*	*0.044**
Updatability of the initial map (Q2.3)	3.13	2.50	3.00	2.87	1.269	0.530
Complexity of the initial map (Q2.4)	2.50	2.75	2.00	2.43	2.806	0.246
Completeness of the initial map (Q2.5)	3.75	3.50	3.86	3.70	1.505	0.471
Robustness of the initial map (Q2.6)	***3.75***	*3.25*	*2.71*	*3.26*	*6.461*	*0.040**
Map outcome (overall)	**3.42**	**3.24**	**2.95**	**3.22**	**2.980**	**0.230**

* At least one type of initial maps is different with 95% significant level

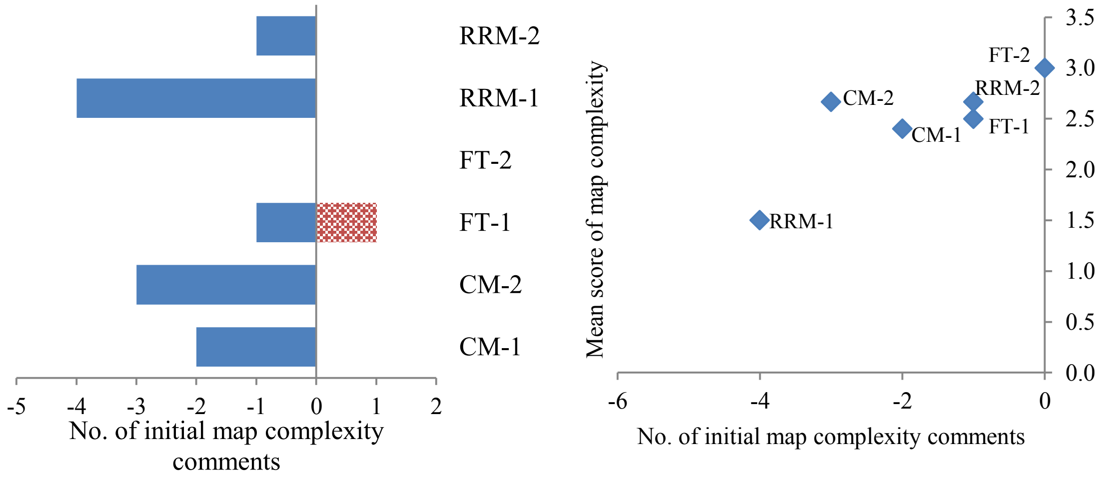
Table 4-7 Mann-Whitney U statistics, Z and p-value for comparison between each pair of initial maps on transparency and robustness criteria

	Transparency of the initial map (Q2.2)			Robustness of the initial map (Q2.6)		
	CM & FT	CM & RRM	FT & RRM	CM & FT	CM & RRM	FT & RRM
Mann-Whitney U	32	11	11	19	10.5	14
Z	1.000	-2.080	-2.080	-1.554	-2.104	-1.778
p-value	1.000	0.038*	0.038*	0.012*	0.035*	0.075
Difference	**CM FT RRM**			**CM FT RRM**		

* Pair of initial maps is different with 95% significance level

Although results for other sub-criteria are not significantly different, the comments from essays are analysed to examine the reflections of students on their initial maps. The interesting finding concerns the complexity of the initial map: all members in group RRM-1 gave the lowest score to show low satisfaction because of the map complexity; see Figure 4-4 (a)–(b). Furthermore students in group RRM-1 mentioned that their RRM was unsuitable for representing of the real case study since it was difficult to understand and to communicate with others.

The number of comments on the complexity of the maps from the essays revealed that the least number of comments on this issue was presented by group FT-1 and group FT-2. On the other hand, it is clear that when an initial map is too complex, it may negatively influence how well it represents the case study.



a. Number of initial map complexity comments

b. Number of comments and mean score of initial map complexity

Figure 4-4 Number of comments and mean score of initial map complexity categorised by groups

Besides the complexity of the model, various other comments can be summarised by initial maps as shown below.

Students in group CM-1 and CM-2 provided very good feedback on their CM. They mentioned that *"Understandability and usefulness of this map is undoubted"*. According to their perception, CM is easily to understand for cause and effect relationships, for clarifying risks which represent the initial information of the case study, for presenting information realistically and for covering almost every detail of information. Interestingly, some students think that CM could be easily adapted to new risks not covered in the original information in the case study: *"The map also provides information of risks what might appeared which probably not covered from the original information of the case study"*. They also used CM to provide a number of questions to identify new approaches for information collection or actions. One student mentioned that *"CM can overcome some communication obstacle"*, implying that CM is a success for competent and cooperative groups members. A few negative feedback comments (which students were instructed to make in brief sentences) were made on the unclear risk concepts, and on the complexity of the model, as mentioned in general by other groups.

Students' essays from groups FT-1 and FT-2 provided both positive and negative feedback on the modelling outcome. Some students mentioned that their FT helped them to gain a better understanding of risks in the case study: *"FT helps me to analyse about the causes of risks. It is good solution that makes me to see each cause of risk and connect them together* *from top event to basic events"*. Some of them thought that FT made the case study easier to understand, but their FT was slightly different from the original case information since they had included their own assumptions of the systems.

Students in groups RRM-1 and RRM-2 provided less positive feedback from the modelling outcome since they were more focused on the drawbacks of the complexity of RRM. One of the students mentioned that *"It would be a useful method of demonstrating risks to others providing the map can be kept concise and relationships aren't too complex"*.

To sum up, of the three methods, RRM was given the lowest score for 4 out of 6 criteria; especially the complexity criteria and strong comments were made in contextual analysis. In contrast CM and FT are scored much better than RRM in transparency of the model outcome and CM is better than the other two in robustness of the initial map. More positive comments on the CM were made in the essays than for the others. CM clearly stands out as the best method in terms of students' satisfaction of initial map outcome.

4.6.1.2 Difficulty of initial map structuring process

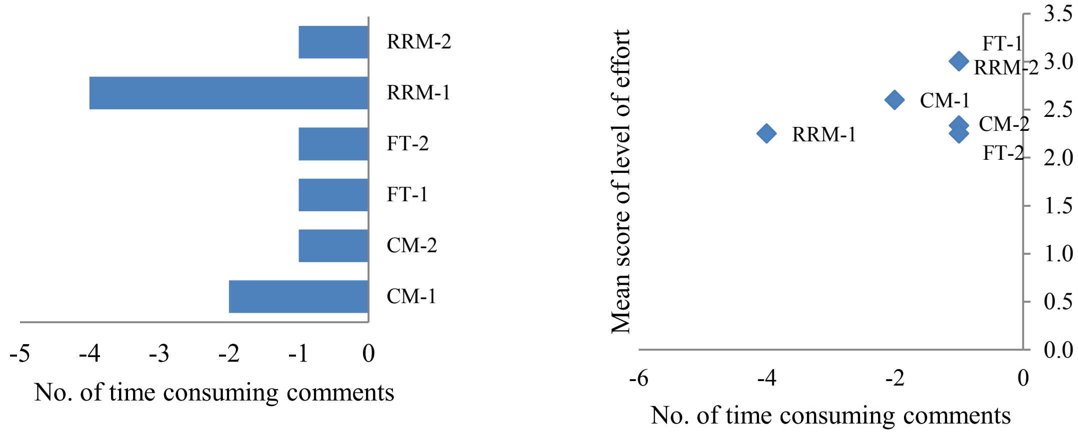
The level of perception on the difficulty of the initial map structuring process is evaluated via Q2.7–Q2.10 from questionnaire II; however, this showed no significant differences between the three initial maps (see Table 4-8). Therefore the analysis focused on the comments from students on their experience of structuring their initial maps, in their answers to the 'How difficult/easy' question in essay I. The difficulty of the particular initial map process will be analysed by how time consuming the process was, difficulties in identifying risk events, difficulties in identifying relationships, and difficulties in identifying the scope of the SC model.

Table 4-8 Mean score of perceptions on particular sub-criteria for the initial map process difficulty and p-value of Kruskal-Wallis test

Sub-criteria for the process difficulty	Mean				Kruskal-Wallis	
	CM	FT	RRM	Total	Chi-Square	p-value
Effort to develop the initial map (Q2.7)	2.50	2.63	2.57	2.57	0.256	0.880
Process difficulty of the initial map developing (Q2.8)	2.88	2.88	2.57	2.78	1.638	0.441
Brainstorming difficulty of the initial map developing (Q2.9)	2.75	3.00	3.14	2.96	1.491	0.475
Confidence of applying the initial map with other case studies (Q2.10)	3.50	3.25	3.29	3.35	0.419	0.811
Process difficulty (overall)	**2.91**	**3.00**	**2.89**	**2.91**	**0.040**	**0.980**

1. How time consuming the process was

The required time to complete task is important because of the constraint of resources for model implementing in real organisations. Figure 4-5 (a) shows that there is at least one comment from each group on this issue, perhaps driven by the fact that all groups revised their maps several times, especially group RRM-1. Figure 4-5 (b) shows the number of comments on how time consuming the process was and the level of effort (Q2.7) required by individual groups to develop their initial map.



a) Number of time consuming comments

(b) Number of time consuming comments and mean score of level of effort

Figure 4-5 Number of comments on 'time consuming' and 'level of effort' during initial map structuring, categorised by groups

Group RRM-1 shows the worst 'time consuming' result: they provided many comments on this issue and gave a low score on effort level, which means they spent a lot of effort to structure their complex initial map. The feedback from group RRM-2 is provided differently from that of group RRM-1, because the group members decided to focus only a single risk concept rather than follow Manual I step by step.

The individual initial maps appear to be time consuming for different reasons. For RRM it stems from a requirement of the process: students in group RRM-1 strongly believed that the process of using a pair-wise relationship matrix to capture relationships between risks was very time consuming (even though it is not a very difficult task). One of the group members mentioned that it took three hours to develop a pair-wise relationship matrix to structure the RRM for only 15 risk events. For FT the problem was learning the relevant symbols and one student stated that *"A lot of effort had to be put in for the initial stages of the map. This was the hardest part of the task."* For CM it was not so much the process that was time consuming but rather having to build an understanding of the case study and summarise everyone's opinion of possible risks. One student said that *"The construction of the (CM) map itself is not very difficult but it was time consuming."*

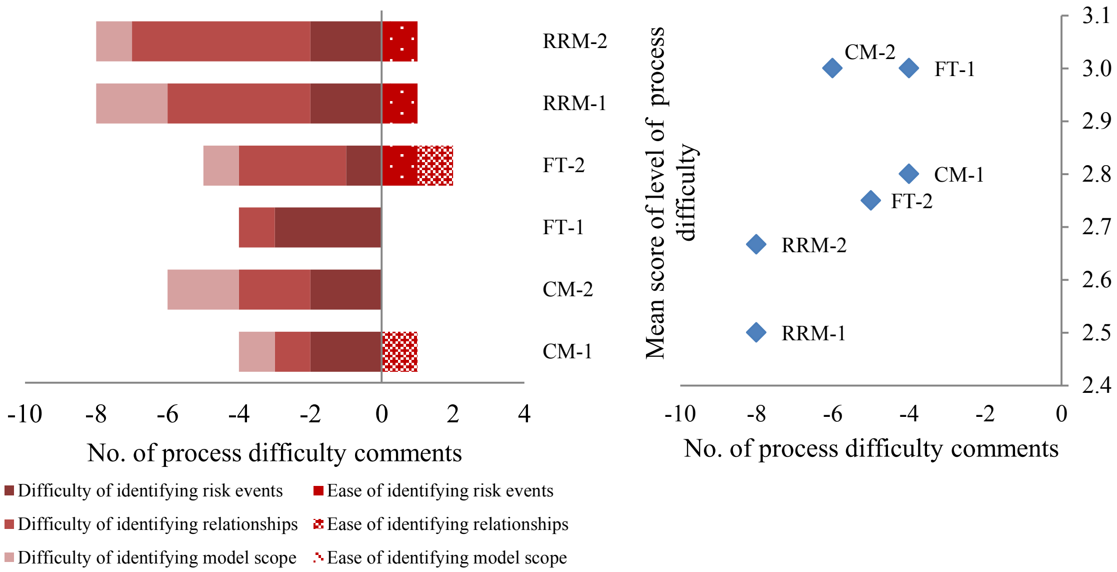
Messages from the essays are similar to observations made during the activity. Groups CM-1, CM-2 and RRM-2 were able to finish their first draft of their initial maps in the session (two hours) although they had to revise their maps later on. Neither group FT-1 nor group FT-2 finished the FT map in the session since they took almost the whole section to read the manual carefully in order to understand symbols and methods. Group RRM-1 spent time on discussion and structuring the pair-wise relationship matrix and came up with a very complex structure with a lot of links. It was found that group RRM-2 have experiences in RR so they did not follow the manual to develop RR and RRM initially and ended up by identifying the high level risks so they can finish their map in the session although they revised their RRM later on. This comparison shows that in terms of the reasons of why a process is time consuming, CM is the most efficient while RRM practitioners should be aware of practical issues with a real organisation since the method is open to the huge number of adverse events in different level of risks. Therefore applying the RRM process in a real organisation may not be practical, or it may need to be adjusted.

2. *Perceptions on process difficulty and emerging practical issues*

Difficulty of the process will be analysed in two ways. Firstly, how difficult or easy it was to structure individual map: data is collected by considering the process to identify risk events, relationships, and model scope. Secondly, issues emerging during the process are summarised by the three themes noted previously: difficulty of identifying risk events, difficulty of identifying relationships and difficulty of defining the scope of the map.

Unsurprisingly, difficulty was pointed more than easiness, because students were learning new techniques; see Figure 4-6 (a). Group RRM-1 and group RRM-2 provided maximum numbers of negative comments on the overall process, especially on the difficulty of identifying relationships. On the other sides, similar numbers of difficulty comments were expressed by the FT and CM groups. Figure 4-6 (b) clearly shows that group RRM-1 and group RRM-2 are in the bottom left quadrant, distinguished from other groups by the number of comments they make (on their essay) and perception of process difficulty (Q2.8).

Although the numbers of comments on difficulty shown above are similar, participants were faced with different issues, and they implemented different types of initial maps. The emerging practical issues during structuring the initial maps are summarised in Table 4-9 by ten issues from three keys process of identifying risk events (i)–(v), identifying relationships (vi)–(ix) and identifying scope of the model (x), by types of initial maps.



(a) Number of process difficulty comments categorised by three themes

(b) Number of process difficulty comments and mean score of level of process difficulty

Figure 4-6 Number of comments and mean score of process difficulty during the initial map development, categorised by groups

Table 4-9 Emerging practical issues during initial map structuring

Emerged practical issues	CM-1	CM-2	FT-1	FT-2	RRM-1	RRM-2
i. Confusions of difference between the process map and CM	■	■				
ii. Untransparent understanding of the SC system or operational system	■	■				
iii. Unique map structure can lead to lack of confidence		■	■	■		
iv. Difficult in identifying top event					■	■
v. Do not understand meaning of risk					■	
vi. Difficult to structure the logical flow by symbol			■	■		
vii. Difficult to decide the (direct) relevant relationships – so many links are defined and it becomes too complex to understand					■	■
viii. Too high level or too general event identified so it is difficult to identify the links						■
ix. Prior perceptions can change the results of the map structure			■			■
x. Difficult to identify scope of the map from SC/SC is complex to define scope of the map	■	■			■	■

a. Issues related to identifying risk events

The specific comment from students who worked with CM (especially group CM-2) related to the confusion between the process map and CM: *"We tried to build a map from given information by following each activity; we finished with the map that looked like process flow"*. For example, they defined a causal concept as 'inventory' rather than 'medicine out of stock from the inventory' which is not the adverse event but rather agents or activities in the supply chan. They realised their CM was not in the right format when they were asked to structure qualitative BBN by checking criterion in task 2, so they revised their CM before moving to the qualitative BBN structuring process. Some students in the CM group mentioned that they wanted to know more detail of hospital service operations, which the case study information did not provide, in order to define related adverse events. A student (CM) mentioned that *"The process of building causal map is not as difficult as I thought because the difficulties of making this map depend on the understanding of entire operation system."*

Students who developed FT pointed out that because they believed there was only one right format for FT, they felt reluctant to structure the right FT. The FT is used to capture adverse events in the wider and more opened system of SC, using OR gates or AND gates to link basic events. This can stimulate the perception of a mature and concrete rather than a flexible model for presenting beliefs. For example, they had developed two versions of FT which linked to the given top event, 'The specific medicine that for a specific inpatient is not available'. One linked the faults supply function of two main service systems, 'Unavailable medicine on stock list' and 'Non available medicine on stock list'. Another version was developed from sources of medicine supply such as 'Unavailable in ward', 'Unavailable in dispensary', 'Unavailable in CDC' etc. The model can be developed by identified unavailability of medicines in the paths of either version. However, it made for confusion and in the main discussions a student stated that *"I was thinking that there is only one right model and my team and I were struggling to approach the best FT map"*. This issue was also mentioned by a student in group CM-2 because he thought that he was not sufficiently confident to develop his map and asked researcher about the accuracy of the map.

A top event was not provided for group RRM-1 and group RRM-2 since they had to design the top event from their identified risk items in RR by following the process. So the top events in RRM from groups RRM-1 and RRM-2 may not be the same. These groups found the top event was difficult to identify since there are so many links that could be identified by the pair-wise relationship matrix, especially when the risk events were defined in the high level, i.e. with no detail of operation. In addition some students in RRM-1 did not understand the meaning of 'risk' so they held a discussion about it during the process of identifying risks in the RR format. The other groups did not mention this confusion since it was explained by 'adverse event' rather than as 'risk'. It was not an issue for group RRM-2 either, since they understood and were familiar with definition of 'risk', although they identified risk events (called as 'risk items' in RR) at a very high level.

b. Issues related to identifying relationships

Some students in FT group pointed out that *"The most difficult part is not about understanding the icons but make the map logical with all connections"*. They therefore specified that the way to put all information from the case study into a tree map structure was harder than they thought. Furthermore a student indicated that *"There is noticeable difference between theory and practice."* Understanding Boolean algebra is a basic required knowledge for FT, therefore background knowledge is really significant when the FT is implemented. A student in group FT-1 made the point that the different levels of knowledge and different backgrounds of people (such as from engineering or business backgrounds) in the team influenced the way that FT was used.

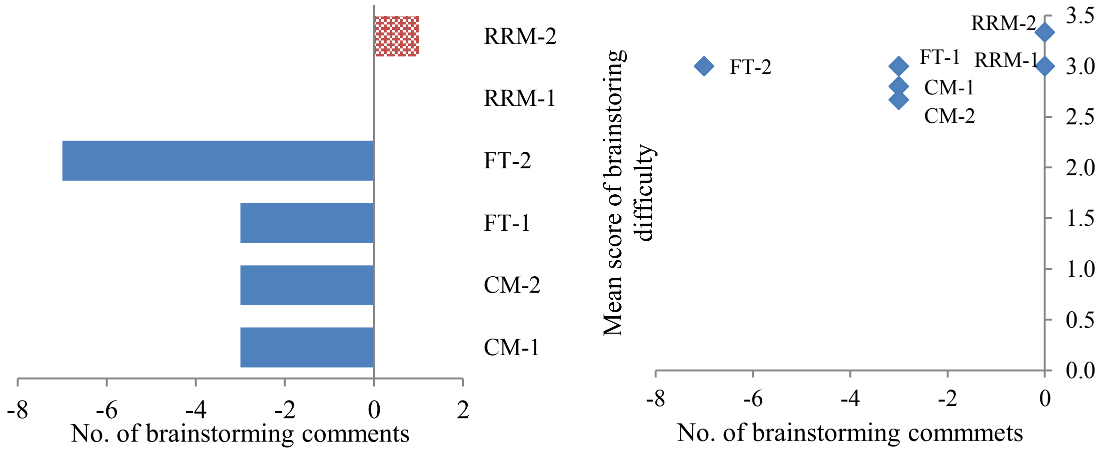
Members of group RRM-1 raised the issue that they had many risk items and they also linked to each other. A student in group RRM-2 said "*Most of the debate surrounded certain risks where the relationship meant that one risk might lead to the other ultimately but not directly."* A lot of links were defined and discussed since the risk items were identified independently from the previous knowledge in RR. This shows that although previous knowledge of risk items may be independently available, it may not support the new perception of the systemic risks. The main issue from group RRM-2 members, experienced students able to use their existing knowledge of RR in project risk management to identify risks in high level view, was: *"We struggled to* *determine the relationships between risks because each of our risk tittles covered a range of possibilities."* This is because the high level risks were difficult to explain and difficult to observe. Another obstacle for members of group RRM-2 was their own previous knowledge. They believed that risks should be viewed at a high level as a big picture so they did use the new methods of modelling risks at a lower level in the SC process. They reported that was very hard for them to change their perception by trying to identify relationships dependently. *"We were all used to identifying and classifying risks as a series of separate possibilities therefore it was harder to change that perception and try to identify relationships."*

c. Issues related to identifying the scope of SC modelling

Only simply hospital SC process and relevant stakeholders are provided in the case study documents and students were asked to structure the initial maps from their understanding of adverse events in the provided SC case study. Some students required more details in operation to be able to identify adverse events and their relationships. Students who worked with CM-1 and RRM-1 defined the vast and complex of SC scope (according to the provided case study) make them cannot define where they should start and when they can stop identifying adverse events.

3. *Difficulties with the brainstorming process*

Brainstorming is main approach by which students are encouraged to develop their initial map. It is assumed that they have that same level of authority and they can operate their workshops by themselves. It is clear from students' essays that students in group RRM-2 had no difficulty working together as they had done so before. The other groups needed to learn to work with new colleagues. The number of comments about brainstorming difficulties was greatest in group FT-2: they complained about working ineffectively with their group members; see Figure 4-7 (a). However, other groups rated the difficulty of brainstorming with their team (Q2.9) very similarly; see Figure 4-7 (b).



(a) Number of brainstorming difficulty comments

(b) Number of brainstorming difficulty comments and mean score of difficulty of brain storming

Figure 4-7 Number of comments and mean score of brainstorming difficulty during the initial map developing, categorised by groups

There is no general pattern to distinguish between initial maps since the difficulties of brainstorming are influenced by personal characteristics, cultures, and languages etc. rather than the type of assigned initial map. Furthermore, students mentioned unbalanced contributions in their group members – some members were confident and dominated while others were shy and looked for consensus. This can lead to difficulties in combining different thoughts and finalising initial maps. The process of managing and balancing the power of experts should be considered carefully when the BBN modelling process is applied in a real organisation.

4.6.1.3 Satisfaction with team learning

Interestingly, students from all groups perceived the benefits gained from group workshop at a high level (a score of more than 3.5 out of 5); see Table 4-10. This means that the perception scores across the initial map types (assessed by using the Kruskal-Wallis test) are not significantly different. In general students provided positive feedback on learning in a team. Some students were satisfied with working with their team members and mentioned the benefits gained from the group workshop. Some students thought brainstorming a really crucial stage in structuring their map as it allowed them to express their own point, discuss with other group members and to combine different thoughts to come to an agreed answer.

Table 4-10 Mean score of perceptions on particular criteria for the satisfaction of team learning during initial map structuring and p-value of Kruskal-Wallis test

Criteria for the team learning	Mean				Kruskal-Wallis	
	CM	FT	RRM	Total	Chi-Square	p-value
Sharing personal insights to develop the initial map with the group (Q2.11)	3.75	3.75	4.14	3.87	1.052	0.591
Understanding another's point of views to modify the initial map (Q2.12)	4.00	4.00	4.43	4.13	2.059	0.357
Appreciation by one another to develop the initial map (Q2.13)	3.88	4.13	3.86	3.96	0.603	0.740
Satisfaction of team learning (overall)	**3.88**	**3.95**	**4.14**	**3.99**	**0.540**	**0.760**

4.6.2 Comparing perceptions on the qualitative BBN structuring

The second analysis will summarise student reflections on task 2 (to develop a qualitative BBN from their initial maps). The qualitative BBN drawn from their assigned initial maps and their perceptions will be analysed quantitatively from questionnaire III and qualitatively from essay II. It was found that the quality of the initial map is the main influence on their perceptions in this task. Furthermore there is no variety of feedback from the content analysis, so general practical feedbacks will be explained rather than counting numbers of comments as was done in the previous section. At 95% significant level there is no statistically significant difference between the perceptions of satisfaction of the qualitative BBN, difficulty of process to transform initial map to qualitative BBN and satisfaction of the team learning; see Table 4-11.

Table 4-11 Mean score of perceptions on overall and particular three areas and p-value of Kruskal-Wallis tests on qualitative BBN structuring

Criteria	Mean score: Questionnaire III				Kruskal-Wallis	
	CM	FT	RRM	Total	Chi-Square	p-value
Satisfaction of map outcome	**3.67**	3.43	3.21	3.45	3.68	0.16
Difficulty of the process	3.06	**3.34**	2.68	3.03	4.43	0.11
Satisfaction of team learning	3.88	3.81	**4.00**	3.90	0.91	0.64
Overall	**3.53**	**3.51**	**3.23**	**3.43**	**2.10**	**0.35**

4.6.2.1 Satisfaction with qualitative BBN map

When sub-criteria of satisfaction of the qualitative BBN are compared, it is found that students perceived statistically significant differences on robustness of the qualitative BBN (Q3.6) between at least one qualitative BBN structured from three initial maps; see Table

4-12. The robust criterion shows how well people who do not involved in developing the qualitative BBN understand and interpret all the variables. Table 4-13 shows that the perceptions of students on robustness of qualitative BBN developed from FT and CM are not different but are significantly different from the qualitative BBN developed from RRM.

The next step was to harmonise analysis of the refletive essays with the statistaical testing analysis, since it is unclear whether the qualitative BBN can improve understanding by comparing CM and FT maps, because feedback from individual groups is varied. However, it is a clear message from students that the qualitative BBN is better than RRM. Generally, the qualitative BBN aims to simplify initial maps so they can be quantified later. For CM, some students mentioned that *"The simplification process (task 2) might affect the clarity of this map"*. On the other hand some students believed this process can help to reduce confusion and redundancy of some links. For FT, one student mentioned that Boolean relationships via OR gate or AND gate (see Appendix C.3) are easy to apply because of the straightforward nature of the rule, so she believed that FT illustrates the connections of risks and causes in a better way than qualitative BBN. But another student thought that a qualitative BBN map was easier and clearer when it came to understanding the relationships of cause and effect. Students in the RRM group were agreed that qualitative BBN provided readers a fine understanding of the risks and that qualitative BBN was much simpler to understand, having fewer arrows going into number of locations. A student said that *"From it we were able to understand the risk and could easily add our mitigating actions to it"*. It was also found that the qualitative BBN map was much clearer to interpret than the RRM from the previous exercise: this therefore would seem a much better tool to illustrate risks to stakeholders.

Table 4-12 Mean score of perceptions on satisfaction of map outcome for qualitative BBN structuring and p-values of the Kruskal-Wallis test

Sub-criteria	Mean				Kruskal-Wallis		
	CM	FT	RRM	Total	Chi-Square	df	p-value
Understanding risks from BBN (Q3.1)	3.75	3.57	4.14	3.82	2.690	2	0.261
Transparency of BBN (Q3.2)	3.88	3.14	3.29	3.45	5.229	2	0.073
Updatability of BBN (Q3.3)	3.25	3.43	2.71	3.14	2.800	2	0.247
Complexity of BBN (Q3.4)	3.38	2.71	2.57	2.91	3.799	2	0.150
Completeness of BBN (Q3.5)	4.00	3.86	3.86	3.91	.489	2	0.783
Robustness of BBN (Q3.6)	*3.75*	*3.86*	*2.71*	*3.45*	*8.330*	*2*	*0.016**

* At least one type of qualitative BBN is different with 95% significance level

Table 4-13 Mann-Whitney U statistics, Z and p-value for comparison between each pair of initial maps on robust and process difficulty to structure qualitative BBN

	Robustness of BBN (Q3.6)			Process difficulty of qualitative BBN developing (Q3.8)		
	CM & FT	**CM & RRM**	**FT & RRM**	**CM & FT**	**CM & RRM**	**FT & RRM**
Mann-Whitney U	26	8	7	7	11.5	2.000
Z	-0.279	-2.500	-2.350	-2.773	-2.245	-3.010
p-value	0.780	0.012*	0.019*	0.006*	0.025*	0.030*
Difference	**FT CM RRM**			**FT CM RRM**		

* Pair of initial maps to develop the qualitative BBN is different with 95% significance level

4.6.2.2 Difficulty of transforming an initial map to qualitative BBN

The process difficulty criterion (Q3.8) is significantly different among the qualitative BBN maps; see Table 4-14.

Table 4-14 Mean score of perceptions on process difficulty criteria for qualitative BBN structuring and p-values of the Kruskal-Wallis test

Criteria	Mean				Kruskal-Wallis		
	CM	**FT**	**RRM**	**Total**	**Chi-Square**	**df**	**p-value**
Effort to develop BBN (Q3.7)	2.75	3.43	2.14	2.77	5.941	2	0.051
Process difficulty of developing BBN (Q3.8)	*2.88*	*3.86*	*2.29*	*3.00*	*13.669*	*2*	*0.001**
Brainstorming difficulty of developing BBN (Q3.9)	2.88	3.00	3.14	3.00	1.277	2	0.528
Confidence in applying the BBN with other case studies (Q3.10)	3.75	3.29	3.14	3.41	1.496	2	0.473

* At least one type of qualitative BBN is different with 95% significant level

Next, the process difficulty sub-criterion is subjected to further hypothesis testing to compare each pair of initial maps. Table 4-13 shows that students provided significantly different scores on process difficulty to structure qualitative BBN from individual initial maps. The ranking of the mean score from high to low (least difficult to the most difficult) is FT, CM, and RRM.

The difficulty of the main process involved in transforming initial maps to a qualitative BBN depends on the type of the initial map and also the quality of the initial map. Obvious evidence shows that the FT can be modified to qualitative BBN more easily than CM and RRM since the Boolean logical structure reduces the effort of checking provided criteria to structure BBN. Students stated that it is quite easy to transform FT to qualitative BBN since they were almost the same.

General observation and analysis of essay feedback on the perception of the provided process reveals that the students found it difficult to understand the conditional independence property which is one of the four criteria (see Section 3.2.1). A student mentioned *"I find out it is difficult for me to understand three kinds of the relationships* [conditional independence] *stated in the manuals".* However, some students thought checking BBN assumptions helped them to examine the map more carefully.

For example members of RRM-2 reported that they structured too high a level of initial map. Group CM-2 identified risk events as activities in the process map when they were considering the four criteria, by including arrows that can represent only direct effect from cause to effect as one of four criteria to transform an initial map to qualitative BBN (Section 4.3.2.2). The members of group RRM-1 started to revise their complex RRM so they spent a lot of time on checking all criteria and discussing how to reduce links that did not follow the rules.

4.6.2.3 Difficulty with identifying the variable and state description

Carrying out the variable and state description is an important link between the identified risk concept to the variable and state format of BBN. Furthermore, the variable and state description can be used to reinforce the initial assumptions and provide the coherence needed to understand the initial causal links. Nevertheless some students mentioned a difficulty in identifying multi-states such as 'Significant', 'Partial' or 'No problem'. They may not have enough information from the case study to define those complex states. One student stated that *"I experience the difficulty when I try to identify the state description within each variable. It is hard for me to distinguish clearly the significant state from partial state."*

4.6.3 Comparing perceptions between initial map and qualitative BBN

Perceptions of the maps were collected repeatedly by questionnaires (II and III) and tested by Wilcoxon signed rank test; see results in Table 4-15.

It is found that students who work with CM do not perceive any significant difference between their CM and qualitative BBN for any sub-criteria. For FT there were significantly different perceptions on the difficulty of the process to structure qualitative BBN and FT (p-value = 0.038). Students also provided different perception scores on the ability of the maps to be updated (p-value = 0.02) and on how easy it is for people not involved in developing the model to understand the model (p-value = 0.046). On the other hand, the perceptions on understanding qualitative BBN and RRM are significantly different (p-value = 0.014). The mean of scores of qualitative BBN and RRM on understanding risk is positive (score of 0.86), so students found that qualitative BBN provides better insight into understanding risks in the case study than RRM; they also mentioned that RRM is too complex; see Section 4.6.1.1 and Section 4.6.4.

Table 4-15 Wilcoxon sign rank test statistic classified by types of initial maps and difference score of particular sub-criteria

Difference of sub-criteria between BBN and initial map	CM			FT			RRM		
	Mean	Z	p-value	Mean	Z	p-value	Mean	Z	p-value
Understanding risks	0.13	-1.00	0.317	-0.29	-1.00	0.317	0.86	-2.45	0.014*
Transparency	0.13	-0.58	0.564	-0.57	-1.63	0.102	0.43	-1.34	0.180
Updatability	0.13	-0.38	0.705	1.00	-2.33	0.020*	-0.29	-0.71	0.480
Complexity	0.88	-1.84	0.066	0.14	-0.38	0.705	0.57	-0.97	0.330
Completeness	0.25	-1.41	0.157	0.29	-1.41	0.157	0.00	0.00	1.000
Robustness	0.00	0.00	1.000	0.57	-2.00	0.046*	0.00	0.00	1.000
Effort to develop	0.25	-1.41	0.157	0.71	-1.18	0.238	-0.43	-1.34	0.180
Process difficulty	0.00	0.00	1.000	1.00	-2.07	0.038*	-0.29	-1.00	0.317
Brainstorming difficulty	0.13	-0.58	0.564	-0.14	-0.58	0.564	0.00	0.00	1.000
Confidence of applying to other case studies	0.25	-1.41	0.157	0.00	0.00	1.000	-0.14	-1.00	0.317
Sharing personal insights	-0.25	-1.00	0.317	0.00	0.00	1.000	-0.14	-0.18	0.854
Understanding another's point of view to modify	-0.13	-1.00	0.317	-0.14	-0.58	0.564	-0.29	-0.82	0.414
Appreciation by one another to develop	0.38	-1.73	0.083	-0.29	-0.82	0.414	0.00	0.00	1.000

* Perception between qualitative BBN and initial map are different with 95% significance level

4.6.4 Comparing the compatibility between initial map and qualitative BBN

According to the statistical hypothesis testing provided in Section 4.6.3, there is statistically no difference between perceptions of the effort needed to develop qualitative BBN and to the equivalent effort needed to structure any of the initial maps. The complexity between the initial map and qualitative BBN can be compared using actual map components to show how much change has taken place between them, as a representation of their compatibility; the results are summarised in Table 4-16.

Table 4-16 Numbers of variables, links and ratio between them of initial map and qualitative BBN

Group	Initial map			Qualitative BBN		
	No. of variables	No. of links	Ratio	No. of variables	No. of links	Ratio
CM-1	30	33	1.10	30	31	1.03
CM-2	26	28	1.08	26	27	1.04
FT-1	23	24	1.04	12	11	0.92
FT-2	48	52	1.08	23	24	1.04
RRM-1	15	46	3.07	18	33	1.83
RRM-2	10	19	1.90	16	20	1.25

The numbers of links and variables of the initial maps for all groups were reduced when they were transformed to qualitative BBN. The highest ratio of complexity reduction was presented by the RRM map from group RRM-1 (the second highest is RRM from group RRM-2). During the process of adjusting RRM to the qualitative BBN, the groups increased the number of variables and reduced the number of links, so the complexity ratios are considerably reduced. On the other hand, there are only slight differences between FT or CM and qualitative BBN, which shows that FT or CM are compatible in structure to the qualitative BBN. In addition, CM is simple so students in groups CM-1 and CM-2 can interpret and structure their CMs with similar numbers of variables and links, while the number of variables and links of FTs and RRMs vary. Since FT allows repeating basic events rather than having to link from the same basic event the numbers of variables and links are greater than other types of initial map. This indicates that CM is not only competitive in terms of transforming from initial map and qualitative BBN, but is also robust (because similar levels of complexity between groups (CM-1 and CM-2) which implemented the same initial maps).

4.7 Suggested Initial Map Technique

According to the model results, which were analysed by statistical testing or content analysis/exploratory data analysis, RRM is the least efficient method but there is no best method for every analysis aspect. Suitable methods for aiding SC experts thinking to identify risk events and their relationships, arising from the analysis of overall outcomes, lies in two main aspects: satisfaction of the model and process difficulty, and practical issues (see the final section of Table 4-17).

Table 4-17 Summary results of particular analysis to propose the suitable initial map technique

Analysis aspects	**Statistical testing**	**Content analysis and Exploratory data analysis**		
1. Comparing perception on the initial map structuring				
1.1 Satisfaction of map outcome	***CM/FT (Q2.2) & CM (Q2.6)***	*- (Complexity) RRM*	*+, - FT*	*+* ***CM***
1.2 Difficulty of the process	No statistical difference			
1.2.1 Time consuming		RRM from required process	FT from learning symbols	**CM from building understand of the case**
1.2.2 Perceptions on process difficulty and emerging issues		Fewer comments of difficulty and lower level of difficulty (High score of Q2.8) - **CM/FT**		
		Ability to manage emerging issues (see Table 4-18) - **CM**		
1.2.3 Difficulty of brainstorming process		Individual characteristics		
1.3 Satisfaction from team learning	No statistical difference	All		
2. Comparing perception on the qualitative BBN structuring				
2.1 Satisfaction of qualitative BBN map outcome	***CM/FT (Q3.6)***	*Depending on the quality of the initial maps (not types of maps)*		
2.2 (Less) difficulty of transforming an initial map to qualitative BBN	**FT (Q3.8)**			
2.3 Difficulty of identifying the variable and state description		General		
3. Comparing perceptions between their initial map and qualitative BBN	***CM*** *similar to BBN*			
4. Comparing the compatibility between initial map and qualitative BBN		**CM**		
Conclusion				
Satisfaction of the model (initial model and qualitative BBN)	***CM***	***CM***		
(Less) process difficulty and practical issues	**FT**	**CM**		

1. *Satisfaction of the outcome*

The summary of statistical testing of satisfaction outcome shows that, for both initial map and the qualitative BBN, CM has the highest score of overall satisfaction perception on the initial map outcome; see Table 4-5, especially in the transparent (Q2.2) and robustness (Q2.6) aspects. Furthermore, robustness of the qualitative BBNs developed from CM and FT is perceived significantly differently from that of RRM (Q3.6); Table 4-13. A comparison between CM and qualitative BBN outcome shows no significant different between them (Table 4-15): this means that they maintain the same level satisfaction of their maps. There are statistical differences between qualitative BBN and RRM (the BBN helps a better understanding than RRM) or qualitative BBN and FT (the BBN is better in updatability and robustness than FT); see Table 4-15. However, perception scores of qualitative BBN developed from FT and RRM for those three criteria are not significantly different from CM; see Table 4-12 and Table 4-13. Therefore it can be concluded from the statistical testing of student perception that CM maintains a higher level of satisfaction than FT or RRM.

According to the perception on the initial map or qualitative BBN which are analysed by content analysis, it is found that students who develop CM are satisfied with their CM by provide only positive feedback of their CM while students who developed FT and RRM providing some negative perceptions as have explained in Section 4.6.1.1. In addition, since quality of the initial map is substantial to the process to structure the qualitative BBN, the good perception of CM is relevant to the satisfaction of their qualitative BBN.

2. *Process difficulty and practical issues*

According to the statistical testing, the difficulty of developing the initial maps are not significantly different (see Table 4-8) but FT is outstanding technique in the process of transforming FT to qualitative BBN provided by Question 3.8 (see Table 4-13). It is found the students perceived the less difficult of the process to structure the qualitative BBN from FT than initially structuring FT (see Table 4-15). However, according to the content analysis FT may not be the great choice to be implemented (see Section 4.6.1.2).

Furthermore, analysis of providing suggestions to solve emerging practical issues (Table 4-9) shows that practical issues of CM can be managed while the issues from other techniques are hard to solve as they occur as a result of the inherent nature of the techniques (see Table 4-18). One of the main issues for FT is that learning symbols and understanding the methods depends on individual background knowledge and this can be a sensitive issue in the SC. Since SC is multidisciplinary (Knoppen and Christiaanse, 2007), there is no guarantee that FT will work well with people in all fields. For RRM, Table 4-18 shows that most of the technical problems arising are difficult or impossible to manage and it is therefore hard to prepare action to cope with them. When the top event cannot be provided before starting the structuring of RRM, it makes the process more difficult because the purpose of the model is not known. In addition it may be very difficult to change the expert's perceptions on how RR becomes RRM by identifying risk dependently and also at a high level (a problem group RRM-2 encountered), and this could have a crucial effect on the quality of the qualitative BBN. Students noted that someone with the same background as they had would struggle to work out how to understand RRM.

Table 4-18 Suggestions of solving emerged practical issues for each initial map

Emerged practical issues	CM-1	CM-2	FT-1	FT-2	RRM -1	RRM -2
i. Confusion of difference between the process map and CM	Clear explanation of risk events not activities or agents in the SC					
ii. Untransparent and understanding of the SC system or operational system	Should not be a problem to work with the real SC experts					
iii. Unique map structure can lead to lack of confidence	Clear explanation of no right or wrong map but only represent their belief of the system					
iv. Difficult to identify top event						
v. Do not understand meaning of risk	Using 'adverse event' rather than 'risk'					
vi. Difficult to structure the logical flow by symbol						
vii. Difficult to decide the (direct) relevant relationships as so many links are defined and it becomes too complex to understand	Define only direct links with SC process flow					
viii. Too high level or too general event identified so it is difficult to identify the links						
ix. Prior perceptions can change the results of the map structure						
x. Difficult to identify scope of the map from SC/SC is complex to define scope of the map	Set assumptions of the model or Define clear SC boundary					

It was also found that numbers of variables and links of CM and qualitative BBN (developed from CM) are almost the same (see Section 4.6.4), which is one of the reasons why these two maps are so compatible. The different types of experiment analysis lead to the clear conclusion that CM should be used as the proposed initial model rather than FT and RRM to structure the qualitative BBN in SC risk context.

4.8 Concluding Discussion on BBN Structuring Process

The implications of the experimental findings on BBN structuring are synthesised in this section to provide recommendations for further developing a suitable process to use with the real SC people. There are nine recommendations, of which six are new (1–6) and three are similar to those in the existing BBN literature (7–9).

1. *CM is the recommended approach rather than FT and RRM to be applied in this context*

Explanation was provided in Section 4.7.

2. *Provide a higher degree of facilitating rather than using self-learning to operate the process of BBN structuring*

Students were able to structure different types of initial map because they have less limitations on time and effort that the real experts have. Furthermore the sequential process which involves many stakeholders needs a person who can be a coordinator between stakeholders and can operate the modelling process. Observations showed that each group required several workshops to learn and structure (and revise) their maps. The requirements of BBN itself, such as defining state and variable description and checking assumptions of BBN, make the process difficult. Moreover participants from the real organisations need strong motivation to implement a new technique about which they may not be confident, and to control misunderstandings of the process arising from experts' prior knowledge (such as identifying too high level risks or viewing risk independently as a RR). Since the available time of real expert is costly and limited, asking them to learn how to structure initial map and qualitative BBN and organise series of workshops would be challenging.

3. *Agree the scope of SC boundary before identifying risk events*

SC is an open system and is dynamic as its boundary keeps changing. New suppliers, new customers or new strategies can change the SC system but a BBN is a static model (see Chapter 2). Therefore restricting the SC boundary scope can stabilise the system and maintain the same basic of understanding, reducing the amount of discussion required in the group workshop, and it can help to identify adverse events more easily.

4. *Awareness of confusion between process map and CM*

A process map is one of the regular tools for people who are working in SC. It shows how products can flow from one place to another in the SC. However, team members may become confused when asked to structure CM by causal relationships, see Section 4.6.1.2. A suggested procedure to reduce the confusion is to ask them to identify all possible risk events related to particular agents and then asking them to link them from cause to effects. This should eliminate confusion because they will be asked to think of only adverse events, before linking them later.

5. *Awareness that prior perception of experts in industry can change as result of this study*

The new approach of capturing risk dependency by implementing BBN, introduced for SC risk modelling, changes the prior perceptions in risk management. The existence of traps from previous knowledge was observed in the experiment in group RRM-2 (see Section

4.6.1.2), where the members were experienced in RR project risk management. They were used to identify risks at a high level rather than identifying adverse operational events and causal relations. Therefore, to control confusion arising from their experiences of RR, the process should encourage and motivate team members to think about risks differently by leading them away from RR.

6. *Top event should be provided to the experts before start BBN construction*

The evidence in the experiment confirmed the standard process of developing a model with a defined model objective represented by top event. When the top event was not provided for RRM-1 and RRM-2, team members were confused and unable to properly define the relationship, leading to a complex map and lower quality of the model.

7. *Dealing with unbalanced contributions when constructing CM by group working*

Although the group workshop has recognisable good benefits from which students can gain when they structure the qualitative BBN map, there are general drawbacks of group workshops; see Section 4.6.1.2. An interesting suggestion made by the students during the experiment was: *"The construction of an individual map, by each team member, before the second session could have helped to a better understanding of the case and it could have provided a sense of ownership of ideas, increasing the confidence of some team members when debating."* Students confirmed that their teams coped well with language or culture barriers, characteristics of keeping silent and shy or being confident or some group members' dominant attitudes affecting the confidence of the silent members. They were able to develop the balance of the group and this led to agreement over the solutions the group proposed.

Unfortunately, real experts may not be available to structure their own map during their own time without motivation and support. Therefore the process needs to be adjusted by structuring individual maps with the individual experts (by interview) and then combining the resultant maps before having a group workshop to discuss and structure their agreed map. A series of interviews and workshops develop BBN in this way already exists in the literature (Hodge et al., 2001; Walls et al., 2006).

8. *Using the term 'adverse event' rather than 'risk'*

The issue of the meaning of 'risk' being unclear was raised by one RRM-1 group member. Since 'risks' have to be defined in RR before transfer to RRM, RRM-1 members found the definition unclear to them. The manual for other groups used the term 'adverse event', which caused no confusion. In a real organisation, it would be safer to use 'adverse event' to ensure clear communication with the experts. This issue has been discussed in the literature (O'Hagan et al., 2006; Walls and Quigley, 2001).

9. *Motivating participants to express their belief of the problem domains by telling them that there is no 'right' or 'wrong' model*

An initial map is a 'soft technique' that aims to capture beliefs of the experts in SC risk. This may different from 'hard models' that they have experienced and creating an 'accurate model' might be their concern. Therefore they may not comfortable in expressing their own beliefs about adverse events. Observations made during the experiment indicate that it is important to properly explain the techniques and reassure participants that there is no 'right' or 'wrong' map, to help to improve their confidence: this confirm what has been suggested in the literature (Renooij, 2001).

Chapter 5 Conceptual BBN Risk Modelling Process Design

The 'applicable' BBN modelling process for this thesis will be developed by aiming to solve challenges in implementing BBN to support risk analysis in SC. These challenges were set out in Section 3.4; the theoretical BBN has also been grounded in SC risk, which is explained in Section 3.1. In this chapter, we propose a conceptual modelling framework that can explain interactions at the component level, see Section 5.1. After that, guidelines for linking adverse events in SC scope under the knowledge boundary of participants in individual organisation units by linking stock-availability and supply-ability are explained in Section 5.2. More detail on the rationale of process design will be explained in Section 5.3, after which the process can be designed by going through eight essential stages, as explained in Section 5.4, called the *primary BBN SC risk modelling process*.

5.1 Conceptual Modelling Framework Development

SC can combine with multiple stakeholder organisations facing different adverse events. Therefore the BBN SC risk model should be able to link their perceptions by considering the boundary of stakeholders' perceptions on the SC process. According to the precise definition given in quantitative modelling for risk analysis, risk is *"a random event that may possibly occur and, if it did occur, would have a negative impact on the goal of the organisation"* (Vose, 2008, p. 1). In other words, there is a mainly negative relationship between random **adverse events** and the **SC goal** of the organisation.

Since the relationship between strategic goals and SC performance measurement is vital (Beamon, 1999; Stevenson and Spring, 2007), the SC goal should be broken down to measurable event level via a combination of performance measures (Melnyk et al., 2004). For example, lean SC aims to reduce cost but agile SC focuses on the flexibility and response to demand and so they may focus on response rates or response times. Furthermore SC performance is not only relevant to the SC goal but also links to SC risks or adverse events, as confirmed by a variety of studies, for example by empirical study (Ritchie and

Brindley, 2007b), survey (Wagner and Bode, 2008), analysis of ad-hoc data (Hendricks and Singhal, 2005a, 2005b), and proposed frameworks to analyse SC (Van der Vorst and Beulens, 2002) etc.

As a result, we focus the major concept for risk modelling by the logical relationship between effect (represented by SC performance) and cause (represented by adverse events); see Figure 5-1.

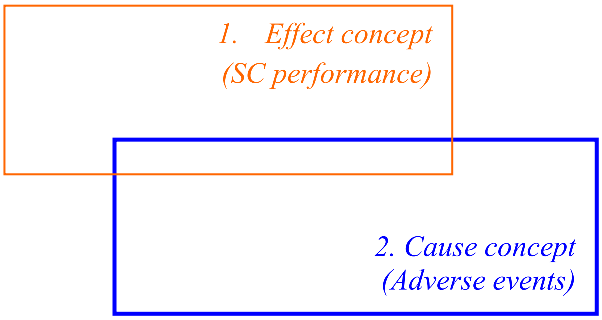
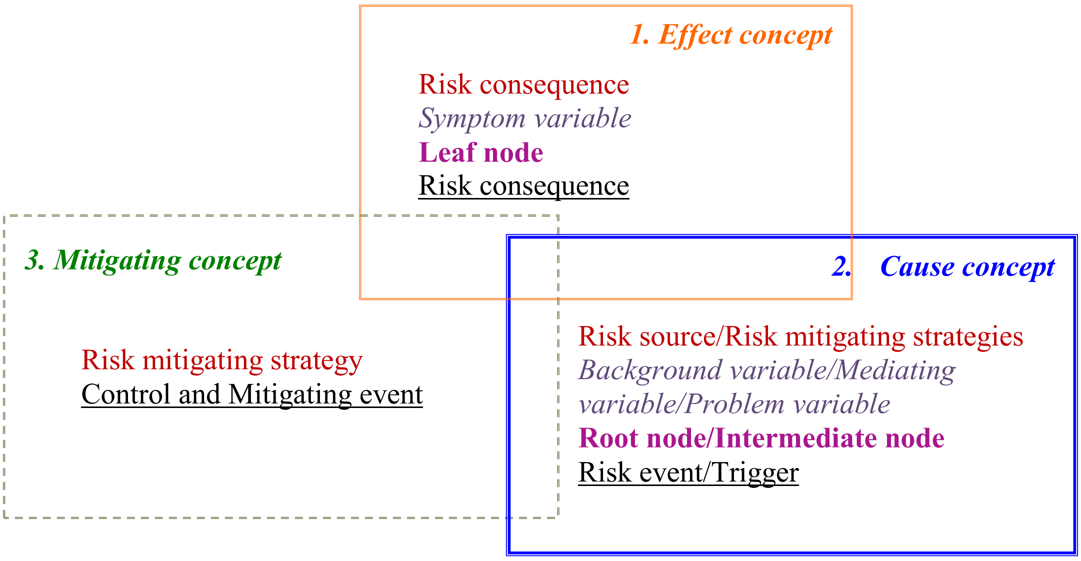


Figure 5-1 The two major concepts of the initial conceptual modelling framework

Next these two concepts can be developed and broken down into components by defining causal pathways in the conceptual elements that support BBN SC risk modelling. The components are first examined from the literature within SC risk and BBN, to integrate both areas before proposing the BBN SC risk conceptual modelling framework.

A variable in BBN literature has been classified into leaf variable/symptom variable, root variable/background information variable, and intermediate variable/mediating variable (Kjaerulff and Madsen, 2008; Korb and Nicholson, 2004). Jüttner et al. (2003) define four basic constructs of SCRM: SC risk source, risk consequences, risk drivers, and risk mitigating strategies. Recently, Fenton and Neil (2012) suggested classifying BBN variables involved in risk analysis as risk consequence, risk event, trigger, control and mitigrating event. The components in BBN and risk especially in SC are similar as can be shown in see Figure 5-2.

After relevant conceptual components are defined, the causal pathways of those components are considered in order to show how the BBN can capture systemic risks at the concept level. Cause-effect relation is selected (from possible types of relationship given by Neil et al. (2000); see Appendix E) as the main type of relationship to capture interaction among adverse events by the BBN SC risk model. The risk consequence/leaf variable/symptom is identified by SC performance (Y) in the effect concept by linking from intermediate event (X) and root cause (Z), called the root cause/background information/risk driver/trigger. The final component is mitigating strategy (*W*) which can be a control and migrant/risk mitigating strategy in the mitigating concept. Mitigating actions are generally of two types: reducing the probability of adverse events (in the cause concept) or reducing negative impact on SC performance by different actions (Khan and Burnes, 2007; The Royal Society, 1992; Viswanadham et al., 2008), see Figure 5-3.



Source: Analysed from Kjaerulff and Madsen (2008), *Korb and Nicholson* (2004), **Jüttner et al.** (2003), Fenton and Neil (2012)

Figure 5-2 The component analysis of the initial conceptual modelling framework

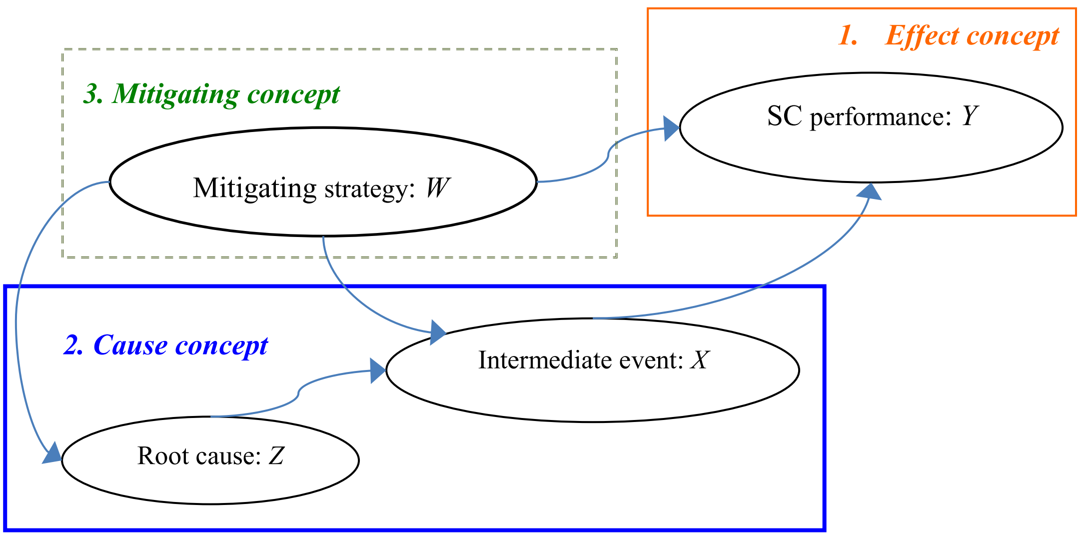


Figure 5-3 BBN SC risk conceptual modelling framework

The conceptual modelling framework shows the high level components and possible causal relations needed to capture risk in this research. For the next stage, the main defined concepts are also analysed to provide the basic knowledge for individual concepts in order to be able to understand the causal-effect relationship in this context. Therefore the three main concepts (effect, cause and mitigation) will be explained in SC risk context; see Section 5.1.1–Section 5.1.3.

5.1.1 Supply chain performance factors and possible loss of performance in the effect concept

Early performance measurement studies emphasised financial measurement but the disadvantages of this in comparison with nonfinancial measures (at the operational level) have been explained by, for example, Ghalayini and Noble (1996), and Melnyk et al., (2004). Performance measurement has been defined in various ways (Lockamy and Spencer, 1998) either by qualitative or quantitative methods (Chan, 2003). Performance measurement study has defined metrics[4] for different functions, such as performance measurement in inventory (de Vries, 2007), logistic audit (Van Landeghem and Persoons, 2001), operations (Hendricks and Singhal, 2005b). Although there is no unique performance measure, those scholars have defined some measurable factors in common.

In the modelling perspective, the level of study (strategic, tactical, or operational), see Section 1.1.2, is the key to determine the balance of SC performances. The performance measurement system can coordinate across levels of SCM from strategic to operational level (Melnyk et al., 2004) by using specific SC performance measures (Ghalayini and Noble, 1996). The financial metric will measure the performances related to money while the operational focus will allow the measurement of resources and outputs.

The SC performance variable(s), the main components in the effect concept, should be defined at the operational level. In this research, the SC performance measurement suggested by SMART (Ghalayini and Noble, 1996; Kelvin and Richard, 1988) is selected to provide the framework of the SC performance factors at the operational level, in four categories; see Figure 5-4.

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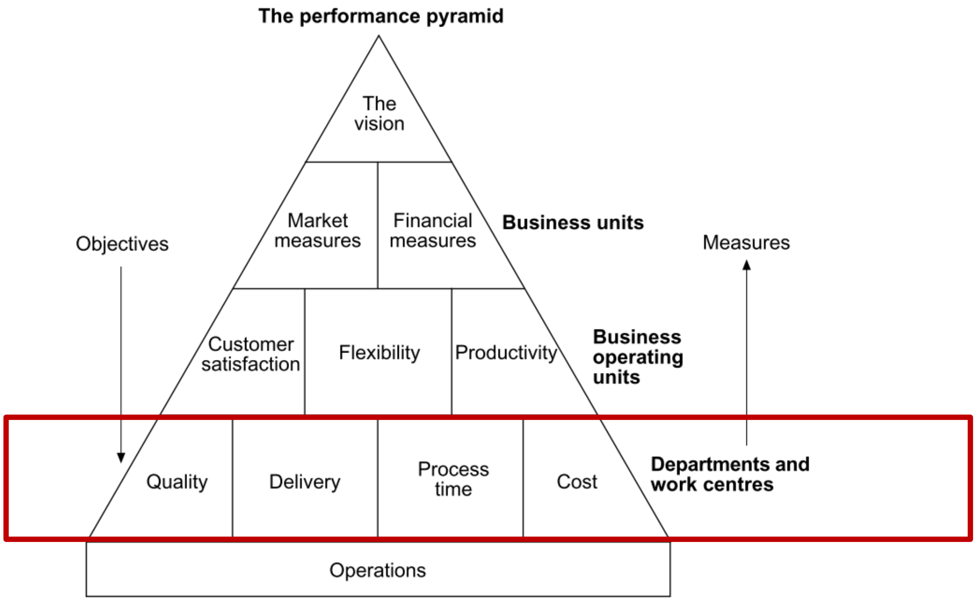
[4] **A metric** is a standard for measurement of the performance of a supply chain or process (Supply Chain Council, 2012, p. 1.0.2).



Source: Ghalayini and Noble, 1996

Figure 5-4 A four-level pyramid of objectives and measures

1. *Cost* is the key factor for operations in any business not only in SC and the metrics to measure cost can be defined in total or individual for particular functions e.g. total cost of production and cost of delivery, cost of distribution etc. Cost is the money or effort for the required quality, delivery and process time (Kelvin and Richard, 1988). Operational staff may not perceive adverse events which are relevant to cost, but we can define adverse events which are relevant to waste of resource rather than define cost as a top event directly. However, Ghalayini and Noble (1996) indicate that cost is a 'lagging metric' since it is the result of something that has already happened, and it may not be useful as it is out of date.
2. *Process time* is relevant to a set of activities which are linked by step and can be a key when defining contract or business agreements. Therefore time can be a metric of SC performance in operation e.g. total time in the process (actual process or waiting time), cycle time, length of inventory turnover, length of time for which the shop can operate unattended, lead time (flexibility). Individual departments can control their own plans which will include the activities with or without adding value to the products. The definition of time is standard throughout the manufacturing system; measurement of time is clearer than measurement of quality.
3. *Delivery* can be defined in different metrics, such as number of on time deliveries, number of stock outs, response time, quotes lead time, order fulfillment lead time,

shipping errors etc. In general it can be measured by two aspects of delivery – quantity and timeliness to meet customer expectations.

4. *Quality of product* is very broad in meaning. One of the definitions of production quality is: reliability, durability, aesthetics, and perceived quality (Kelvin and Richard, 1988). Furthermore it is difficult to define general metrics since the suitable quality of one product may be defined differently from that of another. Sometimes it can be evaluated from number of customer complaints.

The similarity between the definitions of possible 'loss' and 'performance factor' is noted in the literature. Possible loss has been categorised by Jacoby & Kaplan (1972) and have been cited in many papers (Cousins et al., 2004; Ellegaard, 2008; Harland et al., 2003; Mitchell, 1995) as financial loss, performance loss, physical loss, psychological loss, social loss and time loss. Therefore *loss of performance* is the main interest for BBN SC risk modelling and is identified from the suggested SC performance categories above.

5.1.2 Sources of risk in the cause concept

This section will focus on explaining possible sources of risks which have been classified in Section 1.2.2 (supply-side uncertainty, demand-side uncertainty, external environment, and vulnerabilities in their own organisation) as elements in the cause concept. This makes it possible to classify the potential sources of risk from individual stakeholders' perceptions of the SC. The source of risks will be used to show how to link adverse events from one stakeholder to another as part of *the core risk modelling framework*; see Section 5.2.

5.1.3 Risk mitigating strategies in the mitigating concept

Some organisations prepare to cope with uncertainty by different strategies and this can affect the SC process system. How much the effects of adverse events can disrupt the SC performance depends on how well current mitigating actions are implemented. The interaction of risk mitigating policies for different aspects has also been shown via the concept of risk-reward relationship (e.g. Chopra and Sodhi, 2004). The understanding of possible risk mitigating actions should therefore be defined as a key concept for systemic risk modellers. General risk mitigating actions have been clearly explained by Vose (2008) especially in terms of implementing different risk mitigating strategies in different situations (Figure 5-5).

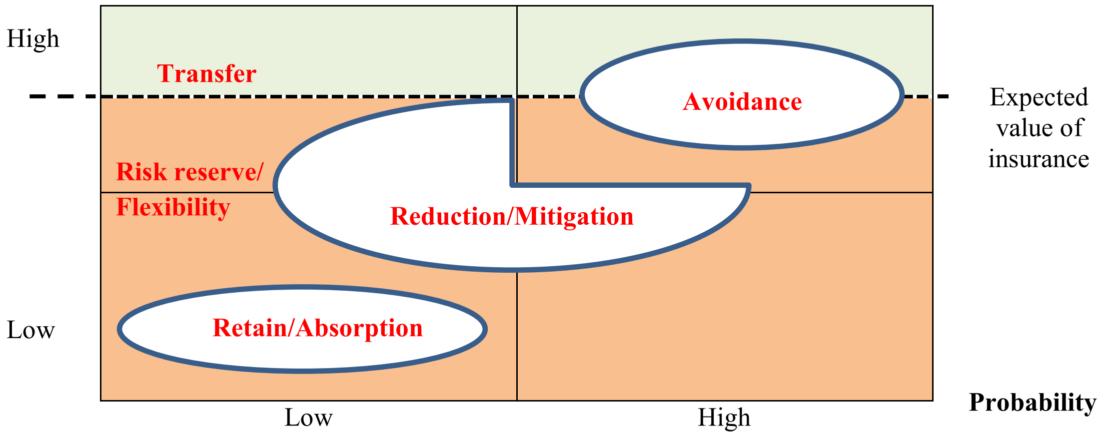
1. *Risk avoidance* aims to escape taking risks by dropping activities that can cause adverse events; however, this may result in lost opportunities to earn more profits. Examples of risk avoidance are dropping specific products, suppliers, or customers when they are found to be unreliable or unacceptable (Jüttner et al., 2003), selecting tested technology rather than new and original technology (Vose, 2008). This mitigating action is suitable for risks that can happen frequently and, when they occur, can generate high impacts to the organisation.

2. *Risk transfer* aims to shift bad consequence to others by purchasing insurance or outsourcing. However, outsourcing should only be employed for basic components rather than core or innovative parts which may stimulate the level of risk from intellectual property. Common practice in risk transfer is to sign contracts that guarantee a certain level of performance and set penalties for when the contractor fails to meet it. Insurance is an attractive option when that the value of the loss when the adverse event happens is above the expected cost of insurance. Risk can also be transferred to SC partners such as by changing to just-in-time delivery to suppliers to reduce entire inventory risks or using make-to-order manufacturing (Norrman and Jansson, 2004) which allows longer lead times for production.

3. *Risk reduction/mitigation/control* aims to reduce likelihood or impact of the loss by increase the level of contingency; however, this needs to be done at the strategic level because relevant high level of cost is involved. This option is suitable for any level of risk that is not severe (high probability and high impact) by trading off between benefits and costs.

4. *Risk reserve/flexibility* aims to increase responsiveness by adding some reserve (buffer) to cover risks or using redundancy policy as the traditional SCM such as multiple sourcing etc. Reducing lead time can provide a quicker response or a new policy of postponement can form part of a flexibility to reduce dependencies of forecasting and increase ability to deal with variability and uncertain demands. This risk reserved option is suitable for small or medium impact risks.

5. *Risk retention/absorption/acceptance* can be called self-insurance, because some risks are not critical so the cost of insuring against those risks may be higher than the cost of the loss if the adverse event happens. This option is suitable for risks that are not significant because they have both low likelihood and impact, compared with the cost of control.



Source: Developed from the description by Vose, 2008

Figure 5-5 Mapping risk management strategies with levels of probability and consequence

In practice the decision maker may be satisfied with their current level of risk with respect to the risk-reward trade-off. In other words some decision makers may think that they have spent too much on resources (money, time, etc.) for managing risks which may not necessarily happen, so they may want to reduce their level of risk protection, such as by reducing safety stock level, in order to reduce cost (Vose, 2008). However, this option can lower the public credibility of the organisation, which may adversely affect the organisation's reputation and image. Another option is gathering more data to reduce uncertainties of unknown (epistemic uncertainties) in order to make a robust decision (Ellegaard, 2008; Vose, 2008). Besides the direct strategy to manage risks, knowledge creation is useful as it can help to reduce either probability or the effects of risk effectively (see more discussion in Ellegaard, 2008).

5.2 Core Risk Model in Supply Chain

After the relevant factors are classified for particular concepts, the interaction between them will be extended from the BBN SC risk conceptual modelling framework (Figure 5-3) by the core model to explain how to link by causal pathways between stakeholders in SC. *Stock-availability and supply-ability* is the nature of the SC process that shows the relationship from cause of supplier ability to effect of stock ability so it is proposed as the core link of causal pathway from one to another stakeholder.

Within the cause concept, individual stakeholders can face four different sources of risks, categorised as supply-side uncertainty, demand-side uncertainty, external environment, and vulnerabilities in their own organisation (see Section 5.1.2). Furthermore their activities are a part of the SC process and they can take different roles in different relationships. For example the supply ability from a supplier can represent the supply-side uncertainty influencing the unavailability of a product in the focal organisation unit. In addition, the unavailability of the product in the focal organisation unit could then be defined as supply-side uncertainty for customers. However, the availability of the product within the organisation unit is not just caused by suppliers' inability to supply but also by demand-side uncertainty, external environment (disruption) or the vulnerabilities in their own organisation unit.

Within the effect concept, SC performance element(s) should be identified as the top variable(s) of the model. However, the model cannot capture all adverse events for all dimensions of SC performance, especially in the SC scope, as that would require a lot of detail and may be too complex for users to understand. Therefore only one performance variable should be defined as a top event in the BBN model. In addition the current mitigation strategy in the SC process is relevant to prepare a redundant system or a backup system (but in different levels) to increase system reliability and reduce the impact on the SC performance. Furthermore the back-up system also links to stock-availability and supply-ability as the traditional mitigating strategy. All three concepts of modelling framework shown in Figure 5-3 can be expanded to the element levels to show interaction among individual stakeholders by the core model: depicts as an example of the causal relationship linking risks from two stakeholders. The core risk model can provide the abstract anticipated model which can be used to explain how to combine them to develop the BBN SC risk model.

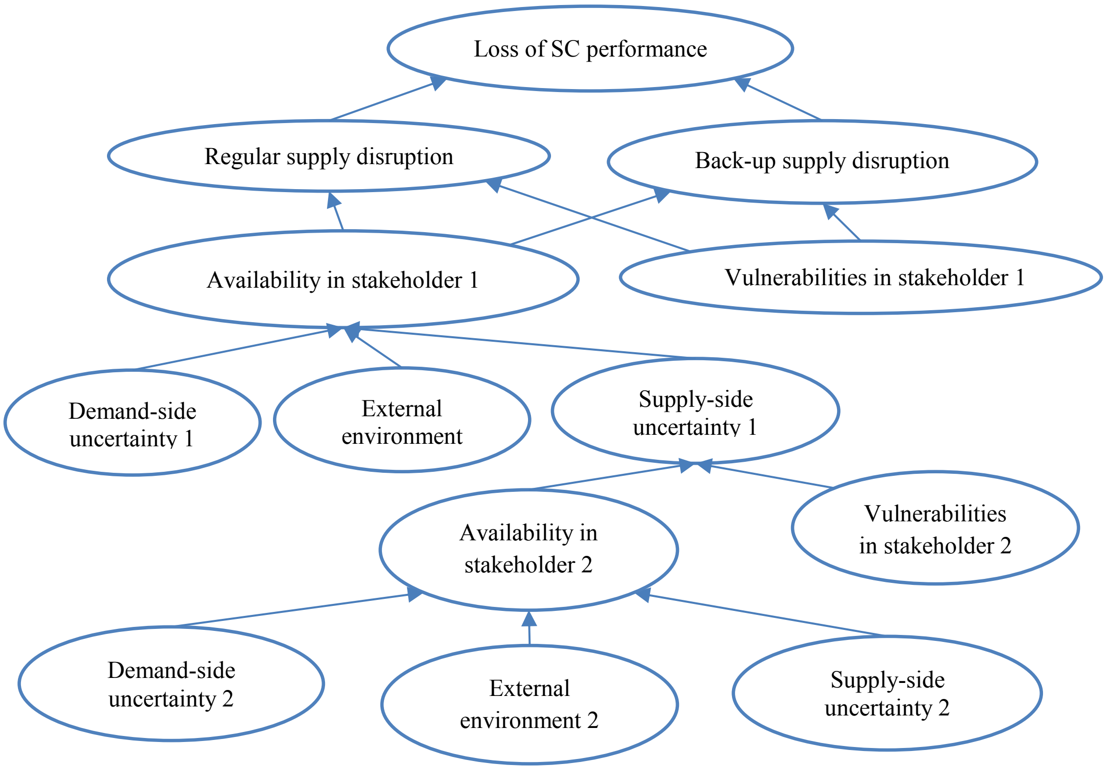


Figure 5-6 The core risk model in SC (stock-availability and supply-ability) for 2 stakeholders

5.3 Rationale for Designing BBN SC Risk Modelling Process

The very process of eliciting the data (in risk analysis) is vital: often, the process itself appears to be more useful than the actual output of the analysis. The data-collection process should stimulate communication in an open atmosphere in which possible problems can be admitted, and precautionary actions examined, while the essential optimism in the project team is preserved (Bowers, 1994, p. 9).

The design of the process is essential because it should be able to stimulate and improve the participating of experts by sharing their perceptions with their stakeholders. The available BBN processes are challenged by requirements of implementing BBN to support risk analysis, as was explained in Section 3.4. To structure a modelling process able to manage the challenges in the context, six useful sources are modified or investigated for this study.

Firstly, the issues of concern to problem structuring for BBN are defined by four critaria, as explained in Section 3.2.1; these will be used to transform the general casual map into BBN format. Secondly, model validity under the assumption of no true data being available is reviewed as explained in Section 3.2.2 before proposing the essential criteria for model validation. These criteria are also taken into the process in order to define the validating model, to ensure that the outcomes of the model can be used to support risk analysis with confidence. Thirdly, the techniques of aiding experts to identify systemic risks in the problem structuring process are also explored by experiment with the SC students, in order to investigate perceptions of SC experts before selecting the suitable techniques and approaches that support the problem sructuring process (see Section 4.8). Fourthly, the BBN SC risk modelling framework, explained in Section 5.1, is used to provide guidelines for linking adverse events in SC scope by the core risk model (see Section 5.2). Fifthly, the standard approach of eliciting probability from experts' knolwdge developed by the Decision Analysis Group at Stanford Research Institute (the SRI approach),see Merkhofer (1987), is adjusted for this study for the instantiation modelling process. Finally, many modes and techniques are reviewed from the literature and suitable options for particular stages are selected by aiming to use the simplest and most transparent methods (explained in this section). How those inputs can be used to overcome the challenges in implementing BBN to support risk analysis in SC and then influence the design of the *primary BBN SC risk modelling process* will be summarised in Figure 5-7. The discussion of rationale for designing the *primary BBN SC risk modelling process* will be explained in this section under three main processes: problem structuring, instantiation and inference.

Generally the way to carry out the modelling process should be facilitated by an analyst; this was a finding of the experiment (see Section 4.8 (2)). The participating expert panel, which can provide perceptions of adverse events in the modelling process, consists of a decision maker and a number of representatives of particualr stakeholders. To ensure that all adverse events and relationships in the network can be captured, support from the decision maker's perception is required. The model will also capture specific details at the operational level from operational experts representing stakeholders.

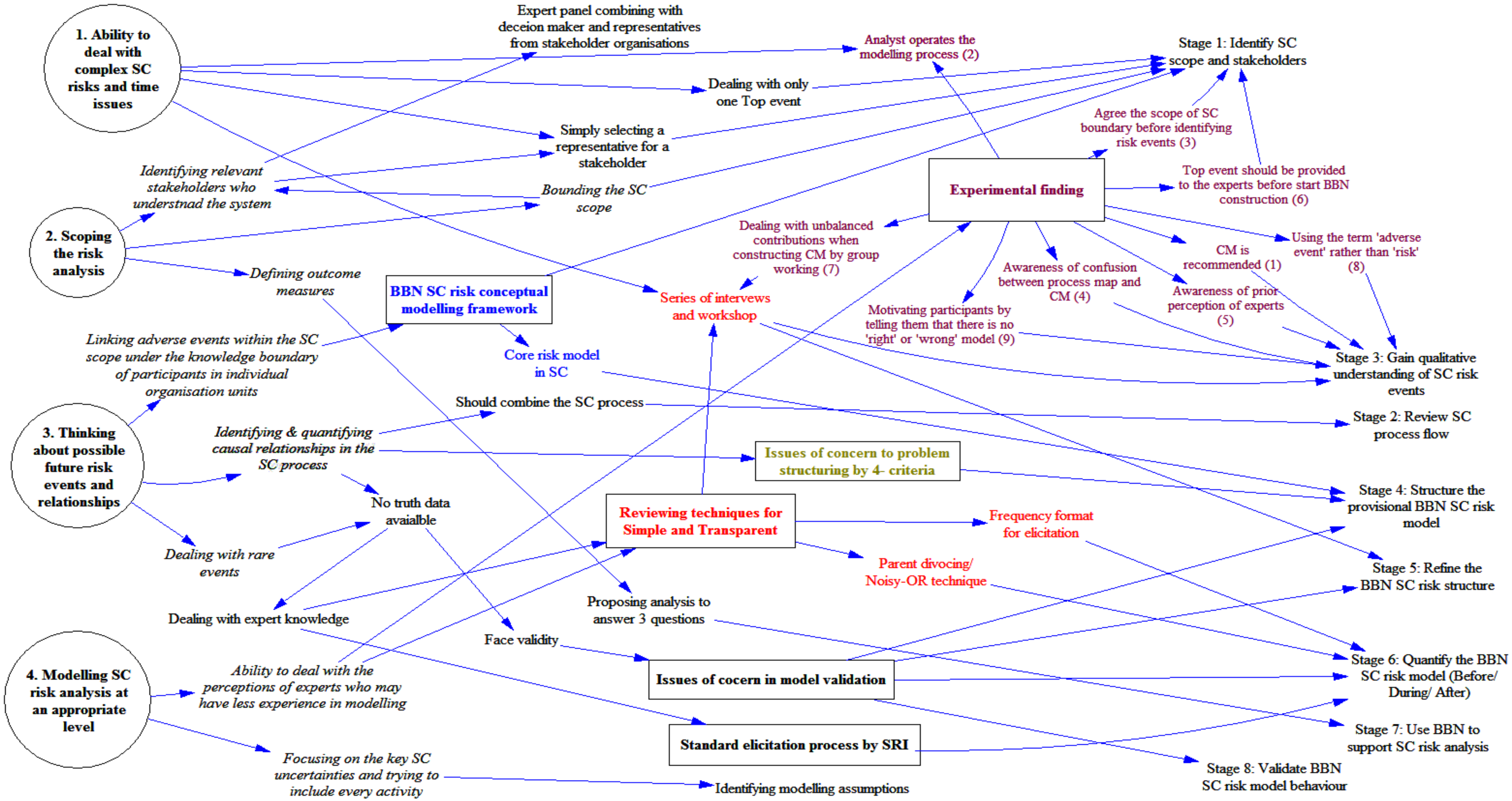


Figure 5-7 Summary of rationale for designing the primary BBN SC risk modelling process

5.3.1 Problem structuring process for BBN SC risk model

Problem structuring aims to capture systemic risks qualitatively which it is called as qualitative BBN. Problem structuring is developed to manage unstructured problems related to multiple actors, multiple perspectives, incommensurable and/or conflicting interests, important intangibles or key uncertainties (Mingers and Rosenhead, 2001, 2004).

Different ways of structuring the BBN are reviewed from options of qualitative elicitation (Meyer and Booker, 2001) and risk identification methods (Rosenau and Githens, 2005). Although common risk identification methods such as brainstorming, interviewing, use of questionnaires and checklists, document reviewing and so on are available in the literature, the face-to-face interaction between the expert(s) and facilitator or analyst (O'Hagan et al., 2006) is recommended. Therefore interviewing or workshop discussion is identified as a suitable way of collecting knowledge from experts. However, individual interviews alone cannot provide the agreed structure of BBN SC risk, especially the linkages between adverse events, and using only group workshops is difficult to conduct in practice for many reasons. Firstly, using group discussion does not always operate effectively since individual stakeholders operate in different functional areas and face different risk events. The time taken to identify adverse events for individual stakeholders may waste other experts' time. Secondly, risk in SC can be understood as 'operational error' and may not avoid the connotation of blame or reprobation (Fischhoff, 1989) especially when it involves stakeholders in SC. Thirdly, the bias arising because of workshop participants keeping silent and following the majority cannot be managed in a short session, as evidenced in the experiment with SC students (Section 4.8 (7)). Interestingly, weaknesses of particular methods can be reduced by combining a series of interviews with a workshop, successfully implemented in applications (Hodge et al., 2001; Walls et al., 2006).

The five essential stages within problem structuring process and the reasons for identifying those essential stages will be explained in this section.

Reasons to identify stage 1: Identifying SC scope and stakeholders

According to the BBN SC risk conceptual modelling framework (Section 5.1), the main requirement of the model to secure SC performance is identifying the top event in the effect concept. Knowledge of a top event can help the experts to identify adverse events more easily, especially in SC scope; see Section 4.8 (6). Furthermore, the boundary of the SC has to be identified in the initial stage to determine the scope of the model and number of relevant stakeholders and possible adverse events in the cause concept. It was also found that knowing the scope of SC helped students in the experiment to identify possible adverse event more easily; see Section 4.8 (3). Finally implementing static BBN (see Section 2.3.6) within the SC risk context requires a time frame to be defined, to control the variation of perceptions in the different time frames which could not be handled by the strict static nature of the BBN. Therefore there are four main requirements to be defined at the initial modelling stage.

1. SC performance
2. SC boundary
3. Stakeholders
4. Time frame

Reasons to identify stage 2: Review SC process flow

Developing the model of beliefs should underpin the basic understanding of the SC process to show how they interact; this can then be used to determine relevant relationships of cause-effect as the structure of the BBN. The process flow or process map is therefore very important. Firstly the BBN is a belief model that can be developed from perceptions of experts. To understand an expert's perceptions on the SC system, an analyst who may not be the expert in their SC process needs a basic understanding of the SC system, and can get this by learning from the process map. Secondly, the BBN SC risk model is developed to represent the risk in the current SC by combining perceptions from different stakeholders, so the standard process flow should be a referencing point to help explain the current SC process to participants. Thirdly, direct relationships are required for the BBN so the SC process flow can help to identify only direct effects and exclude indirect effects of BBN structuring (which is a part of stage 4). Finally, the process flow can be used as a tool to identify adverse events by asking experts to consider adverse events which can occur in particular activities (see stage 3).

Reasons to identify stage 3: Gain qualitative understanding of SC risk events

Face-to-face interview is selected as the method for collecting operational experts' initial perceptions by the analyst, since only one expert can be dealt with at a time and the analyst should not worry about dealing with a group (Meyer and Booker, 2001). This method is more flexible: it is easier to arrange to meet experts individually rather than try to organise a group session or workshop, since the experts work in different organisation units and they have heavy responsibilities. Moreover, an expert will be more relaxed in identifying adverse events which are caused by their stakeholders as there will be reduced confrontation resulting from different perceptions among stakeholders (Fischhoff, 1989; Walls and Quigley, 2001). Finally, the expert panel can comprise both high level and operational experts: high level expert view can provide the reasoning flow of the whole SC, and operational experts can provide the detail. Individual interviews to identify adverse events can therefore suffer from *management bias* by experts trying to identify risks which only are accepted by their boss but can prevent the occurrence of *group thinking bias*, where some experts keep silent to follow the majority, trusting on other experts' ideas rather than express their true beliefs.

The feasibility of implementing these techniques in the SC student experiment confirms that CM is the most suitable technique to help experts identify systemic risks naturally; see Section 4.8 (1). In addition, CM can be used to communicate with all experts effectively (Williams et al., 1997). Furthermore CM is similar to BBN in being able to present cause-effect relationships (Neil et al., 2000; Huff, 1990). This compatibility eases the transformation from CM to BBN (Nadkarni and Shenoy, 2001; 2004). Therefore both the literature and experimental results indicate that CM can be trusted as a suitable technique to capture the relationships between adverse events and be developed to BBN.

***Reasons to identify stage 4* - Structure the provisional BBN SC risk model**

This stage aims to combine perceptions on adverse events collected by CM from individual experts into a main map in BBN format called the *provisional BBN SC risk model.* This stage is the responsibility of an analyst who will need three key skills to be able to carry it out. Firstly, the analyst has to understand, by checking the four criteria (see Section 3.2.1) what issues of concern there are to the problem structuring process for the qualitative BBN format. The general CM is different from the qualitative BBN so after the causal relationships have been identified by individual experts, the analyst needs to check the relationship under the BBN property. Secondly, the analyst needs to understand how the BBN SC risk conceptual modelling framework can show the core risk modelling in SC (see Section 5.2) to be able to link individual perceptions of individual stakeholder in the flow of causal concepts in the SC scope. Finally the analyst needs to know how the variable and state descriptions (explained in Section 3.1.3) will be developed into BBN format.

***Reasons to identify stage 5:* Refine the BBN SC risk structure**

The group session should be arranged after individual interviews to provide an opportunity for experts to see the dependencies between expert judgements (Walls and Quigley, 2001) although they work in different stakeholder organisations. In addition the group session will help to define the gap between their respective perceptions as a piece of the whole model

(Fischhoff, 1989). Furthermore it allows them to share their own experiences and discuss any disagreement over perspectives, to better develop and refine the BBN map as a part of model validation (see Section 3.2.2) of the modelling structure. After they are familiar and confident with information that they have provided from the previous interview in stage 3, the group session can help to develop the ownership of the refined BBN maps from the expert panel and then they are willing to move to the harder task, quantification.

5.3.2 Instantiation process for BBN SC risk model

> *There is no single correct protocol for expert elicitations and that somewhat different designs may be better in different specific context* (Morgan and Henrion, 1990, p. 158).

There are three possible ways to identify the probabilities for BBN – using a mathematical model, retrieving probabilities from databases or eliciting from experts (Houben, 2010; Kjaerulff and Madsen, 2008). Because the mathematical relationship between adverse events is unknown, and the databases are limited and hard to access (see Section 3.4.3), probability elicitation from expert knowledge is mainly selected to populate BBN quantitatively. The literature points out that standard probability elicitation can be implemented to reduce biasness of judgement collecting from subjective knowledge (van der Gaag et al., 1999; Walls and Quigley, 2001). Unfortunately, the main literature on generic process of expert judgement elicitation provides guidelines for a high level state (Bedford et al., n.d.). Some proposed processes are developed to overcome the biases but they are time consuming while fast elicitation methods have been invented but they cannot cope with bias very well (Renooij, 2001). Since there is no single standard process that can be implemented in all cases, the design of the instantiation process will be adjusted from the standard probability elicitation SRI approach.

Reasons to identify stage 6: **Quantify the BBN SC risk model**

Additionally the SRI approach is selected to use for controlling the bias during elicitation, applying six elicitation states (for discrete variables): motivate, structure, condition, encode, verify and aggregate. These aim to control possible biases. SRI has been reviewed and widely implemented effectively (Merkhofer, 1987) and has been successfully implemented by many studies (e.g. Hodge et al., 2001; Zitrou, 2006). SRI and suitable techniques discussed above can be adjusted to provide the practical guideline for 'stage 6 – Quantify the BBN SC risk model'. We have modified the SRI process in order to cope with practical challenges.

Because of their ability to deal with complexity and issues of the process being time consuming, *individual interviews* for variables that are only relevant to particular stakeholders are selected for developing the process rather than using workshop to elicit probability for the whole model. The size of the CPTs is exponential in the number of parents (variables linked into). When there are many arrows leading to an effect variable, the size of the CPT will dramatically increase and can be a big barrier to implement the model in real practice. The size of CPTs is a serious bottleneck in BBN model development (Langseth and Portinale, 2007; Zagorecki and Druzdzel, 2004) so a parent divorcing technique, see Appendix F.1, and Noisy-OR, see Appendix F.2, are implemented.

Confirmation comes from extensive psychological studies that experts tend to find the probability assessment difficult (Renooij, 2001) and the BBN quantitative process is much harder and more time consuming than the qualitative part (Coupé, 2000). It is very difficult for experts to deal with multivariate beliefs (Sigurdsson et al., 2001). If they find that it is too hard for them or they cannot answer, they may deny providing those probability numbers. Employing a suitable model and approach are vital to the success of model development and the *frequency/odds ratio* technique is selected from available techniques.

Since we implement expert judgement as the main input of the model and use a 'Noisy-OR' technique as an approximation, there could be concerns about the accuracy of the model outcome. However, we can argue that the BBN SC Risk model aims to provide model outcome in risk assessment to support *"a critical process for helping top management to make informed prioritisation and resource allocation decisions"* (Sodhi and Tang, 2012) rather than provide a highly accurate risk estimator. Therefore, we believe that data from expert judgement are good enough to provide prioritisation results and also practical for modelling risks in SC scope.

The proportion format estimates more accurately when presenting information in a frequency format (numbers per one hundred or per one thousand) rather than in absolute number format between 0 and 1 (Oakley; 2010 citing the experimental result given by Gigerenzer; (1996)). Likewise, frequency format is more suitable for aleatory uncertainty than estimating proportion (Oakley, 2010) and it requires less training people, while absolute numbers is suitable for technical people (Merkhofer, 1987). An uncertainty of the SC process relevant to routine work at the operational level is more randomness (aleatory uncertainty) so experts may perceive adverse events in frequency format as similar to the way they perceive their routine work. Furthermore the drawback of the process being time consuming (Renooij, 2001) means that the research design allowed each expert to elicit probability numbers only from the part of the process under their own expertise and not the whole model. Therefore the main questions for quantification in this research will apply estimating frequency to elicit subjective probability.

5.3.3 Inference process for BBN SC risk model

The inference process for BBN SC risk modelling process aims to provide the outcome and to validate the results.

Reasons to identify stage 7: **Use BBN to support SC risk analysis**

The algorithm of BBN inference was developed to support complex BBN calculations via the available software packages but we propose GeNIe software for this modelling process as have been explained in Section 3.2.3. However, the provided outcomes should be able to support risk analysis which involves answering three questions; see Section 3.1.5.

Reasons to identify stage 8: **Validate BBN SC risk model behaviour**

The second workshop will be arranged after outcomes of model to support risk analysis are provided, at the last stage of the process stage 8 – validate BBN SC risk model behaviour. This workshop aims to validate the model outcomes; see Section 3.2.2.

5.4 Primary BBN SC Risk Modelling Process Design

The eight essential stages of primary BBN SC risk modelling process have been developed and discussed in the previous section also summarised in Figure 5-7. In this section we will provide the details of how particular stages should be implemented in a real case study as shown in Figure 5-8.

The design of this process involves balancing between the limitations of resource, the large scope of SC, and quality of the model. Therefore the minimum requirement of three main relevant roles are defined: a decision maker, who is the problem owner or is responsible for signing off on a decision and providing the overview of the adverse event in SC; experts, who need to know the parameters of their operational SC process; and an analyst, who has experience of probability and understands the primary BBN SC risk modelling process. The main responsibility to drive the process falls to the analyst, who must collect input from a decision maker and experts.

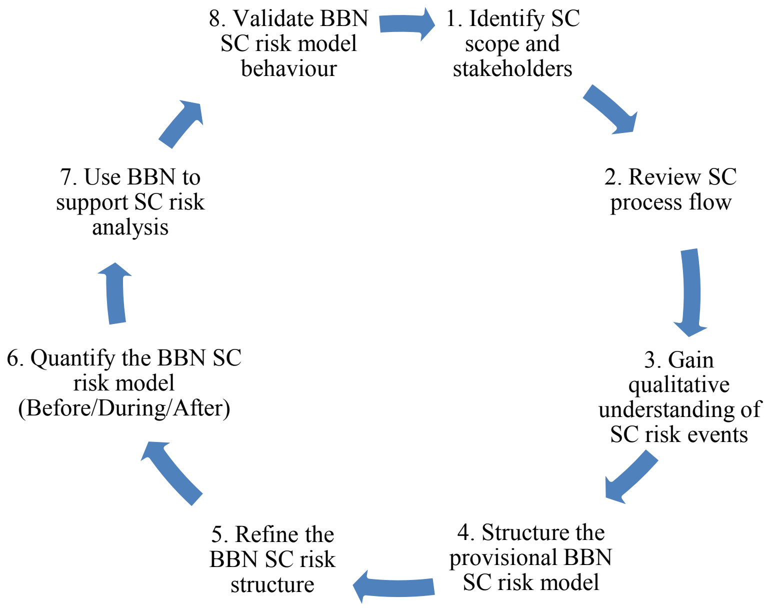


Figure 5-8 The BBN SC risk modelling process design

5.4.1 Stage 1 – Identify SC scope and stakeholders

The initial stage in BBN SC risk model development is to define the scope of the model by several interviews with the decision maker.

1. *SC Performance*

The analyst should ask the decision maker to consider the goal of his/her SC by considering the type of their product before identifying measurable or observable SC performance to identify as a top event. The defined SC performance should then be interpreted as an observable event (the top event). For example if the decision maker focuses on speed and time, the top event may be identified as on time delivery or transportation, lead time of assembly etc. A focus on cost might lead to the identification of the top event as cost of delivery, cost of inventory, or cost of sourcing etc. Because of the large scope of modelling in SC, it is recommended that only one top event is identified, to reduce complexity of the BBN SC risk model.

2. *SC boundary*

The analyst should ask the decision maker to consider the geographical SC boundary that defines the modelling scope and can help to form the expert panel, since the BBN SC risk model is defined by the relationship between stock-availability and supply-ability from stakeholder one to another.

3. *Stakeholders*

After the SC boundary has been agreed with the decision maker, the decision maker nominates representatives of particular stakeholder organisation units (the 'experts'). However, there are different tiers of suppliers and customers so it is impossible to include all supplier and customer units in the BBN SC risk modelling panel. One or two stakeholder representatives in particular tiers should be identified to form the expert panel and a formal invitation should be sent to them.

4. *Time frame*

There is no rule about how this should be done: the decision maker can define any time frame which the model can cover – a month, a year etc. If the process runs over longer than the defining time frame, the model can be updated and it assumes that the model will not change during the defined time frame.

5.4.2 Stage 2 – Review SC process flow

The completed process map linking all activities between organisation units may not be available in one place. The analyst should collect the documents of the SC process for particular stakeholders and then review and combine them into the SC process within the SC scope. The accuracy of this process should be confirmed with the decision maker and other experts.

5.4.3 Stage 3 – Gain qualitative understanding of SC risk events

Part of the design is to conduct a series of individual interviews to structure a set of CMs for individual stakeholders from experts as a small piece of the whole BBN SC risk model. The entire map can be controlled and confirmed by the CM developed by the decision maker, but he/she may not be able to quantify some events in operational detail.

One result from the experiment with SC students is that the interview protocol used to structure CM should be wary of using the word 'risk' and should use the term 'adverse event' instead (see Section 4.8 (8)). Furthermore clear explanation of how to capture interrelationships between adverse events by CM should be explained at the initial stage, to avoid the confusion between the BBN SC risk model and prior perceptions of RR (see Section 4.8 (5)). A key message to help in the motivation stage is to ensure that experts, when they identify adverse event and relationships from their beliefs, know that there is no right or wrong answer (see Section 4.8 (9)). Finally the protocol should suggest that experts identify all possible adverse events before asking them to link those adverse events from cause to effect. This design intends to control confusion between CM and process map (which arose during the experiment – see Section 4.8 (4)) because experts can think of events rather than process activities.

5.4.4 Stage 4 – Structure the provisional BBN SC risk model

This process is the responsibility of the analyst, who requires four main skills; see Section 5.3.1. The provisional BBN SC risk model should be structured using the procedures below.

5.4.4.1 Combine identified adverse events with the core risk model

The links can be made by considering the relationship of product supply activity as part of *the core risk modelling framework* – see Section 5.2 – so individual CMs will be transformed into pieces of the *provisional BBN SC risk model*. Additionally BBN properties should be checked by the four criteria of conditional independence, reasoning underlying cause-effect relations, distinguishing between direct and indirect relationships, and eliminating circular relations, as explained in Section 3.2.1. Apart from assessing the main four criteria, during the model development the analyst and decision maker may define a list of modelling assumptions in order to limit the modelling scope, since a single model may not be able to represent every single case in reality. If some adverse events are left out of the defined assumptions which have agreed with the decision maker, they cannot be included into the provisional BBN SC risk model and it should be explained to the experts why they are excluded.

5.4.4.2 Develop the variable and state description

The adverse events from CM have to be modified into variable format to be able to quantify uncertainty. A simple way to transform an adverse event to a variable is by defining two states 'Yes' and 'No' (for two-state variable); see Section 3.1.3. The definition of particular states and variables should be recorded from the interviews to structure CMs (stage 3). This process of recording in the proper format is a part of linking between CMs and the provisional BBN SC risk map.

5.4.5 Stage 5 – Refine the BBN SC risk structure

The discussion of the map as a whole in a group workshop is very significant process, designed to make sure that all experts are agreed and understand the provisional BBN SC risk map which includes not just their own input but also stakeholders' input. The provisional BBN SC risk model can show in BBN format the reasoning flow from all related adverse events. Disagreement or conflict of perceptions of merging the CM to structure provisional BBN SC risk map should be discussed. The workshop should last 2–3 hours (Hodge et al., 2001). The protocol to validate BBN with the expert panel in the workshop should be prepared effectively, developed from the literature (Morgan and Henrion, 1990; PRAM, 2004). The direction of checking the model within a group workshop should start from the top event and then consider the logic down to the root causes, called 'stepping backwards' (Cain, 2001; Smith et al., 2007).

Validation is then carried out by taking the model structure and variable descriptions and asking for feedback from the experts in the workshop, using guideline validation questions (see Section 3.2.2):

Clarity test
Do all variables and their states have a clear operational meaning to all stakeholders?
Variable definition and relation checking
Are they named usefully?
Are state values appropriately named?
Are all relevant variables (under the modelling scope and assumption) included?

5.4.6 Stage 6 – Quantify the BBN SC risk model

The quantification process can be simplified by separation into three parts: before, during, and after elicitation.

5.4.6.1 Before elicitation

Before elicitation, the analyst should prepare questions for elicitation and validate them before implementing them with the real experts.

1. Prepare questions

Questions of probability elicitation, using the frequency format, should be developed for two types of variables, root cause variables and effect variables in the BBN.

Generally Fischhoff (1989) explained the process of experts mental translation when the their mental representation of knowledge varies from the elicitation format given by interviewers. They start to identify the aspects that they know which are relevant to the questions, retrieve the knowledge from memory and then translate it to the form acceptable to the elicitation. The transformation during the process can lead to information being lost so developing questions close to the expert's perceptions is very important.

For managers, frequency format (e.g. number of cases in 100) or absolute value format (e.g. 0.30) may be familiar from reports or documents. On the other hand, operational experts perceive their regular routine work so they may perceive number of adverse events during working time, such as per day, per week, etc. If the operational experts were asked to use the regular frequency format (e.g. to think in terms of 100 operations) and provide the frequency of adverse events, they would have to retrieve the memory from their perception and transform to the format which was asked. Different perceptions of frequency from managerial and operational experts stimulate two set of questions, Set A and Set B.

Two sets of questions (set A and B) will be prepared for individual experts to choose during the real elicitation (stage 6) and questions examples are provided in Section 9.2.6.1. The two sets can be developed for root cause variable and effect variable. Additionally the effect variable can be distinguished by two types of quantification – normal method or by implementing Noisy-OR technique, see Appendix F.2. The examples of set A and B questions will be shown in Section 9.2.6.1 to avoid duplication.

2. Validate variables and states

Process consistency checking should be validated by the analyst; see Section 3.2.2. The guideline for checking is as below:

Consistency checking

Are the state dimensions (e.g. a week, in a month etc.) and state units (orders, products, units etc.) across different eliciting questions consistent?

Are all state values useful or can some be combined?

Next the questionnaires and the process should be pre-tested to get feedback on the questions and the format of elicitations (Walls and Quigley, 2001). Prior to the interview, it is recommended that the expert is given an outline of the questionnaire or questionnaires (Walls and Quigley, 2000): this provides the expert an opportunity to officially declare all his concerns about question design.

5.4.6.2 During elicitation

A questionnaire is the tool used for collecting probability by structured interview with the same group of experts who identified the BBN SC risk structure. The suggested time for elicitation is about 1–2 hours (Arthur and Gröner, 2005). A suggested protocol for quantifying the BBN SC risk model sets out three stages.

1. Explain the expectation of the subjective knowledge – Motivating (SRI)

The expectation of the subjective knowledge elicitation and assumptions of the model should be explained at the start. Furthermore, it has to be clearly explained to the experts that the answers should represent their subjective belief of the likelihood of particular adverse events so they need not be worried about historical data. This explanation aims to reduce the pressure caused by the personal interest, known as *motivational bias* (Renooij, 2001; Walls and Quigley, 2001).

2. Show a short training example – Conditioning/Training expert (SRI)

The use of a short training example aims to explain the style of questions that will be used by questionnaire for probability elicitation. Since the questions are developed to suit with the experts' perceptions on frequency numbers, this should be explicit for them. Therefore the full training as suggested in the probability elicitation suggested in SRI process (Merkhofer, 1987) may not necessary for this modelling procedure.

3. Experts complete the questionnaire –Elicit, encode and document expert belief (SRI)

A self-answering format of questionnaire is used because experts may not have the confidence to answer questions during interview, particularly if they want to check some information before completing it. However, during interview experts should have the chance to read through the questionnaire and discuss unclear questions before taking the questionnaire with them and an appointment is made to pick it up.

5.4.6.3 After elicitation

After the probability numbers are collected, there are three sub-stages to completing the quantified BBN model.

1. Aggregation

Most variables can be elicited by only one expert if those variables are perceived and sourced in their own organisation units. However, some variables should be identified by a few experts and these can be aggregated to represent probability across the whole system. Average is a simple way of aggregating probability.

2. Input numbers into the software

All probability collected from questionnaires should be entered into the GeNIe software (this will not be explained in detail by this thesis). The practitioners can learn to use GeNIe software on their own. The main process of using any software is similar since the collected data are transformed to probability format and input into software for PTs or CPTs.

3. Verification

A recommendation of this thesis is that, for verification, the analyst re-checks data entry – whether numbers have been input correctly, whether the aggregations of probability have been calculated correctly, etc.

5.4.7 Stage 7 – Use BBN to support SC risk analysis

5.4.7.1 Suggest the model analysis to support SC risk analysis

The guideline of risk analysis by this model can be provided by answering three SC risk analysis questions, as explained in Section 3.1.5.

1. Estimating occurrence of event (of focus variables) to answer: 'what is the chance of a particular adverse event occurring?'

When the decision maker wants to estimate the current level of adverse event occurrence on the focus variables/events or top event, they can directly interpret from the *marginal probability* of the focus variables. The marginal probability represents the current chance of particular variable happening, called in this research *current probability*.

2. Prioritising risk through diagnosis risk prioritisation to answer 'What are the main risks that cause supply failure?'

The expected initial outcome of the model is to stress high-risk items. Many adverse events that could occur are reflected in the SC system, and decision maker may want to identify vital adverse events. Since risk is the function of probability and impact, both factors should be a part of prioritisation. Risk prioritisation by the BBN SC risk model will rank adverse events using their *Normalised Likelihood (NL)*; see Section 3.1.6.2. NL is a ratio of adjusted probability given the focus variables are observed (e.g. top event) and current probability of particular cause events.

3. Exploring different scenarios to answer 'What is the impact of (combination of) uncertain events on supply through the chain?'

The majority of BBN applications are able to support decision making by implementing scenario analysis via defining focus variables and scenario variables. A focus variable (or a few focus variables) is considered when a set of scenario variables are assigned specific states and then the *marginal posterior probability* or *adjusted probability* can be calculated to compare different scenarios.

5.4.7.2 Sensitivity analysis to validate the modelling outcomes

The results from sensitivity analysis will help experts judge how best to use the model to support risk analysis, by comparing the result of analysis with their perceptions.

Evidence sensitivity analysis is suggested for this study. Individual variables can generate different effects on the top event which can be detected by main effect evidence sensitivity analysis. The analyst can start by selecting a variable (not the top event) and changing its state to two extreme states. For example if the variable is bivariate variable which can take *Yes – No* states, the two extreme value of the states could be set as *1 – 0* and then *0 – 1*. If there are more than two states, the two extremes that are highest and lowest (e.g. *1 – 0 – 0* and *0 – 0 – 1*) should be set. Some variables are qualitatively defined and should be set as extreme as possible. When each side of extreme state value has been set, the probability of the top event has to be recorded. After that the analyst has to change the probability of the input variable back to the original value before carrying out the same process for all variables in the network. After all variables has been defined and recorded, a Tornado diagram (a type of bar chart where the categories are listed vertically) can be used to represent the effect of extreme deterministic states of particular input variables on the top event (Fenton and Neil, 2012). However, the tornado graph is not supported by the GeNIe software so Microsoft Excel was used to develop it.

5.4.8 Stage 8 – Validate BBN SC risk model behaviour

Face validity workshops can be arranged to investigate whether the experts are comfortable with the results of the model analysis. The workshop should start by explaining the logic of the model and reminding participants of the assumptions made in order to prepare a basic understanding before they are shown the results. The model outcomes should be validated in the two main aspects of robustness and appropriate model behaviour via sensitivity analysis and results of scenario analysis. For model validity (Section 3.2.2), feedback from experts can be recorded by asking them to provide feedback based on the questions below.

Model is robust (Sensitivity analysis)

Are the sensitivity analysis results acceptable for experts? Or are the ranges of concerned variables specified in the map? (Include or exclude some variables)

Model behaves appropriately (Scenario analysis)

Are experts comfortable with the results of the scenario testing?

After the analyst shows the scenario analysis to the experts and allowed them to provide their set of scenarios, the experts can provide feedback from reviewing the adjusted probability of a focus variable given the observed scenario variables. If the experts do not feel comfortable with the results, the analyst can carry out an additional eliciting process and, if necessary, adjust the model.

The primary BBN modelling process is designed in this chapter. However, the implications for the real case study need to be explored and will be explained in further chapters.

Chapter 6 Medicine Supply Chain Risk Case Study Methodology

SC risk is the domain of practice than of research…if it does not pass muster with practitioners then perhaps it is not really about SC risk (Sodhi and Tang, 2012, p. vii).

The case study rationale proposed by Yin (2003) is selected to explore how feasible it is to construct the BBN in SC risk model with the real SC people that is the last research objective. This chapter discusses why the case study was selected and how gathering information to evaluate BBN SC risk modelling process was designed.

6.1 Rationale for Conducting a Case Study

Generally there are different perspectives of Operational Research and Operations Management on the same problem domain (MacCarthy et al., 2013). Since a model aims to represent a part of reality, (see Section 2.1). However, the only implementing Operational Research modelling methods cannot guarantee that it is relevant with the realistic and existing Operations and SC problems (Sanders, 2009). Furthermore the knowledge contributing on the same problem by modellers and empiricists may not be shared (Dooley, 2009). Therefore both modelling and empirical methods were designed for this study to cope with those drawbacks. In addition it can also create the communication between practitioners and academics (Sanders, 2009) which we believe as the key of success in the model applications to support SC risk analysis.

Although BBN is not a new mathematical modelling theory, the BBN modelling process was developed for SC risk analysis by this study. The approach of BBN application in the area of SC risks, the main focus of this research, is new and this perspective makes it suitable to implement by case study (Stuart et al., 2002). In addition the exploration of how feasible it is to construct the BBN in SC risks within the real organisation can be answered by collecting a contemporary set of events, but since the case study is dealing with behavioural events there is little or no control over them (Yin, 2003).

6.1.1 Rationale for selecting a single case study

The reasons to select a single case study rather than multiple case studies, as put forward by Yin (2003) are set out below.

1. Disruption of the SC is very important and topical, to SC in general but especially in hospital medicine SC so if BBN SC risk modelling process can be applied in this scope as a typical case, other similar cases should also be able to implement the modelling process.
2. The size of SC is very large and relevant many stakeholders, so representatives of particular defined stakeholders have to participate in a sequential process by following the eight stages. Under this demand of tasks to be observed and also evaluated in individual stages from the set of experts, a single case study is able to generalise real implementation.

The single case study utilises analytical generalisation – generalisation from the set of results to broader theory rather than inferring to the population by statistical generalisation such as sampling (Stuart et al., 2002; Yin, 2003) – so a case study does not intend to be representative or use a sample as would be done using sampling or survey techniques (Stuart et al., 2002; Yin, 2003).

6.1.2 Rationale for selecting evaluation criteria by participants

Evaluation criteria for the model can be defined differently depending on the purposes of the model. Therefore factors for evaluating defined criteria and sub-criteria of this model have been reviewed from relevant fields suitable for different purposes: general modelling comparison (McCarl, 1984; Tako and Robinson, 2009), project risk management (Chong and Brown, 2000), Bayes linear model (Revie, 2008), SC diagnosis tool (Brun et al., 2006; Salama et al., 2009) and the decision analytic model (Akehurst et al., 2000). However, it is found that the various criteria defined to evaluate models in general fall into three categories: model technique, model validation, and modelling process and model outcome evaluation (see Appendix G).

BBN can be evaluated as a good model technique since it is shown as the 'suitable' model than other candidate models to model in this context as have been explained in Chapter 2. Furthermore the BBN is also developed from the mathematical theory to explore uncertainty, is shown in Section 3.1. According to the model validation, the process of validating the BBN model outcome has been included as a part of the modelling process; see Section 5.4.8 (e.g. using sensitivity analysis or scenario analysis) can confirm that the right model is built.

Only the last model evaluation category of modelling process and model outcome evaluation will be the main focus of implementing the case study. The rationale for selecting the evaluating criteria for the modelling process will be defined in this section.

'Practical process' and 'useful model' are two aspects which can help in the evaluation of the modelling process and model outcome. They can represent the feasibility of implementing the modelling process, since those aspects can provide trade-off information between two essential aspects for potential users. Therefor evaluation criteria should base on what the participants can perceive, i.e. on data which can be collected as the initial source of information. The evaluating criteria and sub-criteria by participants are defined and summarised in Figure 6-1.

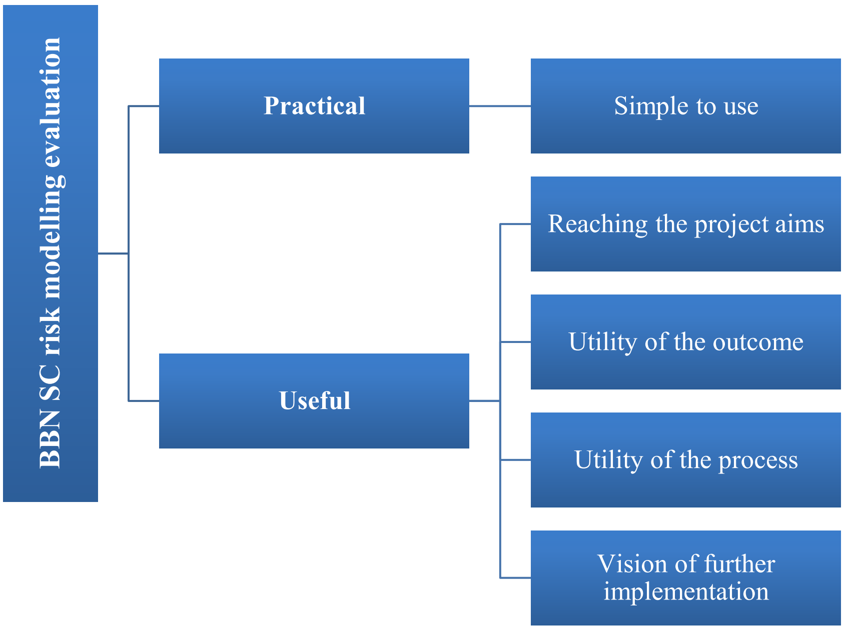


Figure 6-1 Summary of the criteria and sub-criteria of modelling evaluation by participants

6.1.2.1 The practical criterion

The practical criterion is defined as the simple criterion (Revie, 2008) or viable criterion (Mitchell, 1993) and is selected to help evaluate model in practice with the participants. The general evaluation can be measured by how simple the process is to use at particular stages by participants. The defined practical problems also provide the issues of the modelling process and can be used to find possible solutions to improve the modelling process later on.

6.1.2.2 The useful criterion

A (risk) model needs not mirror the perceived reality perfectly; rather, it needs to abstract reality 'adequately' for the model's anticipated use (McCarl, 1984, p. 153).

Generally, usability can be evluated by users (Finlay, 1988) who are the decision maker and experts in this case study. The sub-critera to represent the usefulness of the modelling are identified from two aspects. Firstly, usefulness can be evalauted directly from the ability to serve particular objectives already defined by the decision maker before starting to develop the model. *"A model should be developed for a specific purpose (or application) and its validity determined with respect to that purpose"* (Sargent, 2005, p. 130). Secondly, the BBN SC risk model is developed in the SC, which is relevant to many stakeholders, so the benefits should be available for all stakeholders rather than serving only decision maker demands. Once the criterion of usefulness to all stakeholders is defined, sub-criteria to represent users' perceptions of usefulness can be identified in this research as the utility of the modelling outcome, utility of the modelling process and vision of further implementation. These sub-criteria were adapted from the concept of model usefulness as a communication tool, learning tool and aid to strategic thinking (Tako and Robinson, 2009). Using the experts' perceptions of the model, firstly the utility of the modelling outcome by this model can serve as the communication tool for experts, and secondly, the utility of the modelling process can serve as a learning tool rather than a black box tool. Finally, if the model is useful for them, they can define more model applications to support their works for future development in different areas to support strategic thinking.

6.2 Overview of the Planning for the BBN SC Risk Modelling Case Study

The BBN SC risk modelling case study starts from applying the initial design of BBN SC risk modelling activities in Section 5.4 with the real SC case study. Learning from the implementation process and observing emerging evidence can support the modelling evaluation of the feasibility of implementing BBN in the SC risk context. The reflections of the practical concerns based on the case study can provide a list of suggestions which can be used to improve to modelling process (Benbasat et al., 1987). Therefore the proposed BBN SC risk model is the anticipated outcome of the case study. The overview of the case study is explained in Figure 6-2.

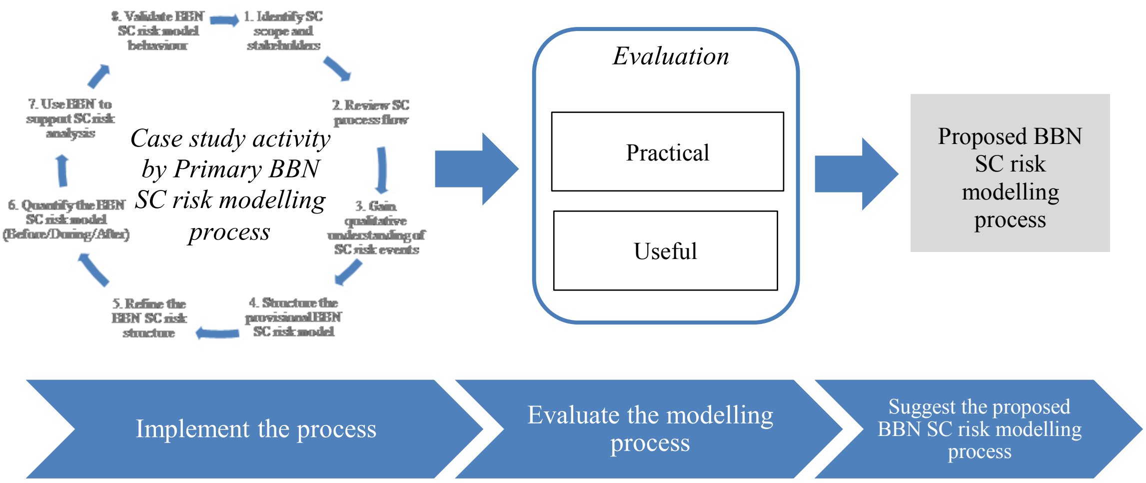


Figure 6-2 Overview of planning for BBN SC risk modelling case study

6.2.1 BBN SC risk modelling process for case study activities

The primary BBN SC risk modelling process, designed and explained in detail in Section 5.4 by the eight essential stages, is chosen to underpin the case study activities in the case study.

6.2.2 Instrument development for BBN SC risk model evaluation

The criteria and sub-criteria designed in Section 6.1.2 are used to design instruments for collecting data. Besides the evaluations from participants' perceptions (decision maker, experts), the observations by the researcher are also taken in to account to reach a summarised finding from the case study, as summarised in Table 6-1. The instruments for model evaluation are developed by mixed-methods of data collection – questionnaires, interviews, feedback sessions and observation – each designed to suit different criteria of the modelling evaluation. Furthermore details of sub-criteria are defined by comparing with the literature as explained in Table 6-2.

Getting a better understanding of risks is the main purpose of risk analysis: *"risk analysis is to help managers better understand the risks (and opportunities) they face and to evaluate the options available for their control"* (Vose, 2008, p. 7). Therefore it is a main question to evaluate general purpose of the risk analysis from participants' perceptions (i.e., a question asking if a better understanding has been gained). The relevant factors of usefulness are also identified by implementing criteria similar to the evaluating factors provided by Tako and Robinson (2009). Other factors such as efficiency or economy are out of the modelling process evaluation scope (see Appendix G) since they are out of participants' perception scope. It is left to future users to provide the formal evaluation of these factors.

Table 6-1 Evaluation category and data collection methods

Perception	Category	Data collection methods		
Decision maker and experts	Practical	***Simple to use and visions of further implementation of the BBN SC risk model*** by feedback workshop	***Simple to use*** by questionnaire (A)	
	Useful		***Utility of model outcomes*** by questionnaire (B), ***Utility of modelling process*** by questionnaire (A),	***Reaching project aims*** by interviewing decision maker
Analyst	Practical and useful	**Practical problems and benefits gained from model** by participant-observation: Evidence from the case study		

Table 6-2 Summary of factors and data collecting methods for evaluating practical and useful criteria by decision maker(s) and experts

Criteria for this thesis	Proposed evaluation	(Chong and Brown, 2000)	(Revie, 2008)	(Tako and Robinson, 2009)	(Akehurst et al., 2000)	(McCarl, 1984)
1. Practical						
Simple to use	Questionnaire (A) and feedback workshop (II)	Easy to use	Simple to use			
2. Useful				Usefulness (result)		
2.1 Reaching project aims	Interview decision maker		Meet the project aims			Contributes to making better decisions
Model understanding*	QB1.6			Model understanding		
2.2 Utility of model outcomes	Questionnaire (B)		Comparison with the current process	*Communication tool*		Performs compared to alternative model
Communicable	QB1.2			Communicable		
Natural of result	QB1.3			Nature of results		
Interpretation of results	QB1.4			Interpretation of results	Interpretability	
Realistic	QB1.5	Realistic		Realistic outputs		
Awareness of effects on SC*	QB1.1					
2.3 Utility of the modelling process	Questionnaire QA4.2			*Learning tool*		
2.4 Visions of further implementation from the BBN SC risk model	Feedback session			*Strategic thinking*		

Note: *Aim for this research

6.2.2.1 Questionnaire

Two questionnaires were developed to evaluate the modelling process and outcome, questionnaires A and B, rating levels of difficulty from score 1 to 5 by closed-ended questions; see Appendix H. Questionnaire A was developed to evaluate the practical criterion and usefulness of the process by simply asking how easy or difficult it was to implement particular stages in which the decision maker and experts were involved. They were able to rate their perceptions and also express their opinions about particular processes in open-ended questions. On the other hand, the usefulness of outcomes from the risk analysis (questionnaire B) is difficult for participants to evaluate since to specify a level of usefulness of the BBN SC risk model without anything to reference it against depends merely on guessing or feeling. McCarl (1984) suggested that to show how well a particular model performs a comparison could be made to the alternative models. Using as a reference tool available risk analysis (RR) can help the experts to decide on the level of usefulness of the BBN model. Different criteria which can represent the usefulness of the model outcome are reviewed from the literature (Appendix G) and are used to develop questionnaire B (see Appendix H); to the design evaluates (and compares) the RR in parallel with the BBN SC risk model.

6.2.2.2 Feedback workshop

As planned in the process design, both decision maker and experts take part in developing the BBN SC risk model. The feedback workshop is selected as the method by which they can share their opinions on the process and on the modelling analysis outcomes. The main questions posed during the workshops were:

How difficult or easy was the modelling process?

How useful is the resulting BBN SC risk model?

What recommendations are there for further development of the BBN SC risk model?

6.2.2.3 Interview decision maker

The decision maker is the key person who can judge the usefulness of the BBN SC risk model outcome. During interview they were asked three questions.

Do the results from BBN model help you to serve the defined purpose (i.e. gain a better understanding of their SC) in your supply network?

What do you think of the presented analysis (which has been shown in the final workshop)?

Do you have any particular decision issues of supply chain risk management in your mind after you have seen the analysis of the BBN SC model?

6.2.2.4 Participant-observation

The analyst takes a role as researcher, so the researcher participates in the case study rather than only being a passive observer which is called participant-observation. The resulting observations and reflections can be collected to evaluate Practical and Useful criteria. Evidence of the practical issues from implementing the BBN SC risk modelling process are obtained from the fieldwork observation (which is a suggested qualitative method of evaluation; see Patton, 1987).

1. *Practical process*

How difficult was it to participate in particular stages of the BBN SC risk modelling process design and can you provide any suggestions to improve the modelling process?

2. *Usefulness*

Usefulness of the model can be evaluated from the analyst perspective (bearing in mind the defined scope of this study):

a. *Systemic risk*: Different risk prioritising results provided by dependent or independent approach
b. *Support risk analysis*: How the model can support risk-benefit trade-off as a management tool
c. *SC scope*: Usefulness of developing model in SC scope
d. *SC risk in SC process activity*: Usefulness of developing model with the operational experts.

6.3 Protocol Design for the Case Study

A process of implementing a case study has been suggested in the context of SCM (Koulikoff-Souviron and Harrison, 2005) and Operations Management (Stuart et al., 2002). Three main steps of doing case study will be explained in this section.

6.3.1 Reasons for selecting National Health Service Greater Glasgow and Clyde hospital medicine supply chain as a case study

A case study is a difficult process since it is expensive in cost and time expended. However, it should be able to help to contribute the fourth research objective. A single case study is selected in this research (for reasons noted above) and the National Health Service Greater Glasgow and Clyde (NHS GG&C) hospital medicine SC is selected for the following reasons.

Firstly effect of SC risk in medicine SC is substantial (than other products) so the risk management for NHS GG&C is already a major goal of the organisation, as can be shown from the statement below:

The overall goal of risk management is to have an environment of 'No Surprises' where we understand the risks we face and eliminate or control them to an acceptable level, by creating a culture founded upon assessment and prevention of risk (NHS Greater Glasgow & Clyde, 2007: 5).

The goal of the organisation fits well with the BBN SC risk model because BBN can help to support risk analysis to improve the understanding of risks in the SC. In addition, according to the definition of systemic risk in SC which we proposed for this research (Section 1.2.3), the analysis of systemic risk is very substantial to the main operation of the healthcare service.

Secondly, normally the large scope of SC means involvement with different organisation units and distances, which is a main barrier to data collecting. However, the NHS GG&C hospital medicine SC is mainly bounded in Glasgow so there is no practical constraint for this case study.

Finally the participants in the hospital medicine supply chain are representatives of SC people who may not necessary be modelling experts (e.g. engineers): the NHS GG&C hospital medicine SC is very representative of people who have a lot of specialist knowledge (in this case, in medicine), but they may have less experience in modelling and using probability language. All in all, the NHS GG&C hospital medicine SC is a suitable case study for this research.

6.3.2 Data collection for evaluating BBN SC risk modelling process

The unit of analysis can help to define the boundaries of a theory by helping to clarify the phenomenon under investigation (Barratt et al., 2011), based on evidence and data collected from the case study. Therefore the actual source of information in this case study identifies the decision maker and experts as the main participants. However, data can be collected from different sources (see explanation in Section 6.2.2). This is called methodological triangulation. The data collection methods implemented in different phases of modelling are explained below.

Before the process is started, *Available documents* are collected to improve understanding of the current SC process. The main information focusing on risks of the case project comes from RRs. There are several versions of RRs, available from different stakeholders: RR for PPSU Pharmacy and Prescribing Support Unit (PPSU), NHS GG&C (Version 2009); RR for Acute and Mental Health Pharmacy Service, NHS GG&C (Version 2011); and RR for MMyM, NHS GG&C (Version 2011). The RRs are confidential documents of the organisations so they are cannot be shown in this thesis.

During the implementation of the primary BBN SC risk modelling process, *Participant-observation* is conducted by the analyst. Challenges and difficulties of particular stages are observed during the process of constructing the BBN SC risk model, so the insider's view, provided by the analyst who is also the observer, can be assessed during running the BBN SC risk modelling process (Patton, 1987; Yin, 2003). Moreover analyst can also manipulate minor events during implementing the BBN SC risk modelling process by using participant-observation (Yin, 2003). The second half of the validating BBN SC risk model behaviour workshop (stage 8) can be used as a *Feedback workshop*. The experts are asked to provide feedback on the process (Practical) and outcome (Useful) during the workshop and the feedback is recorded by voice recorder.

After finishing the whole of the primary BBN SC risk modelling process, the next stage is to *Interview* the decision maker who will be first to use the model. This is carried out by asking open-ended questions to capture insight and perceptions on the outcomes from the BBN SC risk model. The interview is recorded by voice recorder to ensure that the perceptions are recorded accurately. Furthermore, two *Questionnaires* (A and B) are employed to collect perceptions from the decision maker and from the experts to evaluate the process (Practical) and outcome (Useful) quantitatively. Note that the decision maker and the experts are required to complete both questionnaires.

6.3.3 Data analysis methods

Data analysis for the case study can be implemented by combining both qualitative and quantitative evidence. However, analysing the case study evidence is difficult because of techniques that are poorly defined (Yin, 2003). This section will summarise the relevant methods of analysing the results for BBN SC risk modelling process evaluation, from different sources of data as shown in Figure 6-3.

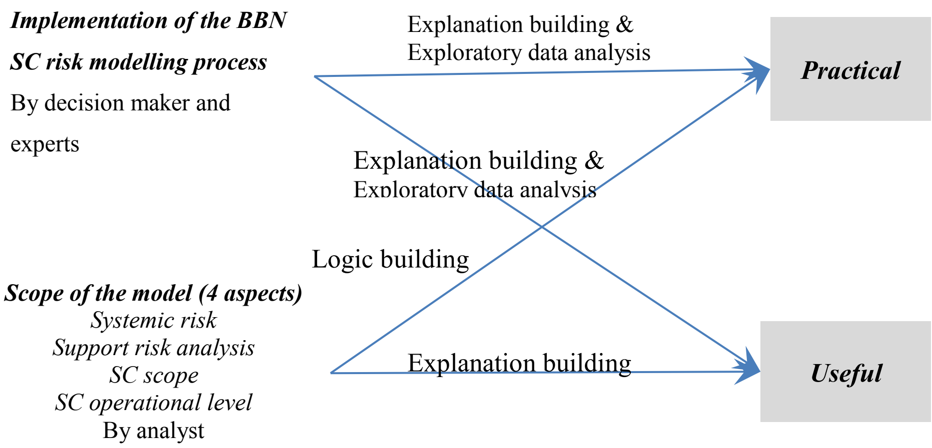


Figure 6-3 Summary of analysis from case study

6.3.3.1 Exploratory analysis from questionnaire

Mean score of perceptions from evaluating both questionnaires can be used to provide quantitative evidence to address trends for comparative purposes by graphical chart rather than by estimating parameters from the survey population. For example the perception score of the model can help to gain a better understanding when the perceptions of the decision maker (managerial expert) and experts (operational experts) are compared.

6.3.3.2 Explanation of building and logical building analysis from multiple sources of data

This process can be used to explain the 'practical' and 'useful' criteria by explanation building and logical building, which are selected from defined analysis types in a case study by Yin (2003) and an analysis of evaluation methods by Patton (1987). Explanation building is analysing qualitatively by using quotations or observations to represent evidence relevant to the evaluation themes to be explored and the implementation process. Logic building is used to capture practical issues by identifying the main causes of those issues (especially causes from the scope of the model). Since the particular practical issues will be defined, the solutions of solvable issues will be implemented to improve the primary BBN SC risk model for proposing the BBN SC risk modelling process after finish the case study.

6.4 Operational Considerations in this Case Study

6.4.1 Process for establishing and gaining volunteering in the case study

In order to invite a focal organisation to contribute in the case study, the clear BBN SC Risk modelling process design should be explained to the decision maker. The results of the BBN model should also be demonstrated to the decision maker before any agreement is reached to participate in a case study. In the case study we constructed the dummy BBN model for NHS GG&C from the report *NHS Greater Glasgow and Clyde Acute Pharmacy Redesign Project November 2010* (Bennie et al., 2010), which contains past information of the organisation. The dummy BBN was structured from causal statements derived by analysing causal connectors such as if-then, because, since, as, so etc. appearing in narrative or text (however, this process is not shown in this thesis). Next the instantiation process was implemented by the modeller who estimated probability numbers. Finally the inferences of the dummy BBN model were propagated to demonstrate the dummy results to the decision maker. After the decision maker saw the demonstration, the decision maker agreed to participate in this research case study to implement the BBN SC risk modelling process design, and agreed to act as a host to invite his stakeholders.

6.4.2 Ethical research for case study

Since the process of BBN SC risk modelling is mainly using information from experts in the organisation, ethical issues are relevant and the researcher must ensure that the research is done ethically. The key feature of this research is experts volunteering to participate, and they were invited by giving them clear information to explain the project and how they can contribute to the research. Firstly, this research was not a source of risk for them since they had permission from their top manager to share their belief of adverse events for modelling purposes. Secondly, the researcher was aware that data were confidential and storage for either hard-paper or soft data had to be secure. Thirdly, data were used anonymously and participants were told that they had the right to withdraw data from the case study at any time. Furthermore, permission from the individual experts was required for them to be audio recorded. All information was explained to participants in a participant information sheet to ensure that they were happy to participate in this research and they were asked to sign the consent form. This research also received approval from the departmental ethics committee.

6.5 Criticisms Test for Judging a Case Study Design

The quality of the case study research design (not the BBN model) in this research should be evaluated. Evidence of case study evaluation will support a review for judging the credibility of the research. The evaluation of the modelling process is the main design underlying data collection and data analysis in this case study. Construct validity, internal validity, external validity (generalisability), and reliability are case study quality criteria suggested by Yin (2003).

Firstly *construct validity* is validated to show correct operational measures were in place, by showing the use of different sources of evidence (as explained in the section on data collection: Section 6.3.2) which can define a sufficient data set. Secondly *internal validity* refers to setting up the logic models. This study demonstrated case study validation in the data analysis process by implementing the explanation building and logical building analysis (see Section 6.3.3). For example, logic building was used to explain logic practical perceptions of the modelling scope and this leads to revisions of the proposed BBN SC risk modelling process for potential users in the future (see Section 6.3.3.2 and Figure 8-4). Thirdly, *external validity* can ensure that the research finding can be generalised. Generally they may use *replication logic* to test and replicate the findings in multiple contexts. Although, this study employs a single case study of the hospital medicine SC, the analytical generalisation by implementing the modelling process can be expressed (as explained in the rationale to select single case study, Section 6.1.1). Finally, *reliability* can be validated from the expression of the process of implementing the BBN SC risk modelling process and also the process for the model evaluation (see Section 6.2.1–Section 6.2.2). These protocols can provide detailed processes which are able to be repeated to collect perception data that this will yield reliable results.

This case study not only can satisfy the general quality criteria provided by Yin but also can fulfil two specific recommendations of implementing Operational Research model in Operations Management problem domain suggested by MacCarthy et al. (2013). Firstly the managerial expert or decision maker was designed as a part of unit of analysis for the model evaluating of this case study, see Section 6.3.2, so the evidence of managerial relevance in modelling studies can support the existence of the model working in this problem domain. Secondly the improve understanding of the SC risks in the system was defined as the key model evaluation criteria, see Section 6.2.2. If the model can improve understanding of the system, the empirical study can provide real insights and add real value in Operations Management.

The case study activities and designed protocols either for model development or the modelling process evaluation were implemented in the case study. The results from implementing the modelling process to construct the BBN SC risk model and the outcomes to support risk analysis will be shown in Chapter 7. Additionally, the results of the modelling evaluation from the case study will be explained in Chapter 8.

Chapter 7 Case Analysis of Medicine Supply Chain Study

In this chapter, information on the NHS GG&C hospital medicine SC case study will be provided. In addition the results of implementing the procedure of BBN SC risk modelling process will be presented by showing the modelling assumptions, full developed BBN SC risk model and results of the model analysis to support risk analysis.

NHS GG&C is the largest NHS organisation in Scotland and serves a population of 1.2 million (NHS Greater Glasgow and Clyde, 2012). In 2010, a redesign of the health service was initiated, with the major change being to the medicine SC. The new system, centralised with a Pharmacy Distribution Centre (PDC), serves to stock medicines from multiple suppliers and to replenish medicines to the variety of services in the GG&C zone. However, the scope of the BBN SC risk model in this study is for the hospital medicine SC, which deals with medicinal supplies to inpatients.

There are fourteen hospitals in the National Health Service Greater Glasgow and Clyde (NHS GG&C) zone. These can be identified as the agents on the demand side of the PDC. In each hospital, there is a hospital dispensary/pharmacy and ward cupboards (the number of which depends on the size of particular hospital). Recently, an innovation in medicine management, which involves connecting an inpatient to the SC via Patients Own Drugs (POD), referred to as MMyM (Making the Most of Your Medicine), was implemented in the GG&C zone. In the MMyM system, an inpatient is required to take his personal medicines to the hospital when he is being admitted (that is, Patient Own Drug). The quality of all medicines taken to the hospital as a POD is assessed before being stored in the patient's locker. In addition, the main medicines required for any specific treatment are stocked in the special ward(s) in which the patient is admitted. If an inpatient needs medicines that are not available in the ward stock – either being unavailable in the stock catalogue or out of stock at the time – staff can use the Individual Patient Supply (IPS) system to order the particular medicine as an urgent request, as a back-up process. The hospital dispensary will then be responsible for filling this request. If the medicine is not available in the hospital dispensary,

dispensary staff can follow a standard process to source the medicine from other wards in the local hospitals, PDC, other suppliers or other hospitals, in that order of priority. All medicines for a particular inpatient will be stored in a personal POD locker that is located at the patient's bedside. At the moment, in individual hospitals, two main medicine management systems are operated in parallel – the conventional and patient own drugs (MMyM system). MMyM will eventually replace the conventional system.

On the supply side of the PDC, all general medicines can be ordered by the PDC and delivered to the PDC, primarily from wholesalers and manufacturers. In the process of procurement, the order for medicines will be sent to the contracted wholesalers or manufacturers. The National Procurement organisation establishes the national contract for all NHS boards in Scotland in order to take advantage of competitive medicine prices. Under the contract all health boards in Scotland can order the medicines from suppliers who won the contract at the agreed price. To keep the cost at a minimum, the PDC orders medicines under the contracts. As Figure 7-1 shows, either a wholesaler or a manufacturer who has not signed the contract with the National Procurement can be the back-up source if the *PDC needs the medicine urgently and can afford the higher price.*

Since NHS GG&C hospital medicine is planning high capacity to be able to absorb the uncertain inpatient demands from particular stakeholders, it is classified as an agile SC (see Section 1.1.4). Furthermore the IPS system is in place to prepare a redundant medicine supply system to respond to inpatient's needs via urgent orders.

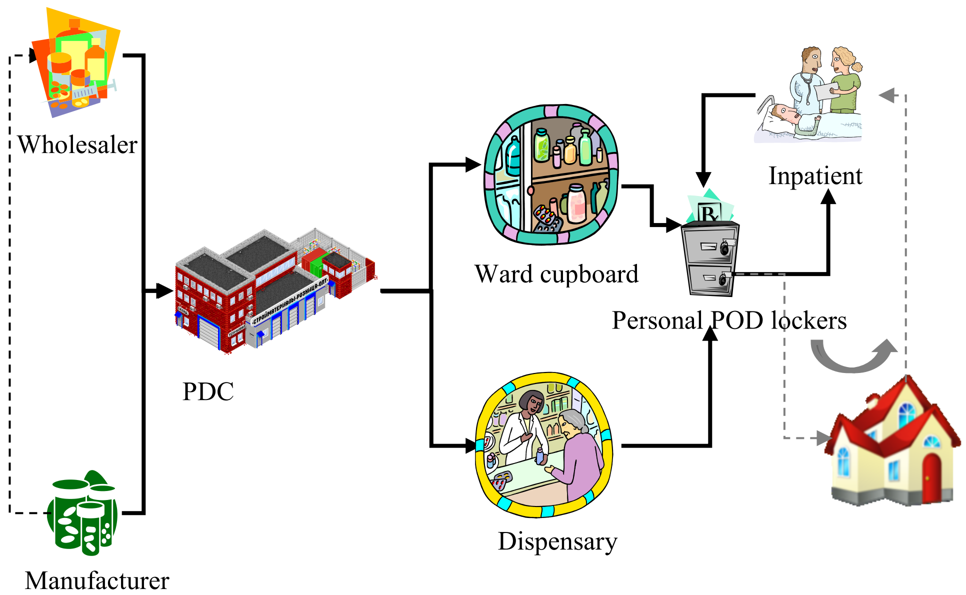


Figure 7-1 NHS GG&C hospital medicine SC

7.1 Purpose of the BBN SC Risk Model

The initial meeting between the analyst and the decision maker of NHS GG&C was held before proceeding with the BBN SC risk modelling. The decision maker was the Lead pharmacist of the NHS GG&C for Acute and Mental Health Pharmacy Service, responsible for ordering, distributing, assembling and dispensing medicines to hospitals in the GG&C zone. He was asked to define his expectation from the model in order to support his risk analysis. While no specific design issue was raised, the decision maker expected to gain a better understanding of the medicine SC, as he stated:

"My expectation from this is that we are able to understand the risks in the current SC and we develop techniques resulting from the model which will allow us to better manage those risks."

An understanding can be conveyed by taking a cause and effect approach: by observing the success of the hospital medicine SC with the occurrence of adverse events at the operational level. A dominant event which can be used to measure the success of the hospital SC via the SC performance is that of *providing the right medicine to the right patient at the right time*. This was defined as the top event of the BBN SC risk model. Therefore, the BBN model in this study was developed to capture the interrelationship between adverse events within the hospital medicine SC, in which various organisation units were involved. All interactions of adverse events in the model can express to improve the understanding of the decision maker and operational staff as to why the right medicine could not be supplied to the right patient at the right time.

7.2 Brief Explanation of Building the BBN SC Risk Model for NHS GG&C Hospital Medicine Supply Chain

The major boundary of the relevant organisation units was determined in order to define the modelling scope and form the expert team from stakeholders. Four main, defined organisational units were identified – the PDC, supplier, hospital dispensary, and ward, as shown in Figure 7-1. The PDC is the central organisation unit which links the network of suppliers and customers in different layers. However, as it was impossible to invite all customers and suppliers in different tiers to develop the model, the representatives of particular defined stakeholders were invited to form an expert panel. The eight invited experts, comprising key staff across the main SC operational areas, participated in the development of the BBN SC risk model.

The expert panel consisted of the following:

A decision maker, who was the Lead pharmacist in Acute Care divisions
Seven experts:

Two Distribution staff from the purchasing and distributing departments of the PDC unit,

Two Pharmacy technicians, who worked in a dispensary,

A Lead pharmacy technician, who worked in the MMyM medicine management system and coordinated the ward and inpatients,

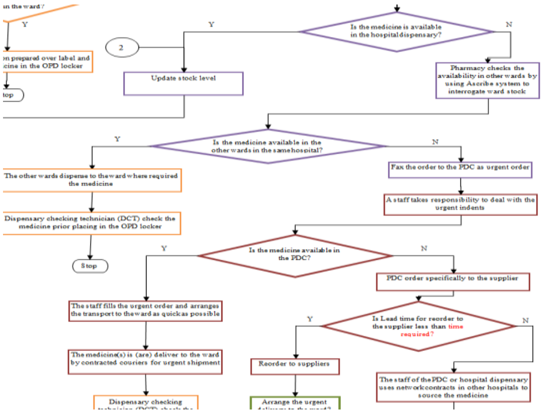
A Pharmacist, who worked as a supplementary prescriber for inpatients medication,

A Pharmaco-logistics adviser in National Procurement, who dealt with the national, contract with suppliers and could take perceptions on behalf of supplier units

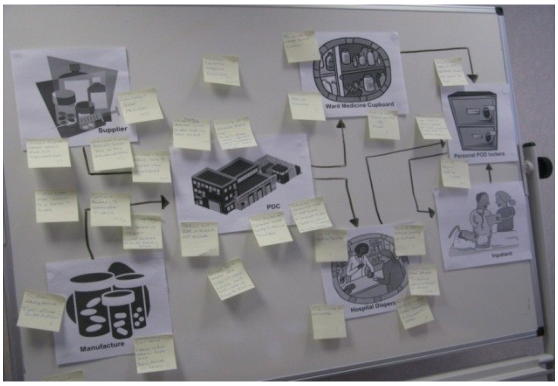
Unfortunately, during the model developing process, the Pharmaco-logistics adviser was subject to job relocation and, consequently, withdrew from the project. Due to time constraints, a replacement expert could not be sourced. Therefore, a total of seven experts participated in the complete model development. The boundary of the model was adjusted by excluding representatives from suppliers' units. However, their adverse events were still identified and captured in the model, but to a limited degree only from the perceptions of PDC.

Generally the modelling scope was defined by agreement with the decision maker (stage 1) before the supply process flow was combined in the defined SC scope (see Figure 7-2 (a)) and was then confirmed by the decision maker (stage 2). Next all experts were interviewed individually and asked to develop individual CMs (stage 3) in their working place; see example CM in Figure 7-2 (b). The analyst modelled the provisional BBN SC risk model (stage 4; see Figure 7-2 (c)), and presented it to the expert panel in Workshop (I) - the 'Refine the BBN SC risk structure' workshop (stage 5). The agreed model structure was prepared for quantification and divided into sub-models as they related to individual experts. Structured interviews, arranged in the expert working place specific to particular parts of the model, were conducted to quantify the model (stage 6.2). The numbers obtained from the individual experts were input into the model and, using GeNIe software (see Figure 7-2 (d)), the results were analysed by the analyst (stage 7). The last workshop was arranged to show the results of the analysis to the expert panel, see stage 8 of the suggested BBN SC risk modelling process. In this way, feedback on the main developing processes and the model results were obtained from the expert panel and subsequently used to evaluate the BBN SC risk model.

By following the suggested eight stages of the primary BBN SC risk modelling process, it was developed with the support of and in collaboration with the expert panel. The expert panel participated in a sequential process for ten months (March–December 2012), to construct the BBN SC risk model through at least eighteen interviews and three workshops which operated with seven experts (eight experts at the start). Apart from stages 4 and 7 of the eight stages, the model was constructed by iteration with the decision maker and experts. After the model was constructed, it was followed with the model evaluation by questionnaires and an interview with decision maker. All details of data collection for the model developing and the modelling process evaluation are summarised as a timeline in Figure 7-3 and is shown more detail in Appendix I.

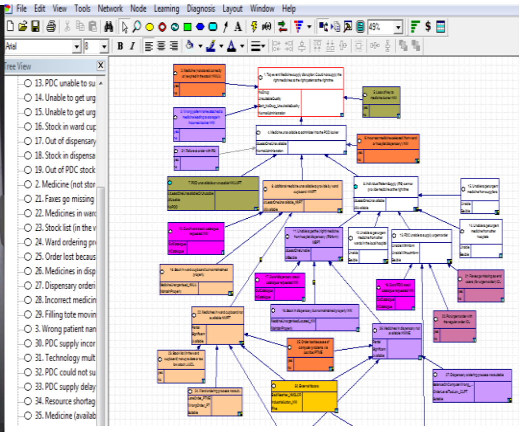


(a) A part of the process flow of medicine supply activities (stage 2)



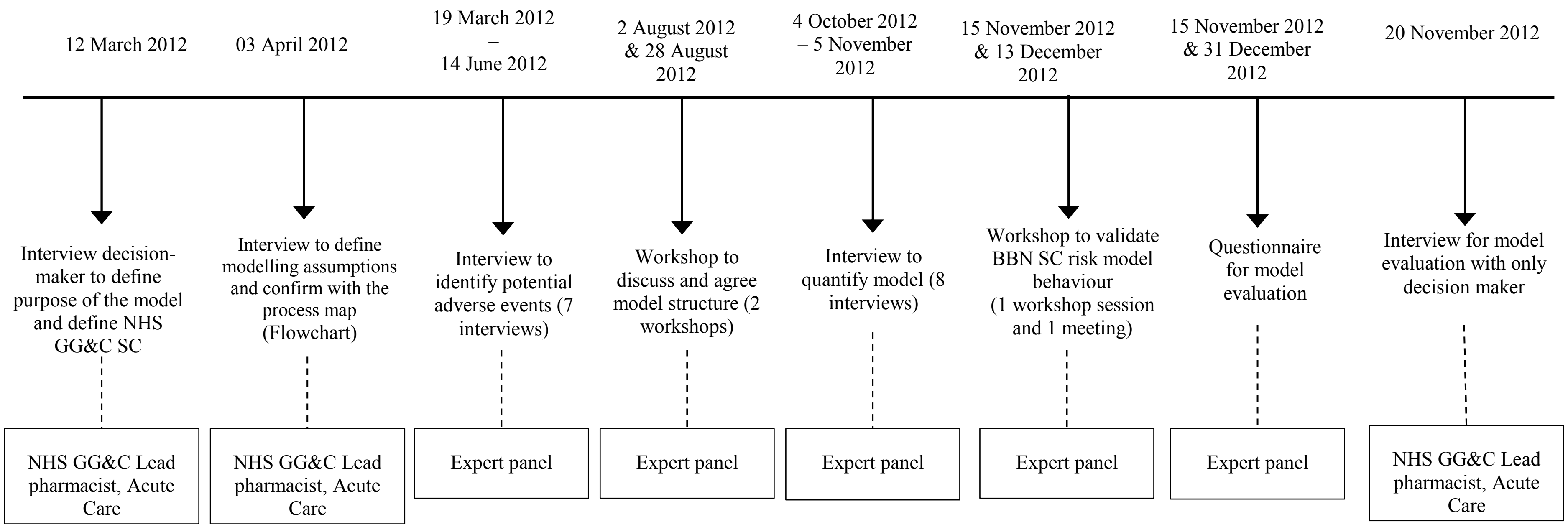
(b) Adverse event identification which was developed by decision maker (stage 3)

(c) Provisional BBN SC risk model which was taken into the workshop (I)



(d) A part of BBN SC risk model which was developed by GeNIe software

Figure 7-2 Example pictures during implementation of the BBN SC risk modelling process in the case study



BBN SC risk model construction (only stages which are relevant with expert panel)						BBN SC risk modelling process evaluation
stage 1	stage 2	stage 3	stage 5	stage 6	stage 8	

Figure 7-3 Summary time-line of the BBN SC risk model with NHS GG&C hospital medicine case study

7.3 Modelling Assumptions to Develop BBN SC Risk Model for the Case Study

A huge number of adverse events can occur in the SC; however, in reality all possible cases cannot be modelled due to limited resources. The model assumptions are highlighted during the model development process, especially during 'Identify SC scope and stakeholders' (stage 1) and 'Review SC process flow' (stage 2). Not only can the modelling assumptions be referred to by all experts under the same basic of modelling scope, but also they can improve awareness of recognition of the model for interpreting the analysis results under limitations. All necessary assumptions of the NHS GG&C BBN SC risk are shown in Table 7-1 and are described in more detail in the paragraphs that follow.

Table 7-1 Included-excluded assumptions of the NHS GG&C BBN SC risk model

Items		Included	Excluded
1.	Time frame	Current (May 2012 to April 2013) During day time (when dispensary opened)	Past or future
2.	Process Risks	SC risks	Clinical therapy errors Medical information risks Prescribing errors etc.
3.	Medicines	General medicines	Cytotoxic medicines Vaccines (and Cold chain) Controlled drugs Unlicensed drugs etc.
4.	SC flow	Forward supply	Reverse supply (return or exchange)
5.	Current mitigation	Original medicines (in the first drug Kardex[5])	Alternative medicines
6.	Standard process	Standard process of Individual Patient Supply (IPS) system	None standard process of Individual Patient Supply (IPS) system

7.3.1 Time frame

Assumption: The model should cover adverse events which can occur only during the daytime in a year.

Time is an element that can destroy the static property of the BBN. Since some adverse events can vary during different seasons, the time frame to be considered within the scope of

[5] Drug Kardex is a trade name for a card-filing system that allows quick reference to the particular needs of the patient for certain aspects of nursing care. Information about medications, activity levels, level of self-care, diet treatment, and care is usually included in the system. Each institution has its own format for nursing documentation (Heath, 1995; 47).

the project should be a year rather than a season. This will allow the main risks, in general, to be shown. The time frame for the project has been specified as a year (May 2012 to April 2013). Secondly, the experts have claimed that the process for urgently obtaining medicines for IPS when the hospital dispensary is closed is different from the standard process (explained at Section 7.3.6). As the dispensary does not open 24-7 (it is closed during the night and/or on the weekend for some hospitals), the assumption agreed upon by the experts and the analyst is that the dispensary is open only during daytime hours. This assumption was, therefore, reflected in the model.

7.3.2 Process risks

Assumption: Only adverse event occurring in SC activities will be included; assume that other processes operate properly.

By considering the event 'Medicine supply disruption: Could not supply the right medicine to the right patient at the right time', there are other adverse events from relevant activities are involved. However, the model will be assumed to scope only risks in the SC activities.

7.3.3 Medicines

Assumption: General medicines which have the same SC process can be included in the modelling scope.

Special medicines, such as cytotoxic medicines, vaccines (and cold chain), controlled drugs and unlicensed drugs, generally require different processes of storage, ordering and delivery. For example, cytotoxic medicines need special store and delivery in order to reduce the chance of contamination of other medicines. On the other hand, vaccines are the cold chain which needs to keep separately in the refrigerator and need special package during delivery. Furthermore, controlled drugs and unlicensed drugs require a special order procedure in order to control the numbers using them. Therefore those medicines are excluded and only general medicines which have similar supply processes will be included in the scope of the model.

7.3.4 SC flow

Assumption: Only adverse events that occurred in the medicine forward flow process can be included in the model.

Reverse medicine supply processes, such as return or exchange processes, are outside the modelling scope. The reverse SC can generate a feedback loop causal reasoning that destroys the hierarchical structure of the BBN, which is a main property of (static) BBN (see Section 3.2.1). For example, when a hospital dispensary orders medicine A but the PDC supply the wrong medicine (B) to the dispensary, this could cause medicine A to be unavailable in the dispensary and have to be returned to the PDC; this is known as reversed SC. However, before the PDC can receive the returned medicine, it has expired; or the PDC may have received new lot of medicine from suppliers so they may not have space to stock returned medicines. Although medicines can be returned to the supplying sources at times in a reversed SC, this process was excluded from the scope of the model.

7.3.5 Current mitigations

Assumption: The alternative medicine process is excluded from the defined standard process.

The IPS system is available as a back-up process to order supply medicine urgently, representing another mitigating action if medicine cannot be obtained in time, by using another process to determine the alternative medicine with the new drug Kardex. However, this is highly reliant on judgement and not a standardised process.

The experts have mentioned that when they cannot provide the medicines given in the drug Kardex, they can use this mitigation process to supply the alternative medicines. However, using alternative available medicines required a re-judgement for those alterative medicines. Although alternative medicines can reduce the negative impact of drug unavailability on inpatients, it cannot show the real-SC performance. Furthermore, sourcing alternative medicines involves a different procedure from the ordinary medicines and the process takes place after failure to obtain the original medicines. Therefore, it was excluded from the modelling scope.

7.3.6 Standard process

When the relevant process maps were shown to individual experts for confirmation during interview, they mentioned some special situations when the IPS standard process cannot be implemented. For example, the standard process to find urgent medicines through the IPS system is: 1. Hospital dispensary, 2. Other wards, 3. PDC, 4. Suppliers, and 5. Other hospitals (which may start parallel with finding from suppliers). They mentioned that when the hospital dispensary is closed, e.g. at night time or weekend (for some hospitals), they cannot follow the standard process so will contact the PDC directly. Therefore time of admission was also set as an assumption in order to maintain the understanding of the standard process of the IPS system.

7.4 Full Model Structure and Model Quantification

7.4.1 Full BBN SC risk for NHS hospital medicine supply chain

The full BBN SC risk model contains 66 variables, representing risk events, and 69 arcs, as shown in Figure 7-5. The top event is defined as '1: Could not supply the right medicine to the right patient at the right time'. All variables are indexed with different numbers, starting from the top event. From this point forward individual variables in the map will be called 'V' and follow the index to make indicating particular variables easier by looking at the index number (ID) rather than finding the long-full name of variable in the map, Figure 7-5. The maximum number of ID is greater than number of variables since some variables have been merged or deleted during the modelling process.

The essence of the adverse event causal flow, using the conceptual modelling framework, which links stock-availability and supply-ability as a suggested core model to link adverse events among stakeholders (see Section 5.2), is explained further in this section in Figure 7-4. The primary reason for not being able to supply the right medicine to the right patient at the right time (V1) can be that the medicines are unavailable to administer into the POD locker (V4). The medicines may not be available in the POD locker for one of two reasons: either the medicines could not be provided by the ward where the patient is admitted (V8) or the IPS (back-up system) could not provide the medicines at the right time (V9). In the first instance (that is, the medicine could not be provided by the ward), it is possible that the medicine was not available in the ward cupboard (V22) or the medicines that are out of the ward stock list are requested because the inpatient did not bring their own medicine with them or they are not of good enough quality to be used (V7). In the second instance (that is, the IPS is unable to provide the medicine at the right time), it may not have been possible to source the medicine by urgent order from dispensary (V11), other wards in the same hospital (V12), the PDC (V13), other hospitals (V14) or suppliers (V15). In practice they may try to find the medicine from other hospitals and suppliers at the same time. Given that the main supply of the IPS is the dispensary, the dispensary would not be able to supply the medicine if it is unavailable in dispensary stock (V26). Medicines in the ward stock cupboard and dispensary would not be available (V26, V22) if the PDC could not supply the medicines

(V32). A main reason of 'unable to supply medicine to the dispensary (and also ward)' is 'incomplete order fulfilled by PDC' (V52). The majority of incomplete orders/supplies are as a result of the medicines being unavailable in the PDC stock (V36). The PDC is the main medicine stock in NHS GG&C, with a safety stock of nine days' supply, thus allowing adequate time for the PDC to be re-stocked before the medicines are depleted. If medicines still cannot be obtained from the PDC's suppliers within a week (V41), the medicines in PDC stock may not be adequate to supply to the sites (wards and dispensaries) that could be caused by unavailability of medicine from supplier's stock (V69). Apart from the core stock-availability and supply-ability relationship described above, many other adverse events can be generated during the SC process. These can be linked, as shown in the full BBN SC risk model in Figure 7-5. The model structure can show the causal relationship but it may not completely indicate the level of uncertainty for an event. Uncertainty of adverse event – i.e. whether it occur or not – needs to be differentiated by different states of each variable. Most of the variables in the BBN SC risk model were developed for two simple states: '*Yes*' and '*No*'. The states can indicate whether or not an adverse event has occurred and then level of uncertainty of particular states can be quantified with different probability numbers.

7.4.2 Brief explanation of the model quantification

Questionnaires for probability elicitation were prepared from the Full BBN SC risk model struture by the analyst/researcher. Since individual experts quantified only adverse events that were relevant to them, they can quantify only part of the model. If some variables were perceived by more than one participant, those variables were elicitted from more than one expert and then aggregated. The list of questions were prepared for individual experts, and the process to develop the questions will be explained in detail in Section 9.2.6.1. Generally, eliciting a relative frequency number for a variable by set B questions were mainly based on a series of questions, and some of these questions can be shared with other variables. Therefore, we grouped the relevant questions to reduce the overall effort required. For example, question 11, 12, 14-1, 14-2 and 15 aim to elicit the probability number for V60, V59, V35-1, V35-2 and V39 (in the full map). Since the relative frequency to represent probabiilty can be calculated based on the same the number of medicine in PDC stock, they were grouped and elicited at the same time; see Figure 7-6 (a). Furthermore, the effect variable could also reuse the same based numbers which may be already elicited from the root cause varaibles; see the example of the list of questions to elicit CPT of 'PDC supply incomplete order' (V52), see Figure 7-6 (b).

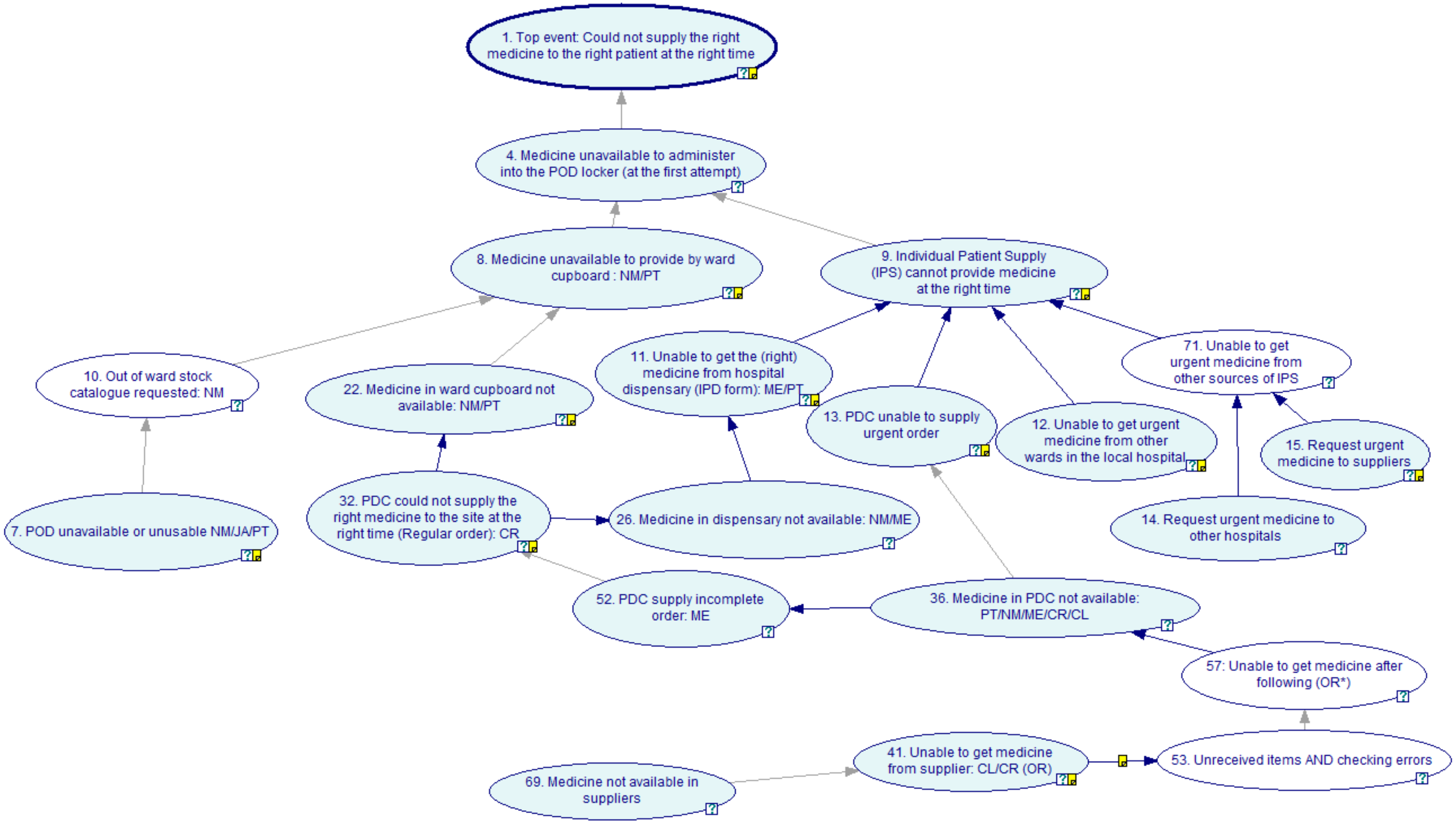


Figure 7-4 Extracted BBN SC risk model for NHS GG&C hospital medicine SC

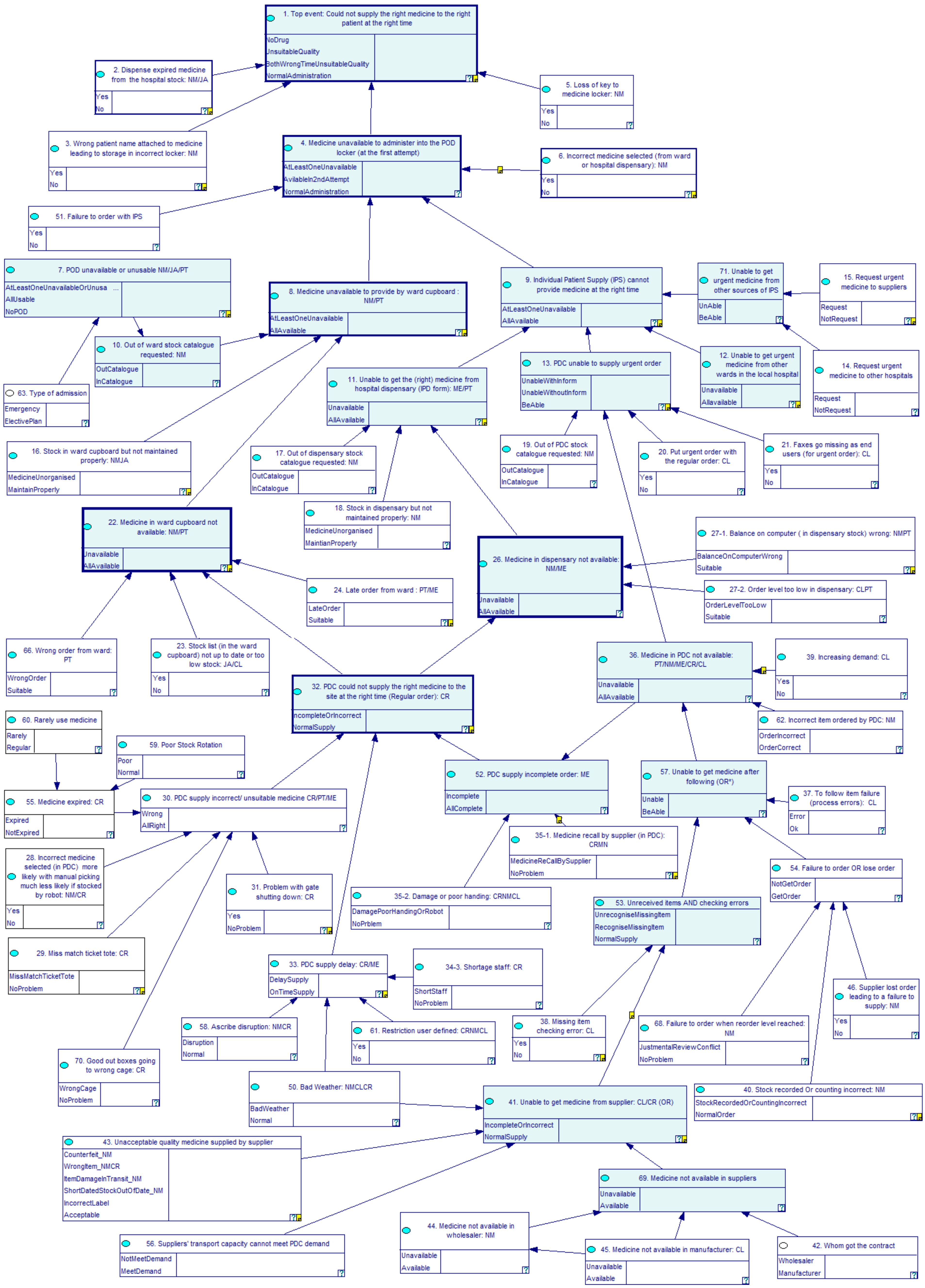
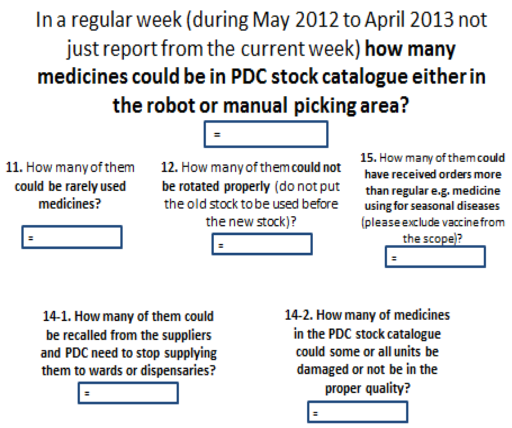


Figure 7-5 Full BBN SC risk model for NHS GG&C hospital medicine SC

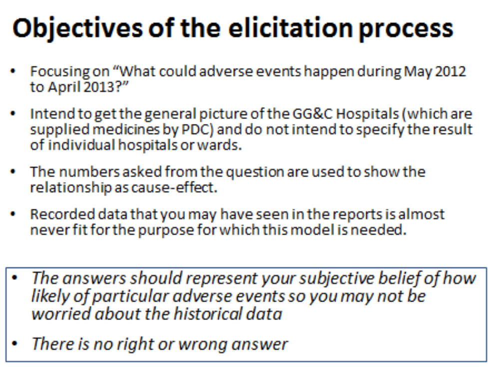
During the internview to elicit probabilities, we motivated the experts by explaining what we expected from the probability elicitation (Figure 7-6 (c)) and we showed a short training example, (Figure 7-6 (d)) for which we use the cancer example to show the question format. Once the experts understood the purpose of the probablity eliciting process, we asked them to answer a list of real questions.



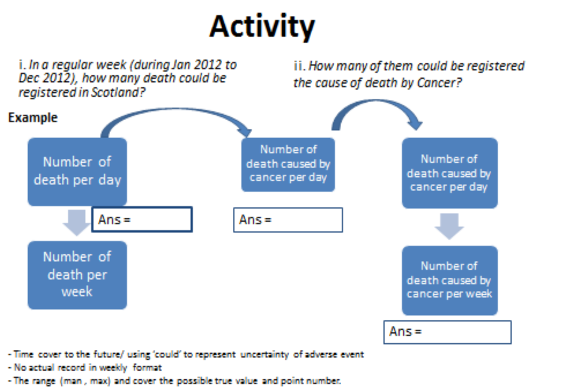
(a) Example of questions to elicit numbers to clacluate probalbity of some of root cause variables

In a regular week (during May 2012 to April 2013 not just report from the current week) how many medicines could be in the PDC stock catalogue either in the robot or manual picking area?		
Ans *		
How many of them could be recalled from the suppliers and PDC need to stop supplying them to wards or dispensaries?	How many of medicines in the PDC stock catalogue could some or all units be damaged or not be in the proper quality?	In a regular week (during May 2012 to April 2013 not just report from the current week), how many medicines could not be available in the PDC?
Ans* (Q14-1)	**Ans* (Q14-2)**	**Ans* (Q5)**
In a regular week if there are medicines which are re-called from suppliers, how many of them could not be supplied or be supplied incompletely to the hospitals? {When there is no problem about robot going down or error/ resource shortage in PDC}	**In a regular week if there are medicines which are damaged for some or all units in PDC stock, how many of them could be supplied or be supplied incompletely? {When there is no problem about robot going down or error/ resource shortage in PDC}**	**In a regular week if there are medicines unavailable in PDC, how many of them could not be supplied or be supplied incompletely to the hospitals? {When there is no problem about robot going down or error/ resource shortage in PDC}**
Ans =	**Ans =**	**Ans =**

(b) Example of eliciting number to calculate required probalbity for CPT of PDC supply incomplete order' (V52)



(c) Objective of the elicitation process



(d) Short training example shown to experts

Figure 7-6 Sample of documents used during interview to quantify probabilities

7.5 Results of the Model Analysis

The aim of analysing the BBN SC risk model is to improve the current understanding of the existing risks within the NHS GG&C, as defined in Section 7.1. Standard BBN analysis is implemented generally to address three questions which are important to decision makers (see Section 3.1.5):

1. What is the chance of a particular adverse event occurring?
2. What are the main risks that cause supply failure?
3. What is the impact of (combinations of) uncertain events on supply through the chain?

Before the results of prioritisation can be shown, symbols must be defined.

Symbol	Definition
Vx.y	is the ID to identify adverse event (variable) and state.
Where	
x	indicates the variable index.
y	indicates the state index of each variable or adverse event.
Example 1	*(Multi-state variable)*
V1.1	indicates 'Could not supply the right medicine to the right patient at the right time. *No drug'* This means that the right medicine could not be supplied to the right patient at the right time because there was no drug available in the POD locker at the time it was required.
V1.2	indicates 'Could not supply the right medicine to the right patient at the right time. *Unsuitable quality drug'*
Example 2	*(Two-state variable)*
V22.1	indicates 'Medicine in ward cupboard not available. *Unavailable'* This means at least one medicine in the ward cupboard is not available.
V22.2	indicates 'Medicine in ward cupboard not available. *Available'*

The results of the BBN inference can be implemented by using GeNIe software and then presented as charts or graphs using Microsoft Excel. Three suggested analysis features are shown in this section.

7.5.1 What is the chance of a particular adverse event occurring?

The chance of a particular adverse event occurring can be shown by a marginal probability which refers to the probability of individual adverse events occurring at the present time (that is, during May 2012–April 2013). All adverse events in the model shown in the full BBN SC risk model can be estimated. This section will show only the important events which reflect stock-availability from different stakeholders, by proposing six focus variables which are parts of the core links of the model.

Under the defined assumptions of the model, it is found that 53 in 1,000 times (simply interpreted as number of inpatients) accessing the medicines in the POD locker resulted in not being able to get the right medicine at the right time. This was mainly caused by unavailable medicine to administer into the POD locker (approximately 53.6 in 1,000 times). The right medicine could not be supplied by PDC in 35.7 out of 1,000 deliveries to the sites (either ward or dispensary). It was also found that in 4.8 out of 1,000 occasions medicines (indicated unavailable medicines in ward by codes) in the PDC stock were not available: this is a similar level to the level of unavailable medicines in the ward (4.8 in 1,000 medicines) and higher than the level for unavailable medicines in the dispensary (3.8 in 1,000 medicines); see Table 7-2.

Table 7-2 Current probability prediction of the core variable representing stock-availability and supply-ability concept

ID	Adverse events	State	Current probability
1.1	Could not supply the right medicine to the right patient at the right time because of no medicine in the POD locker	*No Drug*	0.053127
4.1	At least a medicine is unavailable to administer into the POD locker	*At least one unavailable*	0.053573
22.1	Medicine in ward cupboard is not available	*Unavailable*	0.004848
26.1	Medicine in dispensary is not available	*Unavailable*	0.003795
32.1	PDC could not supply the right medicine to the site at the right time (Regular order)	*Incomplete or incorrect*	0.035724
36.1	Medicine in PDC is not available	*Unavailable*	0.004841

7.5.2 What are the main risks that cause supply failure?

The BBN SC risks model is developed from various agents/organisation units linked in the NHS GG&C SC. Many adverse events have been identified and it is impossible to mitigate all of them, due to constraints on resources (such as numbers of staff, time, and money). Therefore, risk prioritisation can help the decision maker identify the major risks to be managed under the limited resources and help to manage the risks effectively.

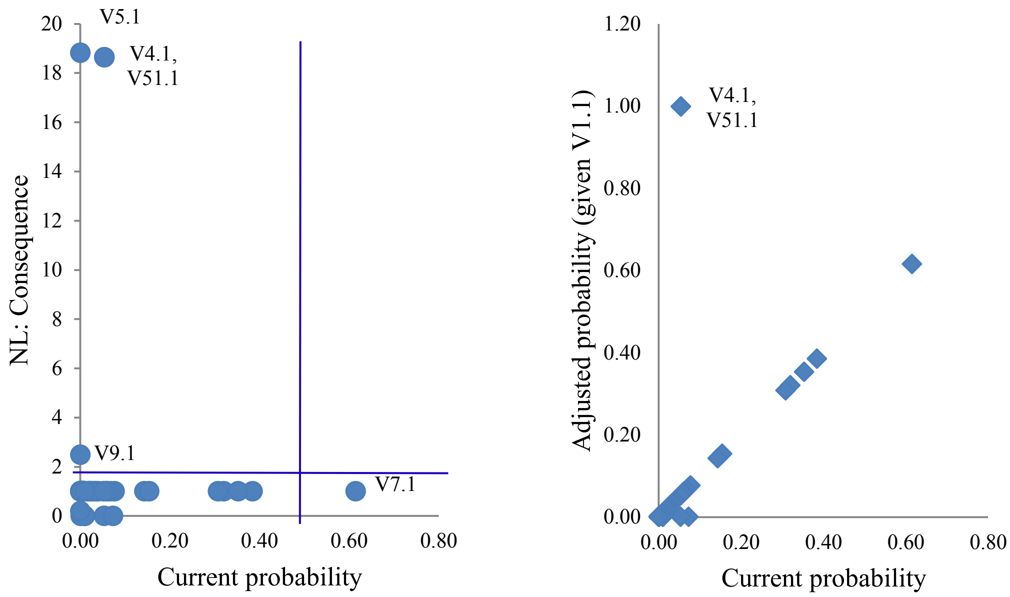
Since risk composes of probability and consequence elements, both elements are proposed for risk prioritisation via a two-dimensional graph similar to a risk matrix. The Normalised Likelihood (NL) is the index proposed for measuring the impact of (causal) adverse events on the focus variable, see Section 3.1.6.2. The adjusted probability of individual adverse events is diagnosed by calculating marginal posterior probability, which is the probability given the observed event of the top event. On the other hand, the current probability is the probability of particular adverse events occurring when there is no event that is observed; it can be referred to as marginal probability.

For example: The impact of particular adverse events on the top event ('Could not supply the right medicine to the right patient at the right time') due to the unavailability of drugs in the POD locker (V4.1) can be measured by NL. It is the ratio of adjusted probability that at least one medicine is unavailable in the POD locker (V4.1) given the observed top event that there is no medicine to supply patient at the right time (V1.1) and current probability of adjusted probability of unavailability of medicines in the POD locker (V4.1); see probability numbers in Table 7-3.

Table 7-3 Crucial adverse events prioritised by NL which is the ratio of adjusted probability given the top event is observed and current probability

ID	Crucial cause evidences	State	Current probability	Adjusted probability	NL
V5.1	Loss of key to medicine locker	*Yes*	0.000100	0.00189	18.82295
V4.1	Medicine unavailable to administer into the POD locker (at the first attempt)	*At least one unavailable*	0.053573	0.99822	18.63288
V51.1	Failure to order with IPS	*Yes*	0.053570	0.99816	18.63288
V9.1	Individual Patient Supply (IPS) cannot provide medicine at the right time	*At least one unavailable*	0.000037	9.27E-05	2.48659

When NL of a variable is equal to 18, it means their belief about the occurrence of the variable when no medicine to supply patient at the right time (V1.1) is observed is adjusted by 18 times comparing with its current probability of occurrence. The current probability and NL are used to represent the probability and consequence of individual risk events by the dividing graph into four quadrants similar to a matrix; see Figure 7-7 (a) which categorises high or low probability and consequence. However, the standard range is not defined and the users can judge the categories by considering the spreading of risk events on the graph. Since NL > 1 shows the sensitivity of a particular adverse event once the top event is observed, the cut-off point for categorising low-high consequence is defined at NL = 2. In addition levels of probability can be categorised as low-high, with a simple cut-off point at 0.5, so the graph can be divided into four quadrants for this example. It can be seen from Figure 7-7 (a) that most adverse events are of low probability and low consequence and therefore they may not require any mitigation (this is the retain/absorption of risk mitigating strategy explained in Section 5.1.3). Furthermore, it can be seen that there is no crucial adverse event which is of high probability and high consequence. In addition, the event of 'POD unavailable or unusable. *At least one unavailable or unsuitable*' (V7.1) can be classified as a risk having high probability but low impact.



(a) (b)

Figure 7-7 Risks categorised by current probability and consequence to the top event represented by NL

The main risks that are of low probability but that have high impact on the disruption of medicine supply are 'Loss of key to medicine locker. *Yes*' (V5.1*),* 'Medicine unavailable to administer into the POD locker. *At least one unavailable'* (V4.1), 'Failure to order with IPS. *Yes*' (V51.1) and 'Individual Patient Supply (IPS) cannot provide medicine at the right time. *At least one unavailable*' (V9.1). However, the current probability of 'Loss of key to medicine locker. *Yes'* (V5.1) is very low, almost 0, at 0.000100. Thus, NL of V5.1 is calculated by dividing by current probability numbers. Though its adjusted probability increases to only 0.00189, NL becomes 18.82; see Table 7-3. In this case, 'Loss of key to medicine locker. *Yes*' (V5.1) is not dominant when it assessed with the current probability of adverse event and adjusted probability (see Figure 7-7 (b)).

According to the model structure, once the medicines are unavailable to be admitted into the POD locker (V4.1), there is no medicine to be supplied to the right patient at the right time (V1.1). In addition, 'Failure to order with IPS. *Yes*' (V51.1) and 'Individual Patient Supply (IPS) cannot provide medicine at the right time. *At least one unavailable*' (V9.1) also leads to 'Medicine unavailable to administer into the POD locker. *At least one unavailable*' (V4.1). However, NL of V9.1 is less than V51.1 by a factor of seven, which shows that the main cause of unavailable medicines in the POD locker is from the failure to order medicine rather than from the problem of operating the IPS system.

Furthermore 'Failure to order with IPS. *Yes*' (V51.1) and 'Medicine unavailable to administer into the POD locker. *At least one unavailable*' (V4.1) show substantial differences between the probability of current adverse event and the adjusted probability; see Figure 7-7 (b) which shows these variables in the upper of diagonal line which represents the equality of both probability values. And since both V4.1 and V51.1 present similar probability values (see Table 7-3), it can be deduced that 'Failure to order with IPS. *Yes*' (V51.1) leads to 'Medicine unavailable to administer into the POD locker. *At least one unavailable*' (V4.1) with high correlation. Therefore, if the probability of 'Failure to order with IPS. *Yes*' (V51.1) can be reduced, the probability of 'Medicine unavailable to administer into the POD locker. *At least one unavailable*' (V4.1) will automatically be reduced. Of the top four crucial events adverse to the top event, it is suggested that consideration of the correlation among them indicates that 'Failure to order with IPS. *Yes*' (V51.1) should be mitigated as the first priority.

Apart from risk prioritisation by considering the top event of the model, 'Could not supply the right medicine to the right patient at the right time' due to the unavailability of drugs to supply (V1.1), users from different agents in the SC (such as wards, dispensaries or the PDC), may desire prioritisation of other risks which can affect stock availability. This can be achieved by using the same method shown in the above section and changing the focus event to be 'Medicines in ward cupboard not available. *Unavailable*' (V22.1), 'Medicine in dispensary not available. *Unavailable*' (V26.1), or 'Medicine in PDC not available. *Unavailable*' (V36.1). This will benefit all participants, rather than showing the impacts only on the top event, but they are not shown in this thesis.

7.5.3 What is the impact of (combinations of) uncertain events on supply through the chain?

Exploring joint adverse events can improve the understanding of possible effects when adverse events happen simultaneously and the scenario analysis can be used to support risk management. This aids in preparing the mitigating plans and/or improving the reliability of the system. The effects of scenarios can be measured using focus variables by comparing the adjusted probability (marginal posterior probability) to show the effects of setting scenarios and current probability (marginal probability). The first scenario case below will show a single scenario exploration and the last two cases will present by comparison a set of scenarios.

Case 1: The occurrence of bad weather

Bad weather (V50) is one of the external factors that can disrupt the SC. Bad weather can generate problems in logistics in the defined NHS GG&C hospital medicine SC therefore ‘Bad weather’ (V50) can lead directly to the event of ‘Unable to get medicine from suppliers’ (V41) and ‘PDC supply delay’ (V33) as shown in Figure 7-5. However, the impact of bad weather can affect the availability and supply ability of medicines at different sources and it can be evaluated with six main focus variables which represent the core SC performance for individual agents in this model. The focus variables and scenario variable are set and indicated as follows.

Focus variables (Effect variables):

V1.1: ‘Top event: Could not supply the right medicine to the right patient at the right time. *No drug*’

V4.1: ‘Medicine unavailable to administer into the POD locker (at the first attempt). *At least one unavailable*’

V22.1: ‘Medicine in ward cupboard not available. *Unavailable*’

V26.1: ‘Medicine in dispensary not available. *Unavailable*’

V32.1: ‘PDC could not supply the right medicine to the site at the right time (Regular order). *Incomplete or Incorrect*’

V36.1: ‘Medicine in PDC not available. *Unavailable*’

Scenario variable (Observed variable):

V50.1: ‘Bad weather. *Bad weather*’

The geographical limits of the modelling scope, NHS GGC&C Hospital medicine SC (see Figure 7-1), limit the subjective probability of bad weather to the local area rather than on a global scale. Furthermore, bad weather can be defined by different levels so for this case study it was defined as weather conditions that can stop transportation for several days in a week. For example during Christmas, some suppliers use DHL to deliver medicines. In bad weather, DHL did not deliver all parcels to Scotland as parts of Scotland were inaccessible.

According to the elicitation, experts believed that weather bad enough to stop transportation in Glasgow is a rare event. Thus, bad weather cannot generate a substantial impact on the medicine availability of different stocks in the SC, sources which may already have their own safety stock. The radar map (see Figure 7-8) and Table 7-4 show the minor difference between adjusted probability current probability and of medicine unavailability in the ward, dispensary and PDC stock, represented by V22.1, V26.1 and V36.1 respectively. As a result, a huge impact on supply ability to the POD locker (V4.1) and then to an inpatient (V1.1) would not be experienced. However, the impact of the bad weather on the ability to provide a regular medicine supply to the sites at the right time by PDC (V32.1) is crucial as it increases from 0.0357 for current probability to 0.4196 for adjusted probability after an incident of bad weather in Glasgow.

Table 7-4 Current probability and adjusted probability given the occurrence of bad weather, and difference between both probability values of the six focus variables in the NHS GG&C hospital medicine SC

Adverse events	State	Current probability	Adjusted probability	Difference
Could not supply the right medicine to the right patient at the right time because of no medicine in the POD locker (V1.1)	*No drug*	0.0531	0.0536	0.0005
At least a medicine is unavailable to administer into the POD locker (V4.1)	*At least one unavailable*	0.0536	0.0536	0.0000
Medicine in ward cupboard is not available (V22.1)	*Unavailable*	0.0048	0.0432	0.0383
Medicine in dispensary is not available (V26.1)	*Unavailable*	0.0038	0.0075	0.0037
PDC could not supply the right medicine to the site at the right time (Regular order) (V32.1)	*Incomplete or incorrect*	0.0357	0.4196	0.3839
Medicine in PDC is not available (V36.1)	*Unavailable*	0.0048	0.0097	0.0049

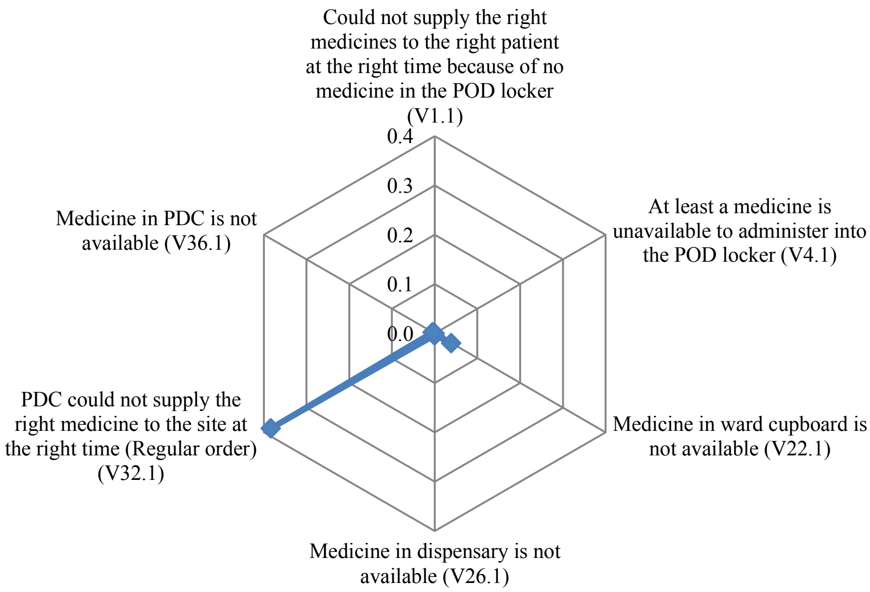


Figure 7-8 The difference between adjusted probability by given the bad weather happen and current probability of the focus variables in the NHS GG&C hospital medicine SC

Case 2: Stock unavailability in different sources in the hospital medicine SC

There are three main stocks – the PDC, the ward and the dispensary. The number of wards can vary, depending on the capacity of the hospital, but there is only one dispensary/pharmacy in a hospital. The scenarios analysis will define the unavailability of medicine as a combination of the unavailability within these three stocks. Although there are multiple wards and dispensaries/pharmacies in the NHS GG&C, this scenario will consider the stock of a ward and a dispensary linked to the location where an inpatient is admitted. The probabilities of focus variables are used to compare current probability and adjusted probability, given the five scenarios observed. The focus variable and scenarios are set and indicated as follows.

Focus variable:

The reason why the right medicine could not be supplied to the right patient at the right time could be one of three states – *No drug* (V1.1), *Unsuitable quality* (V1.2), or *Both no drug unsuitable quality* (V1.3).

It is possible for more than one medication be provided to an inpatient at a time and for more than one medicine to be in the POD locker.

Scenario variables:

Scenario 0: Current situation

Scenario 1: Medicine not available in the PDC (*Unavailable* state V36.1)

Scenario 2: Medicine not available in the ward (*Unavailable* state V22.1)

Scenario 3: Medicine not available in the dispensary (*Unavailable* state V26.1)

Scenario 4: Medicine not available in the ward, the dispensary (*Unavailable* states V22.1, V26.1)

Scenario 5: Medicine not available in the ward, the dispensary, and the PDC (*Unavailable* states V22.1, V26.1, V36.1)

The bar chart in Figure 7-9 shows that the medicine unavailability in the various stocks may slightly impact on the probability to supply medicines with unsuitable quality, or with the wrong time and unsuitable quality, to the inpatient. However, when both ward and dispensary stocks are not available at the same time or all three stocks are unavailable at the same time, the probability of being unable to supply the right medicine to the right patient at the right time because of no medicine in the POD locker increases from 0.053 to 0.068 and 0.123 respectively.

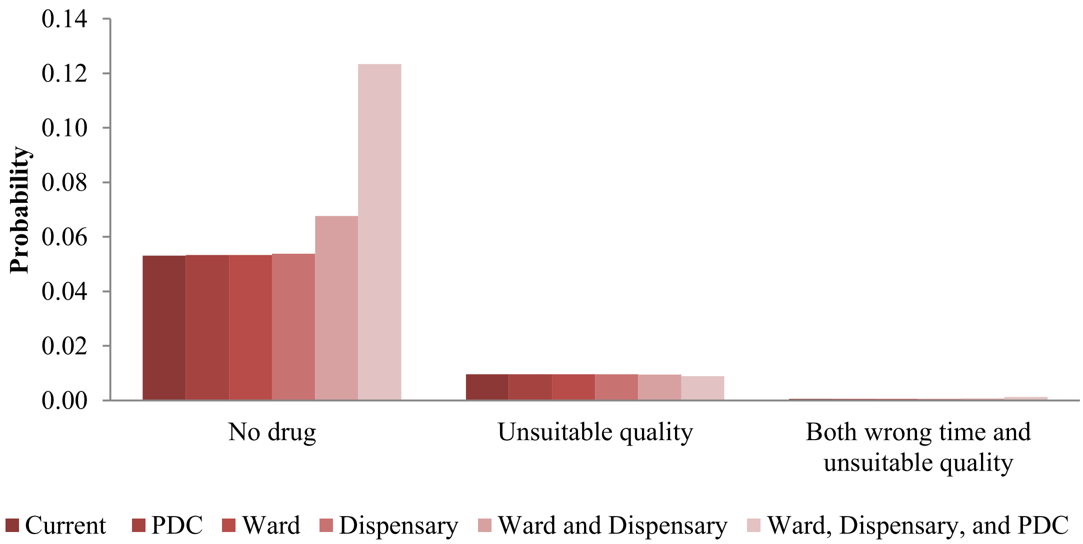


Figure 7-9 Comparing effect on ability to supply the right medicine to the right patient at the right time when different scenarios of stock unavailability in the GG&C SC are observed

Since the medicine unavailability in particular stocks does not cause the supplying of medicines of unsuitable quality, the defined scenarios would not change the probability of providing such medicines from the current state. The probability of providing medicines both at the wrong time and of unsuitable quality will have little effect on the scenarios.

In the case study, redundant or back-up medicine supply systems, such as the IPS (Individual Patient Supply) system exists. Therefore, the medicine supply system can be secured very well and the high level of responsiveness to an inpatient can be maintained. When the main sources of medicine supply and the back-up system do not work at the same time, the impact on the inpatient can be dramatically increased (adversely), as can be seen from the scenario comparison. This example shows the analysis of combining adverse events.

Case 3: Comparison between emergency admission and elective admission

An inpatient can be admitted either via emergency or elective admission. The reasoning flow of types of admission will influence whether the inpatient takes his/her own drugs (POD) so this can be a cause of their medicines being unavailable or unusable (V7.1). If the medicine is not stocked in the ward cupboard (V10.1), that medicine cannot be provided by the ward cupboard (V8.1) and will have to be ordered from the IPS system. If the medicine cannot be obtained from the IPS system either, it may not be available to administer into the POD locker (V4.1). Thus, the patient may not get the right medicine at the right time, since the medicine cannot be supplied into the POD locker (V1.1). Therefore the focus variables and scenario variables are set and indicated as follows.

Focus variables:

V1.1: 'Top event: Medicine supply disruption: Could not supply the right medicine to the right patient at the right time. *No drug*'

V4.1: 'Medicine unavailable to administer into the POD locker (at the first attempt). *At least one unavailable*'

V8.1: 'Medicine unavailable to provide by ward cupboard. *At least one unavailable*'

V10.1: 'Out of ward stock catalogue requested. *Out catalogue*'

V7.1: 'POD unavailable or unusable. *At least one unavailable or unusable*'

Scenario variable:

Type of admission can be shown as two states – *Emergency* (V63.1), and *Elective plan* (V63.2)

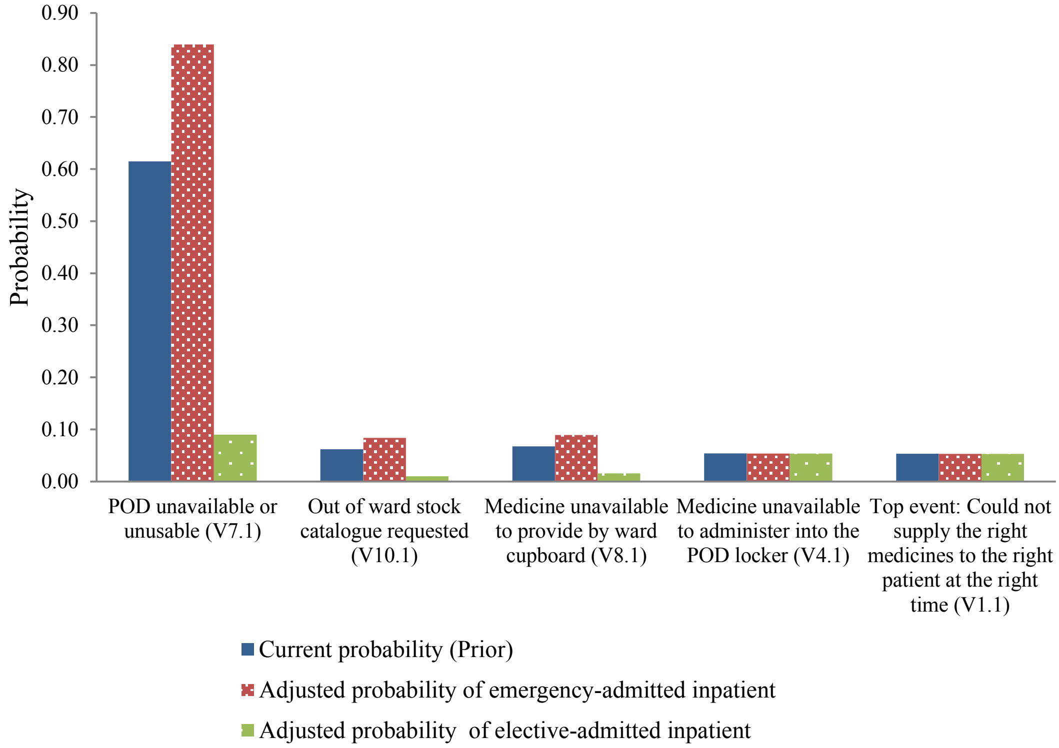


Figure 7-10 Comparison of current probability, adjusted probability of emergency admission, and adjusted probability of elective admission for series of effect events

The bar chart in Figure 7-10 shows that the probability comparison between both types of admission can be compared to all related focus variables. A notable increase can be observed in the probability of inpatients who do not bring their own drugs or who cannot use their currently taken drugs from home – around 85 in 100 medicines by emergency-admitted inpatients compared to only 9 in 100 medicines by elective-admitted inpatients. Furthermore, 84 in 1000 medicines are unavailable for emergency-admitted inpatients but only 6 in 1,000 medicines are unavailable for elective-admitted inpatients because they are not in the ward stock catalogue so those medicines are not prepared in the ward cupboard (V10.1). This represents the similar probability of being unavailable to provide medicines by wards (V8.1). However, it can clearly be seen by comparing the ability to administer into the POD locker (V4.1) to supply the medicines to the right patient at the right time (V1.1) that the type of admission does not generate a substantial impact on the treatment for inpatients, because several back-up systems are in place to mitigate this.

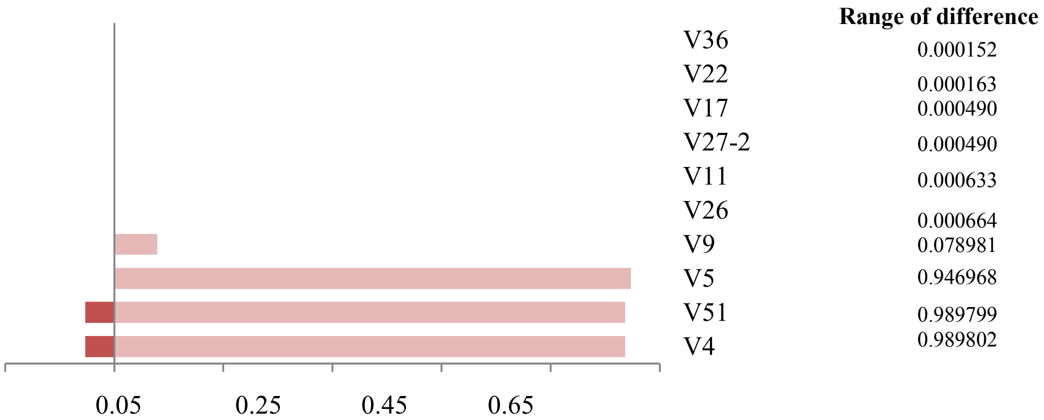
7.6 Sensitivity Analysis

Evidence sensitivity analysis is used in this thesis to depict the effect that changing input cause variables in the network has on the top event (effect variable). The sensitivity analysis is depicted by the Tornado graph; see Section 5.4.7.2. The length of a bar is the range of difference between the effects of the two extreme states of a cause variable on the specific state of the effect variable. In other words it is the difference of adjusted probabilities for a specific state of the effect variable by setting two extreme states of a cause variable. Therefore the length of the bar corresponds to each sensitive variable which impacts on the top event, while the vertical axis shows the current probability of the top event in a defined state.

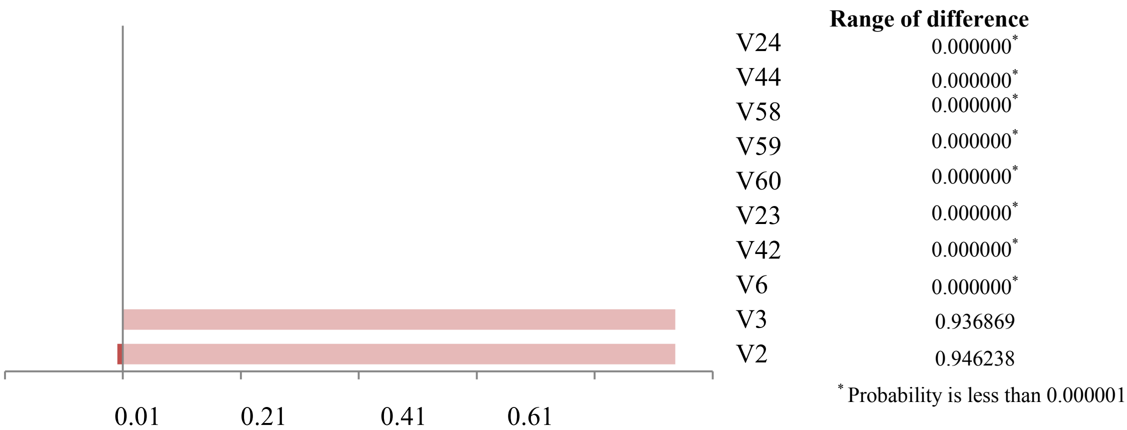
There are four defined possible states of the top event 'Could not supply the right medicine to the right patient at the right time' (V1): *No drug* (V1.1), *Unsuitable quality* (V1.2), *Both no drug and unsuitable quality* (V1.3), and *Normal admission* (V1.4). The sensitivity analysis will show the top ten cause variables which can impact on the individual three adverse states (V1.1–V1.3) of the top event, as shown in Figure 7-11 (a)–(c). In Figure 7-11 (a), the longest bar represents 'Medicine unavailable to administer into the POD locker' (V4). The adjusted probability of 'Could not supply the right medicine to the right patient at the right time' being '*No drug* available in the POD locker' goes from 0.0001 (given *Normal administration* (medicine) into the POD locker effect) to 0.989802 (given *At least one unavailable* to administer (medicine) into the POD locker effect), while the current probability of 'Could not supply the right medicine to the right patient at the right time' being '*No drug* available in the POD locker' is 0.053127, as measured by the vertical axis. The second and third biggest impacts on the top event being *No drug* are 'Failure to order with IPS' (V51) and 'Loss of key to medicine locker' (V5) respectively.

In addition, 'Dispense expired medicine from the hospital stock' (V2) and 'Wrong patient name attached to medicine leading to storage in incorrect locker' (V3) are the top two events that can generate an impact on the top event 'Could not supply the right medicine to the right patient at the right time' (V1) that is being *Unsuitable quality* (V1.2).

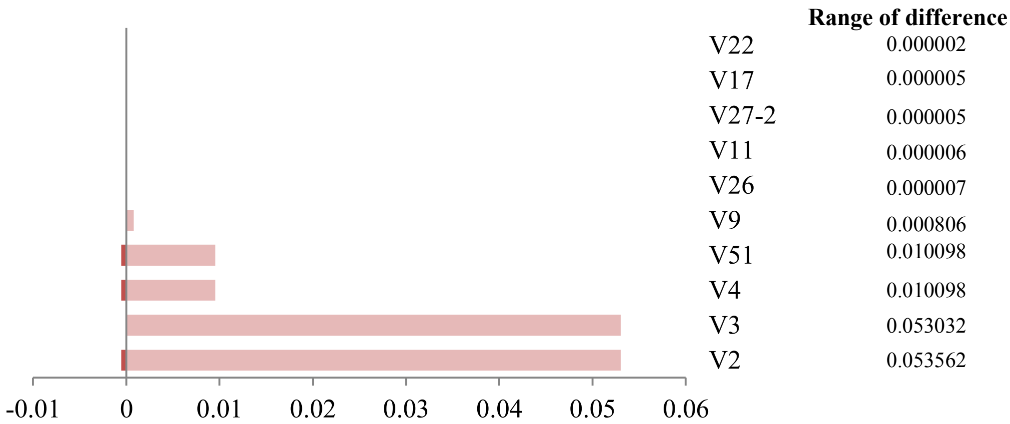
Finally 'Dispense expired medicine from the hospital stock' (V2) and 'Wrong patient name attached to medicine leading to storage in incorrect locker' (V3), 'Unavailable to administer into the POD locker' (V4) and 'Failure to order with IPS' (V51) are the top four of the most impact on the top event 'Could not supply the right medicine to the right patient at the right time' (V1) that is being *Both no drug and unsuitable quality* (V1.3).



(a) Could not supply the right medicine to the right patient at the right time because of *No drug* (V1.1*)*



(b) Could not supply the right medicine to the right patient at the right time because of *Unsuitable quality of drugs* (V1.2)



(c) Could not supply the right medicine to the right patient at the right time because of *Both no drug and unsuitable quality* (V1.3)

Figure 7-11 Tornado graph showing the most impact (top ten of cause variables) on individual three adverse states of the top event

7.7 Summary of the BBN SC Risk Model Validation Results

Five validating criteria from literature can be identified: clarity test, agreement on variable definitions and relations checking, consistency checking, model robustness (sensitivity analysis) and appropriate model behaviour (scenario analysis); see Table 3-1. They are combined in the suggested BBN SC risk modelling process in stages 5, 6 and 8 (see Section 5.4). All parts have been operated within the real empirical study of NHS GG&C hospital medicine SC. The clear evidence is that the eight stages of the BBN SC risk modelling process were completed: all evidence to support the model validation by the five criteria will be explained in detail and can be summarised in Table 7-5.

Table 7-5 Summary of the BBN SC risk model validation

Criteria for BBN SC risk model validation	Relevant stage of the BBN SC risk modelling process	Results
Clarity test	stage 5	Expert panel checked and revised
Agreement on variable definitions and relations checking	stage 5	Expert panel checked and revised
Consistency checking	stage 6	Analyst checked from the questions for probability elicitation
Model robustness (sensitivity analysis)	stage 8	Expert panel accepted the sensitivity analysis
Model behave appropriately (scenario analysis)	stage 8	Expert panel accepted the results of scenario analysis

1. *Clarity test*

The clarity test is a part of stage five for validating by participants; see Section 5.4.5. During the workshop all variables and states were presented to the expert panel to ensure that they are clear in operational meaning to all stakeholders. Since most of the variables are in the form of simple binary variables or two-state variables (constraints of implementing the Noisy-OR technique) and use similar names as the adverse events to show the negative events which were given by individual experts, all experts thought the variables and states were simply and clearly defined.

2. *Agreement on variable definitions and relations checking*

Besides the clarity test, agreement on the variable definitions and relations checking is also a part of validation in stage 5; see Section 5.4.5. Inappropriate names of variable and states in the provisional BBN SC risk model were revised, based on the experts' comments.

In the workshop, the state of top event 'Could not supply the right medicine to the right patient at the right time' (V1) was adjusted from '*Bad quality*' to '*Unsuitable quality*' by suggestion from the experts.

In addition the workshop provided the chance for the expert panel to discuss and modify the model structure, and once it was modified it was ensured that all agreed on the variables and relations in the BBN structure. Additionally, in the group workshop, the experts were able to introduce more adverse events. For example, 'Failure to order with IPS' (V51) was added and linked to 'Medicine unavailable to administer into POD locker' (V4).

3. *Consistency checking*

Consistency checking is a part of stage 6 in the primary BBN SC risk modelling process; see Section 5.4.6. It can be validated by the analyst before elicitation by preparing questions to obtain probability details from the experts. The questions should be clear in time scope and unit dimension, especially for set B, to elicit the proportion of each variable to calculate the probabilities. A proportion should be calculated from the ratio of numbers which are elicited from the same unit under the same time scope.

The major variables are defined by binary states which can categorise particular variables clearly, without confusing different events, and do not need to specify definitions of particular states such as *Yes/No* or *Unavailable/Available* etc. Some binary variables were combined to a multi-state variable to reduce the complexity of the model. Furthermore the units to construct questions which are developed from variable descriptions had also been checked. Therefore the model had been validated by consistency checking process by analyst.

4. *Sensitivity analysis*

Sensitivity analysis shows the sensitivity of the changing of evidence variables on focus. The sensitivity analysis is prepared by the analyst (see Section 7.6) and then taken to the workshop (II) as a part of the Validating BBN SC risk model behaviour in stage 8 by the expert panel. It aims to provide the answer to '*Are the sensitivity analysis results acceptable for experts?*'

After the sensitivity analysis was shown to the experts, they accepted the modelling results since the both sides of the extreme states were in the acceptable probability range of the effect on the top event. Furthermore the greatest impact on the top event for individual stages was also acceptable under the defined modelling assumptions.

5. *Scenario analysis*

Scenario analysis (case based evaluation) is prepared by the analyst (see Section 7.5.3), and then taken to be presented to the expert panel in the workshop (II) for validating BBN SC risk model behaviour (stage 8). Since time was limited in the validating workshop, selected scenarios were presented and then experts were asked to explore their own scenarios before providing feedback.

The following section describes responses from experts for some scenario examples.

Scenario: The occurrence of bad weather (Case 1)

During the scenario exploration in the 'Validate BBN SC risk analysis' workshop session, different scenarios from the model were accepted by the expert panel, for example, the result of exploring the effect of 'Bad weather'. The group of experts agreed that bad weather is not a major risk in their SC and it is unlikely to affect inpatients: it has not been that bad for a long time and there are medicine safety stocks in many places in the SC system. Their belief is similar to the analysis results from the BBN SC risk model.

Scenario: Stock unavailability in different sources in the hospital medicine SC (Case 2)

The scenarios of medicine unavailability in different sources in the SCs were presented. The decision maker was impressed with this scenario analysis since it can show how synergistic adverse events impact on the top event. When the individual adverse events happen, they may not generate a substantial impact on the top event, but they can when they happen at the same time.

Experts were asked to set their own scenarios and explore the results on the top event, bearing in mind the list of modelling assumptions (see Section 7.3) such as excluding other relevant activities such as clinical therapy errors, medical information risks, prescribing errors etc. The probability of some variables might not show the same figure as the report from recorded data, especially on the estimation of current probability of particular adverse events. However, the experts accepted the results since they believed they were valid. The decision maker provided good feedback since it is make sense to him and confirmed his belief about the security of the SC system. Furthermore, the operational experts did not argue with the results since no extreme value was shown.

7.8 Awareness and Recommendations on How to Use the Results of BBN SC Risk Model Analysis

Although the BBN model results claimed validity as shown in Section 7.7, awareness of using the results from risk analysis has to be specified clearly to remind the users of the interpretations from the model outcomes. The important awareness are the following:

1. At the first stage, the BBN SC risk model is developed from beliefs of the group of experts during a specific period of time (May 2012 to April 2013 for this case study). Furthermore the probability numbers are quantified by a representative of agents in the system at the operational level for the whole SC rather than for specific wards or hospital dispensaries such as a staff in a ward, as some other wards may define subjective numbers differently. Therefore the results of analysis should show the rough chance of occurrence of individual adverse events rather than focus on the accuracy of the model results. As can be seen from the results of model analysis, the outcomes are based on comparisons – between different scenarios, different variables, or between the current probability and adjusted probability for the same variable, etc.

2. The BBN SC risk model is developed under a set of assumptions. When the model results are used for making any decision, users have to be aware of those assumptions. For the case study, assumptions were, for example, the exclusion of the process of using alternative medicines with inpatients; and the model was developed only for the daytime, rather than considering also night time supply when the dispensary/other suppliers are closed. When using the results to support any decisions, the decision maker should understand the assumptions and use the model results carefully.

3. It is recommended that the BBN SC risk model defines only one top event (see Section 5.4.1), in order to control the complexity of the model. This means it is unable to show the interaction between SC performance factors such as cost, time, or quality or different effects from the same adverse event. The analyst could consider defining more than one top event but this has not been explored by this empirical case study.

4. Users should be aware that some rare events (shown as small percentages) can transform to a huge number per total units of period consideration. For example, though from the case study the different scenarios change the percentages by only

small proportions on the top event, this can be converted to the equivalent of a huge number of inpatients or medicines in a year.

The important information from the case study and results from implementing the primary BBN SC risk modelling process were shown in this chapter. It is clear that the model can provide results to support risk analysis, as shown in Section7.5. Furthermore, the results of the modelling process evaluation were also collected during implementation and after finishing the model development, as explained in Section 6.2.2. Evaluating data are also analysed, as presented in the next chapter.

Chapter 8 Evaluation of Medicine Supply Chain Risk Case

This chapter presents evidence to support the modelling process evaluation, collected by following the evaluating criteria of **P**ractical and **U**seful aspects. The participant evaluation of the BBN SC risk modelling process will be explained in Section 8.1. Furthermore the formal evaluation of participants' perceptions, including the observations during the modelling process, that can support the specifying of practical problems (and suggestions to deal with them) is also presented; see Section 8.2. Finally, the last section provides this researcher's perspective on the benefits of implementing the BBN in this research scope.

8.1 Modelling Process Evaluation by Decision Maker and Experts

Perceptions on the modelling process were evaluated by the participants – i.e. the decision maker and operational experts after finishing the whole modelling process via questionnaires (see Section 6.2.2.1) using a Likert scale. The summary of evaluating results in the 'practical' and 'useful' criteria (by comparing with RR) is shown in Table 8-1.

Table 8-1 Summary of the BBN SC risk modelling process evaluation by participants

Criteria for modelling process evaluation	Results provided by participants			
Practical				
Simple to use	✓ (For stage 3, 5 & 6.2) with score 2 to 4.5			
Useful				
Reaching project aims	✓ (score of 4)			
Utility of model outcomes	Managerial		Operational	
	BBN	RR	BBN	RR
Support awareness of systemic risks	✓		✓	
Communication of major risks from stakeholders		✓	✓	
Ability to interpret the output results	✓		✓	
Understand the outcome without misinterpretation	✓		✓	
Realistic results	✓		✓	
Utility of the modelling process	✓ (score of 4)			
Visions of further implementation from the BBN SC risk model	✓			

8.1.1 Practical - simple to use

As part of the primary BBN SC risk modelling process, the experts took part in three main input stages to construct the BBN SC risk model: 'Gain qualitative understanding of SC risk events' (stage 3), 'Refine the BBN SC risk structure' (stage 5), and 'Quantify BBN SC risk model–During elicitation' (stage 6.2). Data on the level of their perceptions of the difficulty of participating in the various stages were collected by Questionnaire A (Appendix H). The model was developed with contributions from both the decision maker who is a managerial expert and from operational experts, and they may perceive the difficulty of the process differently. The comparison of the level of perceptions is categorised by two group of experts based on four returned questionnaires: see the bar chart in Figure 8-1.

Generally, the BBN SC risk modelling scope is developed to capture adverse events at the operational level, so unsurprisingly the managerial expert perceived the process as being more difficult than operational experts. The managerial expert gave a score from 'difficult' to 'normal' (perception score is 2–3), while the operational experts rated higher in every category. The biggest difficulty for the decision maker was the process of structuring the CM and quantifying probability, while the operational experts rate the probability quantification as the most difficult, but still scored it as 'normal' (perception score is 3). Next the level of difficulty for individual stages will be explained in more details.

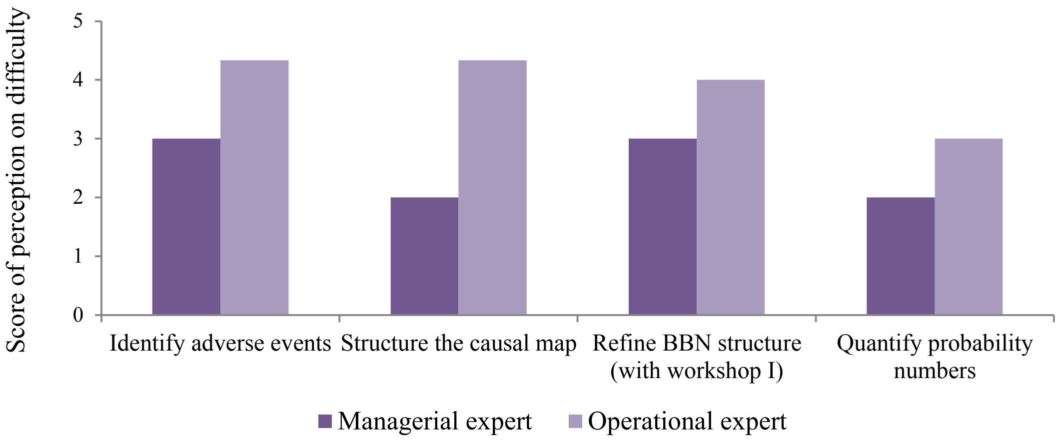


Figure 8-1 Score of perception on difficulty to develop the BBN SC risk model perceived by participants

8.1.1.1 Gain qualitative understanding of SC risk events (stage 3)

Two activities of the modelling in this stage are to identify adverse events and structure relationships of the CM. From the questionnaire results, the managerial expert scored this as 'normal' (perception score is 3) while the operational experts thought it easy (perception score is 4.33). Furthermore, the managerial expert thought the process of identifying links between adverse events to structure a CM was difficult for him (perception score is 2) but the operational experts defined it as easy (perception score is 4.33). The managerial expert provided scores that indicated more difficulty than perception of operational experts that the other way around: the managerial expert had to identify all possible adverse events for the entire SC, whereas operational experts identified adverse events only under their organisation units, related to their routine work. It was found that within the time limit of two hours, the decision maker had to structure CM from the whole SC for 31 adverse events. Furthermore he had decisions to make on a lot of possible arrows, because a root adverse event can generate effects by linking to many other adverse events, so it was a difficult task for the managerial expert.

On the other hand, the operational experts also provide very good feedback at this stage. Identifying adverse event in their routine work is not difficult for them. Furthermore, the process of structuring a CM by individual interviews gave them more confidence since they were more open and relaxed when it came to mentioning some adverse events caused by other agents. An operational expert mentioned at the beginning of the model development that they did not want their individual perceptions to offend other experts who might have different perceptions. The process of collecting individual experts' perceptions before combining them as a provisional model and taking it to the workshop for discussion reduced potential confrontation or face-to-face disagreements which would have influenced what they really wanted to say.

8.1.1.2 Refine the BBN SC risk structure (stage 5) in workshop (I)

After the operational experts had identified and structured the CM, they attended the workshop (I) to refine the provisional BBN SC risk model (stage 5). The managerial expert gave a 'normal' (perception score is 3) level of difficulty, but the operational staff found that it was easy for them (perception score is 4). All experts (managerial and operational) provided quite a high score in this process since they were more confidenced with their CMs which represent the real system. It was observed that the CMs structured by operational experts and the managerial expert were similar. Furthermore both managerial expert and operational experts were more confident in sharing their perceptions of the defined causal relations with their stakeholders after they had identified their CM from individual interview in the previous stage.

8.1.1.3 Quantify BBN SC risk model (stage 6.2)

In relation to the analysis from the feedback questionnaire, both managerial expert and operational experts gave the lowest scores for the quantification part, since they observed that it was the most difficult part, especially for the managerial expert (perception score is 2.0). The operational experts scored it at a 'normal' level (perception score is 3.0). This is because the managerial expert can quantify only some root cause variables and most of the adverse events have not been perceived in operational detail. When he was asked to quantify some operational adverse events, it was difficult for him and he said *"Frequency stuff (for probability elicitation) has confidence with a lack of absolute precision (record or report) normally"*. On the other hand, the operational experts can perceive those adverse events but they may not record them precisely so they may not be confident of providing the subjective numbers in this way. By the application of probability eliciting questions which were developed to match operational perceptions of the detail of probabilities in the operational process (set B questions, Section 5.4.6.1), it was found that the operational experts can understand the process of identified probability and an operational expert said that *"It is easy for them to quantify answers on the real items"*. However, some operational experts preferred to check information from the record before completing the quantification questionnaire, as they did not want to estimate anything, being used to work with accuracy, or they are not confident to quantifying numbers at the first interview; the questionnaire was left with them in order to allow them to check the recorded data or update their beliefs. Experiences from the empirical study found that under the time pressure and heavy routine tasks, the experts could not find the recorded report in the required format for the quantification questionnaire; and then the following interview with subjective numbers was implemented. An expert mentioned that "*At the first thought, we think that we can give the information and got the information preparing for filling the questionnaire. Once I am back to look at the questionnaire, I need more explanation."*

The second attempt, following the quantification protocol by interview, went very well and experts were more comfortable in answering the questions since they had already seen and were familiar with them. Furthermore, during the time between the first interview for quantification to the second attempt, experts were able to notice and record numbers during their working routine.

8.1.2 Useful

The four sub-criteria to represent the usefulness of the BBN SC risk model are evaluated by comparing with RR, see Questionnaire B, Appendix H.

8.1.2.1 Reaching the project aims

At the initial meeting with the decision maker before starting the BBN SC risk modelling process, the decision maker defined his expectation as to *improve his understanding of the SC*; see Section 7.1. Therefore, the general evaluation of reaching the project aim can be evaluated from improving the decision maker's understanding gained from the provided analysis outcomes of the model shown; see results in Section 7.5. After the results of the analysis were presented to the expert panel in the final workshop (stage 8), the evaluation of the decision maker was solicited by interview. Furthermore, during stage 8, all experts were able to see the results of the risk analysis and had a chance to define their scenarios for evaluating from the model. Therefore experts were able to evaluate their understanding of risks in their SC by comparing with the RR; see Questionnaire B, Appendix H.

Both the managerial expert and the operational experts agreed that the results of analysis from the BBN SC risk model helped them to better understand risks in their SC. The managerial expert provided the feedback of 'normal' understanding for RR and 'clear' understanding for the BBN SC risk model. The operational experts rated the BBN SC risk higher than RR but not by a significant factor; see Figure 8-2.

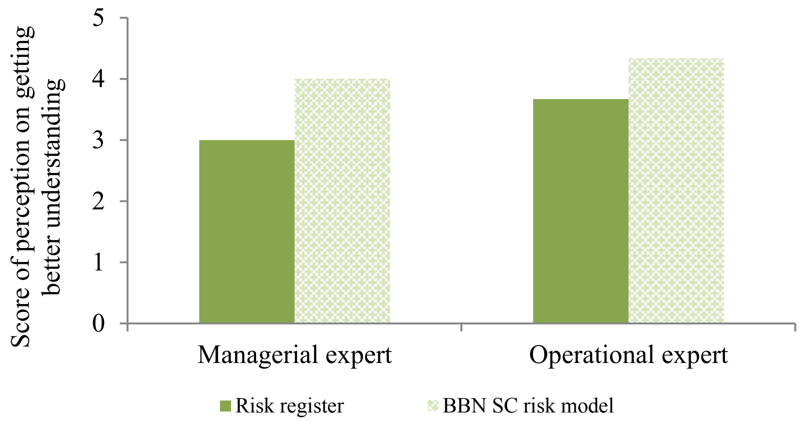


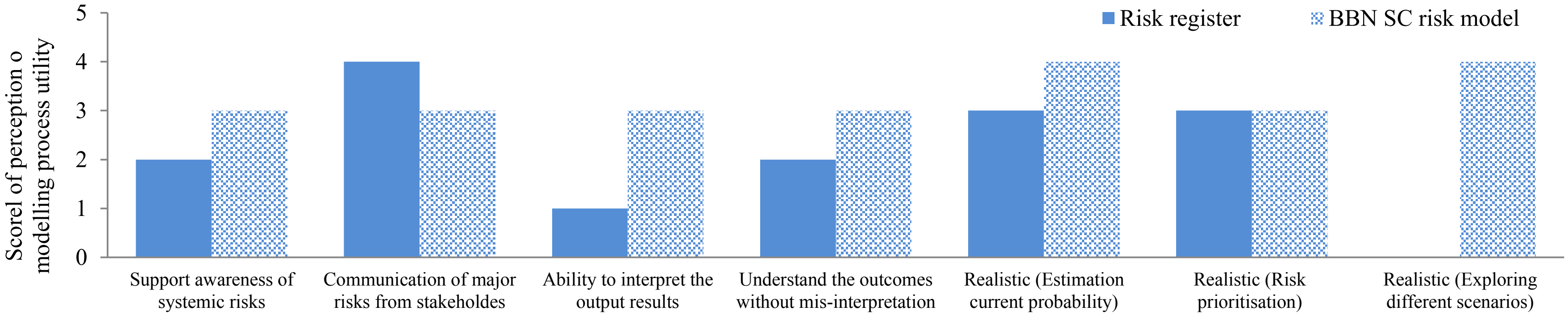
Figure 8-2 Score of perception on getting better understanding of risks in their SC, classified by types of expert

Furthermore, the decision maker thought the BBN more valid than RR: "*The BBN was developed from consensual thing. It is not one person give the opinion but they put a figure on it and the difference between those and this to the top event.*" So he believed that it gave valid priorities because the model showed the cause-effect among different stakeholders at the same operational level on the top event (known as the horizon influence). RR is developed in the vertical perspective so the RR at the operational level is developed to support the next level of management. Positive comments on the utility of the BBN SC risk modelling process were summarised in Section 8.1.2.3.

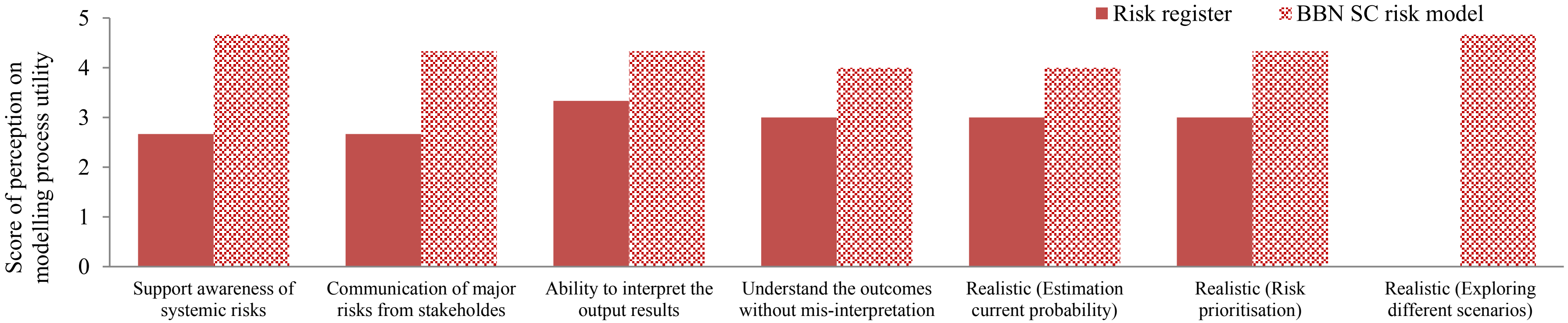
When the different scenarios were explored by changing observed variables, it showed that those adverse events do not generate a huge effect on the top event (supply the right medicine to the right patient at the right time). The model outcomes can show that the current NSH GG&C SC is well operated with a very good back-up system, although the main back-up process of supplying alternative medicines was excluded from the modelling scope. The decision maker provided a good feedback since it made sense to him (validation) and it confirmed his belief about the security of the SC system. He mentioned that *"We might be able to understand key areas of risk to work on but actually what it be more valuable to do it all me to be reassured that is really quite important that we have a robust SC. We can reassure that the system is totally new but can produce the right outcome and we have a quite powerful safety"*. Furthermore the general feedback from the decision maker on the BBN SC risk model after all risk analysis was shown to him was: *"I thought that is really powerful to show effect of different scenarios to the probability of final outcomes as **'A light bulb moment'** when you understand it"*.

8.1.2.2 Utility of the BBN SC risk model outcomes

The utility of the BBN SC risk model can be evaluated by five criteria: supporting awareness of systemic risks (model understanding of interrelationship), communication of major risk from stakeholders, ability to interpret the output result, understanding the outcomes without misinterpretation by other people who are not a part of the expert panel, and realism of result from estimation of current probably, risk prioritisation, and exploring different scenarios. All possible criteria to evaluate the usefulness of the model are developed to be compared with their RR, since the managerial expert and the operational experts may perceive the utility of the model differently. The results of analysis for utility criteria are shown in Figure 8-3 (a) and Figure 8-3 (b).



(a) Managerial expert's perception



(b) Operational experts' perception

Figure 8-3 Score of perception on model outcome utility of different factors by comparing between RR and BBN SC risk model

In general it was found that operational experts rate the utility criteria of the BBN SC risk model higher than RR, and most of the comparison criteria for managerial perception provided better feedback for the BBN SC risk model than for RR. Only the perception on the 'realistic' aspect of the risk prioritisation analysis is rated as same as RR, and only the ability to communicate major risks to stakeholders is perceived better in RR than in the BBN SC risk model by the managerial expert.

The interrelationship between adverse events represented by the model can support increasing the awareness of the adverse events across the entire SC. It was clearly observed by the operational experts that the BBN SC risk model can represent this criterion better than the RR (perception score are 4.67 and 2.67). Since they have seen RR or are involved to develop RR for their own organisation unit, they can distinguish the difference between both tools. Furthermore the managerial expert reported finding that the degree of supporting awareness of the adverse event to defined SC is 'difficult' by using RR (perception score is 2) but 'moderate' level by using the BBN SC risk model (perception score is 3).

Interestingly the managerial expert was more satisfied with the communication of the major risks from stakeholders provided by RR than that provided by BBN SC risk. He thought that RR can provide the major risk clearly (perception score is 4) but the BBN SC risk model can communicate the major risks only at moderate level (perception score is 3). The reason for this is that the ranking of risks by RR is straightforward so the major risks can be prioritised by risk matrix and obtaining a risk priority is easier. The decision maker discovered that he could identify the top five of the most important risks from RR on a judgemental basis of rating probability and impact independently.

However, the managerial expert determined that the expression of probability format provided by BBN SC risk analysis was easier to interpret than the rating format given by the RR (perception scores are 3 and 1 respectively). He rated RR results as 'very difficult' to interpret, since numbers 1 to 5 are categorised roughly and it is difficult to explain those numbers explicitly. On the other hand, he rated the BBN SC risk results at a 'moderate' level since probability language can be explained as a chance of events can occurred, which is more explicit. When the analysis of risk prioritisation from the BBN SC risk model was shown, he thought it was more meaningful, as the results from the model explain 'chance of occurrence' which is clearer than the RR which shows 'rating number', which is unrealistic. The perceptions at the operational level is that they can interpret the meaning of results of the BBN SC risk 'very easily' (perception score is 4.33), and 'moderate' in RR (perception score is 3.33).

All outcomes were shown to the experts in workshop II, and they were asked to evaluate how difficult it was for other people who have not been involved in the modelling process to understand the model results. Both the managerial expert and operational exerts rated the BBN SC risk model one level better than RR. Bearing in mind the realistic outcomes of estimation current probability, risk prioritisation and support decision making by exploring different scenarios that were shown in workshop II, experts were asked to evaluate how realistic the modelling results were. Both the managerial expert and operational exerts rated the BBN SC risk model equal or better than RR, rating BBN between scales of 3 to 5 but RR at 3. So the highest score showing the best analysis outcomes by BBN relates to the realistic results after exploring different scenarios, something which RR is unable to provide.

Generally the realistic outcome of the scenario analysis can be presented only by the BBN SC risk model and not by the RR, so the rating of the RR in scenarios analysis cannot be evaluated. The BBN SC risk model can show the combinations of contingency of adverse events as different scenarios to link to the top event (supply the right medicine to the right patient at the right time). According to feedback from the questionnaire, the managerial expert was satisfied with the scenario analysis more than average (perception score is 4) while the operational experts expressed considerable satisfaction (perception score 4.67).

8.1.2.3 Utility of the BBN SC risk modelling process

The managerial expert and the operational experts agreed that they can gain a better understanding of adverse events in the medicine SC from other stakeholders by having a discussion during the model development. They provided an average score of about 4 (out of 5; Q4.2 in Questionnaire A) which means that their understanding improved from the modelling process more than their expectation.

The modelling process can lead them to discuss and perceive from other stakeholders' points of view how things can go wrong in the medicine SC, since they can hear and view the explanations regarding various adverse events. In addition, the managerial expert mentioned that *"people down here have never benefited from that reception (of RR). So they do not see the actual exist and what effects that they have on the chain. Taking them to the workshop they get the whole picture of the system. To me it is quite helpful."* He believes that they would benefit from taking part in the workshop since they get the whole picture of the system, not just their part. They may not get this in the process of RR development, so they do not see the actual effects that they have on the SC.

The operational experts can gain knowledge of solving problems by participating in the development of the BBN SC risk model. An operational expert pointed out that during the initial stage of BBN SC risk modelling (asking about the process and problems as the risks in their organisation units), they were able to look at problems and find ways of resolving them. In addition, an operational staff member mentioned that she learned a lot about the process to be followed and how to solve the problems. Furthermore an operational expert also expressed interest in identifying interrelationship between risks from cause to effect, because generally the experts would perceive and focus on effects of the adverse events on them rather than define their main causes as the way to construct the BBN SC risk model and she stated: *"I enjoy structuring the causal map. Working back way was very interesting and very different from any piece of work I have done before"*.

Evidence that can show the utility of modelling process is that when staff understand cause and effect relationships, they will accept some adverse events which they believed to be important but were out of their control. For example, 'shortage of staff in the PDC', an event with a high chance of occurring, was identified by an operational expert since she had to deal with the results of this adverse event. However, during the process of quantification, she had to provide the effect of 'Shortage staff' (V34-3) on the 'PDC supply delay' (V33) and she found that it did not generate the huge effect she thought, so she realised that it did not affect the PDC medicine supply. This is one of benefits which the managerial expert found – that it can improve the understanding of the operational experts as to why they cannot cope with all possible adverse events.

8.1.2.4 Visions of further implementation from the BBN SC risk model

The utility of the model outcome and visions of future implementation from the BBN SC risk model can be investigated from the empirical study. Most experts would like to use the model for training purposes. The relationship representing cause and effect can be used to show the results of adverse events which may be caused by the staff who do not follow the procedure. It can help to improve the awareness of and carefulness in their tasks. In addition some experts proposed using the model to communicate to other people who were not involved in the project, to show the outcomes of level of risks in their hospital medicine SC after the redesigned project of centralised medicines to the PDC in 2010. One expert suggested implementing the model as a format of new risk recording, by considering the interaction between events in the same way as keeping updates and monitoring risks regularly in RR, since this would be very useful for the organisation in the long term.

After all results have been presented, the model can guide the refinement or improvement of the hospital medicine supply system. Several improvement options were generated by decision maker which in summary were:

1. How much contingency stock would be needed? He would like to use the BBN SC risk model to explore new policies that can achieve the same system resilience from a cost management perspective by reducing stock levels by choosing between The just-in-time or back-up system with safety stock in medicine SC.
2. The options of safety stock should be in a variety range of medicines, or keep the high volume of medicines in the dispensary stock. Since the PDC can turn stock over much more quickly than in the dispensary, it can reduce the number of expired medicines.
3. They can improve the service quality by reducing the chances of occurrence of adverse events, in order to reduce work load on staff. Some adverse events cannot generate a huge impact on the top event because they are resolved by the staff under the defined mitigating system but more efforts are required from operational staff.
4. They can improve the resilience or the quality of the service by aiming to reduce the chance of being unable to supply the right medicine to the right patient at the right time (if it is at no cost).

The evaluation of those options can be implemented for further improvements from this BBN SC risk model.

8.2 Practical Problems and Suggestions

Besides the evaluation of the BBN SC risk model by the participants' perceptions, the observed practical problems and reflection by the analyst during implementation of the BBN SC risk process in the case study are summarised. The practical problems are identified by sixteen issues which can be categorised into four areas: model project management problems (1–4), managing participant's problem (5–6), technical problems related to analyst (7–11), and technical problems related to participants (12–16). Their causes are indicated in order to provide possible suggestions for solving them or to understand the nature of the domain. A logic diagram of these possible practical problems is shown by Figure 8-4.

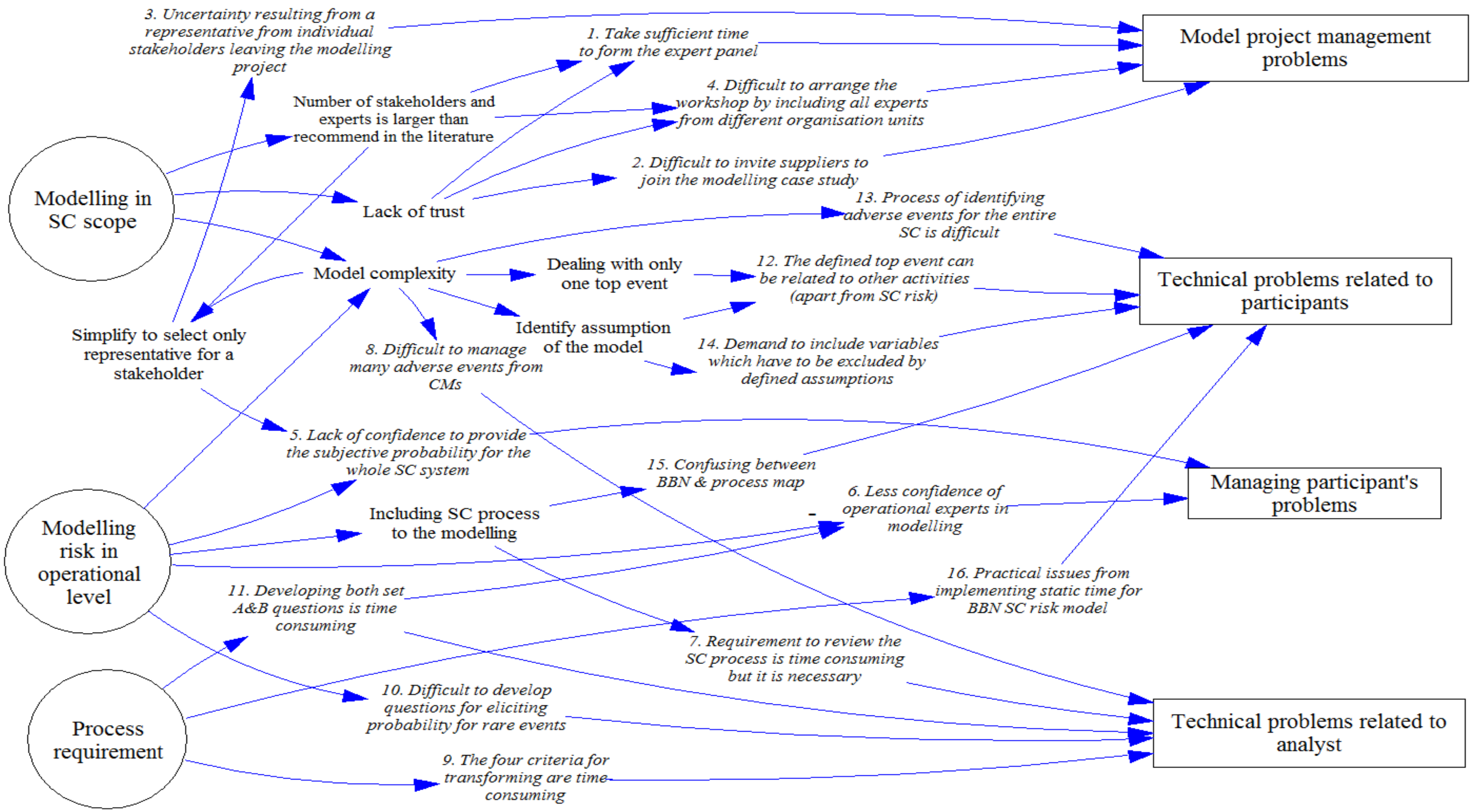


Figure 8-4 Practical problems observed by the analyst during the case study

1. *Take sufficient time to form the expert panel*

It is unsurprising that forming the full expert panel to develop the BBN SC risk model took a very long time. Although several invitations were sent via emails by the decision maker and analyst, the responses regarding participation in the modelling project were delayed for three months, demonstrating a lack of trust on sharing adverse events in a big group of stakeholders. In addition, there is no formal agreement in SC corroborations for sharing information to manage risk in SC scope.

It was found that strong support from the decision maker in explaining expectations of the project and the utility of the model was very helpful, improving levels of trust; consequently the experts decided to participate in the modelling project. Furthermore it was noted that clear information on the time involved and clear objectives should be provided to the potential experts. Alternatively, if a formal agreement of the model could be developed (as for RR), this could resolve this practical issue. Furthermore, once the initial model was developed, it can be updated for later years, a less time-consuming task.

2. *Difficult to invite suppliers to join the modelling case study*

The agreed SC boundary of the BBN SC risk model included considering the ability to access either the experts or information from relevant stakeholders.

The case study of hospital medicine SC found that the base of pharmaceutical manufacturers is not in the UK: the NHS medicine SC is global and complex (Gravesa et al., 2009). This means that the NHS medicine SC becomes less visible. One of the main difficulties in the case study was finding a representative from the supplier side, because the PDC, defined as the focal company, has never had experience of sharing information or working in projects with their suppliers. Therefore an expert from NHS National Procurement was invited as a representative of suppliers, since it is an organisation that works closely with suppliers by establishing the national contracts for all NHS boards in Scotland in order to get competitive prices. An expert from National Procurement agreed to participate. However, she had to leave (for job relocation) before the project finished so the modelling scope had to reduce by combining risks from the supplier side from only the perceptions of the PDC.

The recommendation for further study is to spend more time and effort in inviting suppliers to participate on the modelling team.

3. *Uncertainty resulting from a representative from individual stakeholders leaving the modelling project*

According to the design of the BBN SC risk modelling process, a representative for a stakeholder was invited to participate in the modelling team to cope with the scope of the problem domain. It was found that to be a practical problem when one of them leaves the project before it is ended. The modelling process is the longitudinal data collection and experts should be involved in the whole process of the BBN SC risk construction in order to prevent errors due to the possible existence of different definition for certain variables (Renooij, 2001). When an expert cannot stay for the entire process, having to recruit new experts affects the quality of the model – but it may be necessary, or alternatively the scope of SC has to be adjusted. During the implementation of the process in the case study, an expert (the representative of the suppliers) left the modelling project so the modelling scope was adjusted to cope with the problem. However, other experts contributed in the structuring of the model until it was completed. The key reasons for keeping the experts as part of the initial project, even although there is no formal agreement or formal cooperation, are trust and ownership. One of the experts mentioned that *"I was more open when analyst spend some time to communicate and the evidence to show that the analyst go to meet [other experts] to collect data from individuals"* so the standard process to collecting data would be a good evidence to improve their trust. Another key to the success of the modelling process was the ownership feeling: although no participant quotation shows this, it was observed during the workshops when they had a chance to explain adverse events in their part to others.

4. *Difficult to arrange the workshop by including all experts from different organisation units*

As the model involved many stakeholders or organisations and there was no formal agreement from their organisations to develop the model, it was very difficult to find the same free time slot from participants' regular routine work to arrange a workshop, especially as pharmacist work involves human life. Therefore working on the long-term planning by arranging the workshop in advance can help to book their time and avoid delay to the modelling project.

5. *Lack of confidence to provide the subjective probability for the whole SC system*

An issue arose from simplifying the scope by inviting exerts who are representatives of individual stakeholders in the SC – e.g. inviting a staff member of a hospital ward of a hospital – to identify adverse events and quantify probability from their perceptions on the

NHS GG&C hospital medicine SC in fourteen hospitals. When they were asked to quantify probabilities of adverse events which they may not perceive in their place of work but they thought could occur in some other hospitals, they were reluctant to provide an estimated probability.

Therefore, the analyst should motivate the expert to define the best guess of probability from all covered hospitals in the zone which could face those adverse events.

6. *Less confidence of operational experts in modelling*

The fact that the operational experts lacked confidence could be observed during the process of eliciting subjective probability. Since generally the main task of operational experts is to deliver or operate their routine works, they may have less experience of modelling or making a subjective judgement. Furthermore, medicine SC is a part of the pharmacy business and it involves experts specialising in medical service (such as pharmacists) whose work could impact human life. An expert mentioned that they are familiar with working with accurate numbers rather than approximate numbers. Therefore the procedure to elicit numbers for probability quantifications should be designed carefully by considering the level of difficulties, level of perceptions and experts' backgrounds.

Two types of questions were developed to explore the different perceptions of managerial and operational experts. The process needed to motivate the experts and explanation that the BBN SC risk model is the model of their belief or perceptions in their routine work so it is no right or wrong answer. Additionally the analyst should give them time to build their confidence by giving them the questionnaire if they want to check with records before answering the questionnaire.

7. *Requirement to review the SC process is time consuming but it is necessary*

The SC process is a main requirement when developing the BBN SC risk model so the SC processes of particular stakeholders should be linked together as the SC process map. The understanding of the SC process is a basis of the BBN SC risk model development. In the case study, it was found that particular stakeholders had their process map but it did not link entirely to the SC, so a flowchart technique was selected to develop the SC process flow by linking all operational activities together. Since the process within operational level is complicated, the flowchart is very complex and time-consuming to prepare.

Although developing a process map is time consuming, it is very important to the modelling process, not only for the analyst but also for experts. An expert found that during the interview to structure the individual CM (stage 3), flowcharting the process map helped in identifying additional adverse events and was useful for structuring the CM.

"If no process, we will not understand the cause-effects which would be wrong".

Reviewing the process flow by flowchart helped to define more assumptions of the agreed system, such as considering only general medicines (rather than specific medicines), excluding backward SC (such as the exchange and return process), excluding the current mitigating process (such as choosing the alternative medicines when the request medicine is unavailable) etc. Those assumptions were presented along with the process of model development and also when the outcomes of model analysis were presented.

Obviously evidence can show that experts who understood the SC process could understand the provisional BBN SC risk model even though there was initial confusion between them. An expert who did not understand the SC process asked many questions, so time was spent on explaining the process. As a result the workshop could not be completed in time and an extra workshop had to be arranged. For a future project, it should be ensured that all experts understand the defined SC process so the workshop can cover all intended ground in time, including time for discussion the BBN model.

This stage is therefore a main part of the modelling process. The recommendation to develop the SC process flow will be shown in Section 9.2.2.

8. *Difficult to manage many adverse events from CMs*

Many adverse events from different CMs have to be managed and a lot of variables have to be defined to develop the description. It is not difficult but it takes time and has to be managed properly to make sure that all adverse events are considered. The GeNIe software uses different colours to identify stakeholders as the sources of adverse events but it is time-consuming to use when many adverse events are identified. Furthermore when some adverse events can occur from more than one source, GeNIe would need to present in different colours and this can get confusing if the model is very complex. Future analysts may decide to use different and better techniques to solve the burden of considering many variables.

9. *The four criteria for transforming are time consuming*

A large number of variables can be a practical issue if the process is not defined effectively. The four criteria were defined by Nadkarni and Shenoy (2001, 2004) as conditional independencies, reasoning underlying cause-effect relations, distinguishing between direct and indirect relationships, and eliminating circular relations. The implementation of these four criteria in the BBN SC risk model was explored in the case study. It was found that the issue of linking from effect to cause (abductive reasoning), was not presented because all experts were asked to link adverse events from cause to effect during the manual development of CM (Stage 3 – Gain qualitative understanding of SC risk events). In addition, it was noted that assumptions of the model boundary and scope have been defined in stages 1 and 2 (e.g. excluding reverse SC flow at the operational level; see Section 7.3) so circular relations were also not shown in any CM. Only 'conditional independencies' and 'distinguish between direct and indirect relationships' were observed during structuring the provisional BBN SC risk model, so only two criteria are suggested for the modelling process later on, to reduce the workload and time spent on criteria checking.

10. Difficult to develop questions for eliciting probability for rare events

The special set B questions (see example in Section 9.2.6.1) were developed by asking frequency per time units, which suits the way experts perceive events (i.e. per week, per month etc.). If questions (either set A or B) define a short period such as a week, the experts may not be able to observe some rare adverse events that happen only a few times in a year. Therefore the boundary of time should be extended and the analyst may adjust the period of consideration in the questions during elicitation interviews.

11. Developing both set A and B questions is time consuming

Both set A and B questions were prepared (see example in Section 9.2.6.1) and given to individual experts, who were asked to select only one set to answer. This was very time-consuming. Since operational experts prefer to use set B question while managerial expert prefer to use the set A questions, suitable type of questions should be prepared for different types of experts: there is no need to prepare both sets of questions.

12. The defined top event can be related to other activities which are out of SC scope

It is recommended that only one top event is defined, to simplify the model and reduce complexity, as was noted at stage 1. In this case study the top event was 'Could not supply the right medicine to the right patient at the right time'. However, apart from medicine supply there are many other processes relevant to whether an inpatient can get the right medicine at the right time (or not), such as clinical therapy errors, medical information risks, prescribing errors etc. Therefore the assumption was made that those processes were functioning correctly, in order to scope only the risks in medicine SC activity. Therefore some identified adverse events in CMs were excluded. Some experts commented that the model would not therefore represent the true effect on the top event when they consider top event down to the possible causes. Therefore the main purpose of the model (to provide result of risk analysis in SC) and its practical limitations should be explained clearly to them.

13. Process of identifying adverse events for the entire SC is difficult

This practical problem can occur when the decision maker is asked to identify all possible adverse events in the entire SC. It is not an issue for other operational experts because they can define adverse events which are only related to their own organisational units.

Although it is difficult for the decision maker, it is an important process because it ensures that the links of the entire SC (in stage 4) cover all main relevant adverse events. The analyst can advise the decision maker to think of only direct relationships, which can reduce the number of unnecessary arrows and the complexity of the map. If the logic linking between adverse events is still unclear, the analyst can allow the adding of a new adverse event as an intermediate event until the decision maker is satisfied with the CM.

14. Demand to include variables which have to be excluded by defined assumptions

Some interesting adverse events were defined but they were outside the modelling scope of the SC process and were therefore excluded. During the workshop, when participants were asked to consider from the top event down to the cause variables, they tried to include these excluded variables since they were related to the top event. An expert mentioned that "*the model is too much exclusion"*. One of the assumptions they discussed was the agreed standard IPS system process to get urgent medicine (back-up supply system). The standard process is: 1. Hospital dispensary, 2. Other wards, 3. PDC, 4. Suppliers, and 5. Other hospitals (which may start parallel with finding from suppliers). This means that the full range of sources cannot be queried during weekends or at night when the hospital dispensary may be closed in some hospitals, so it was defined as 'only daytime during weekdays' in the assumptions. However, an expert was trying to include 24-7 activities into the model in order to see the real picture of the system. The balance between demand and ability of model to reflect reality can be discussed, and it is a main constraint when the scope of the model is defined to be as large as the SC rather than the smaller organisation unit.

15. Confusion between BBN and process map

One obvious finding from the case study was the confusion between BBN and process map. BBN is the new model which experts have not used before but they may familiar with the process map. The process map shows the flow of activities, especially in an operational process, while the BBN SC risk model can show the causal relationships of adverse events (logical relationship) rather than activities flow. The relationship of adverse events in the

BBN SC risk model is not the same as the process map. One of the discussions of the relationships in the provisional BBN SC risk model showed this confusion in the process when an inpatient does not take his/her medicines and the staff have to check those medicines from the ward stock where the inpatient is admitted. If medicines are not available in the ward stock, the staff have to source them from the hospital dispensary. Therefore the process can show the link of activities from 'Checking inpatient own drugs', 'Checking availability of medicines from the ward stock' and then to 'Checking the availability of the medicines in the hospital dispensary', a simple activity flow as shown in Figure 8-5.

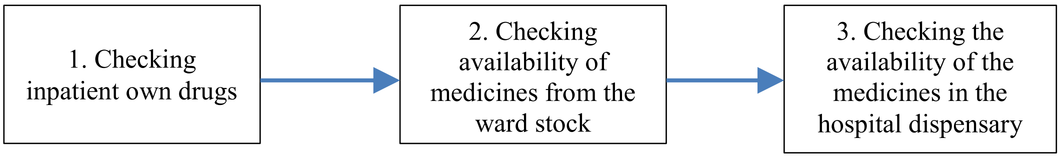


Figure 8-5 Example of simple process map

However, the provisional BBN SC risk model structure maps the causal relationships between adverse events; see Figure 8-6. 'Patient own drug (POD) unavailable or unsuitable' (V7) can be a cause of 'Out of the ward stock catalogue requested' (V10) since generally the ward will stock only special medicines for specialised treatments. Hence it can lead to 'Medicine unavailable to provide by ward' (V8). However, 'Medicine unavailable to provide by ward cupboard' (V8) is not a cause of 'Unable to get the medicine from the hospital dispensary' (V11), since the dispensary is designed to be a main source of back-up system to cover wide rages of medicine. Therefore in the full map, there is no arrow between 'Medicine unavailable to provide by ward cupboard' (V8) and 'Unable to get the medicine from the hospital dispensary' (V11). The arrows between adverse events do not necessarily follow the flow of activities in a process map.

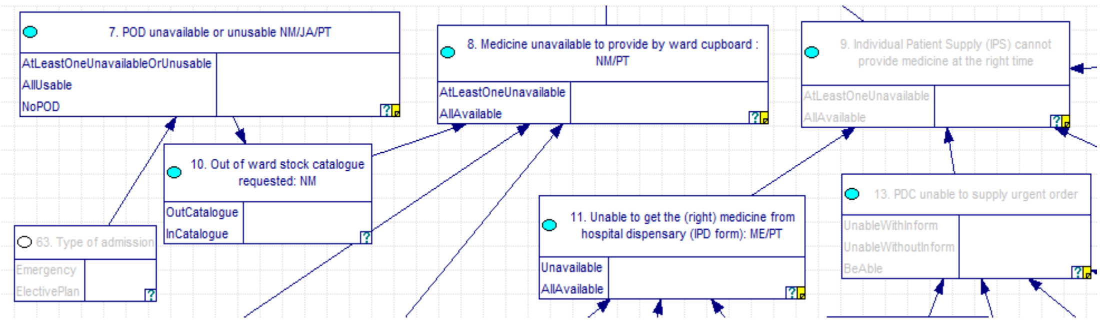


Figure 8-6 A part of the BBN SC risk model to compare with the process map

There was no confusion between maps in the stage 3 – Gain qualitative understanding of SC risk events, since the process to structure CM was designed to identify all possible adverse events before asking them to link all adverse events as a CM. Therefore participants were able to structure the CM from cause to effect without being confused by the process map. However, when they saw the provisional BBN SC risk map which links all adverse events as a whole in the workshop (stage 5), they have to link possible adverse events from the understanding of activities, so the confusion between those two maps became an issue. In general, some experts may have experience of developing process maps and as a result of this familiarity might mistakenly think that the provisional BBN SC risk is similar to a SC process flow.

Although there was confusion between BBN and the process map, the map can help participants to understand the BBN which has been explained in Section 8.2 (7).

16. Practical issues from implementing static time for BBN SC risk model

The ‘static time’ characteristic is one of the main technical assumptions of the BBN SC risk model; it captures causal effect relationship rather than the dynamic time influence of the stock level and the flow of medicines (see discussions in Chapter 2). Although the static BBN is developed to cope with risk during a period of time (e.g. defining 1 year for this empirical BBN SC risk model), it needs to be updated regularly. During the process of BBN SC risk model development, some adverse events identified earlier, in stage 3, were taken out from the model during the quantification (stage 6), as the experts thought they had already been solved. Implementing static BBN is feasible but there is a need to keep updating it (as for RR).

8.3 Benefits Gained from the BBN SC Risk Model

Benefits from using the BBN to support risk analysis, from the researcher perspective, are explained in this section.

8.3.1 Different risk prioritising results provided by dependent or independent approach

Modelling to capture interrelationships between adverse events to support risk analysis in SC can demonstrate the new aspect of analysing risk dependently rather than, as is more normal, independently. In the case study, the different results of risk priority from those two aspects were explored.

During the process of validating the BBN SC risk model behaviour (workshop II), all experts were asked to identify the first priority risk (probability and impact) from all events in the model which will affect the top event. This question aims to mimic the RR process of defining the highest risk adverse events without considering the interactions between them. They were all agreed that 'POD unavailable or unusable' (V7.1) was the top crucial risk. However, the result of risk prioritisation from the BBN SC risk model given in Section 7.5.2 shows that main causes of V7.1 are generated by 'Loss of key to medicine locker' (V5), 'Failure to order with IPS' (V51) and 'Medicine unavailable to administer into the POD locker' (V4). It was found, by diagnostic analysis from the flow of causal relationship by the BBN SC risk model, that although 'POD unavailable or unusable' (V7) had a very high chance of occurrence (Figure 7-7) it would not generate a substantial impact on the top event. This shows how the results from the RR and the BBN SC risk model can be different. Results of prioritisations from the BBN SC risk analysis may not be what the experts expect, since they (experts) rate highest risks without considering the relationship of risk events and do not take the back-up system into consideration. After the experts understood the mechanism of relationships between adverse events used by the BBN SC risk model, they agreed the analysis results.

Another benefit of implementing dependent perspectives to support risk analysis is the ability it creates for exploring different scenarios to show effects on the SC. The dependence relationships presented by BBN SC risk model show the combination of adverse events which could happen at the same time, something RR cannot do (Fenton and Neil, 2012). In the case study, there are redundant or back-up medicine supply systems such as the IPS (Individual Patient Supply) system so it can secure the medicine supply system very well and maintain the high level of responsiveness to an inpatient. When the main sources of medicine supply and back-up system do not work as the same time, the adverse effect on inpatients rises dramatically, as can be seen from the relevant scenario comparison (see Section 7.5.3).

8.3.2 How the model can support risk-benefit trade-off as a management tool

"If you do not take risk, you will not drink champagne" (Asbiørnslett, 2008, p. 19).

Risk-benefit trade-off is important for the decision making of mitigating action in risk management. Risk-reward trade-off is presented in literature. Chopra and Sodhi (2004) explained that reducing risk may also reduce profit at the current level of efficiency, but if efficiency of the SC is improved, risk can be reduced while the profit can still be increased. Some scholars (Kleindorfer and Saad, 2005) suggest mitigating risk by balancing between cost of mitigating and cost of disruption. Since budget is always limited, the lowest risk which can be achieved within budget is the main target; therefore cost-benefit is also an important tool in risk management (Frosdick, 1997). However, trade-offs to define the suitable level of risk and benefit is also dependent on the attitude or perception of the organisation to risk taking (Frosdick, 1997; Harland et al., 2003). For risk management in the SC scope, reaching a fair and balanced division of risk and benefits depends on the joint effort and type of collaboration (Harland et al., 2004). According observations during the BBN SC risk model is a visual model and becomes a suitable tool to communicate or negotiate to find the balance of risk and benefit which may affect several stakeholders in the SC, provided they can collaborate over risk management.

Risk-benefit trading off can be explored by using the BBN SC risk model, as the model is developed for the static assumption (no time element involved) and so shows the current level of effectiveness of the current SC. Using the current system, different scenarios can be explored to help decision makers find the new balance of risk and benefits by supporting the identification of new mitigating actions which aim to improve efficiency of the SC process. In the case study, different scenarios were explored to show the cause-effect relationships which can support the idea of risk-benefit (to show effect on the focus variables e.g. top event). The decision maker explained that the scenario analysis could confirm the resilience of the medicine SC, so it could support his strategic thinking that he may not need to invest money to increase the reliability of the system but they may improve service quality, reducing workload, or reduce cost instead by keeping the same resilient level.

At the next stage the decision maker can take the BBN SC risk model to show the risk-benefit results and discuss them with his stakeholders before deciding to take further actions.

8.3.3 Develop model by linking in supply chain scope

"SN complexity increases, risk increases" (Harland et al., 2003, p. 60).

In the academic research, information gathering is suggested as a strategy to reduce risks in SC (Mitchell, 1995) and to improve SC visibility (Christopher and Lee, 2004). Gathering information from networks of suppliers and customers to develop a risk management strategy seems to be the ideal method to reduce risks (Harland et al., 2003). Furthermore, information sharing is an approach that reduces the potential conflict of one party trying to get benefit from another (Khan and Burnes, 2007). In practice, risk management strategies are implemented by either partner rather than by cooperation between parties (Ritchie and Brindley, 2007a). An effective relationship should be developed, along with trust, but it has to deal with conflict of interests among parties. It is unusual for a company to provide a detailed level of sensitive and commercial information (Ritchie and Brindley, 2007a). Furthermore, sharing adverse events can be seen as bad practice, as it reveals the vulnerability of their own organisations to suppliers and customers. Therefore, practical issues were observed during the BBN SC risk model development.

Although there were challenges in getting participants on to the team to develop the BBN SC risk model, and difficulties in scheduling the workshops, the usefulness of the outcomes from developing the model more than made up for this. The model result showed that effects from individual adverse events caused by other stakeholders may not generate substantial effect on the top event, but when more than one adverse event happens at the same time, they can generate substantial effects; Section 7.5.3. Furthermore stakeholders can use the model to analyse the adverse events which could strongly influence their own organisations. One of the main advantages of modelling in the SC scope is that it helps to improve the trust and understanding between stakeholders: their working together was part of the design process. Communication at the SC level is stimulated, and the equal status assigned to participants can contribute to more effective knowledge transfer than contractual arrangement: this is a key to the success of risk management (Bowers, 1994; Ojala and Hallikas, 2006). This modelling case study also shows that network co-operation can help to identify areas of risk management effectively, by defining joint efforts (as suggested in the literature; see Hallikas et al., 2004). This is the initial phase for partners to develop relationships in the network, then move to risk management to work out the optimum strategy for finding the balance of risks and rewards between organisations.

8.3.4 Developing model with the operational experts

Although the challenges in implementing the modelling process with operational experts who may have less experience in modelling had been considered (see Section 3.4.4) and suitable techniques had been prepared to be simple and transparent (see Section 5.3), trust and confidence was still an issue, as was discovered during implementation of the case study. Furthermore the practical issues were also observed and explained in Section 8.2 (6). The benefits which participants can gain from the BBN SC risk modelling process (see Section 8.1.2.3) outweigh the challenges.

In interview, the decision maker said he was satisfied with the process of BBN SC risk modelling, since it helped operational experts to see the whole risk in SC, developing their overall understanding. This makes the BBN SC risk model different from RR.

8.4 Summary

It is clearly that the BBN SC risk modelling process is practical and useful for both decision maker and operational experts. According to the analyst's perspective, the process went very well although practical problems were identified; see Section 8.2. Most of the practical problems are caused by the nature of the modelling scope rather than by requirements of the modelling process (see Figure 8-4). Although the nature of modelling scope is difficult to manage, the primary BBN SC risk model was well operated but needs a little improvement. Additionally reflecting on practical problems can provide useful information for future users: they can be aware of the problems and prepare the solutions in advance. Benefits gained by application of the BBN in SC via BBN SC risk modelling process from the research perspective are discussed in Section 8.3. The clear evidence is that applying BBN via systemic risks, support risk-benefit analysis, risk analysis in SC scope and working with the operational experts is useful.

All in all, the modelling process evaluation finding by participants, together with the identified practical problems and suggestions by the analyst for solutions, provides evidence to support a practical contribution to industry. Furthermore the primary BBN SC risk modelling process which has been implemented in the case study will be improved by correcting the practical problems before suggesting the proposed BBN SC risk modelling process (shown in Chapter 9).

Chapter 9 Proposed BBN Supply Chain Risk Modelling Process

After the BBN SC risk modelling procss design proposed in Chapter 5 was explored within the NHS GG&C hospital medicine SC case study. We can gain an insight into the application of the modelling process. Furthermore the results of process trail in the empirical case can be used to identify practical problems to adjust and revise proposals for the general process in this chapter. The purpose of the general process is to provide a step-by-step process to establish the BBN SC risk model for risk analysis and also provide the example that was implemented in the case study. The experience of conducting the case study provides initial information to approximate the required resources allocation for the planning process which organisations can use to support the decision of implementing the process for their SC.

9.1 Planning Process

There are three main roles contributing to the BBN SC risk modelling process. Apart from the decision maker and operatinal experts as the risk owners, an analyst is required. The proposed process is based on the operation by an analyst.

General resources required for the various stages of the modelling process are shown in Table 9-1. A series of interviews and workshops, set out in eight stages, can be developed over 4–10 months (depending on the availability of the experts). Some stages can be conducted in parallel. Each interview should take 1–2 hours and workshop shouldtake about 3 hours. In summary:

Number of analysts: 1

Number of decision makers: 1

Number of experts: 4–8

Duration of data collection: 4–10 months

Table 9-1 Estimated time by stages of the process and roles

Stages	Experts	Decision maker	Analyst
1. Identify SC scope and stakeholders	-	2 interviews	1 week
2. Review SC process flow	-	1 interview	1 month for document review of the SC process
3. Gain qualitative understanding of SC risk events (Interview protocol)	Individual interviews*	1 interview	1 month** for collecting data by interviewing individual experts
4. Structure the provisional BBN SC risk model	-		1 week for structuring the model
5. Refine the BBN SC risk structure (Refine the BBN SC risk model structure workshop protocol)	1 workshop		1 week for preparing document and may require a facilitator for supporting big groups of experts
6. Quantify the BBN SC risk model *6.1.* Before	-	-	1 weeks for preparing questions
6.2. During	Individual structured interviews*	Interview (for some variables)	1 month** for collecting data by interviewing individual experts
6.3. After	-	-	1 week for inputting probability
7. Use BBN to support SC risk analysis	-	-	1 week for preparing analysis results
8. Validate BBN SC risk model behaviour	1 workshop		1 day

Note: * Depends on number of experts

** Depends on the avaviability of the experts

The BBN SC risk modelling process was designed by considering what the optimum time involvement with the experts should be (i.e. spend minimum time with experts and also the analyst should use up as little time as possible). The BBN SC risk modelling process involves two interviews and two workshops for individual experts: this was acceptable to experts. The decision maker is required for five interviews and two workshops. The main demands on the technical task and co-ordination to operate the modelling process is the responsibility of the analyst: the highest demands were when the BBN SC risk model is first being established; the minimum time required is approximately the four months.

9.2 Doing Process

The process of developing the BBN SC risk model is defined by eight stages as summarised in Table 9-2.

The assumptions list of the model should be created and more assumptions can be added into the list during the modelling development. The list of assumptions is used during all stages involved with the experts by the BBN SC risk model. It can help to ensure that participants provide their perceptions under the same reference conditions, and can help to interpret the results of analysis.

Table 9-2 Summary of proposed BBN SC risk modelling process and procedure

Outcome		Stages	Participants
Problem structuring	Provisional BBN SC risk model	1. Identify SC scope and stakeholders 1.1. SC performance 1.2. SC boundary 1.3. Stakeholders 1.4. Time frame	Decision maker (Interview)
		2. Review SC process flow	Experts & Decision maker (Document review/interview)
		3. Gain qualitative understanding of SC risk events (Interview protocol)	Experts & Decision maker (Interview)
		4. Structure the provisional BBN SC risk model 4.1. Combine identified adverse event with the core risk model 4.1.1. Merge similar adverse events into the same variable 4.1.2. Link relevant adverse events to the core risk model by checking the four main criteria 4.1.3. Check variables which do not follow the defined assumptions 4.2. Develop variable and state descriptions	Analyst
	Refined BBN SC risk model	5. Refine the BBN SC risk structure (Refine the BBN SC risk model structure workshop protocol)	Experts & Decision maker (Workshop)
Instantiation	Full BBN SC risk model	6. Quantify the BBN SC risk model 6.1. Before (Prepare questions & Validate variables and state)	Analyst
		6.2. During (Explain the expectation of subjective knowledge, Show a short training example, and Expert fill the questionnaire)	Experts & Decision maker (Interview)
		6.3. After (Aggregations (for some variables), Input numbers into software, Verification)	Analyst
Inference	BBN SC risk analysis	7. Use BBN to support SC risk analysis 7.1. Prepare risk analysis 7.2. Sensitivity analysis	Analyst
		8. Validate BBN SC risk model behaviour (Face validity workshop protocol)	Experts & Decision maker (Workshop)
Note: 1. Model assumptions should be defined and keep updating as the list of assumptions which experts and analyst can use as the reference during the process of model development and define the constraints of the model outcomes.			
2. Analyst can be allowed to revise the model structure although during the process to quantify the BBN SC risk model (stage 6).			

9.2.1 Stage 1 – Identify SC scope and stakeholders

This stage comprises defining the purpose of the model and modelling scope with the decision maker via several interviews. There are four specific scopes of the model that should be defined, as detailed below. Furthermore, if the SC involves many types of products that have different SC processes, the analyst should ask the decision maker so scope for specific type of products, in order to control potential confusion and develop a list of assumptions to be agreed during modelling process; see example of assumption list in Section 7.3.

9.2.1.1 SC performance

Aim: To identify the top event of the BBN SC risk model.

How: Asking the decision maker to identify an aspect of SC performance which can represent the goal of his/her SC as a measurable or observable event by SC operational staff.

For example the decision maker in the case study defined a specific, measurable or observable adverse performance event to represent SC reliability as *'Could not supply the right medicine to the right patient at the right time'* and this was defined as the top event of the BBN SC risk model.

Supporting tool(s): Operational SC performance categories (Section 5.1.1)

Limitations: Recommend the identification of only one SC performance event, to reduce complexity of the model. Cost was excluded as a top event, and has not been explored by the case study.

9.2.1.2 SC boundary

Aim: To define the geographical SC boundary.

How: Asking the decision maker to identify scope of the SC to model adverse events at the operational level, which is quite detailed. The discussion with the decision maker can help to arrange trade-offs between available resources and scope of the model.

For example, the SC scope was defined by determining the PDC as a focal organisation in the NHS GG&C SC and the network of suppliers was defined as wholesalers or manufacturers who can supply medicines to the PDC. The network of customers was indicated by dispensary and wards before medicines were administered into the POD locker and then supplied to inpatients. However, the model was bounded by excluding the medicine flow after an inpatient left the hospital and also from the flow from manufacturer to the wholesaler, as shown by dashed lines in Figure 7-1.

Supporting tool(s): Geographical SC map

9.2.1.3 Stakeholders

Aim: To identify an expert panel representative of the identified stakeholders.

How: Stakeholders can be identified by the decision maker from the SC boundary scope. The decision maker should suggest experts who can represent stakeholders, to form the expert panel. After the team is suggested, an analyst can provide invitation documents and send them out with recommendations and motivating support from the decision maker. The invitation will be used for motivation purposes, and will briefly describe the process and expectation of participant contribution at each stage of data collection.

For example, there were eight key experts who took a part in the BBN SC risk modelling expert team: a decision maker, seven staff from PDC, National Procurement, hospital dispensary and ward and a supplementary prescriber for inpatients medication (see Section 7.2. for more detail).

Limitation: Define only one representative from each stakeholder organisation, to control the number of experts in the team.

9.2.1.4 Time frame

Aim: To identify an agreed time frame for the coverage of the model.

How: The decision maker can specify a time frame during which the SC system is not likely to change (as a result of new policy or new operations etc.). Alternatively the decision maker can define the same cycle time as their current risk management process. The defined time frame is an assumption that should be clearly explained to the expert panel during the process.

For example, referring to the case study, the BBN SC risk model was defined to cover the year from May 2012 to April 2013. This determination was made to ensure that all possible seasonal adverse events in the hospital medicine SC could be captured by the analysis.

9.2.2 Stage 2 – Review the SC process flow

Aim: To identify and review the process product flow linking stakeholders in the defined SC scope, under the defined modelling assumptions.

How: The process map can be developed by reviewing documents and interviewing the decision maker or experts.

The process flow in particular stakeholder organisations was structured in the case study by reviewing the available documents or available process flow maps and interviewing decision maker or experts. The SC process flow should use the same format of available documents, as it is then easier to communicate to experts. After the SC process flow is developed, it can be used as a tool to communicate with experts: it should be confirmed when interviewing experts in stage 3.

Supporting tool(s): There are number of techniques or frameworks to support SC process flow development. For example, framework of SCOR (the Supply Chain Operations Reference), standard tools such as IDEF0 (Integrated Definition Language), Gantt charts, Process decomposition, or flowcharts.

9.2.3 Stage 3 – Gain qualitative understanding of SC risk events

Aim: Collect perceptions from individual experts.

How: Use the suggested interview protocol and supporting tools to structure CM for particular stakeholders: experts have to be interviewed individually.

The semi-structured interview protocol for gaining qualitative understanding of SC risk events can be shown in four steps as summarised in Figure 9-1.

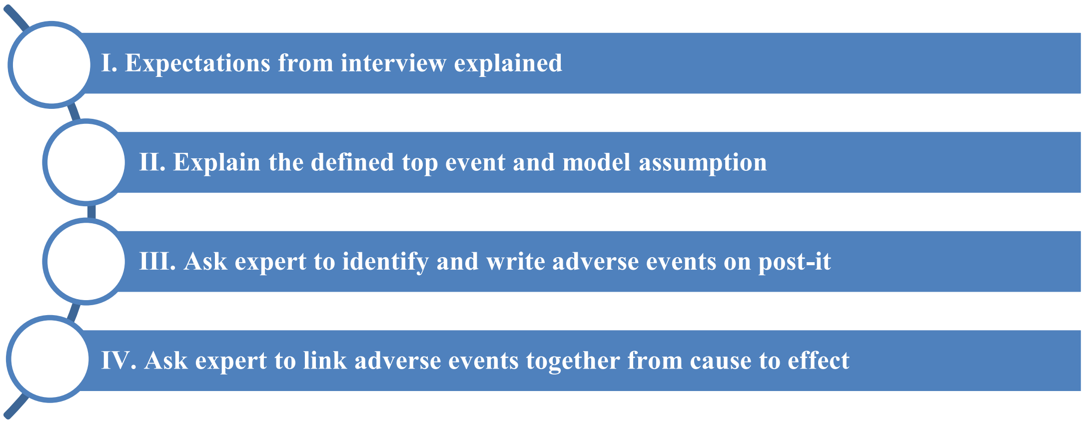


Figure 9-1 Interview protocol to structure CM for stage 3 – Gain qualitative understanding of SC risk events

The first interview should start with the decision maker, so as to understand all possible adverse events in the entire SC. The decision maker's CM can then be used to show as the example to other experts: this can improve trust from individual experts before they start to identify adverse events in their organisation unit. After interview, any remarks or comments on the scope of the model should be updated into the assumption list. The CMs and adverse event definitions which were recorded during interview should be transformed to the soft copy format and sent to individual experts to confirm their accuracy.

During interviews to gain qualitative understanding of SC risk events, an analyst should explain the expectations from the interview: in particular that when identifying adverse events there is 'no right or wrong answer' and the analyst would like participants just to share their perceptions of adverse events. If an expert's memory or imagination fails, so that identification of adverse events is likely to be incomplete, the analyst can ask the expert to study the SC process flow (only for their organisation unit), to help think of more possible adverse events. Finally, each expert was asked to link all identified adverse events together, from cause to effect, to develop the CM.

Supporting tools: Tools that can be used to support risk identification by interview are:

1. *SC Process flow* for supporting adverse event identification (see stage 2).
2. *Terminology list* can help the experts understand some technical words, especially when they are working in different stakeholder organisations or working in different positions.
3. *Monitoring methodology and bias management* is useful resource for the further reading; see also Arthur and Gröner (2005).

9.2.4 Stage 4 – Structure the provisional BBN SC risk model

The analyst uses the responses to structure the provisional BBN SC risk model, by combining CMs from different experts into a BBN and developing the variable and state descriptions.

9.2.4.1 Combine identified adverse events with the core risk model

Aim: To merge adverse events from individual CMs into the same network of BBN structure (the provisional BBN SC risk model).

How: Use the three steps of the suggested procedure.

1. Merge similar adverse events into the same variable

The descriptions of some adverse events are slightly different because they are defined by different stakeholders with different perceptions. But if they in fact refer to the same adverse events, they can be merged. If they propose a single risk event which can be defined as a set of adverse events, the analyst can consider splitting it into two or more variables by considering the clarity of the causal relationships.

During the case study, one member of staff in the PDC defined an adverse event as ‘Delayed supply to a ward’. This had the same meaning of ‘Deliver delay from the PDC’ identified by an expert from the ward, so the two needed to be merged into the same variable. On the other hand, some adverse events can be split into separate variables. In the case study, an expert defined an event as ‘Human errors or manual error (in the process of checking the order at the receiving area in PDC e.g. missing items)’. According to her explanation during interview, this could be divided into two variables: ‘Missing item checking error’ and ‘Put urgent order with regular order’. Since after this stage the adverse event will be transformed into variable format for use in later stages, the ownership of the experts and their interest should be maintained, so the initials of the experts who mentioned particular adverse events should be retained in variable references in the provisional BBN SC risk model.

2. Link relevant adverse events to the core risk model by checking the four main criteria of CM transformation

The core risk model (see Section 5.2) will be implemented to support this stage by combining relevant variables which have been identified in CMs into the same model of the SC. The general core risk model should start by identifying the top event and then identifying the regular supply disruption and back-up supply disruption relevant to the top event.

In the case study, there are two sources of regular medicine – supply by inpatient by taking their personal drug with them: (Patient Own Drug (POD)) or the ward will prepare special medicines which are necessary for inpatients having treatment in the ward. Therefore regular medicine supply disruption can be identified by ‘POD unavailable and unusable’ and ‘Additional medicine unable to provide by ward’ variables. Furthermore the ‘Individual Patient Supply (IPS) cannot provide medicine at the right time’ variable is defined as ‘Back-up supply disruption’ and this is a combination of five urgent supply sources which were included in the model. The major adverse events that were identified similar to the defined variables in the core risk model as the stock-availability and supply-ability concepts were combined as the core of the provisional BBN SC risk model. After the major adverse events were linked, the result was as shown in Figure 9-2.

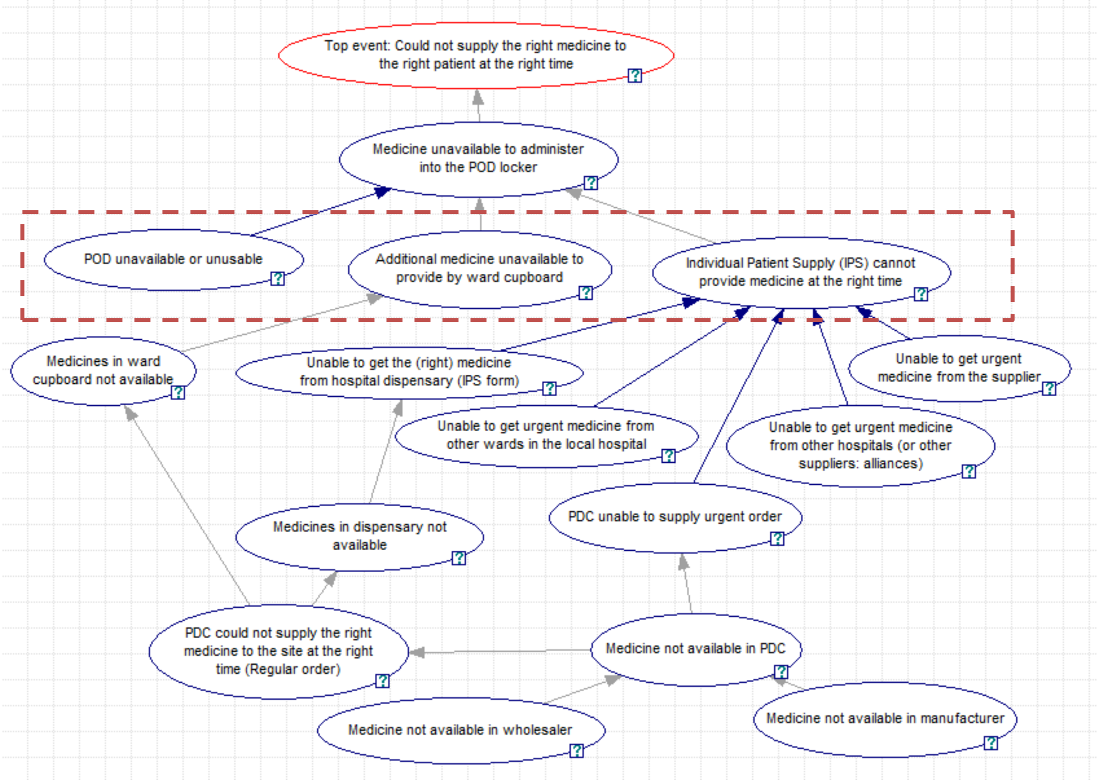


Figure 9-2 Adjust the core risk model in the event level

When the core adverse events/variables are linked, the other events can be combined into the provisional BBN SC risk model by the four criteria of the transforming from CM to BBN, which were explained in Section 3.2.1. After the four criteria were explored in the case study, it was found that only **Distinguish between direct and indirect relationships** and **Conditional independencies** were implemented for checking for transforming.

For example, 'distinguish between a direct and an indirect relationship', was observed in the case study and it was very useful in reducing the complexity of the model. Figure 9-2 shows that 'Medicine unavailable to administer into the POD locker' can occur when the disruption of the medicine supply system (supply-ability) happens. 'POD unavailable or unsuitable', 'Additional medicine unavailable to provide by ward cupboard' and 'Individual Patient Supply (IPS) cannot provide medicine at the right time' already were defined as all possible causes in the core model. Furthermore 'Incorrect medicine selected (from ward or hospital dispensary)' had been identified by some experts in their CM and should be added into the core model. The position to add the variable in can be worked out by considering whether the direct effect from 'Incorrect medicines from ward or dispensary' can affect 'Medicine unavailable to administer into the POD locker' rather than supplying the wrong medicine to the patient. Since the experts confirmed that all medicines should be checked before being admitted into a POD locker or bedside locker, if the medicines are wrongly selected, they cannot be admitted. The staff have to try again to get the right medicines, and this can impact directly on 'Medicine unavailable to administer into the POD locker' if they cannot get the medicine at the second attempt, rather than impacting directly on the top variable (see Figure 9-3).

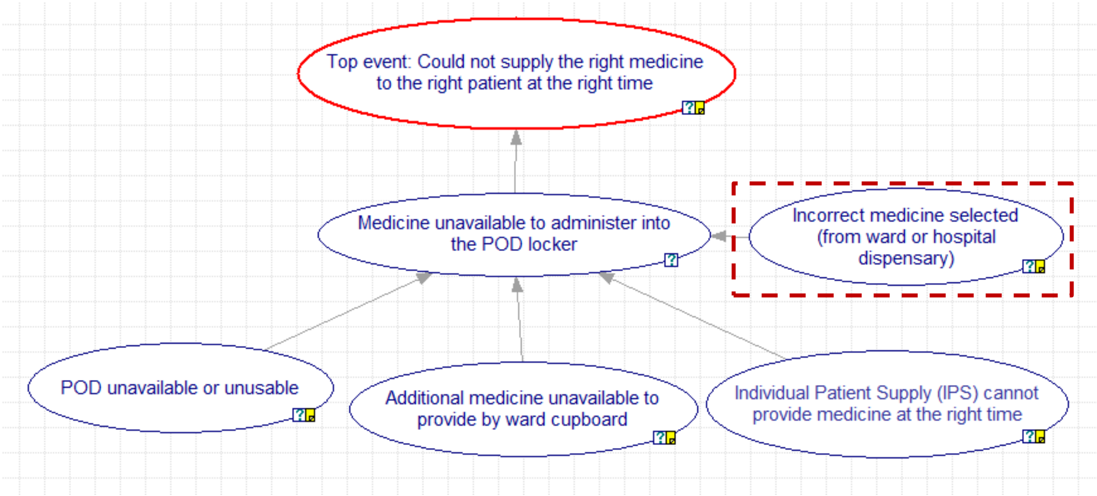


Figure 9-3 Example of conditional independence

Conditional independence can help to understand structure of the model by linking back to the BBN theory and concept. Generally, the conditional independence criterion is automatically accepted after checking direct cause and effect structure to link variables in the core risk model. This criterion can help to ensure that the modelling structure can hold the BBN property of conditional independence (see Section 3.1.2). As an example from Figure 9-3: the serial links of variables or causal chain go from 'Individual Patient Supply (IPS) cannot provide medicine at the right time' to 'Medicine unavailable to administer into the POD locker' and to 'Could not supply the right medicine to the right patient at the right time' as a causal chain (see Section 3.1.2). If staff know that the medicines are unable to admit into the POD locker, the additional knowledge that at least one medicine will not available for an inpatient does not change the belief about whether IPS can provide the medicine or not. If staff do not know whether the medicines are unable to admit into the POD locker, the knowing at least one medicine will not available for an inpatient provides information about 'IPS cannot provide medicine'.

Once more variables are added, some may change the link of the pre-added variables: the criteria checking allows adjusting the variables which have been added into the model.

3. Check variables which do not follow the defined assumptions

During the merging of all defined adverse events into the provisional BBN SC risk map, some defined adverse events may be excluded from the modelling scope because they are out of the modelling assumptions which have made according to the limitation of the model coverage.

For example, ‘Wrong assessment of patient own drug by nurses’ was defined in the raw CM as an adverse event during interview, but it was excluded from provisional BBN SC risk model as a consequence of the defined modelling assumption of assuming that clinical treatments are correct (see the list of assumptions in Section 7.3).

After combining all relevant adverse events from CM into the provisional BBN SC risk model, the raw CM should be recorded to keep track of how adverse events in their CM were transformed into the provisional BBN SC risk model; this record should be given to the individual experts during stage 5 – Refine the BBN SC risk structure.

9.2.4.2 Develop the variable and state descriptions

After the provisional BBN SC risk model is completed the adverse events can be transmitted directly into a variable or a state format. In the large model of the provisional BBN SC risk model, it is useful to identify ID numbers for particular variables so that it is easier to communicate with others.

There are two main types of states: two-state/bivariate or multi-state. The adverse events in CM and variables in BBN are similar in that they can both be defined by two- state variables, showing simply that an event is ‘on’ or ‘off’. Therefore very little changes is made by transforming the adverse event to the variable (see example of ‘PDC supply delay’ (V33) in Table 9-3).

Table 9-3 Example of bivariate-state description for ‘PDC supply delay’

State	State description
Delay supply	Proportion of orders where requested delivery date is delayed outside the agreed window
On time supply	Proportion of orders which is delivered on time

On the other hand, if there is a requirement to explore variables in more detail, multi-state variables can be implemented. From the case study, the top event ‘Could not supply the right medicine to the right patient at the right time’ was identified as a variable in BBN SC risk model. More precisely, the main reasons for it can be listed as '*No drug*', '*Unsuitable quality*', '*Normal administration*', so it is a multi-state variable. When a nurse accesses the POD locker to get medicine for an inpatient, it is possible that several medicines can be prepared for an inpatient at the same time; some medicines may not be available or some of them may not be in a good condition. Since only one state can be happen at a time in order to keep the property of mutually exclusive states, a new state needs to be added: '*Both no drug bad quality'*. Furthermore, it is important to check that all states of a variable can cover all possible events (known as *exhaustive sets*; see more explanation in Section 3.1.3). From the defined states above, all four states can cover all possible events of 'Could not supply the right medicine to the right patient at the right time' variable. The variable and state descriptions of this variable are recorded as an example in Table 9-4.

In the case study, most of the variables in the provisional BBN SC risk model were defined simply such as '*Yes'* or '*No'*, as bivariate variables, because of the constraint of using the Noisy-OR technique (which will explained in stage 6) and it is easier to understand for experts who may not be familiar with modelling (which will be explained in stage 5). However, the size of the BBN becomes bigger since some adverse events cannot be grouped and represented by multi-state variables.

Supporting tool: Core risk model (Section 5.2)

Table 9-4 An example of variable and state description of 'Could not supply the right medicine to the right patient at the right time' (top event)

Variable/state	Variable/state description
Could not supply the right medicine to the right patient at the right time	The event that an inpatient could not get the right medicine at the right time from her/his POD locker (i.e. no later than two time windows (4-8 hours) of the original drug Kardex – excluding the process of getting an alternative medicine).
No drug	At least one medicine in the drug Kardex is not available in the POD locker.
Unsuitable quality	The quality of at least one medicine in the drug Kardex makes it inappropriate to use.
Both no drug bad quality	At least one medicine in the drug Kardex is not available and the quality of at least one other medicine in the drug Kardex makes it inappropriate to use.
Normal administration	All medicines listed in the drug Kardex are available and of the proper quality to use.

9.2.5 Stage 5 – Refine the BBN SC risk structure

Aim: To refine the BBN SC risk model structure into a form with which the decision maker can agree.

How: Take the provisional BBN SC risk model to the workshop for discussion; following the suggested workshop procedure.

The provisional BBN SC risk model was brought to the discussion workshop (I) for modification of the whole SC by the expert panel, after the partials were identified by individual experts. It was necessary to have the decision maker in the workshop in order to get agreement of the refined model structure before moving to the quantification stage.

Since the group of experts is quite large, a facilitator who can operate the workshop was invited, to be assisted by the analyst in managing the workshop effectively. Before the workshop started, the raw CMs, the new record of CMs, provisional BBN SC risk model and variable and state descriptions should give to the experts to support the discussion. The procedure of the workshop, three main suggested steps which should be operated in 2–3 hours, is summarised in Figure 9-4.

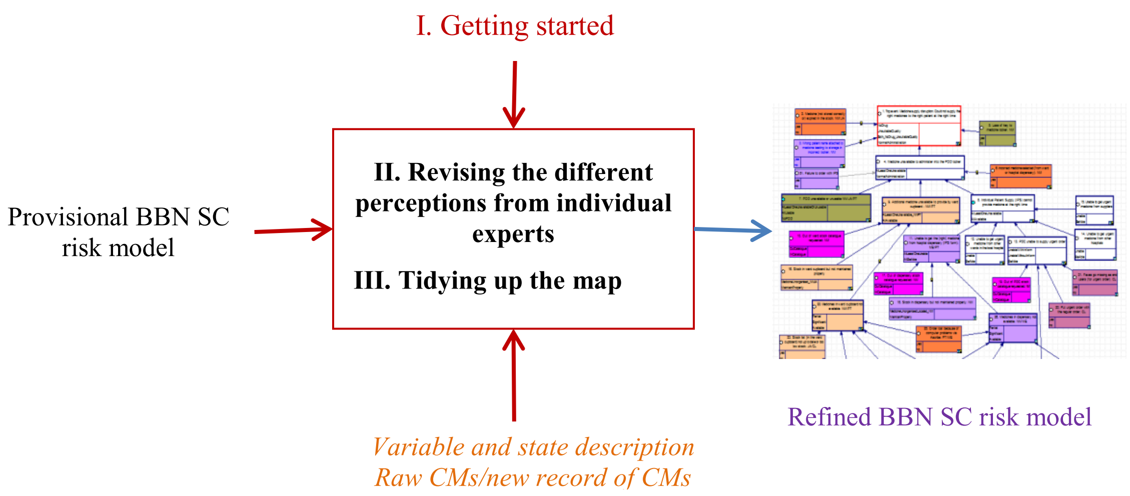


Figure 9-4 Procedure of modifying agreed BBN SC risk structure at workshop

I. Getting started

In the workshop, the facilitator explained the expectations and purpose of the workshop and reminded participants of the top event, scope of the models and modelling assumptions. Next the facilitator explained the process of developing the provisional BBN SC risk model from their CMs; this included a general explanation of the four transforming criteria and limitations of the model.

II. Revising the different perceptions from individual experts

Open discussion on the top variable down to root variables took place under the following guidelines:

1. Recheck whether states or variables which are indicated by only one expert should be included
2. Agree on variable definitions and relations checking (validation purpose).

The BBN structure can be validated by the expert panel using two types of validation: a clarity test and variable definition and relations checking (see the list below).

Clarity test

Do all variables and their states have a clear operational meaning to all stakeholders?

Variable definition and relation checking

a. Are they named usefully?
b. Are state values appropriately named?
c. Are all relevant variables (under the modelling scope and assumption) included?

III. Tidying up the map

During this process, all experts can recheck the flow of the causal adverse events.

Because of time limitations and the large size of the model to be considered, the analyst should ensure that all experts understand the whole SC process, which in turn can help experts to understand the provisional BBN SC risk model better so the workshop will be organised more effectively.

Supporting tools: It is very helpful for all experts to visualise the whole map rather than small pieces. However, the size of the model is too large to be shown onscreen by GeNIe. Using manual post-it and whiteboard or big posters are suitable alternative options, and these were used during discussion effectively.

Limitation: The workshop session should not be longer than three hours.

9.2.6 Stage 6 – Quantify the BBN SC risk model

Aim: To quantify the BBN SC risk model.

How: Implement the suggested process in three parts: before, during, and after quantification.

Before: the refined BBN SC risk structure resulting from the workshop from the previous stage will used to underpin the development of questionnaires for quantification. During: the analyst arranges to interview individual experts to elicit probabilities. After: all subjective probabilities are input into the software and their accuracy is verified.

9.2.6.1 Before the elicitation

Preparing questions and validating variables are the tasks of this stage.

1. **Prepare questions**

Structured interview by questionnaire in the frequency format was the selected method for probability elicitation. While preparing the questions, the analyst can decide to adjust the structure of the refined BBN SC risk model by implementing the Parent divorcing technique (Appendix F.1), for any variable connected to many parents (to reduce the burden of probability elicitation). This reduces the complexity of the CPT and also the complexity of questions.

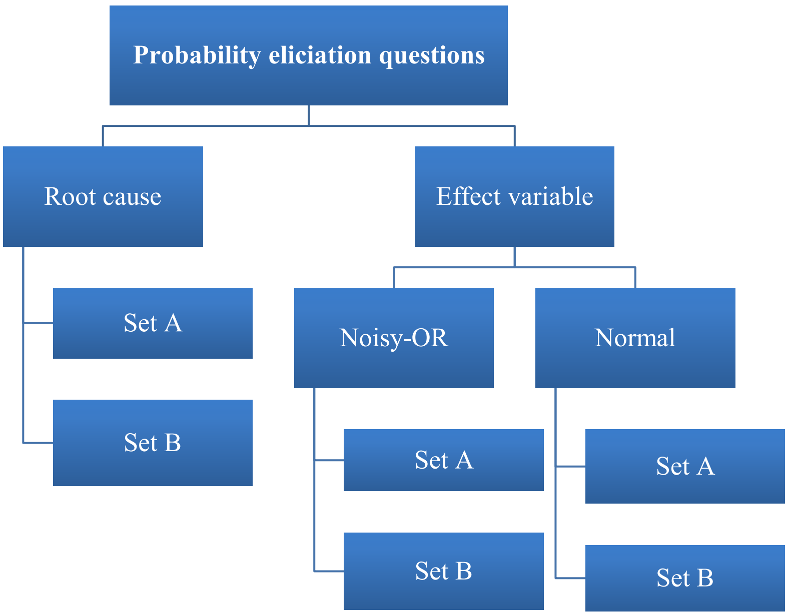


Figure 9-5 Types of questions for eliciting subjective probability

Two alternative sets of questions to elicit probability can be implemented (Section 5.4.6.1). It was found in the case study that set A questions are suitable for managerial expert(s) but set B questions are suitable for operational experts. Those two types of questions can be developed for either root cause or effect variable. Since the effect variables were complex and which required a lot of input, Noisy-OR technique (Appendix F.2) is also useful in reducing size of the CPT, apart from changing the structure of the model by applying the parent divorcing technique (Appendix F.1). Possible types of questions are classified as in Figure 9-5 and example of different types of questions will be presented.

Example of questions shown by types of variable: set A and B questions.

Two types of questions are suggested for managerial and operational experts so example of both types of questions will be shown by types of variables.

a. ***Root cause variable***

A root cause variable is an initial cause which can generate a chain of effects. The probability input for a root cause variable is the chance that the root cause happens. Set A and B questions have been developed for the case study to elicit probability. The question example to elicit a root cause variable can be shown via example of 'Medicine recall by supplier (in PDC)' (V35-1) as:

Set A: *Think about a regular week (during May 2012 to April 2013), in 100 medicines which could be in the PDC stock catalogue, how many of them could be recalled from the suppliers?*

Set B:

1) *In a regular week (during May 2012 to April 2013 not just report from the current week) how many medicines could be in the PDC stock catalogue either in the robot or manual picking area?*

2) *How many of them could be recalled from the suppliers?*

b. ***Effect variable***

Generally the questions can be structured for each effect variable by considering a set of its parent variables. In the example, the causes of 'PDC supply incomplete order' (V52) were identified in the BBN SC risk model as 'Medicine recall by supplier (in PDC)' (V35-1) 'Damage or poor handing' (V35-2) and 'Medicine in PDC not available' (V36); see Figure 9-6.

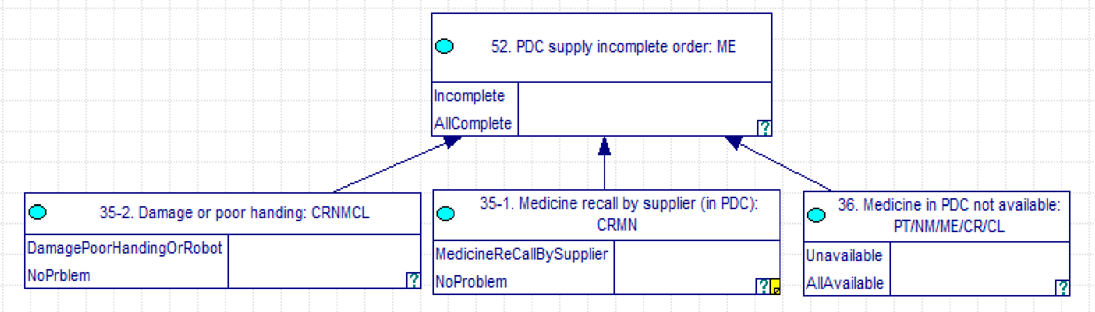


Figure 9-6 Example showing three causes of 'PDC supply incomplete order' (V52)

The analyst can select to use Noisy-OR or normal technique for eliciting an individual effect variable so question examples (both set A and B) of both techniques are provided.

Effect variable (with Noisy-OR technique)

The CPT of an effect variable (*Y)* can be elicited by Noisy-OR from general question format:

> *"What is the probability that Y is present when X_i is present and all other causes of Y that we are considering in the model are absent?"* (Zagorecki and Druzdzel, 2004, p. 882)

According to the example (Figure 9-6), three probability numbers (number of its parent variables) are required for populating the CPT of V52 since a parent cause is set as present the other two will be set as absent. The example to elicit one of three probability numbers can show by list of question(s) for probability of V52 = *Incomplete* (V52.1) when *V35-1.1* (representing present state), *V35-2.2* (representing absent state)*, and V36.2* (representing absent state).

Set A: *In 100 medicines in PDC stock catalogue which could be recalled from the suppliers how many of them could not be supplied or be supplied incompletely to the hospitals? {When there is no problem of damage or poor handing medicine in PDC and problem of unavailability of medicine in PDC stock}*

Set B:

1) *In a regular week (during May 2012 to April 2013 not just report from the current week) how many medicines could be in the PDC stock catalogue*

either in the robot or manual picking area? (Similar question 1 of set B for root cause variable example above)

2) *How many of them could be recalled from the suppliers?* (Similar to question 2 of set B for root cause variable example above)

3) *In a regular week if there are medicines which are recalled from suppliers, how many of them could not be supplied or be supplied incompletely to the hospitals? {When there is no problem of damage or poor handing medicine in PDC and problem of unavailability of medicine in PDC stock}*

   (Question 2 and 3 of set B will be used to calculate probability number as will represent the same as set A.)

Effect variable (with normal technique)

Although the case study implemented Noisy-OR technique for quantification, the question example for eliciting probability numbers by normal technique will be given. According to the example (Figure 9-6), eight probability numbers (which is 2^3) are required for populating the CPT of V52 by normal technique while three probability numbers are required by Noisy-OR technique, see Appendix F.

The CPT of an effect variable can be elicited by normal method from a series of questions which are developed from the combination of all possible states of all parent variables.

What is the probability that Y is in state y when $X_1 = x_1, X_2 = x_{2, \dots}, X_n = x_n$?

when	n	is number of causes of Y
	y	is possible states of Y
	x_i	is possible states of X_i

The example of set of questions to elicit a probability of eight probability number is the probability of V52 = *Incomplete* (V52.1) when *V35-2.2, V35-1.1 and V36.1* can be shown as below.

Set A: *In 100 medicines in PDC stock catalogue which include 'no problem of damage or poor handing medicine in PDC', 'some medicines could be recalled from the suppliers' and 'some medicines could be unavailable in PDC' how* *many of them could not be supplied or be supplied incompletely to the hospitals?*

Set B:

1) *In a regular week (during May 2012 to April 2013 not just report from the current week) how many medicines could be in the PDC stock catalogue either in the robot or manual picking area?*

2) *How many of them could be no problem of damage or poor handing medicine in PDC, some medicines could be recalled from the suppliers and some medicines could be unavailable in PDC?*

3) *In a regular week if there are medicines which is no problem of damage or poor handing medicine in PDC, some medicines could be recalled from the suppliers and some medicines could be unavailable in PDC, how many of them could not be supplied or be supplied incompletely to the hospitals?*

The answers from the set of questions can be calculated as proportions and input into CPT, as explained in Section 3.1.4. Although there are more set B than set A questions, some questions from set B can be reused from root cause variables which may have been answered earlier. From the example above, questions 1 and 2 of the set B questions are similar to questions 1 and 2 of the root cause variable. Therefore in practice when preparing set B questions, they can be grouped for variables which can share the same series of questions, in order to reduce repeating questions and the elicitation interview can be run effectively.

Supporting tools:

1. Noisy-OR technique (Appendix F.2)
2. Parent divorcing technique (Appendix F.1)

2. Validate variables and states

After all questions have been developed, the analyst should validate the consistency of the variables and states, including the defined questions, by following the questions guideline in the list below.

Consistency checking

a. *Are the state dimensions (e.g. a week, in a month etc.) and state units* *(orders, products, units etc.) across different eliciting questions consistent?*

b. Are all state values useful or can some be combined?

The questionnaire should be pretested before implementation. Furthermore, the questions should be sent to the experts before the interview date.

9.2.6.2 During elicitation

The protocol of quantification to elicit subjective knowledge (see Figure 9-7) starts to elicit probabilities with the explanation of the expectations of subjective knowledge. A short training example was shown to help familiarise the experts with format and sequence of questions. After they gained an understanding of the process, the questionnaire could be given to them; and then they were asked them to read through all questions and discuss with any unclear questions. If any participants do not feel confident enough to answer questions during interview (because they want to check some recorded data), the analyst can leave the questionnaire with them and make appointments to revisit for collecting or interviewing.

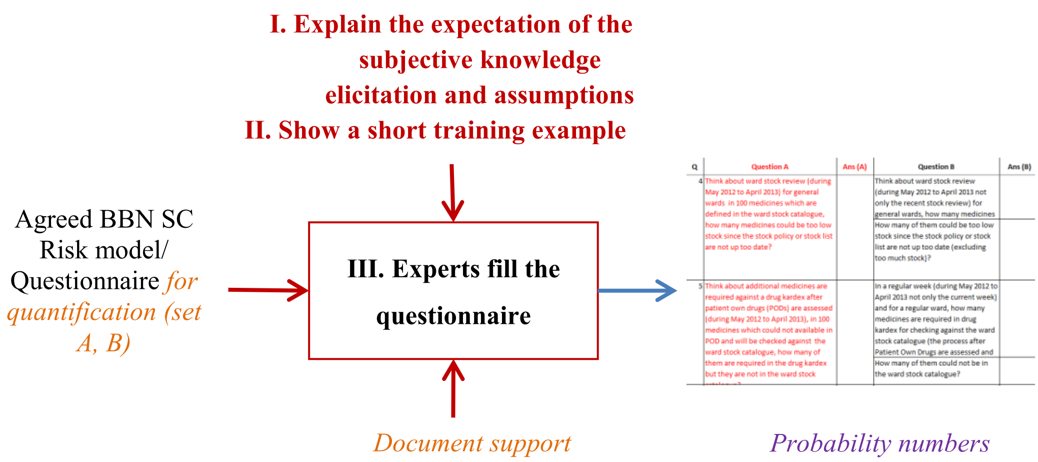


Figure 9-7 Quantification protocol by interview

Limitation: The interview should take no longer than two hours.

9.2.6.3 After the elicitation

After elicitation of all experts, it is the responsibility of the analyst to input the collected data in probability format.

1. Aggregation

Some variables were related to more than one organisation units and their provided values were aggregated. For example, 'Out of PDC stock catalogue requested' (V19) was calculated by aggregating two probabilities from two experts in PDC. One expert provided 0.1667 and another expert 0.02 so the average between the two probability numbers was used: 0.0183.

2. Input numbers into the software

Generally particular variables were elicited by individual experts so the numbers from the questionnaire can be input into the structured BBN SC risks model. The numbers will be transformed into probability format (0–1) and then input into the Probability Table (PT) for root cause variable and Conditional Probability Table (CPT) for effect variable (see Section 3.1.4).

3. Verification

The list of common modelling errors was checked to make sure that all input was carried out correctly. The relevant checks are listed below:

a. *Are the states of variables exhaustive and exclusive?*

b. *Have the input probabilities calculated from proportion numbers been calculated correctly?*

c. *Have the numbers been input into the software correctly?*

9.2.7 Stage 7 – Use BBN to support SC risk analysis

Aim: To provide results to support risk analysis.

How: Implement the guideline of analysis to support estimation (current probability); diagnose main risks; explore different scenarios; prepare the sensitivity analysis for validation.

9.2.7.1 BBN SC risk model analysis

The guideline to support risk analysis of BBN SC risk model links between inference analysis and management requirements using three types of supply risk analysis questions (Table 9-5) which can be supported by GeNIe software.

Table 9-5 Suggested BBN SC risk analysis by linking to managerial requirement

Management	BBN Modelling support
What is the chance of a particular adverse event occurring?	**Estimating occurrence of events** *Marginal probability or current probability* e.g. **Which** risk events are the most likely to occur in the medicine SC?
What are the main risks that cause supply failure?	**Prioritising risk through diagnosis** *Normalised Likelihood (NL)* e.g. Given an observation that an inpatient cannot get the medicines in the right time, **what** are the main causes?
What is the impact of (combination of) uncertain events on supply through the chain?	**Exploring different scenarios to support decision making** *Scenario analysis* e.g. Set the stock out in the SC in different scenarios: **how** might they affect the top event?

1. *What is the chance of a particular adverse event occurring?*

Estimation of probability of current occurrence for individual variables in the BBN SC risk model is represented by the marginal probability, called the *current probability.*

2. *What are the main risks that cause supply failure?*

The analysis of risks does not just consider the chance of individual adverse events happening but also how they can impact on the focusing variable(s). A risk matrix is a table setting out levels of probability and consequences in order to divide the area of the matrix into a grid. Each risk variable can be considered using these two dimensions and roughly classified; see Figure 9-8. Furthermore the 2×2 matrix can be matched with the suggested risk management strategy.

Impact/consequence (representing by NL)

	Low	High
High	Low probability & High impact	High probability & High impact
Low	Low probability & Low impact	High probability & Low impact

Probability (representing by marginal probability)

Figure 9-8 2×2 matrix between probability and consequence level

For the analysis of the BBN SC risk model, the probability of adverse event occurrence can be represented by the *marginal probability* (called as a *current probability***)** of each variable and the impact can be evaluated by NL which is the ratio of *adjusted probability* and *current* *probability*; see Section 3.1.6.2. The adjusted probability shows the updated probability after top events (by diagnostic reasoning) have been observed. Levels of probability (x-axis) and impact (y-axis) can simply categorise risks into four groups.

3. *What is the impact of (combination of) uncertain events on supply through the chain?*

Although no decision making is defined at the first stage of developing the BBN SC risk model, the model can help to improve understanding of experts about their risks via demonstration of supporting decision making by scenario analysis. Scenario analysis can be demonstrated by setting up different situations and then comparing their results. There are two sets of variables: focus variable(s) and scenarios variables. Scenarios are set to be observed in particular states of scenario variables; the results of setting scenarios are measured from the focus variable(s).

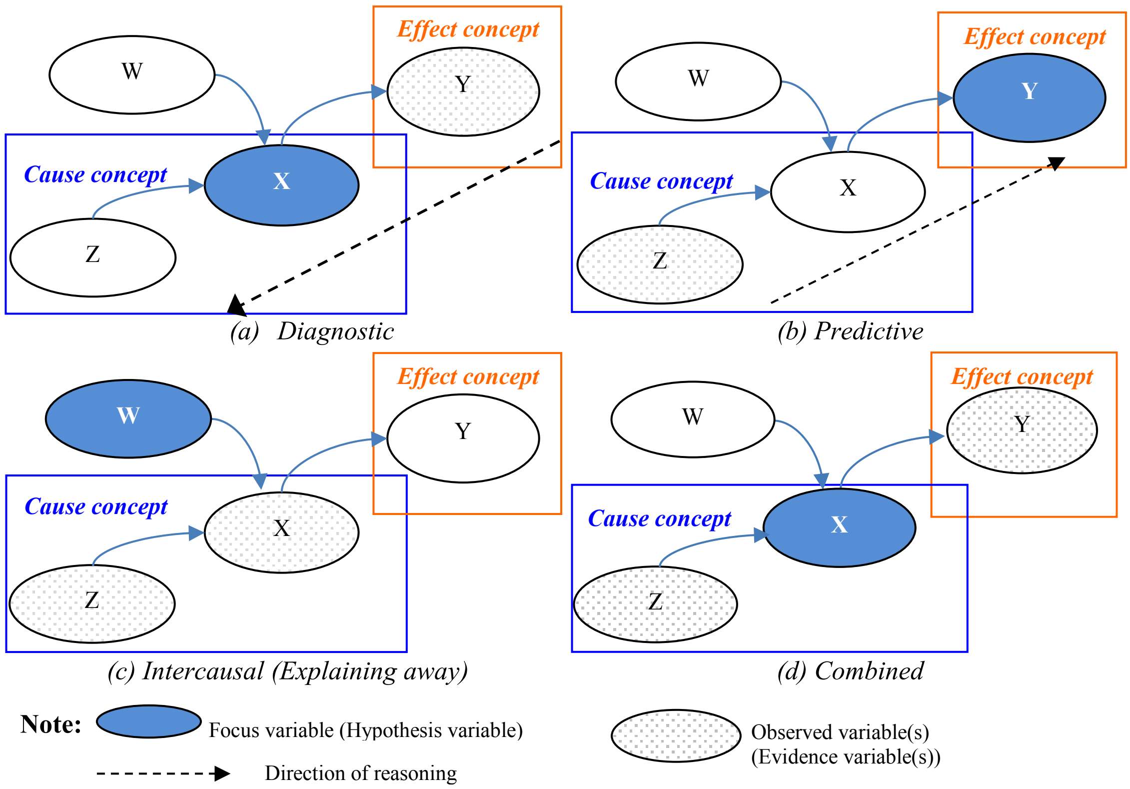


Figure 9-9 Inference types of BBN applied in the conceptual modelling framework

The conceptual modelling framework (see Figure 5–3) can be used to determine direction reasoning. This supports scenario analysis from BBN SC risk inference by using four types of reasoning: diagnostic, predictive, intercausal, and combined reasoning, taking into account positions of the focus variable and observed variables; see

Figure **9-9**. For example, we applied predictive reasoning when we demonstrated scenarios of ‘stock unavailability in different sources in the hospital medicine SC’, see case 2 in Section 7.5.3.

9.2.7.2 Sensitivity analysis

A tornado diagram is selected as the format in which to present the sensitivity analysis – i.e. to show the results of changing observed states from the two extreme values of the states to compare the effect on the probability of the top event. More explanation is provided in Section 5.4.7.2 and an example of sensitivity analysis from the case study is provided in Section 7.6.

9.2.8 Stage 8 – Validate BBN SC risk model behaviour

Aim: Validate the BBN SC risk model outcomes.

How: Arrange the validation workshop; implement the suggested workshop procedure.

The results of the analysis are presented to the expert panel in order to validate the outcome of the BBN SC risk model in workshop (II). The protocol of the workshop was implemented as follows:

I. *Explain the BBN SC risk model structure to remind the experts of the full model which has been developed together, and of all assumptions.*

II. *Demonstrate results of BBN analysis*:

   i. Result of the model analysis; see Section 7.5.

   ii. Sensitivity analysis; see Section 7.6.

III. *Ask experts to explore their own scenarios*.

IV. *Ask for feedback on the model analyse results*.

   i. Are the sensitivity analysis results acceptable for experts? Or are the ranges of concerned variables specified in the map? (Include or exclude some variables)

   ii. Are experts comfortable with the results of the scenario testing?

The feedback from experts can be classified into two parts: model robustness and appropriate model behaviour.

9.3 Summary

The proposed BBN SC risk modelling process aims to provide general guidance for organisations by considering relationships between adverse events to support risk analysis in their SC, especially for hospital medicine SC. As shown by the results from the modelling process evaluation of the NHS GG&C hospital medicine SC case study, the process is suitable for the initial stage of establishing the BBN model to support risk analysis. Subsequently the BBN model should be maintained and updated: this will require less effort than the initial process. The formal routine updating maintenance process will be required and we will suggest in the next chapter.

Chapter 10 Conclusions and Future Work

A systemic risk perspective was the driving force behind the development of a quantitative model for SC risk analysis. The research process involved choosing a suitable model, developing the modelling process and exploring the modelling process in a case study. This chapter summarises the findings from this research as a sequence of four objectives. The contribution to knowledge of this study is based on the proposed BBN SC risk modelling process, which aims to be a generic process for constructing a BBN to support risk analysis in SC; in addition, evidence of the model analysis results and modelling process evaluations of participants' perceptions is provided. We suggest the maintenance process of the BBN SC risk model and also indicate issues to consider for general implementation. Finally, several limitations and suggestions of the modelling process are taken into account when indicating future research.

10.1 Summary of Key Findings

The key findings of this research can be summarised using the sequence of the four objectives that were set to develop a quantitative modelling process to support the analysis of risks in SC.

1. *To make an informed selection of a suitable type of model to capture systemic SC risks*

Systemic risk can be modelled to capture interrelationships between risk events. The candidate models (Failure Modes and Effect Analysis (FMEA), Fault Tree and Event Tree (FT/ET), Discrete Event Simulation (DES), System Dynamics (SD), Petri Net (PN) and Bayesian Belief Network (BBN)) were reviewed and their different characteristics compared (Section 2.4). BBN was proposed as the suitable model for this research since BBN can provide basic SC risk analysis such as risk prioritisation and scenario analysis and it can fulfil other requirements of SC risk analysis. BBN can capture different types of uncertainty in SC, using probability language and logical structure which the risk management team can understand. The most complex relationship, non-deterministic dependence, can be captured by the model and it follows that it will also be able to capture lower levels of relationship complexity. Furthermore, the visual display of the BBN (a natural logic represented by arrows) can support discussion and participation by the risk management team and also others to improve understanding of adverse events in their SC, so BBN can be used as an interactive tool to support risk communication.

2. *To develop a theoretically grounded process for modelling SC risks using a Bayesian belief network*

The BBN theoretical concept was expressed for risk analysis in SC (see Section 3.1) and it will be used to ground the proposed BBN modelling process in this context.

However, there are practical challenges of modelling BBN in SC risk (Section 3.4):

a. ability to deal with complex SC risks and time issues – process should be efficient and not invasive;
b. scoping the risk analysis;
c. thinking about possible future risk events and relationships; and
d. modelling SC risk analysis at an appropriate level.

Therefore, the primary BBN SC risk model (Section 5.4) was developed by aiming to solve those defined implementation challenges. The modelling process was supported by framing the process in particular stages; such as, combining adverse events in SC (Section 5.1), framing process of model structuring and problem validation (Section 3.2), good practice of eliciting knowledge of expert from literature (e.g. standard elicitation process SRI), reviewing techniques in BBN (e.g. Noisy-OR, Parent divorcing), and also conducting the experiment in BBN structuring (Section 4.8 and also objective 3), see Section 5.3. The literature and experiment showed why and how to do particular stages of the primary BBN SC risk modelling process, since the provided information ensured that the process was developed from strong BBN theory in SC risk context, together with guidance on practical concerns arising from the experiment. Next, the feasibility of implementation was explored with the real organisations; see objective 4.

3. *To compare methods for identifying SC risks and structuring their dependencies in the form of a Bayesian belief network*

The challenge of selecting a technique for BBN problem structuring that is able to support SC operational experts thinking through possible adverse events and their relationships, is not available in the literature. Therefore, the experiment to compare three methods (Causal Map (CM), Fault Tree (FT) and Risk Register Map (RRM)) was conducted with MSc SC students; see Section 4.8. The major finding of the experiment was that CM should be selected as the suitable technique to support SC people thinking through possible adverse events.

According to the students' perceptions, students within CM groups were more satisfied with their CM than other groups. Although students indicated that the process of transforming FT to qualitative BBN is the least difficult. The different perceptions of students in FT groups depend on their background knowledge of Boolean algebra as a grounded concept of FT. Therefore, it may be very precarious if the FT method is used with SC staff who come from multi-disciplinary backgrounds. Furthermore, during the session students took a very long time to study the logic and symbols of FT. On the other hand, CM does not require a lot of effort to learn and develop. Although RRM is developed from a RR which may already exist in an organisation, the difficulty of identifying relationships between risk items which have to be identified independently is very difficult: the result is a very complex map with many links. This map is too complex to understand and took a lot of effort to develop both during the RR structuring and transforming from RRM to qualitative BBN. Therefore, RRM is not recommended.

4. *To assess the feasibility of using a Bayesian belief network modelling process to analyse systemic SC risks within a real organisational context*

The NHS GG&C hospital medicine SC provided the case study to explore the implications of the BBN SC risk modelling process. The case study gave clear evidence to show that the modelling process could be implemented within real SC organisations to support systemic risk analysis; see Section 7.5. Furthermore the model can support decision maker to identify the improvement options for their SC; see Section 8.1.2.4.

Additionally, the perceptions of the participants – the decision maker (managerial expert) and also operational staff (operational experts) from different stakeholders – were evaluated by questionnaire, workshop and interview. Participants' perception is defined on practical and useful criteria; see results of the evaluation in Section 8.1. The BBN SC risk modelling process for identifying adverse event (stage 3), structuring CM (stage 5), structuring the refined model and quantifying probability number (stage 6.2), involving the decision maker and operational experts, was evaluated. The operational experts gave higher scores than the decision maker in all states (lowest score 3 from 5), since the modelling process was designed for operational experts. Generally, other operational experts and the decision maker agreed that utilising the BBN SC risk model can help to gain a better understanding of risks in SC; see Section 8.1.2.1. Furthermore, the operational experts all agreed that the BBN SC risk model is more useful than RR; see Section 8.1.2.2, while managerial expert gave a higher score to RR because of its usefulness in communicating major risks to stakeholders. However, the decision maker provided very good feedback on the BBN SC risk model which he could use as a management tool. Finally, the participants also perceived the usefulness of participating in the modelling process; see Section 8.1.2.3, since it led them to discuss and think about adverse events, and then think backward to the causes in order to stimulate ideas of how to cope with them.

Although some of the practical problems, such as the perceptions of SC operational experts, have been considered as challenges in implementing the BBN before designing the modelling process (see Section 3.4) and attempts were made to solve them by designing the BBN SC risk modelling process (see Section 5.3), some of them are still observed and summarised in Section 8.2. Since the design of the model structuring process was developed based on the result of experiment with MSc Supply Chain students, the BBN structuring which involved with real experts (stage 3 and stage 5) in the case study went very well. Only the practical problem of confusing between BBN and process map (see Section 4.8 (4) and Section 8.2 (15)) was still observed in the case study.

10.2 Contribution of the Research

The contribution of this PhD research can be demonstrated in terms of two different aspects.

The first aspects involves proposing a generic BBN modelling process to support SC risk analysis based on expert knowledge. The second aspect is concerned with the soft benefits that participants can gain from being involved in the modelling process.

10.2.1 Proposing a generic BBN modelling process to support SC risk analysis based on expert knowledge

The BBN SC risk modelling process was developed to support risk analysis in a SC. Since there is a lack of historical data that can link individual stakeholders to the whole SC and there is also the requirement of predicting potential risks to support proactive risk management, expert knowledge is the main source to develop the BBN model; see Section 3.3.1. Furthermore, this modelling process can be distinguished from other relevant modelling processes that have been shown in Section 3.3.2, since the existing academic literature had not yet proposed to develop a model purely from experts' knowledge to support risk analysis in SC.

A key point of the present research has been to establish that BBN can be used in SC risk problems; in particular, the research has developed a process to support implementation in the SC risk analysis by aggregation of difference information sources such as literature, experiment and case study. We have investigated ways to cope with the defined possible challenges as summarised in Figure 5-7. In line with the ways in which this thesis has proposed a generic BBN modelling process , the key academic contributions are identified below.

In the problem structuring process (stage 1-5), a key contribution consists of the experiment of structuring a BBN that can help to investigate the appropriate modelling technique (Section 4.7) and to investigate suitable modelling practices, in order to identify possible adverse events and structure the qualitative BBN model (Section 4.8). Furthermore, we propose a specific BBN SC risk conceptual modelling framework to explain the concept of linking adverse events form different stakeholders in order to support BBN risk modelling. The modelling framework is developed by combing components of SC risk and BBN before proposing a framework for linking risks from the different perceptions of individual stakeholders, see Section 5.1 and Section 5.2. The instantiation process (stage 6) to quantify the BBN model is designed on the basis of the perceptions of operation experts (from the case study) to capture suitable probability estimates from their knowledge. The combination of a frequency format with a Noisy-OR technique is suggested to develop the questions for eliciting probability numbers. The emerging two styles of questions (question set A and B) were explored in the case study and a suitable style of questions for different perceptions of managerial and operational experts is suggested in the BBN SC risk modelling process. The question design is also combined with the standard elicitation process of SRI, and the process is adjusted for practical reasons in this problem domain. Finally, in relation to the inference process (stage 7-8), we also propose the combination of the managerial requirements from SC risk analysis with the inference ability of BBN to suggest a general guideline for providing analysis results by asking three main questions, see Section 3.1.5.

Furthermore, the primary BBN SC risk modelling process has been tested in a real application in a hospital medicine SC case study. The feasibility of using the BBN SC risk model to provide the outcomes for particular questions has been implemented in the real case study.

1) What is the chance of a particular adverse event occurring? (see Section 7.5.1)
2) What are the main risks that cause supply failure? (see Section 7.5.2)
3) What is the impact of (combination of) uncertain events on supply through the chain? (see Section 7.5.3)

Multiple methods for data collection of evaluation the modelling process in the case study have been implemented and data analysed. The formal evaluation of whether the modelling process is practical and useful in supporting risk analysis was conducted based on the evaluation evidence of perceptions of participants and decision maker; see Section 8.1. Key insights from the findings from the model evaluation in the case study have informed an effective revision of the primary BBN SC risk modelling process. As a result, the proposed eight essential stages of BBN SC risk modelling process (summarised in Table 9–2) have been developed as a key outcome of this research; see the more detailed description in Chapter 9. The insights from the evaluation research have also allowed us to summarise the possible practical problems and suggestions for future users; see Section 8.2. Moreover, we can provide evidence for future users to show the benefits gained from implementing the BBN SC risk modelling process within the aspects of modelling in systemic risk, SC scope, and SC operational level to be able to provide risk-benefit trade-offs; see Section 8.3. Lastly, the limitations of the implementations of the BBN SC risk modelling process are also defined in Section 10.4.

10.2.2 'Soft' benefits

The application of the BBN SC risk modelling process also yielded distinct benefits to the main decision maker as well as the operational experts who participated in the BBN SC risk modelling process.

The decision maker is the key user of the BBN SC risk model outcomes; examples of the key outcomes are provided to answer three main questions in Section 7.5.1 – Section 7.5.3. Furthermore, the decision maker can define interesting risk scenarios and use the model to show the results accordingly. The decision maker in the case study confirmed that the BBN model can aid him to define options for improving the provision and supply of hospital medicines SC (see Section 8.1.2.4).

More generally, the benefits from developing the BBN SC risk model apply to all participants. We will consider the benefits gained from model outcome and also modelling process. According to benefits gained from the model outcomes, participants have stated that they can gain a better understanding of adverse events in their SC, see Section 8.1.2.1. In addition, the model outcomes can improve participants' consideration of risk events that are relevant to them or generated by them in their SC. Therefore, the model can encourage them to think about how to reduce the chance of adverse events rather than complain to each other. The key to the success of risk management in SC not only comes from the usefulness of the outcomes provided by the model, but also because the process stimulates communication in the risk management team, thereby sharing perceptions and improving the understanding of adverse events. In this context, we may refer to the model implementation in the case study and the summary of the utility of the BBN SC risk modelling process; see Section 8.1.2.3.

Additionally, the decision maker in the case study expects that the model can be used as a tool to communicate evidence to the general operational staff (who are not involved in the modelling process) by showing the effect of policies on the reliability of the system; usually by a visual tool to show staff at the operational level how it can affect their operational tasks. Therefore, the modelling process can contribute by helping operational staff to see the benefits of developing the BBN model, rather than it just being a document to support higher levels of management or audit.

10.3 Maintenance Process

The new approach BBN SC risk model was tried out and shown to be feasible for the NHS GG&C hospital medicine SC. After that, the planning and doing (implementation) for a proposed general BBN SC risk modelling process was suggested in Chapter 9.

Since risks can change from time to time, out-of-date risk data may not be useful to the organisation. Adverse events in the SC can change from the time of model development, such as implementing new mitigating actions, or actions from stakeholders or competitors, market changing, or because of continuous process management. Therefore, if the model is not updated, it cannot provide useful outcomes to support decision making effectively and the model will decay. Not only the BBN SC risk model, but also general risk analysis tools require updating to remain living tools. However, the model is not a formal process and does not provided a formal record (unlike RR); the only way to make senior management maintain the BBN SC risk model for their organisation is to prove that the model supports their decision making to managing risks, as there is no other requirement to include it in their risk management obligations.

If the decision maker decides to maintain the model, we also suggest two levels of model maintenance: updating probability numbers and/or reviewing model structure. However, when the initial BBN SC risk model is constructed by BBN software, less effort is required to subsequently modify and revise the model. The SCRM team should be formed from different stakeholder organisations in the SC and representatives of organisational risk management team from individual organisations should be involved. Since the model is useful for all stakeholders and not only for the decision maker, the maintenance period should fit with the regular review of risk records of particular organisation units: the BBN SC risk model can then be part of risk analysis for individual stakeholders.

Updating probability numbers

When the model structure is not changed, only the chance of particular adverse events can be adjusted or updated. Since this quantification will involve the perceptions of individual organisations, updating probability numbers will have to be carried out internally by the organisational risk management team. They can combine the recorded numbers with knowledge of the expert to provide adjusted probability numbers. The coverage for the initial BBN SC risk model in the case study was for one year: this can also fit with the regular updating cycle time of current risk records. Therefore, the organisation may use the same routine for updating probabilities for the model.

Reviewing model structure

A meeting of the workshop steering group of SCRM team can be arranged to discuss and review the model structure. The new model structure can be revised by the BBN software; however, the questions for probability elicitation should be updated and then the same process of updating probability number by the organisational risk management team should be undertaken. The frequency of model structure reviewing depends on the level of exposure to new adverse events. The decision maker may consider reviewing the model every two years.

When the model can link to different stakeholders, it may be worth implementing new software to develop the new template to support the linking of their input. In addition, different versions of BBN SC risk model should be recorded. Keeping a record means that the organisational knowledge will not be lost as a result of staff turnover, and it can help to monitor and cope with risks which can change during a period of time.

10.4 Issues to be Considered for More General Implementation of a BBN SC Risk Model

As a result of the case study, it can be claimed that generally the BBN SC risk modelling process can construct and develop the analysis of SC risks within a real organisation. However, the keys of success of implementing the BBN SC risk modelling process may not depend on only the proposed process, but also on fitting the model with expectations, the type of SC and on the level of formality risk management that exists in the focal organisation.

1. *Implementing the model as a supporting risk analysis tool for risk management*

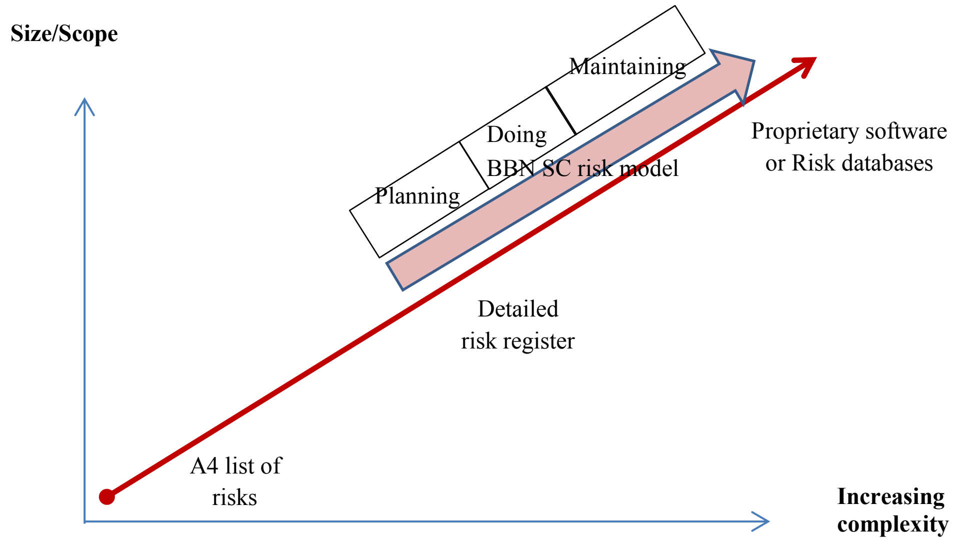
Analysis by using a BBN model outperforms using a risk matrix. However, a risk matrix is a straightforward method and is defined as the analysis method for RR which is fully developed to support auditing purposes (Drewitt, 2008) by rule or law. Therefore, the BBN SC risk does not intend to replace the RR risk matrix.

Replacing the risk matrix by the BBN SC risk model which captures interrelations between adverse events for RR is difficult in practice, since RR is a mature risk record which is *"widely used and accepted approach in risk management"* (Drewitt, 2008, p. 81). Therefore, the BBN SC risk modelling process was shown as the initial phase to confirm the feasibility of implementation in the real organisation, but the modelling process requires more applications to improve maturity for being widely accepted as a standard tool. It needs a long cycle time of learning which is beyond the scope of this research.

If organisations are going to implement the BBN SC risk modelling process, the model should be implemented as the supporting tool for decision making in parallel with the implementation of RR. The BBN SC risk model can ensure that decision maker are able to select suitable risk mitigating actions and the actions can be recorded in the RR for review purposes in the future. Therefore, organisations may consider using the same risk management team to develop those two methods to avoid unnecessary duplication of existing risk management.

2. Suitable phase of risk management formality

Generally, particular organisations implement risk management, but at different levels of formality. The first level starts from using a page of A4 to simply record risks. Another, more mature level, is to develop a detailed RR and use risk database software for risk management process, as shown as Figure 10-1.



Source: Adjusted from PRAM, 2004

Figure 10-1 Level of risk management process formality

The BBN model is able to support risk analysis for any scope or at any level of complexity for risk management; however, if the model fits with the organisation's current interest, its construction will be well supported. The level of an organisation's interest in a risk analysis tool is a reflection of its risk management formality. Since the BBN SC risk model scope is defined at an operational level within SC scope, this can indicate the complexity of the problem domain. Therefore, the model should be suitable for organisations that record details at a complex level, rather than just at the initial phase of implementing risk management. Initially, this is a challenge an organisation, since companies are still learning about and educating their staff in risk management (PRAM, 2004) for their own organisations, rather than considering the wide scope of risks in SC and sharing perceptions with their stakeholders. On the other hand, if organisations have constructed risk databases or invested in proprietary software, then they will be less interested in developing the BBN SC risk model from the knowledge base.

The NHS GG&C case study operated with a formal risk management team and recorded risks in a detailed RR, which were introduced to them during the modelling process. The decision maker was open to the new model for improving decision making as part of the current risk management.

3. *Suitable for modelling risks for SC process*

SC can be roughly categorised as SC project and SC process (see Section 1.1.3). Although the BBN is able to model aleatory and epistemic uncertainty in either SC project or SC process (see Section 2.5, the modelling framework is developed based on stock-availability and supply-ability and linked to stakeholders (Section 5.2), the modelling process is best described as SC process. Therefore the provided modelling process by this research may not suitable to implement it during the creation of innovative products or during business process reengineering (of the SC process).

Business process reengineering (project) can stimulate major changes in SC process and generally BBN is able to model during this phase, since the BBN can capture epistemic uncertainty (i.e. uncertainty arising from lack of knowledge; see Section 2.2.1). However, the proposed BBN SC risk modelling process may not be suitable since the possible adverse events may involve a lot of unknown uncertainties. The proposed process to elicit knowledge of adverse events from experts or question design for probably elicitation (stage 6) needs to be adjusted to fit with the experts' perceptions of the new product or process.

On the other hand, continuous process management can cause constant process improvement, generating minor changes of adverse events from the previous states – but in the main, the SC process will be the same. This phase of continuous process management can be captured by the BBN SC risk model by defining the process for capturing a snapshot which will refer to the reference time (defined in stage 1of the modelling process) and SC process (defined in stage 2 of the modelling process).When as a result of time change the BBN SC risk model is out of date (due to the continuous process management and other factors), the model for the new snapshot should be either modified or reviewed to represent the current SC process; see Section 10.3 on model maintenance. Therefore the BBN SC risk modelling process is suitable for the normal SC process and can represent the continuous change of the process by using sequence of models to represent SC system for particular snapshots.

10.5 Limitations of Research and Suggestions for Further Research

Although the feasibility of implementing the BBN SC risk model in practice was shown, the application of the modelling process is limited in some circumstances. Limitations of this research and suggestions for future research are discussed in this section.

1. *Conducting only one case study is unable to show all possible SC cases*

To provide more evidence of applications of the BBN SC risk modelling process to support SC risk analysis, further case studies should be conducted. First, suggestions for further case studies on different SC aspects of the NHS GG&C hospital medicine SC case study will be proposed.

a. *Further use to include production into the model*

   The BBN SC risk model was explored in the NHS GG&C hospital medicine SC within the areas of logistics or distribution rather than production. An empirical case study with the producing organisations such as manufactory would generalise the application of the BBN SC risks modelling process. Since the process has been developed for general SC, the modelling process will not require revision or modification for (new) application with the producing organisations.

b. *Further use of the BBN SC risk modelling process with different types of product*

   Since different types of SCM can define different goals for their SC, so they can be faced with different vulnerabilities. A medicine SC is generally implemented to be agile SC, to maintain a high level of responding the uncertain demand of customers. The NHS GG&C medicine SC was implement as an agile SC by focusing on patients: the provided top event was 'Could not supply the right medicine to the right patient at the right time'. Further application of the BBN SC risk modelling process for other products which may implement different SCM policies would be able to evaluate the suitability of applications in different product types; this could provide useful suggestions for specific products.

2. *Focus only the supply failure but exclude the* cost *to define a top event*

Cost is an important factor for decision makers and it can be represented by a top event of a general BBN. A limitation of developing the model at the operational level is the practical barrier for identifying cost as one of the top events, or to combining it in the cause variables, since, for operational staff, cost is not their concern and they may not be involved with it or perceive it. Therefore this BBN SC risk model will limit ability to model cost as a top event. Although the BBN SC risk model is unable to show the effect on the cost explicitly via a top event, the decision maker can identify the new policies by setting scenarios which aim to reduce cost or setting scenarios under the cost constraints of the current system by using the BBN SC risk model (see example of defined improvement options in Section 8.1.2.4).

Cost can be defined as a top event, but the modelling process should be defined differently from the BBN SC risk model. Generally, when cost and profit are being estimated or modelled by BBN, simulation will be used rather than expert judgement. Alternatively, the BBN SC risk modelling process should be adjusted to model at the tactical level, inviting experts who have perceptions about cost, relying on historical records rather than using knowledge of experts. However, modelling adverse events related to cost events may involve the use of sensitive information, which the stakeholders may not want to share with their fellow stakeholders, since sometimes stakeholders will become competitors in the future.

3. *Define only one top event by the modelling process*

Although BBN allows identifying more than one top event, only one top event is suggested by this modelling process. Therefore, the model which was developed for a top event to present a SC performance factor cannot show the relationship between SC performances. For example, reliability of the medicine SC to an inpatient as observed via ‘Could not supply the right medicine to the right patient at the right time’ was defined as only one top event; so the model excluded other performance factors, such as cost or quality which may generate negative impact on the quality of the SC system.

If the decision maker requires defining more than a top event, the process should be adjusted by increase number of experts who are able to perceive adverse events affecting different top events. Alternatively the model can be developed by two groups which can construct individual top events and then merge the models together in a workshop. However, this may require more time and resources.

4. *Limit to support decision making by operational level in SC scope*

The BBN SC risk modelling process is defined to support external SC structure scope of management for decision making at an operational level according to the classification level of management in SC risks (Section 1.1.2); see Figure 10-2.

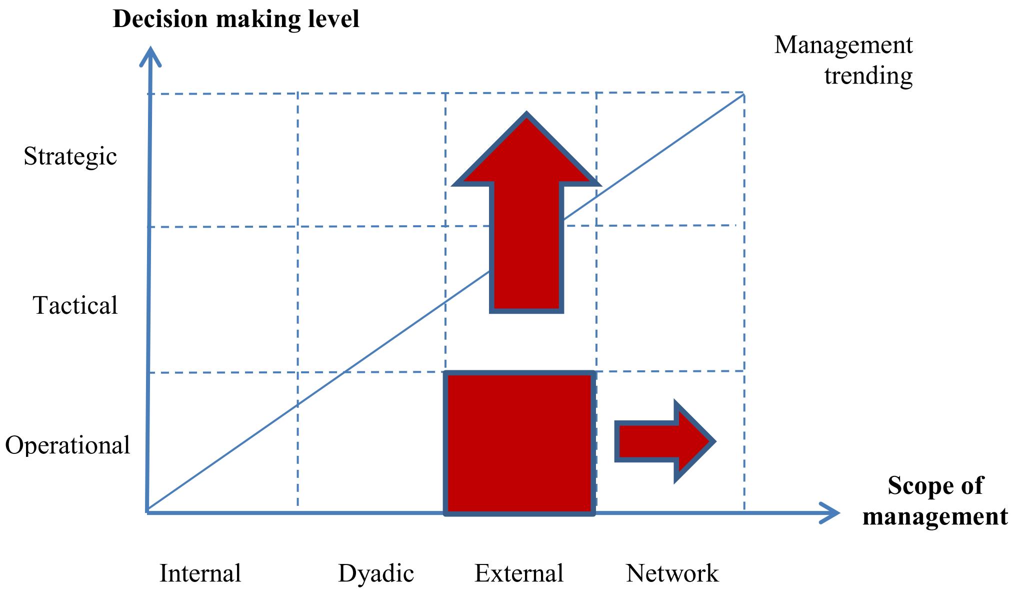


Figure 10-2 Possible ways of developing the BBN modelling process for risk analysis to support management in SC

The scope of risk modelling in SC is complex. Therefore, applying the modelling process in a lesser complex scope will not be difficult. If management wants to extend the process to an SN scope which includes different layers of network of supplier or network of customers (see Section 1.1.1), then the analysis can be used to evaluate suppliers or customers. However, a considerable amount of input would then be required from many stakeholders. The proposed BBN SC risk modelling process can be extended to SN scope but the time resources from a growing number of participants (more stakeholders) will be increased. The required resources for modelling in SN scope can be approximated based on proposed required resourced in planning process by the proposed modelling process; see Section 9.1.

On the other hand if the intention of implementing the BBN model is to support decision making at a higher level (tactical or strategic), the suggestion of using cause and effect relationships to structure the model by the conceptual modelling framework (Figure 5-3) may not be suitable. The higher level of decision making involves more abstract events; these should be suggested and defined by future research.

Additionally, the process to develop the model for higher levels and process to link between levels of decision making – for example, by supporting results from the operational to tactical and then to strategic decision making – are also challenges for further research.

5. *Modify model results validation process from perception of the participants*

In accordance to the BBN SC risk modelling process design, the model structure and analysis outcomes were examined for validating purpose in states 5 and 8 within group workshops. Since the BBN SC risk model is based on the belief of adverse events by operational experts, there is no recorded data available (see Section 3.2.2); the initial validation was designed to use the same group of experts who constructed the model to ensure that 'Is the right model built (as their belief)?'

The recommendation for validation can be improved by holding another workshop (Pitchforth and Mengersen, 2013) with another group of experts who have not been involved in the model constructions. Validation by another group of experts can ensure that the model is valid and can represent the SC. However, the process to deal with the varying perceptions on adverse events and balancing levels of detail and model complexity can be another practical challenge.

Alternatively, after the intiail BBN SC risk model is constructed, data can be recorded as defined inthe BBN SC risk model and used for validating purposes. However, in some rare adverse events which can generatee a huge impact, such as natural diaster, may not be observed and therefore cannot be validated by recorded data during a short period of time: it requires judgemental data.

6. *Cannot support evaluating mitigating options*

Although the current BBN SC risk model aims to support risk analysis and cannot be used to evaluate mitigating options explicitly, the BBN can potentially be improved to support mitigating option selection. Potential risk actions can be added into the current model, adding a *utility node* which can combine the cost into the model. The utility variable is able to include expected *utility* by using of *utility function* (Bedford and Cooke, 2001) for comparing different options and this is a suggestion for future research.

The suggestion of extending the BBN SC risk model to evaluate mitigating options can be explained by modifying the BBN SC risk conceptual modelling framework (Figure 5–3) into Figure 10-3. Generally, the potential actions aim either to reduce the chance of adverse event occurrence or impact on the top event. Therefore potential options can be combined into the current BBN SC risk model by using *decision nodes* (which represent by 'Action' node in the figure). However, these actions will involve costs of installation to set against benefits gained from implementing them; this can be represented by the utility function. After utility and decision nodes are added, the resulting model is called an *Influence Diagram*.

A utility node is quantified by the utility of the possible combinations of outcomes of the parent nodes. The utility node in the extension of BBN SC risk model will be able to evaluate the expected value of different options of mitigating actions. Therefore, decision maker can compare the expected value of particular options to optimise decision of risk mitigating actions.

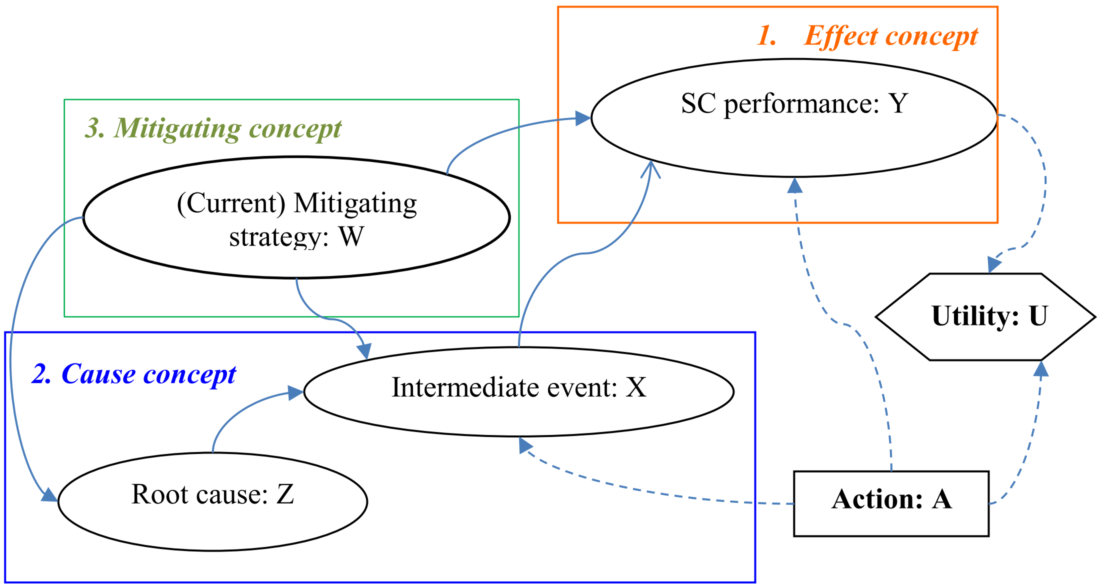


Figure 10-3 Extension of the BBN SC risk modelling framework

How to identify risk mitigating actions in SC relationship is a challenge gap to be explored in future research. Stakeholders should consider the level of their SC relationships in order to agree in sharing decision making to select risk mitigating actions for their SC. Once the decision making involves many stakeholders conflicts of interest about risks become a practical issue and this idea should be explored in future research.

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Appendices

A. Supply Chain Classification Analysed from Literature

Table A-1 The classification of SC classification which is classified by main factor and SC scope

<table>
<tr><th rowspan="2">Main factor</th><th colspan="11">SC scope</th><th rowspan="2">Author(s)</th></tr>
<tr><th>Internal location level</th><th colspan="2">Organisation level</th><th colspan="8">Chain or network level</th></tr>
<tr><td rowspan="4">Level of SN</td><td></td><td colspan="2"></td><td colspan="2">Buyer network</td><td colspan="2">Supplier network</td><td colspan="4">Focal-organisation SN</td><td>(Bi and Lin, 2009)</td></tr>
<tr><td></td><td colspan="2"></td><td colspan="2">Upstream</td><td colspan="2">Downstream</td><td colspan="2">Static network</td><td colspan="2">Dynamic network</td><td>(Mills et al., 2004)</td></tr>
<tr><td>Local SN</td><td colspan="2">Geographical SN</td><td colspan="8">Organisational SN</td><td>(Bi and Lin, 2009)</td></tr>
<tr><td></td><td colspan="2"></td><td colspan="2">Dynamic SN & low degree</td><td colspan="2">Dynamic SN & high degree</td><td colspan="2">Routinized SN & low degree</td><td colspan="2">Routinized SN & high degree</td><td>(Harland, 2001)</td></tr>
<tr><td rowspan="2">A number of stages or tiers in SC</td><td></td><td colspan="2"></td><td colspan="2">Two stage SC</td><td colspan="2">Serial SC</td><td colspan="4">Network SC</td><td>(Capar et al., 2004)</td></tr>
<tr><td></td><td colspan="2"></td><td colspan="2">Single source structure</td><td colspan="2">Multiple single source structure</td><td colspan="4">Multiple source structure</td><td>(Neureuther and Kenyon, 2008)</td></tr>
<tr><td rowspan="6">Characteristics of relationship</td><td></td><td>Horizontal</td><td>Vertical</td><td colspan="8"></td><td>(Hayes et al., 2005)</td></tr>
<tr><td></td><td colspan="2">Internal</td><td colspan="2">Horizontal</td><td colspan="2">Vertical</td><td colspan="4">Diagonal</td><td>(Hinterhuber and Levin, 1994)</td></tr>
<tr><td></td><td colspan="2"></td><td colspan="4">Hard networks</td><td colspan="4">Soft network</td><td>(Rosenfeld, 1996)</td></tr>
<tr><td></td><td colspan="2"></td><td colspan="2">Supply relationships</td><td colspan="2">Agreements Joint-ventures</td><td colspan="4">Regional industrial system</td><td>(Nassimbeni, 1998)</td></tr>
<tr><td></td><td colspan="2"></td><td colspan="2">Social network</td><td colspan="2">Bureaucratic</td><td colspan="4">Proprietary</td><td>(Grandori and Soda, 1995)</td></tr>
<tr><td></td><td colspan="2"></td><td>Fully integrated</td><td colspan="2">Upstream</td><td>Down stream</td><td>Agents</td><td colspan="2">Trading companies</td><td>Tempnet</td><td>(MacCarthy and Jayarathne, 2013)</td></tr>
<tr><td rowspan="4">Characteristics of product type</td><td></td><td colspan="2"></td><td colspan="4">Physically efficient process</td><td colspan="4">Market-responsive process</td><td>(Fisher, 1997)</td></tr>
<tr><td></td><td colspan="2"></td><td colspan="2">Innovative unique Pro. & higher complexity</td><td colspan="2">Innovative unique product & lower complexity</td><td colspan="2">Functional product & higher complexity</td><td colspan="2">Functional product & lower complexity</td><td>(Lamming et al., 2000)</td></tr>
<tr><td></td><td colspan="2"></td><td colspan="2">Phys. efficient SC for functional product</td><td colspan="2">Physically efficient SC for innovative product</td><td colspan="4">Market responsive SC for innovative product</td><td>(Wong et al., 2006)</td></tr>
<tr><td></td><td colspan="2"></td><td colspan="2">Traditional SC</td><td colspan="2">Lean SC</td><td colspan="2">Agile SC</td><td colspan="2">Leagile SC</td><td>(Faisal et al., 2006b)</td></tr>
</table>

B. Supply Chain Risk Classification

Figure B-1 Comparison between proposed source of SC risk classification by this research and literature

	My risk classification	(Chopra and Sodhi, 2004)	(Simchi-Levi et al., 2008)	(Hillman, 2006)	(Tang, 2006)	(Shrivastava et al., 1988)	(Stafford et al., 2002)	(Barroso et al., 2008)	(Wu et al., 2006)	(Harland et al., 2003)	(Zsidisin et al., 2000, 2004)	(Zsidisin, 2003)
1	**Disruptions caused by the external environment**	1. Disruption										4. Disaster
1.1	Natural disasters		1. Natural disasters		1. Natural disaster		1. Physical environment (natural disaster and technology failure)	4. Natural resource	17. Natural/Man-made disasters		8. Environmental, Health, and Safety	
1.2	Geopolitical risks (Regulators)		2. Geopolitical risks	6. Protectionism		4. Regulator risk, 5. Infrastructural risk, 6. Political risk			14. External Legal Issues	9. Fiscal risk, 10. Regulatory, 11. Legal risk	7. Legal	10. Legal liabilities
1.3	Terrorist attacks		4. Terrorist attacks		2. Man-made disaster		2. Human and Social environment (confrontation and malevolence)	5. Man made	16. Security			
1.4	Epidemics		3. Epidemics									
1.5	Global macroeconomic factors (and or Market characteristic)		5. Volatile fuel price, 6. Currency fluctuations 8. Market change	1.General cost increase/inflation					10. Market Strength, 19. Market Characteristics, 18. Politics/Economics stability	8. Financial risk		
2	**Demand-side uncertainty**				3. Uncertain demands			2. Customer		4. Customer risk		
2.1	Changes in demand from final consumers	4. Forecast							15. Demand (Sudden shoot-up of demand)			19. Volume and mix requirements changes
	- Demand (quantity; price) forecasting errors		10. Forecasting accuracy									
	- Actions by powerful buyers											
2.2	Availability & price of substitute products and complementary products (Technological change)											

	My risk classification	(Chopra and Sodhi, 2004)	(Simchi-Levi et al., 2008)	(Hillman, 2006)	(Tang, 2006)	(Shrivastava et al., 1988)	(Stafford et al., 2002)	(Barroso et al., 2008)	(Wu et al., 2006)	(Harland et al., 2003)	(Zsidisin et al., 2000, 2004)	(Zsidisin, 2003)
2.3	Actions by competitors (Existing competitors, Potential new competitors)									6. Competitive risk		
	- Vulnerability of intellectual property rights	5. Intellectual property										
2.4	Problems in managing network of customers											
	- Inventories of finished goods (nature and size)	8. Inventory*										
	- Facilities (capacity – risk of disruption)	9. Capacity+										
	- Transportation (capacity – risk of disruption and delay)	2. Delays+	7. Port delays*	4. Unreliable Logistics service*								
	- Coordination (incl. communication and motivation) problems			10. Poor cross-network communications*								
	Image and reputation#									*7. Reputation risk*		
3	**Supply-side uncertainty**				4. Uncertain supply yields			3. Supply source		3. Supply risk	6. Supplier	
3.1	Availability & price of materials and components	6. Procurement		3. Supplier Failure	6. Uncertain supply costs				12. Continuity of supply (Supply availability etc.)		4. Availability	12. Market price increases
	- Underperformance of suppliers		9. Supplier's performance		5. Uncertain supply lead times				13. Second Tier Supplier (Same second tier supplier)			6. Financial of supplier 8. Information system compatibility and sophistication 9. inventory management (supplier) 11. Management vision (supplier) 16. Quality 17. Shipment quality inaccuracies 18 supply ability

	My risk classification	(Chopra and Sodhi, 2004)	(Simchi-Levi et al., 2008)	(Hillman, 2006)	(Tang, 2006)	(Shrivastava et al., 1988)	(Stafford et al., 2002)	(Barroso et al., 2008)	(Wu et al., 2006)	(Harland et al., 2003)	(Zsidisin et al., 2000, 2004)	(Zsidisin, 2003)
	- Actions by powerful suppliers											13. Number of available suppliers
	- Breakdown in supply partnerships			7. Failure of partnership								
	- Technological change											14.Process technological changes#
3.2	Problems in managing network of suppliers											7. Inbound transportation
	- Inventories of components and materials (nature and size)	8. Inventory*										
	- Facilities (capacity – risk of disruption)	9. Capacity+										
	- Transportation (capacity – risk of disruption and delay)	2. Delays+	7. Port delays*	4. Unreliable Logistics service*								
	- Coordination (incl. communication and motivation) problems			10. Poor cross-network communications*								
	- Outsourcing#	*5. Intellectual property*		*8. Intellectual property infrastructure*								
4	**Vulnerabilities in own organisation**					2. Organisation risk	3. Management failure			2. Operation risk	5. Manufacturability	
4.1	Problems in managing workforce	9. Capacity+		5. Workforce management (skills), 11. Poor working practices				1.1 Human resource	11. Internal Legal issues (Labour union, Labour strikes)			
4.2	Problems in managing technology					3. Technological risk			6. Technical/ Knowledge Resources			14.Process technological changes#
4.3	Problems in managing product & process quality								1. Quality (Lost of customer Reputation)		2. Quality	5. Environmental performance 15. Product design changes
4.4	Problems in managing production schedules	2. Delays+							5. Production Flexibility			3. Cycle time

	My risk classification	(Chopra and Sodhi, 2004)	(Simchi-Levi et al., 2008)	(Hillman, 2006)	(Tang, 2006)	(Shrivastava et al., 1988)	(Stafford et al., 2002)	(Barroso et al., 2008)	(Wu et al., 2006)	(Harland et al., 2003)	(Zsidisin et al., 2000, 2004)	(Zsidisin, 2003)
4.5	Problems in managing productivity			2. Energy Shortages				1.2 Equipment, 1.3 Energy	4. Production Capabilities/Capacity			1. Capacity constraints 2. Cost reduction constraint
	Problems in managing information#	*3. Systems (information infrastructure break down)*		*9. Poor IT infrastructure*								
	Financial#							*1.4 Financial (company)*	*2. Cost (Cost model), 7. Financial & Insurance issues*		*3. Cost*	
	Strategic risks +Other#	*7. Receivables (financial strength of customers)*	*11. Execution problems*			*1. Human risk*			*8. Management related issues, 9. Accidents (Employee accidents etc.)*	*1. Strategic risk, 5. Asset impairment risk*	*1. Design*	

Note: * Both Demand-side and Supply-side uncertainty,

+ Demand-side, Supply-side uncertainty, and Vulnerabilities in own organisation

Risk category which is out of the proposed SC risk classification

C. Experimental Devices

C.1. Experimental Case Study Information: NHS Medicine Supply Chain Case Study

The NHS in UK is one of the well-respected health care providers in the world. Recently, they have employed automated technology, mainly to improve the speed, accuracy, and cost of the health service. Redesign projects were launched in different areas in the UK, with different designs in particular areas where there is a cluster of hospitals in the same area. The chosen design was the decision of the Health Board of the area. One of the NHS areas decided to redesign their pharmaceutical supply chain, examining aspects of the supply chain e.g. inventory policy and automated distribution, using new technology. There are ten hospitals in this area which are supervised by the same Board. These hospitals are meant to use the same policy for their operations. The changes implemented through the redesign project can lead to numerous problems and adverse risk events to make the new system perform poorly, particularly during the early phase of the project. For the new system to be successful in achieving its objectives, the redesign team needs to solve any unwanted events and establish proper mitigating actions to improve the system.

1. Previous situation

De-centralised supply chain

The previous pharmaceutical supply chain was de-centralised, consisting of multiple suppliers servicing multiple hospitals (see Figure C-1). It was found that different wards of different hospitals had different day-to-day operational policies.

Inventory policy

With the old system, each hospital was largely responsible for its own stock control. Since the availability of medication at all times for patients is a crucial factor within the health care service, medications were ordered and stored in bulk. Several issues arose with this system, such as the expiry of drugs, stock maintenance cost and difficulty in managing large stock quantities.

Main problems with the previous supply chain or system

1. NHS continually lagged the private sector in terms of logistics and distribution. Unlicensed medicines and controlled medicines are important security concerns within the supply chain and must be managed properly.

2. Although the scale of pharmaceutical consumption was increasing, constraints on the health care budgets drove the need for efficiency improvements and cost reductions.

3. There could be a risk of error in administering patients' medicines as numerous staff members were involved in the various processes. Furthermore, it was not always possible to have large stock for all medicines in a given hospital, resulting in patients missing their medication at times.

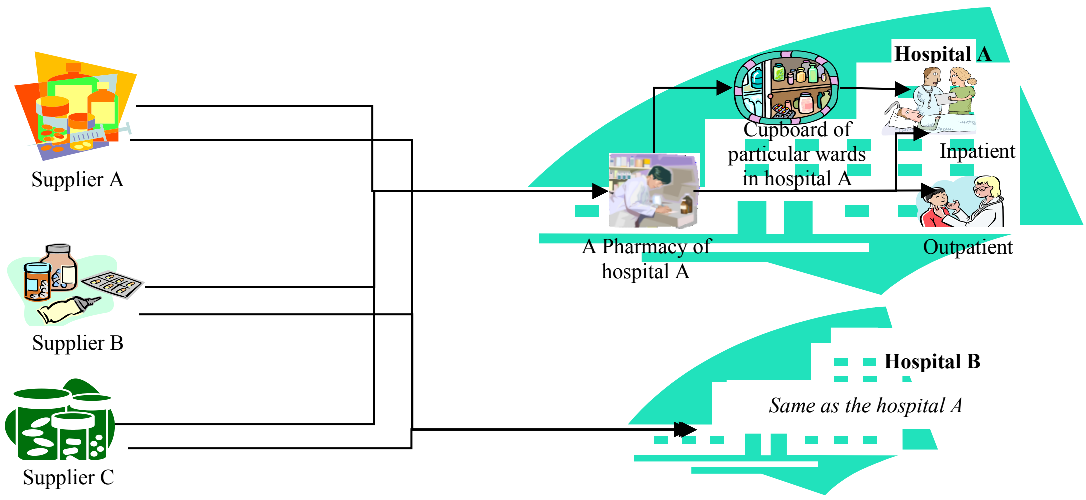


Figure C-1 Previous de-centralised supply chain

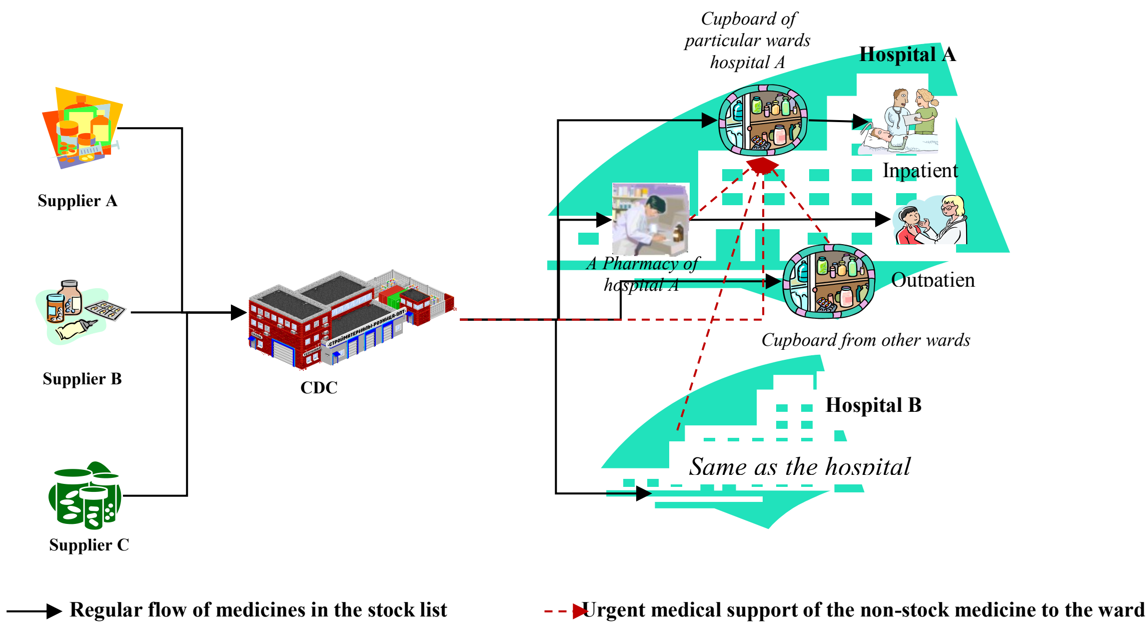


Figure C-2 Current centralised supply chain

2. Proposed distribution system

The adoption of a centralised distribution centre is proposed to be the major change within the pharmaceutical supply chain. It is believed that by having a central stock storage centre, the Centralised Distribution Centre (CDC), from which stock can be distributed to all hospitals within a given area, will reduce the stock holding in particular hospital. In turn, the resources normally used in filling orders, for example, can be released. Furthermore, a centralised storage system can help to release manpower to front-line in an attempt to improve the service to the patient, but it is not intended to reduce overall manpower in the system.

The new distribution centre can be the most critical agent of the NHS supply chain and, therefore, issues associated to its operations will be of major concern to the NHS. For example, an adverse event occurring in the CDC, can affect the entire supply chain. In addition to providing an efficient storage and distribution mechanism for stock, the CDC must also be secure, and provide security for medical information. Therefore, advanced robotic technology is recommended for use within the automated distribution system in the CDC.

The CDC should allow each hospital to store less stock than was previously done. However, the hospital inventories are still crucial to ensuring that patients can receive their medicines on time. This is one of the most significant aspects of control for the new design.

The economies of scale that can subsequently be realised within the entire NHS supply chain due to the new system will result in cost reduction. Simultaneously, customer service can be enhanced.

3. Brief configuration of new system

The new system has been designed to pool the stock at the CDC in order to reduce the stock storage requirements at individual hospitals. The CDC is responsible for replenishing the central stock store but does not cater for serving the requirements of the individual patients. The configuration of the new system is shown in Figure C-2.

The role of the hospital wards:

Each ward in a hospital has a list of stock that should be maintained at an agreed level determined by the hospital pharmacy. In the wards, they apply a periodic review system - if the review interval or the target level are not suitable, it can lead to too much or too less safety stock. There are two types of medications in the wards: those on the ward stock list and those not on the ward stock list.

Medicines on the ward stock list:

The medicines on the ward stock list are checked at regular intervals (2-3 times per week) by the hospital pharmacy. The pharmacy technician takes a manual count of the available medicines on the ward and uses a hand-held device to generate an order, if necessary, by comparing the current stock level with the target stock level. The information from the hand-held devices is transferred electronically to the CDC in a computer room. The CDC deliver the medicines to the wards within the agreed time windows (see detail in the role of Centralised Distribution Centre (CDC)).

Medicines not on the ward stock list:

There are occasions when a ward may urgently need a particular medicine that is not on the ward stock list or is on the word stock list but it is out of stock in the ward. In this instance the pharmacy should seek the medicine at the local hospital pharmacy, or from another ward. The new system facilitates an urgent order mechanism if the medicine cannot be obtained from one of these sources. The mechanism allows an urgent order to be sent to the CDC for immediate processing but the hospital pharmacy has to call the CDC to confirm am urgent order because the software cannot support to distinguish between the regular orders and the urgent orders. If the item is out-of-stock at the CDC, the CDC forwards the emergency indent/request to the supplier. In such a situation, the medicine is delivered directly to the hospital from the supplier. The cost of receiving an urgent delivery from suppliers will be higher than the cost of a regular order. Sometimes, when the item in the CDC is not available for the urgent order, the pharmacy will call to the other hospital pharmacies and arrange the transportation to collect it.

A typical example of such a situation is the admission of an elderly patient, who also suffers from arthritis, diabetes and possibly other non-cardiac complications, into a cardiac ward. While the patient's cardiac medications will be available on the ward, it is very likely that his/her other medications will not be, and the ward will be required to source the medication elsewhere. However, this individual may also be on a particular anti-inflammatory medication for arthritis, insulin for diabetes, etc. If the cardiac ward does not stock these specific items, they have to source them from elsewhere. Typically, the first ports of call are the surrounding wards and the local pharmacy. If the item is not available from these sources, the hospital pharmacy dispensary will need to send urgent order to the CDC. When the CDC still cannot supply the medicine, the hospital pharmacy has to contact other hospitals sites in the zone in an attempt to obtain the medication. The hospital pharmacy is responsible for ensuring that the medication reaches the ward and is therefore responsible for making transportation arrangements, such as a taxi or courier, for collection from the site and delivery to the pharmacy. The pharmacy will then dispense the item to the cardiac ward.

There is no formal record of the number of in-patients who are not administered with their medications on time and the consequent effects to them. The question of not having the medication available on time remains relevant. There is evidence that wards cannot always obtain non-stock medicine by following the procedure to make urgent orders. Furthermore, there are cases in which the medicine is on the stock list but out of stock, due to many reasons such as delayed delivery, receiving wrong orders or no medicine supply from the CDC. Not only do the issues emerge from the CDC but also from the wards, such as improper inventory policy on the ward, or late order placing to the CDC, etc., which can cause problems. Those problems are likely to make staff worry that they will not provide the right medicine to right patient at the right time. They start press order more frequent and stock more medicine. This is not a policy that the CDC is designed to cope with, so it could make problems in the system even worse.

The role of the hospital pharmacy:

A continuous review system is employed for the regular stock list. When the stock level reaches the reorder level, an order is sent electronically from the hospital pharmacy to the CDC via software.

The hospital pharmacy will provide the non-stock medicine to the wards. If the medicine is not in stock in the pharmacy, the pharmacy staff checks the availability of the medicine in other wards in the hospital. If it is not available from these sources, the staff sends an urgent order to the CDC and confirms the order via a call to the CDC.

The role of Centralised Distribution Centre (CDC):

The main role of the CDC is to replenish medicines in the wards and pharmacies in the hospitals within the zone. The CDC can adopt many of the functions previously carried out autonomously at each hospital site. Furthermore the CDC can consolidate the various site orders, thereby benefitting from procurement scale economies and bargains from the suppliers.

The CDC uses a continuous review system, which must define the proper value of re-order quantity (ROQ) and re-order level (ROL) to deal with uncertain demand. Furthermore, both international and local suppliers provide medicines to the CDC. At times, the suppliers deliver the medicines much later than the normally expected lead time or experience a sudden or unexpected failure.

The CDC is equipped with a robotic system that is the largest robotic system in Europe. The NHS does not yet have the experience to deal with the problems occurring during robotic system implementation. The picking head in the robots operate to adjustable internal shelving for stock in and pick the medicines before flowing them down with the chute to the relevant order or 'Tote' box for filling the orders of hospitals. A barcode is used to communicate with the robots as it can used to identify the location of the particular medicine. Thus, the breakdown of one robot will not affect the system. However, sometime problems can arise in the process of transferring products to the wrong order totes.

There are 2 main stocks in the CDC. The major stock is the robotic stock, which includes all medicines that are not challenged by packaging size or barcode. All medicines that cannot be stocked in the robotic system are put in the non-robotic stock area.

When the CDC receives medicines from the suppliers, the CDC staff ensure the accuracy of the orders and the validity of the expiry dates. If there are any problems with the received medicines, the medicine will be moved to either the robot stock or the non-robotic stock.

When the CDC receives the orders from the hospital pharmacy or wards, the orders have to be checked for duplication and the medicines checked for availability. The orders are then selected and printed. The process of filling the order begins by moving the tote to the appropriate chute number setting, matched automatically with the order. After the tote finishes filling from the robotics stock, a light signal indicates if the tote needs to pick medicines from the non-robotic stock. If not, the tote is sealed and moved to the dock classified by the hospitals in order for delivery. If medicines from the non-robotic stock are required, the picking staff will fill the tote manually before re-checking the order, sealing the tote and moving it into the dock area (see Figure C-3). If an order arrives at the CDC before 1 p.m., same-day delivery is applied. If the order arrives after 1 p.m., it is delivered the next day.

The role of suppliers:

The main role of the suppliers is to provide the medicines to the CDC (not directly to the hospitals). Some of suppliers are international, so long-term demand forecasting must be performed for all hospitals in the zone in order to ensure that the stock is available, as the lead time will be longer for international deliveries. The forecast orders can be included in a contract between the supplier and the NHS. For local suppliers, the order can be forecast for a shorter period of time, thereby being more flexible. The amount of medicines can be more easily adjusted.

When medicines are out of stock in the CDC, the supplier may need to fulfil an emergency order from the CDC and send this directly to the ward but this is unusual.

4. Summary

The information above has been produced after the new system was in operation for 6 months. Many supply chain issues exist and are worsening. Several of these can be resolved by making improvements to the system, while others will be resolved as staff become more familiar with the new system. However, due to constraints such as limited time and effort, all issues cannot be immediately solved, or solved at the same time. Thus, considering the complex problem from a systemic view can help the decision team understand how individual issues or risks can affect the system and then lead to a choice of proper mitigating actions. Learning the way to identify and structure risks systemically will be useful tool in helping decision-makers better understand the problem.

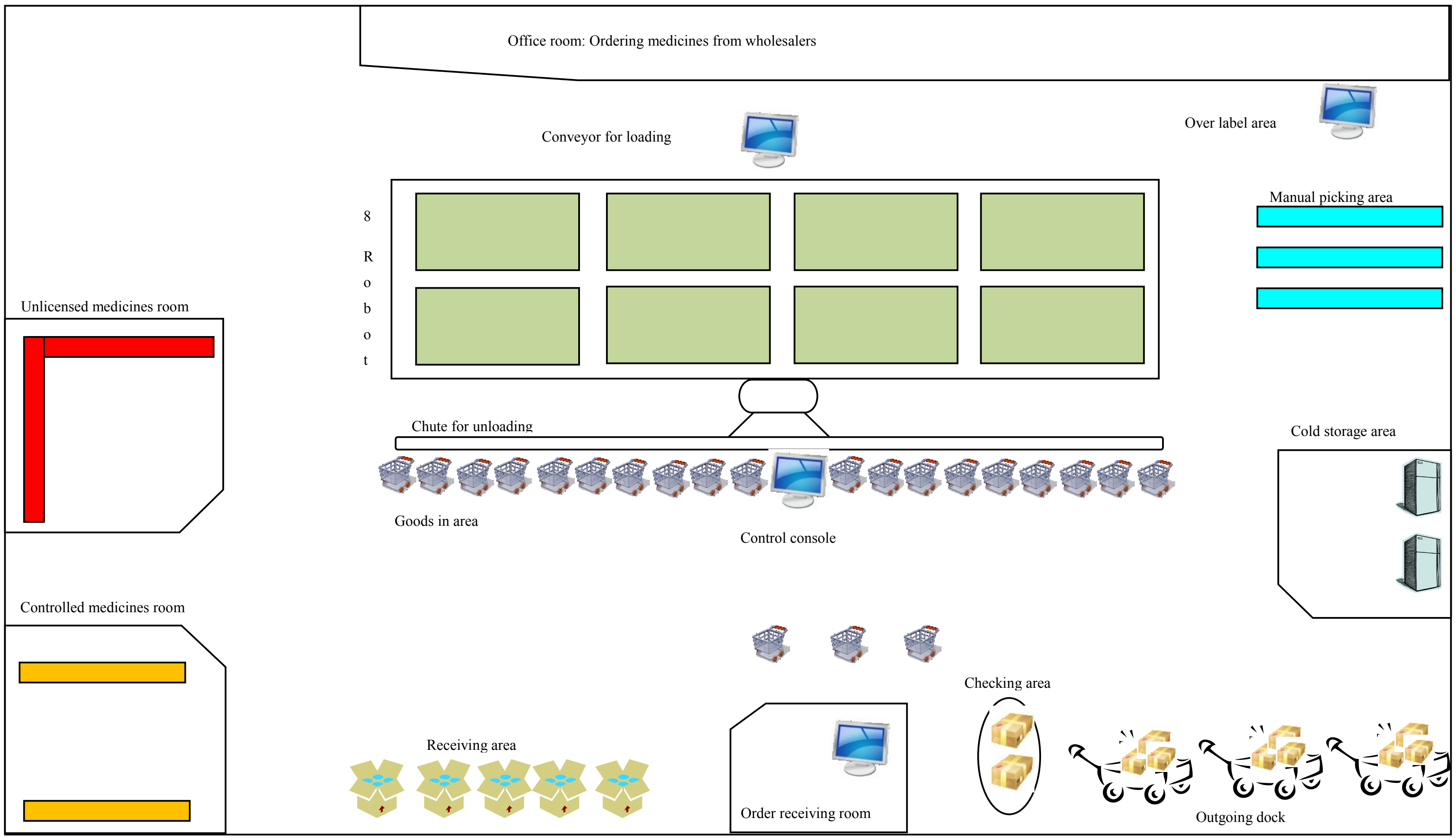


Figure C-3 Centralised Distribution Centre layout

C.2. Manual I: Causal Map

What is a Causal Map (CM)?

"A word-and-arrow diagram in which ideas and actions are causally linked with one another through the use of arrows. The arrows indicate how one idea or action leads to another" (Bryson et al., 2004, p. xii).

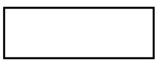
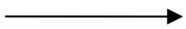
A Causal Map can be applied to describe and understand causal (i.e. cause-and-effect) relationships in a decision problem. It can show the decision outcomes or represent the alternative decision actions in a causal relation (Nadkarni and Shenoy, 2001). Causal Maps have been used primarily to qualitatively describe the variables used by experts in a particular decision domain (Nadkarni and Shenoy, 2004).

However, the Causal Map employed in this case study will be used to identify the causal relationships between uncertainty events from a qualitative (that is, non-numerical) perspective.

Employing a Causal Map in the context of risk identification to show cause and effect relationships is very useful because:

- It can support discussions between managers to identify risks and their relationships
- It can help to surface cultural differences
- It can help different people to contribute different kinds of knowledge
- It can show causal effects (i.e. cause-and-effect relationships)
- It can deal with a large degree of complexity of the various risks
- Causal mapping is carried out using natural language, so it is understandable and accessible to all

Icons or symbols

Symbol	Name	Description
	Causal concept	- Can represent both a cause event and an effect event, because one event can lead to another event, which can itself lead to another event – in a chain of uncertainty events - Should always include a verb - Should ideally consist of about 6 to 8 words - Should avoid 'should', 'ought; 'need', 'must' etc. - Should avoid 'in order to', 'due to', 'through' etc.
	Causal connection	- Is a unidirectional arrow - Can represent 'if-then', 'because', 'so', 'as', 'therefore', 'lead to' etc. - Not chronological (that is, not necessarily related to the passage of time)

An arrow can point from cause to effect in any direction, bottom to top, or top to bottom, or right to left, or left to right. The map can be a visual representation to show how a group of managers perceives an uncertain situation, by representing the interaction of uncertain issues or risks in a case study.

The process to develop a Causal Map

Groups can develop a Causal Map by using simple manual methods. Oval mapping tools or post-its can be stuck to a whiteboard to represent uncertainty events (causes or effects) and then arrows can be drawn to link them in a causal network. A Causal Map should be easy to adjust and be visible to all participants.

We suppose that all participants in the group have a similar understanding of the given case study, so that participants can place the ovals themselves onto the whiteboard. Furthermore, participants can engage with the map in order to add, merge, or delete concepts or links in the map. The Causal Map can be developed by following a clear process. An example will be shown how to develop a Causal Map step-by-step.

1. Identify a key event with an adverse effect on supply chain performance; that is, an event that can damage the overall objective of the whole supply chain. This key adverse event will be the TOP event for the case study.

Example: A company is preparing to launch a new product and intends to start selling it before Christmas. But they would like to know the possible risks that could delay the launch of this product.

The main concern about poor supply chain performance is: 'Product launch is delayed'.

Product launch is delayed

2. Identify the possible causes of this uncertainty event in a hierarchical fashion by using brainstorming to link all causes and effects with arrows.

From their understanding of the case study, group participants can identify 'causal statements' describing any uncertainty events that can lead to the poor supply chain performance identified above (see step 1). A causal statement can be identified from a causal statement that is already mentioned in the case study information or from the participants' own understanding. A causal statement can be partitioned into 'Causal phrase', 'Causal connector', and 'Effect phrase'. This process can help to explain how to define concepts and links.

Example:

Group participant A states that: *"if a supplier delivers a key material late, then the product will have a delayed launch"*.

Causal phrase: A supplier delivers a key material late

Causal connector: would lead to

Effect phrase: The product launch is delayed

The causal phrase with its causal connector can then be added to the map. The phrase should not be too long as otherwise it may not fit into the map.

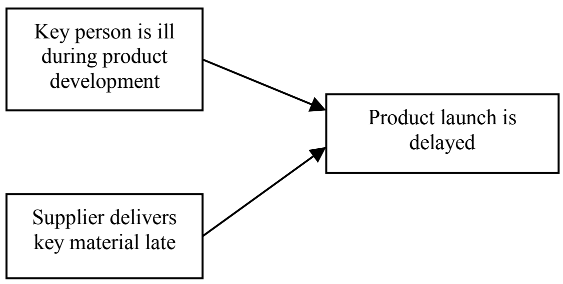
Suppose that group participant B then mentions that: *"the delayed launch of the product could be caused by a key member of staff being ill during the main product development period"*.

Causal phrase: Key person is ill during product development

Causal connector: would lead to

Effect phrase: The product launch is delayed

Example:

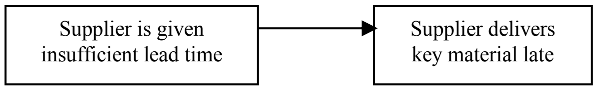


The map can be extended to show the respective causes of the events just added, until no more uncertainty events are proposed as possible causes by the participants. This is known as backward working. The most appropriate length of a chain of uncertainty events depends on the perception of the participants.

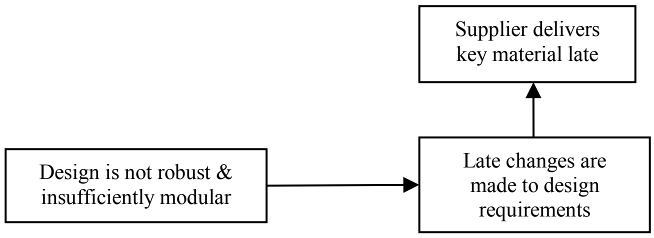
Example:

Why would the supplier deliver the key material late? (Tracking the causes of late delivery by the supplier)

A: *"When the supplier does not have sufficient lead time, the supplier cannot deliver the material on time."*



B: *"The design of the product should be robust and not keep changing. Late changes to requirements from the manufacturer can lead to the supplier not being able to complete the specified material on time."*



The figure below depicts a simple Causal Map of the 'Product launch is delayed' example:

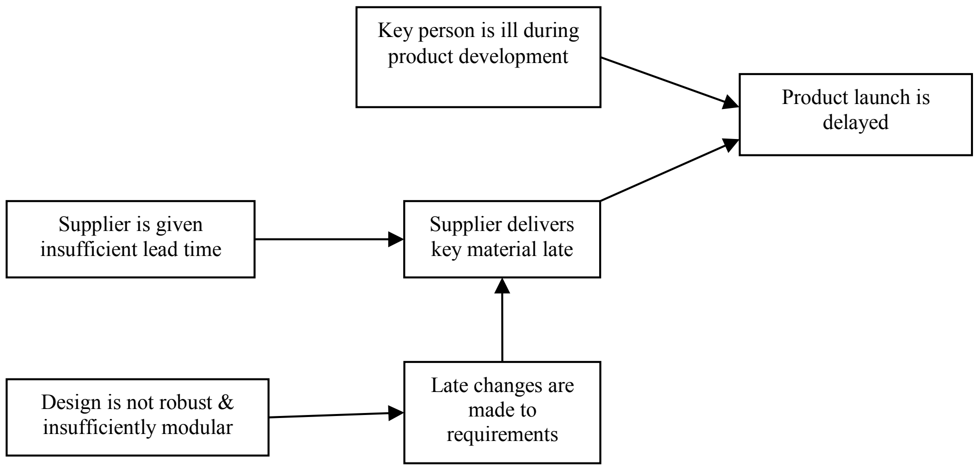


Figure C-4 Example of Causal Map for the 'Product launch is delayed'

3. Tidying up the map

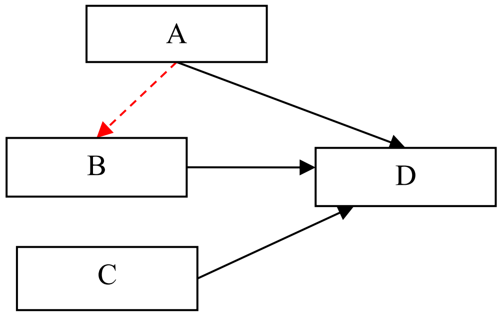
Participants can look for isolated events in the map, or examine the heads and tails of chains of events, to link those events into the rest of the map.

If there are similar uncertainty events that different participants have identified by using different words or phrases, then such events should be grouped or merged into a single event.

The discussion about the precise definition of each uncertainty event can help to tidy up the map and ensure a consensus between the group participants.

Any disagreements about causal links should be discussed, in order to decide whether to add or delete them. Relationships between uncertainty events should be clearly stated and, if necessary, explained in more detail.

Example:



The question here is: does A affect D directly, or indirectly (via B), or both?

Suggestions

A Causal Map can be used to show the perception of an expert group about Supply Chain risk. Since this is a complex problem, there is unlikely to be a 'right' or 'wrong' answer. However, some answers may be better than others(IAS, 2009).

The conceptual modelling framework below can help in developing a Causal Map (Figure C-5).

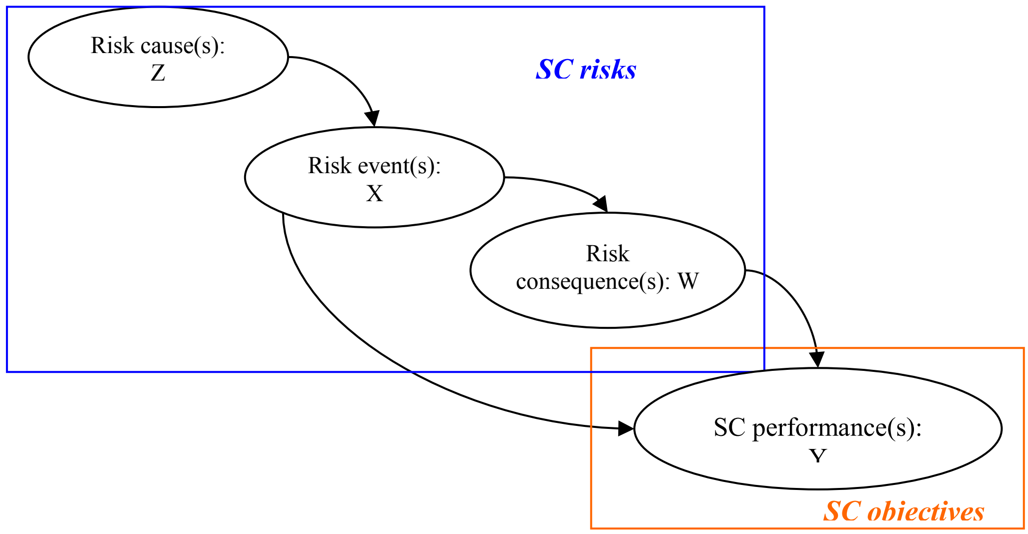


Figure C-5 Conceptual modelling framework supports causal mapping

Initially, an adverse SC performance variable should be defined. One can then try to identify its causes, working backwards.

There is no formal rule to define the level of causal decomposition. The agreement of the team will be used to consider the sufficient level of granularity and to decide when to stop the decomposition of the uncertainty events. A physical boundary and a temporal boundary are recommended in order to help the team define the scope of a Causal Map more easily.

Physical boundary is the scope of the supply chain that can be identified by defining the agents who can be involved in the risks in a supply chain. In the main case study, the physical boundary can be defined by considering the main diagram of the supply chain.

Temporal boundary is the scope of the time frame or related activities. This is useful because some risks can occur during a specific period of time.

One suggestion to modify or tidy up the Causal Map is to use the questions 'How' to ladder to the effects and 'Why' to ladder to the causes. The map can then be extended until no more variables or causes are proposed by the group participants (see Figure C-6).

From uncertainty event (X), when we want to identify its cause events, we can ask: '**Why** could event (X) occur?' When we want to know the effects of event (X), we can ask '**How** could event (X) cause other events to occur?' If the proposed event is already in the map but has not yet been linked with an arrow, we can add a new link to the events. If the proposed event is a new event, both the new event and a new link should be added into the map. On the other hand, existing links could be deleted, if necessary.

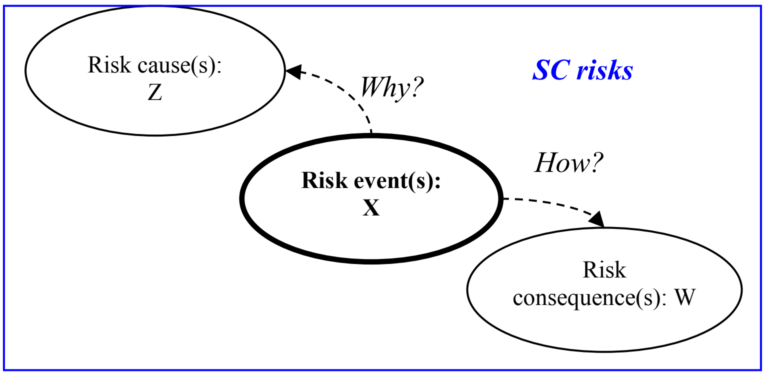


Figure C-6 From uncertainty event (X), the question 'How?' can be used to identify its causes and 'Why?' can be used to identified its consequences

Structured thinking about cause and effect relationships can be facilitated by separating (long) sentences into distinct phrases.

A Causal Map can be developed within a group workshop by using a brainstorming technique. The arguments can be solved during the brainstorming phase. In this way, discussions about cause-effect relationships and the meaning of each event can help a group to achieve a consensus map.

The typical rules of a brainstorming session are given in the Project Risk Analysis and Management Guide (2004) as:

- Encourage wide participation to prevent the session being dominated by a minority
- Do not focus too much on in-depth analysis
- Encourage participants to build on the ideas of others - seek combination and improvement
- Prohibit overt criticism - to encourage participation and to defer judgement where necessary.

Exercise

TOP event: Supply chain breakdown

There may be a lot of uncertainty events that could cause a supply chain to break down. Please develop a casual map for this TOP event by following the process explained above. As this is a short exercise, you could think of about 5 to 6 underlying causes that will link to this TOP event.

Further reading (Optional)

(Nadkarni and Shenoy, 2001)

References

BRYSON, J. M., ACKERMANN, F., EDEN, C. & FINN, C. B. (2004) Visible thinking: unlocking causal mapping for practical business results, West Sussex, England John Wiley & Sons Ltd.

IAS (2009) Investing in an uncertain future: Decision support methods for policy makers. Institute for advanced studies.

NADKARNI, S. & SHENOY, P. P. (2001) A Bayesian network approach to making inferences in causal maps. European Journal of Operational Research, 128,479-498.

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PRAM (2004) PRAM: Project risk analysis and management guide. APM Publishing.

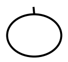
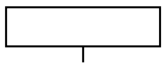
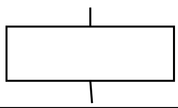
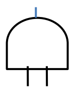
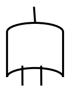
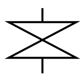
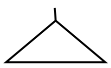
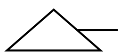
C.3. Manual I: Fault Tree

What is Fault Tree (FT)?

A Fault Tree (FT) is a top-down approach which combines multiple potential failure events to the (single) TOP event. Fault Tree can be used to identify or describe the occurrence of the TOP event under the conditions or factors which cause or contribute to a TOP event as a tree structure. In other words, TOP event can be an undesirable outcome of the supply chain performance that will represent the failure of the supply chain. The occurrence of the TOP event can be defined as the occurrence of the other intermediate events at the finest of detail, BASIC events.

Fault Tree is one of the well-known techniques in order to identify risks especially in the network of interaction between risks. The relationship between a TOP event and BASIC events by using Boolean operations AND, OR, and NOT gate to link from BASIC events to the TOP event.

(Basic) Icons or Symbols

Symbol	Name	Description
	BASIC event	A root cause at the lowest level is a potential cause of the failure of the TOP event.
	TOP event	The focus event describes the system fault or unwilling SC performance.
	INTERMEDIATE event	An event describes the system fault in higher level by combining BASIC events or lower INTERMEDIATE events and link to the TOP event.
	AND gate	The output event takes place if all of the input events occur (input events can be two or more than two events).
	OR gate	The output event take place if any of its input events occurs (input events can be two or more than two events).
	NOT gate	The output occurs if there is no input or input event does not occur.
	TRANSFER in	A gate indicating that this part of the system is developed in another part or page of the diagram.
	TRANSFER out	A gate indicating the branch or group of BASIC events that will be referred in another part of the model by notice from TRANSFER in gate.

Source: Adjusted IEC(60300-3-1), 2003

Fault Tree developing process

The methods of group participation to develop Fault Tree (FT) can be operated by using the simple manual. Oval mapping or post-it can be pasted on the whiteboard to represent a variety of events and then draw gates to link them as the FT structure. The FT should be in the manner the easier to be adjusted and visible for all participants. The FT can be developed by following the process and the example to show how to develop FT step-by-step.

1. Start from defining the TOP event that should be an unwilling event to represent the bad performance of the supply chain

Example:

A company is preparing to launch a new product and expects to sell it before Christmas but they would like to know the possible risks that can delay the product launch.

TOP event: 'Delay product launch'

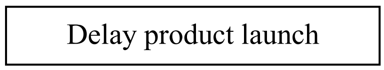


Figure C-7 TOP event in Fault Tree

2. Develop the tree map by finding the sufficient and possible causes for the TOP event
   - o You can extract some of the possible causes in the finest detail in order to identify the BASIC events by brainstorming. A group of BASIC events can be linked to the higher level event as call as an INTERMEDIATE event.

   - o Proper gate can be selected by considering the logic of cause co-operation or the joint of faults.

Example, 'Fire' can be light when 'Leak of flammable fluid' AND 'Relay sparks'. It means Either 'Leak of flammable fluid' or 'Relay sparks' could not light 'Fire'.

Example (Cont.):

The product cannot be launched on time if either the key person gets sick or no key component supplies from the suppliers.

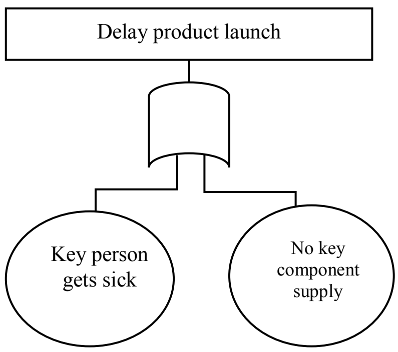


Figure C-8 OR gate represents the causes of 'Delay product launch'

The company has been worried about a key component that is specific and can make the product differ from the previous version. The key supplier has been chosen but the team still prepares a backup plan in case that the main supplier cannot provide the key component, by preparing a list of back-up suppliers. Ordering the key component from back-up suppliers will increase the cost but they need a shorter lead time. If both supplier and back-up suppliers cannot provide the component, it will mean that the company does not have the key component to produce the product. If either one source of suppliers can provide the component, the production will not be disrupted. Therefore, the 'No key component supply' that has been defined as the BASIC events as the Figure C-8 has to be changed to INTERMEDIATE event and an AND gate is added to link both 'Main supplier late' and 'Back-up supplier late' as the new BASIC events.

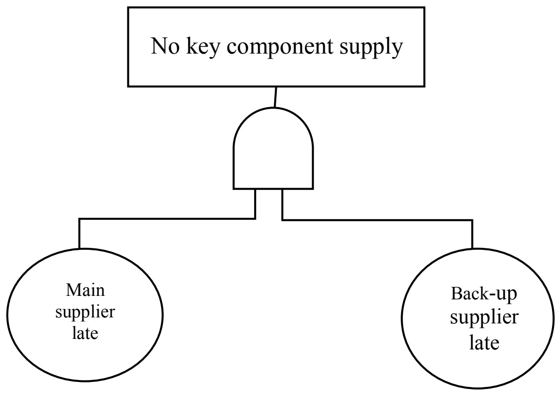


Figure C-9 AND gate represents the causes of Back-up system fail

In addition, we can identify the finer detail of the causes of 'Supplier late' that may come from the company give the main supplier insufficient lead time or make the last-minute changes to requirements. The OR gate is chosen to represent the logical relation to the INTERMEDIATE event: 'Main supplier late'.

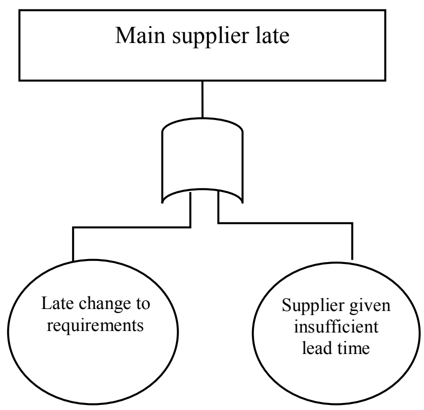
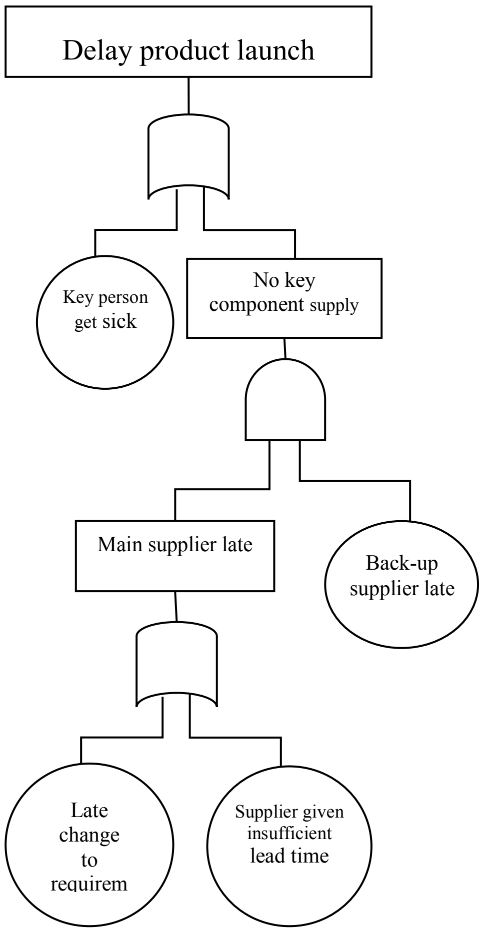


Figure C-10 OR gate represents the causes of 'Supplier late'

The completed Fault Tree can represent all the links from BASIC events to the TOP event via Gates and INTERMEDIATE events as Figure C-11.



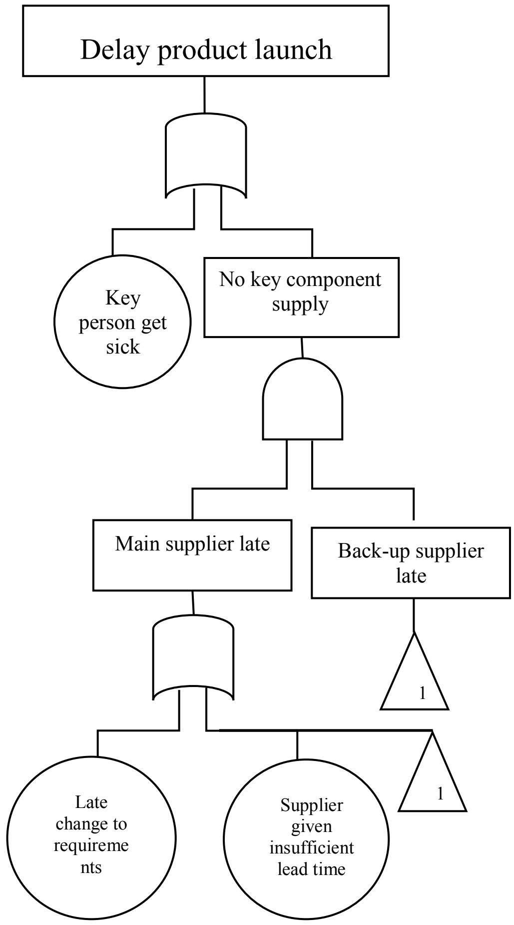


Figure C-11 A full Fault Tree of 'Delay product launch'

Figure C-12 A revised Fault Tree of 'Delay product launch'

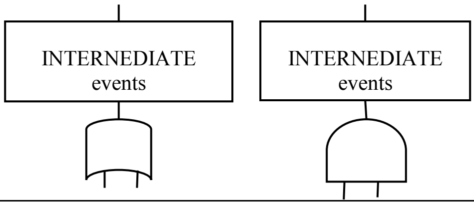
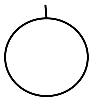
3. Check the map to ensure that all BASIC events have been identified and all gates can represent the correct logic and all BASIC events links to the proper INTERMEDIATE events.

Example (Cont.):

The full model that has been constructed in the 'Delay product launch' can be seen in Figure C-11. Suppose that there are some discussions about the causes of the back-up suppliers cannot provide the components in time. The main reason is they have not got the sufficient lead time because the order will be pressed to the back-up suppliers when the main supplier cannot provide the component in the agreed time. Event though, they may think that 'Late change to requirement' will be a cause of pressing the order to the back-up suppliers, but it may not make the back-up suppliers late deliver component to the company. Therefore, the Fault Tree can be revised to the Figure C-12.

Suggestions

1. Work out the direction of the connection from TOP event to BASIC events or a failure to its causes
2. The general structure of the Fault Tree can be explain as 3 hierarchical categories as A TOP event links with Gates or INTERMEDIATE events to the BASIC events.

A TOP event (the highest layer)	
Gates or INTERMEDIATE events (different layers)	
BASIC events (the lowest layer)	

3. Use descriptive events that make sense and not too difficult to understand (i.e. avoid abstract descriptions)

Example: 'Motor operates too long' versus 'current to motor too long'

4. When the outcome of one branch can be the set of BASIC events to a different INTERMEDIATTE event or gate, we can use the TRANSFER gate (in and out) to make the map less complex.
5. An example below, INTERMEDIATE event (I) consists of three BASIC events, (B OR C) AND D.

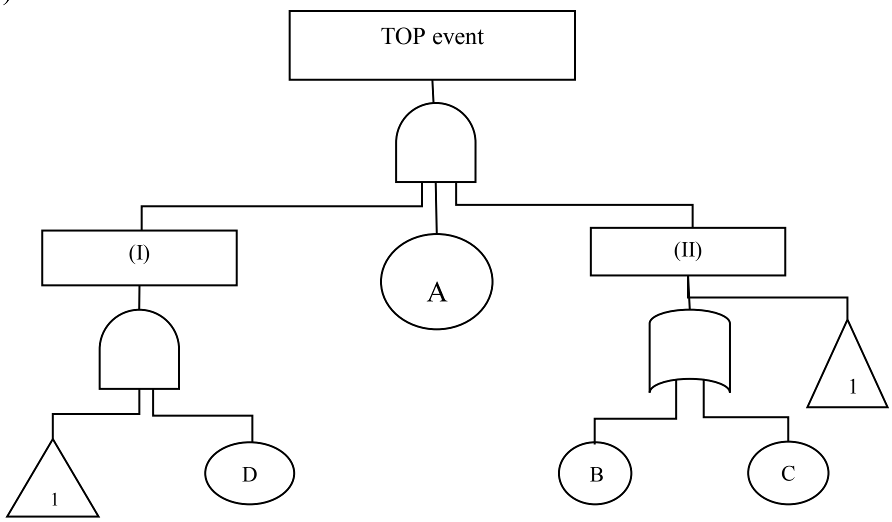


Figure C-13 An example to show how to apply TRANSFER GATE

6. Fully identify all inputs to a particular gate before developing any of inputs further, hierarchical layers.
7. No gate to gate connections
8. The depth of the BASIC events or the lowest event depends on how people perceive a problem.
9. The typical rules of brainstorming session are given in Project Risk Analysis and Management Guide (2004) as:
   - Encourage wide participation to prevent the session being dominated by a minority
   - Do not focus too much for in-depth analysis
   - Encourage participants to build on the ideas of others- seek combination and improvement
   - Prohibit overt criticism- to encourage participation and defer judgement

Exercise

TOP event: System power fails

(Bedford and Cooke, 2001) A security system in a hospital is powered by a generator. If the generator fails then a switching system switches over to a battery. The TOP event, T, is the event that the security system fails through lack of power. The security system has no power if the generator fails and if the back-up system fails. The back-up system can fail in two ways – either because the switch has failed or the battery does not work.

Further reading (Optional)

(Bedford and Cooke, 2001)

Reference

BEDFORD, T. & COOKE, R. M. (2001) Fault and event trees. Probabilistic risk analysis: foundations and methods Cambridge, U.K., Cambridge University Press.

IEC(60300-3-1) (2003) Dependability management - Part 3-1: Application guide - Analysis techniques for dependability - Guide on methodology

PRAM (2004) PRAM: Project risk analysis and management guide. APM Publishing.

C.4. Manual I: Risk Register Map

What is Risk Register?

"A document kept under configuration control, usually within a data-base containing a list of adverse events that might occur" (Williams et al., 1997).

"Risk Register provides a structured approach to recording risk data and generating report" (PRAM, 2004, p. 45).

Based on the register document, the usefulness of the document (Edwards and Bowen, 2005) is:

- Creating a useful risk-related information gained from experiences
- Making this information available for beneficial use on future projects
- Facilitating the use of information to guide change in the organisation
- Ensuring that valuable organisational knowledge is not lost through staff turnover
- Providing an accessible and auditable database of organisational risk management practice

Participants will be asked to develop Risk Register by identifying significant risks and recording them in Risk Register form. The minimum components of Risk Register are recommended by Project Risk Analysis and Management Guide (2004) as Risk ID, Risk title, Risk description, Risk owner, Likelihood, Impact, and Risk response strategy.

Risk ID: The rule to identify Risk ID depends on the agreement of the risk register team. The risk ID in complex Risk Register will combine a few digits to represent different parts of the system. The basic order is recommended as a simple way to identify Risk ID for your case study.

Risk title: The short words, or phrases, or short sentences no longer than 6-8 words. Risk title can be used to show the list of risks that are identified in the workshop.

Risk description: The description can be a couple of sentences to define the risk clearly and simply. It should be able to explain those risks in detail by considering who, what, where, when and how.

Risk owner: Staff's name or role relates directly to individual risks such as logistics manager, Purchasing manager, etc.

Likelihood: A chance of risk event can occur without any existing controls that may be in place. A description of likelihood levels should be defined as a standard definition for the project to make sure that all participants can identify likelihood of particular risks under the same basis. For the case study, participants can use the suggested risk likelihood description below to identify chance of identified risks under your perception (no right or wrong number). The likelihood or chance of a risk occurrence can be classified as: Remote (1), Unusual (2), Possible (3), Likely (4), Almost Certain (5).

Score	Description	Likelihood of occurrence
1	Remote	0% to 10%
2	Unusual	10% to 30%
3	Possible	30% to 60%
4	Likely	60% to 80%
5	Almost certain	80% to 100%

Risk impact: What is the worst case impact, if the full risk should happen? suggested Risk Impact can be described as 5 levels as: Negligible (1), Minor (2), Moderate (3), Major (4), Catastrophic (5). Participants can use this description to consider level of impact of identified risks from the case study by considering the impact on time (Schedule), cost or budget (Financial), or service level (Operational) criteria below.

Score	Description	Schedule	Financial	Operational
1	Negligible	< 2% of Project Timescale (Typically 1 or 2 days)	Loss < 5% of Project Budget	Minimal impact – no service disruption
2	Minor	2% to 5% of Project Timescale (Typically 3 days to 1 week)	Loss 5% to 15% of Project Budget	Minor impact on service provision
3	Moderate	5% to 20% of Project Timescale (1 to 2 weeks)	Loss 15% to 40% of Project Budget	Some objectives partially achievable
4	Major	20% to 50% of Project Timescale (2 to 4 weeks)	Loss 40% to 60% of Project Budget	Significant impact on service provision
5	Catastrophic	50% + of Project Timescale (over 1 month)	Loss > 60% of Project Budget	Unable to function /total failure

Risk response strategy: After the risks have been identified, the risk team should prepare a strategy to manage individual risks. The suggested general strategy can be classified into five categories as:

Strategy	Description
Prevention	Terminate the risk - by doing things differently and thus removing the risk where it is feasible to do so. Countermeasures are put in place that either stop the threat or problem from occurring or prevent it having any impact on the programme/work package
Reduction	Treat the risk - take action to control it in some way where the actions either reduce the likelihood of the risk developing or limit the impact on the programme/work package to acceptable levels
Transference	This is a specialist form of risk reduction where the management of the risk is passed to a third party via, for instance, an insurance policy or penalty clause, such that the impact of the risk is no longer an issue for the health of the programme/work package. Not all risks can be transferred in this way
Acceptance	Tolerate the risk- perhaps because nothing can be done at a reasonable cost to mitigate it or the likelihood and impact of the risk occurring is at an acceptable level.
Contingency	These are actions planned and organised to come into force as and when the risk occurs.

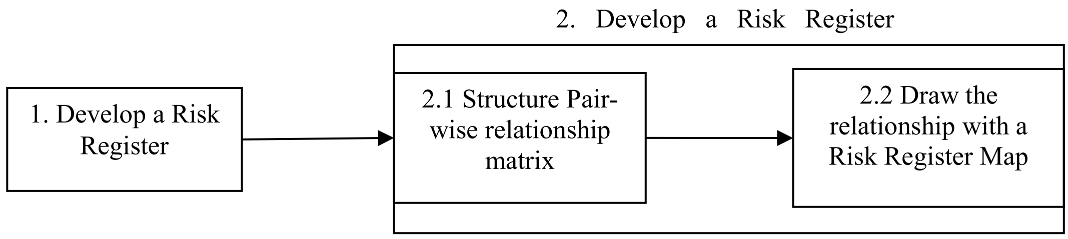
The definition and description of Likelihood, Risk impact, and Risk response strategy are not standardised and normally the risk register team has to develop the agreed definition for their own. After that they can document the particular defined definition of the states in the risk register document. However, this assignment will ask you to use the suggested description above to develop Risk Register for the case study.

What is Risk Register Map?

Risk Register may exist or normally document in the company already (Steel, 2007) especially when the company develop the project to modify or change the regular process. It is developed on the assumption that risks are independent or isolated of each other (PRAM, 2004) so Risk Register may not fully develop under the cause and effect relationship perspective. Therefore, an idea of modifying the Risk Register into a map to represent interrelationship between risk items can help to understand how risks interact to each other, Risk Register Map. Pair-wise relationship matrix will be aided to identify the relationship between risk items.

Risk Register Map developing process

The process of developing Risk Register Map can be defined as 2 main parts by starting from Risk Register development and then developing the relationship of the risk events as called as Risk Register Map.



1. **Develop a Risk Register:**

   There are several methods of risk identification but brainstorming is recommended for this task because it could be used on its own in a completely unstructured manner to engage stakeholders with a group to identify risks and develop Risk Register.

   The methods of group participation to identify risk items can be operated by using the simple manual. Oval mapping or post-it can be written and pasted on the whiteboard to make it visible to all participants. Some similar risk items have to be groped and then record unrepeated risks in the Risk Register form. After that Risk description should be used to explain in more detail of particular risk items. You have to consider the risk owner who takes responsibility of each risk event. The Likelihood, Impact, and Risk response should be identified by following the description given above. An example of simple Risk Register can be shown in Table C-1.

Table C-1 Risk Register example

ID	Risk title	Risk description	Risk owner	Likelihood	Impact	Risk response
1	Delay product launch	If the new product cannot launch before Christmas festival (November 2012), the company will miss the big chance to sell the product. After Christmas, the market will be decreased because they have spent a lot of money for the festival so they have to save money after that.	Production managers	3	5	Contingency
2	Key person gets sick	Because it is the new product so there are a few people taking responsibility of the new product. When he or she gets sick, it is difficult because other colleagues can run the process of new product development.	Product developer team	2	3	Reduction
3	Supplier late	The specific components would be innovative and the team are worried about the intellectual property and do not want their competitors to get the information of new product so numbers of supplier will be limited. Less redundant suppliers will bring to less flexible for the supplier cannot provide the components on time.	Purchasing directors	2	4	Transference
4	Back-up suppliers cannot provide the components	Some components can be ordered from the back-up suppliers that can provide the components to the company with a shorter lead time but the cost of the components will be more expensive.	Purchasing directors	2	3	Acceptance
5	Late changes to requirements	The components may be ordered already but the specification is changed after that so the previous need to be cancelled and new components should be reproduced.	Product developer team	4	2	Prevention
6	Supplier given insufficient lead time	There are many reasons that the company orders the components to late and asks a supplier to provide the components quicker than the lead time.	Production planner	3	3	Prevention
7	Design not robust	When the design keeps changing, the suppliers do not want to prepare any materials to produce the component because they do not want to take the risk to prepare the material that cannot be used when the company changes the design.	Product developer team	2	2	Prevention

2. **Link the risks as a map**

The list of risk items in Risk Register will be used to create a map by defining the relationship between them.

2.1 Structure pair-wise relationship matrix

Based on the list of risks, pair-wise matrix should be structured by crossing risk items both row and column dimension. Next, the participants still have to identify relationships between all possible pair of risk items as four types of relationship. The symbols can be used to represent the direction of relationship between risk items (i: row and j: column) and they can be explained below:

↗ : Risk item row i will help to achieve risk item column j.

↙ : Risk item row i will be achieved by risk item column j.

⤢ : Risk item row i and column j will help to achieve each other.

O : Risk item row i and column j are unrelated.

Participants should brainstorm and discuss to identify the relationship in the matrix. Only upper triangular matrix should be identified as an example in Figure C-14.

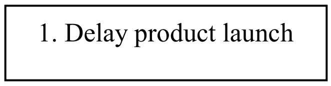
Risk items	1. Delay product launch	2. Key person gets sick	3. Supplier late	4. Back-up suppliers cannot provide the components	5. Late changes to requirements	6. Supplier given insufficient lead time	7. Design not robust
1. Delay product launch		↙	↙	↙	**O**	**O**	**O**
2. Key person gets sick			**O**	**O**	↗	**O**	**O**
3. Supplier late				⤢	↙	↙	**O**
4. Back-up suppliers cannot provide the components					**O**	↙	**O**
5. Late changes to requirements						**O**	↙
6. Supplier given insufficient lead time							**O**
7. Design not robust							

Figure C-14 Pair-wise relationship matrix

2.2 Draw the relationship as a Risk Register Map

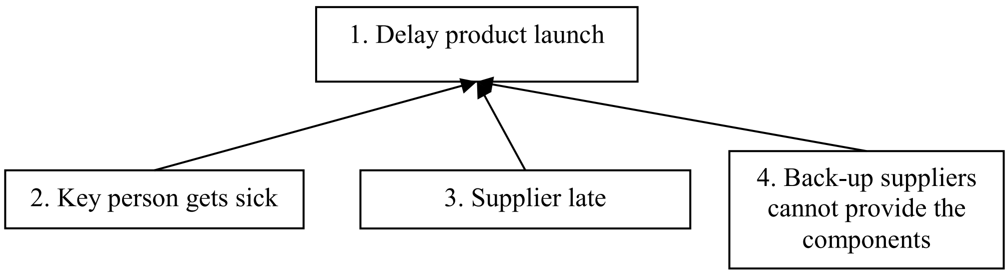
The identified relationships in the pair-wise relationship matrix will be modified into a map. The relationship defined in the matrix will be used to define the direction of an arrow to show relation from cause to effect. The recommendation of drawing the map should start from a risk item that has the largest number of the arrows point to. The Risk Register Map developed from the given example can be seen in Figure C-15.

From Figure C-14, ‘Delay product launch’ and ‘Supplier late’ have the largest number of the arrows point to (3 scores) so we can start either of them but for this example ‘Delay product launch’ is selected.



* For the two-way arrow, we can count the number of arrows point to the risk item as well. For instant, there are 3 scores of counting the number of arrows which point to ‘Supplier late’ from ‘Supplier given insufficient lead time’, ‘late change to requirement’ and from the two-way arrow that link with ‘Back-up suppliers cannot provide the components’.

Next, ‘Key person gets sick’, ‘Supplier late’, and ‘Back-up suppliers cannot provide the components’ are drawn hierarchically.



The lower causal layers should be identified and drawn in the map until all relations are shown in the map.

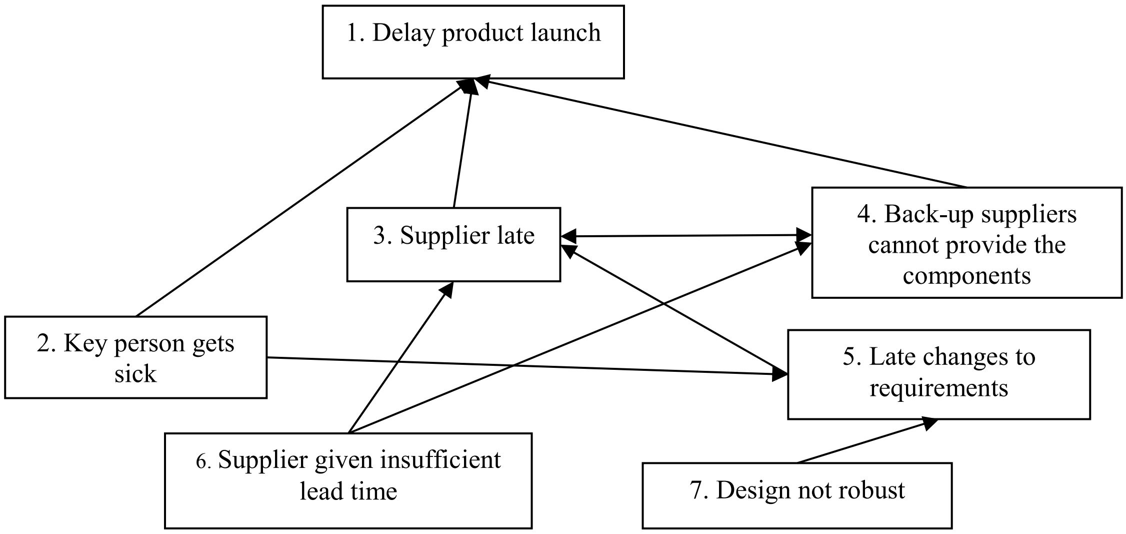


Figure C-15 Risk Register Map of 'Delay product launch'

Suggestions

1. The typical rules of brainstorming session are given in Project Risk Analysis and Management Guide (2004) as:
   - Encourage wide participation to prevent the session being dominated by a minority
   - Do not focus too much for in-depth analysis
   - Encourage participants to build on the ideas of others- seek combination and improvement
   - Prohibit overt criticism- to encourage participation and defer judgement
2. Before the brainstorming, you may have an agreement about the scope of Risk Register to make it easier and reduce the arguments during the process of brainstorming.
   - Physical boundary: Scope of supply chain that should identify the agents who can be involved and included in risks in the supply chain. In the case study, the physical boundary can be defined by considering the figure of supply chain.
   - Temporal boundary: Scope of the time frame or related activity because Risk Register can be updated to be adjusted. Some risks can be significant risks during a specific period of time when the time change, those risk events can already be managed and mitigated.

Exercise

Suppose that you have the short version of Risk Register and you will be asked to develop the Risk Register Map from this Risk Register.

ID	Risk title	Risk description	Risk owner	Likelihood	Impact	Risk response
1	Strategic failure					
2	Natural disaster event					
3	Logistics failure					
4	Geopolitical event					
5	Supply chain break down					

Further reading (Optional)

(Edwards and Bowen, 2005)

References

EDWARDS, P. J. & BOWEN, P. A. (2005) Risk management in project organisations, Sydney, University of New South Wales Press Ltd.

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WILLIAMS, T. M., ACKERMANN, F. & EDEN, C. (1997) Project Risk: Systemicity, cause mapping and a scenario approach. IN KAHKONEN, K. & ARTTO, K. A. (Eds.) Managing risks in projects. London, E&FN Spon.

C.5. Manual II: Bayesian Belief Network from Causal Map or Risk Register Map

Summary of task 2

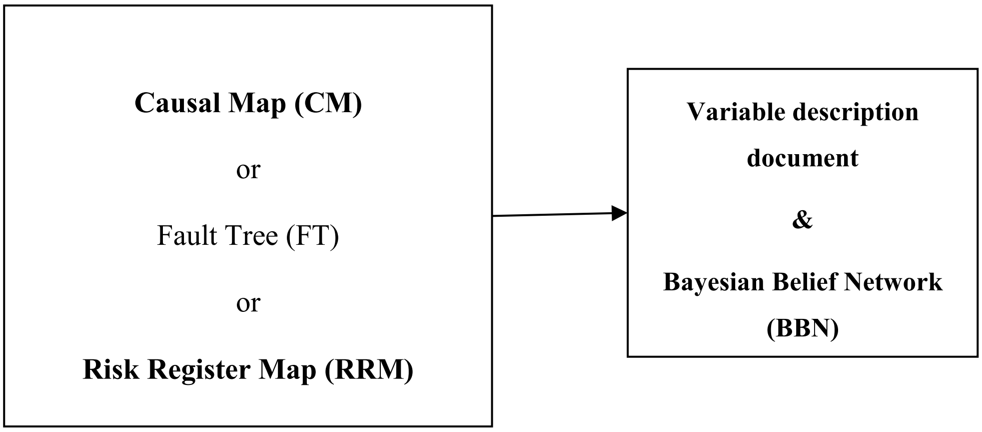


Figure C-16 Summary of the input and outcome of task 2

What is BBN?

> *A BBN is a directed graph whose nodes represent the (discrete) uncertainty variables of interest and whose edges are the causal on influential links between the variables (Bedford and Cooke, 2001, p. 286).*

A Bayesian Belief Network (BBN) is also called a Bayesian Networks (BNs). It is structured as the links between nodes in a network. An arrow pointing from node X to node Y means that X is a *parent* or an ancestor of Y and Y is a *child* or a *descendant* of X. A node with no parents is called a *root* node.

BBNs are developed from **probabilistic graphical models** in order to examine **uncertainty problems** among nodes of interest. This is done by quantifying probability number into *root* nodes and conditional probability numbers into *child* or *descendant* node.

Generally the BBN methodology consists of structuring the problem, quantifying the probability number, and inferring the probability of the systems in different scenarios. BBN is developed to represent uncertainty or risk by assigning the probability number or chance of particular events occurring to each node. We can then predict the consequence of intervention by applying Bayes' theorem (not explained in detail here). For example, a BBN could represent the probabilistic relationships between diseases and symptoms. Given symptoms, the network can be used to compute the probabilities of the presence of various diseases.

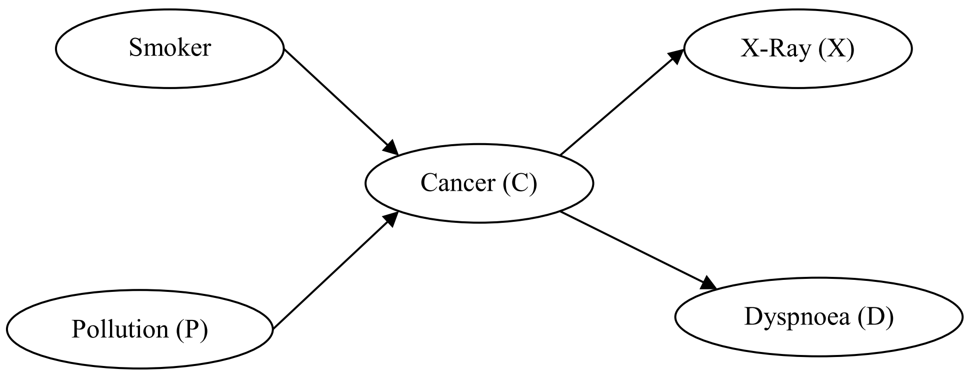
Under the limitations of this course duration, we will focus only on the qualitative BBN to structure the systemic risks that are inter-related to each other. Although this module does not examine the quantifying and inference processes, students should keep in mind that the qualitative BBN will be used to quantify and infer in the next process, so the greater the number of nodes link to the network, the greater the need to quantify the probability number; this will be the barrier for feasible application in the real problem.

The process of quantifying the probability into the BBN will be used to show how much number of probability input is required to the quantification process as the example below but please remember that **you are not required to quantify the number to your qualitative BBN in this class**.

Example: A BBN for lung cancer problem

S	P(s)
True	0.3
Fault	0.7
Total	1.00

X	P(X|C)	
	True	**Fault**
Pos	0.9	0.2
Neg	0.1	0.8
Total	1.00	1.00



D	P(D|C)	
	True	**Fault**
Pos	0.65	0.3
Neg	0.35	0.7
Total	1.00	1.00

P	P(p)
High	0.9
Low	0.1
Total	1.00

C	P(C|P,S)			
	S = Low		**S=High**	
	P=True	**P=Fault**	**P=True**	**P=Fault**
True	0.03	0.01	0.05	0.02
Fault	0.97	0.99	0.95	0.98
Total	1.00	1.00	1.00	1.00

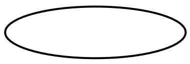
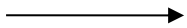
From the example, we can see that for 5 nodes, 2 (from S) + 2 (from P) + 8 (from C) + 4 (from X) + 4 (from D), 20 numbers of probability input will be required. When the model becomes more complex and relates with multi-state variables, a large number of inputs might be required.

The BBN is a well-known model used in the risk and reliability field and is, therefore, very applicable to problems at the operational level. Recently, BBNs have been employed to represent the probabilistic relationships between diseases and symptoms and used to diagnose the diseases based on symptoms. However, applying BBNs to model interaction between risks in the supply chain is much more complex and there are particular issues of concern. Firstly, the supply chain may involve many stakeholders who have disintegrated (risk) databases or who fail to share (risk) information; thus, the availability of historical data in the proper format to support supply chain risk modelling may be limited or nil. Therefore, expert's knowledge will be a possible source of information to structure BBNs in the supply chain risk context. Secondly, when a lot of agents or stakeholders are involved in the development of a model, conflicts of interests may exist. These need to be solved by defining the purpose of the model before embarking on the model development. For example, hospitals are desirous of stocking large quantities of medication in order to supply their patients, but too high a safety stock will incur high costs for the NHS, who operates with a limited budget. Thirdly, the scope of risks in the supply chain should not only be developed by one company or one agent within the supply chain, since the activity of one agent can affect others. When the physical boundary is related to more than one agent, many inter-related risks can be identified, as causal networks. As a result, we cannot escape from dealing with a huge and complex map. This contributes to the difficulty of quantification in the full development of BBN later on.

In order to strike a compromise between the usefulness of BBN and the difficulty of using this technique, BBN can be developed from the modification of initial maps (Causal Map, Fault Tree, or Risk Register Map). The initial maps are developed by brainstorming within groups (Task 1) to identify the significant risks in the entire supply chain. This task will focus on the development of BBN from the initial map so that the BBN structure can be prepared for the subsequent quantification process. The quantification and inference processes **will not be included** in this module. However, you can learn how to structure BBN in order to understand risk interactions and can then define the proper mitigating actions qualitatively. The actions should be considered by being aware of their effects on the entire chain rather than focusing only on the individual risk which can be mitigated.

The initial map can help to identify risks and their relationships. This task will ask you to modify those initial maps to a qualitative BBN. There are some assumptions to make as BBNs are different from other qualitative maps; modellers should therefore be trained to understand the process of BBN development.

Icons or Symbols

Symbol	Name	Description
	Random variable or Node	**Parent node**: the node that an arrow comes from (start node) **Child node**: the node that an arrow comes to (end node) **Root node**: the node that does not have any parents **Leaf node**: the node that does not have any child nodes
	Arrow or Link	In general a link is not necessary to represent the causality but it will be easier for modellers to identify only main direct causal links to represent **conditional independence** that is the basic theory of BBN.

Example:

A simple example shows how to check **the conditional independence** from an initial map. If we already know whether or not it is raining, knowing whether or not it is sunny does not help to further predict if you should carry an umbrella. Here, the two variables, your umbrella carrying and sunshine, are conditionally independent given knowledge of rain.

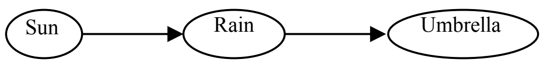


Figure C-17 An example of conditional independence

Conditional dependence is the main assumption of BBN so it should be employed to revise the structure of the initial map. There are three types conditional independence, as explained in the following section.

How to develop (qualitative) BBN in SC risk context from *Causal Map or Risk Register Map*?

In the previous task, each group was assigned different methods in order to identify risks and their relations as an initial map. There are several assumptions that should be examined to modify those initial maps to be a qualitative BBN. There are two main expected outcomes of this task: variable and state description document, and qualitative BBNs map. Both can be developed in parallel and adjusted iteratively.

I. Define variable description document

For each variable or node in the qualitative BBN model, you should document its definition and define the possible states of particular variables. The variable description document can be used to show the same understanding of the variables defined in the BBN. Furthermore, the state of each variable can be used to show all possible outcomes that can affect or stimulate other variables in different ways.

1. **Variable name and description**: There is no rule for defining variable names but it should be clear and understandable. All variables in the map should have already been identified in the initial map but you can revise the name of variable by considering the recommendations below.
   - The variable name length should not be longer than 8 words.
   - Avoid the use of ‘in order to’, ‘due to’, or ‘through’ etc., as these can be represented in the arrows.
   - Details that cannot be contained in the variable name should be explained in the variable description. The variable description answers the questions of ‘What’, ‘Where’, ‘Why’, or ‘How’.

Example:

Variable name	Variable description
Delivery delay to the retailers	Cannot deliver the orders outside agreed time windows to the retailers

From the example above, the variable description is not clear in term of ‘Who cannot deliver the product to the retailers?’ and ‘What are the agreed time windows?’ This can be revised, as follows:

Variable name	Variable description
Delivery delay to the retailers	Distribution centre delivers the products outside agreed time windows (next day delivery) to the retailers

2. **State and State description:** The states of each variable can be levels, values, choices, or options etc. States should represent a set of mutually exclusive events. This means that all defined states of a variable cannot occur as the same time. The definition of each state can be used to explain the difference between or among those states and make sure the all possible states cannot happen as the same time. The state space should cover all possible events that can occur and each state should represent the different effects on its *child* nodes.

Example:

There are different levels of delay delivery that can affect retailers. Retailers will regularly prepare their own safety stock for the normal demand to avoid stock-out during a period of time. When the delivery of goods is delayed by a short period of time, there will not be a consequent lack of stock from the retailers under normal demand. On the other hand, when the delivery of goods is delayed by long periods, longer than the safety stock can cover or over the protection interval, retailers' shelf goods can become out –of-stock.

For variable Delivery delay to the retailers:

State	State description
Significant	No of orders where requested delivery date is delayed outside agreed window for several days as a percentage of total orders (in the specific time)
Partial	No of orders where requested delivery date is delayed outside agree window for a day as a percentage of total orders
No problem	Delivered on time

The state description will be used to explain the particular state in more detail. For example, the difference between 'Significant' and 'Partial' delivery delay states should be defined clearly. Furthermore, each round of the delivery to the retailer cannot be delayed significantly, partially, or on time (no problem) at the same time so they are mutually exclusive states.

When the degree or level of the event occurrence does not matter to the child variable, the state of each variable can be simple states as 'Yes/No' or 'True/False', etc.

II. The guideline to develop a qualitative BBN from Causal Map or Risk Register Map:

The guideline for moving from an initial map to a qualitative BBN is to consider the relationship between variables via links by examining conditional independence, eliminating loop, deductive reasoning, and including only direct relationships. The actions of this process are mainly to simplify the map under the BBN assumptions while keeping the meaning of the initial map. Thus, some links can be deleted or adjusted, or some variables can be merged by adding more state into a variable or deleting redundant variables.

1. Checking the variable connection by considering the conditional independence
   There are three possible connections where information can travel through a variable in a directed graph: *diverging, serial, and converging* connections.

   1) *Diverging connections*: When you believe that Z are relevant to both X and Y, so that X and Y are conditionally independent given Z. Figure C-18 (a) depicts the Diverging connections and Figure C-18 (b) shows the example of Diverging connections.

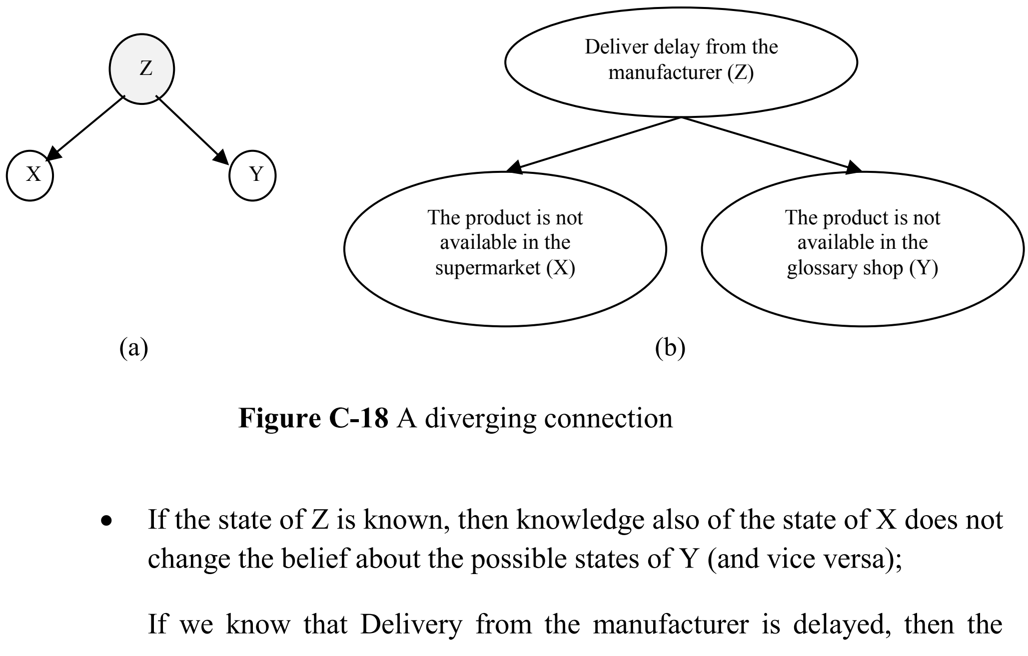


Figure C-18 A diverging connection

- If the state of Z is known, then knowledge also of the state of X does not change the belief about the possible states of Y (and vice versa);

  If we know that Delivery from the manufacturer is delayed, then the knowledge that product is available in the supermarket give us no extra clue on the status of the product in the glossary shop.

- If the state of Z is not known, then knowledge also of the state of X provides information about the possible states of Y (and vice versa);

  If we do not know whether Delivery from the manufacturer is delayed or not, then the knowledge of whether the product is available in the supermarket will give us more belief of the product status in the glossary shop.

2) Serial connections: When you believe that A is relevant to C, that C is relevant for E, and that A and E are conditionally independent given C

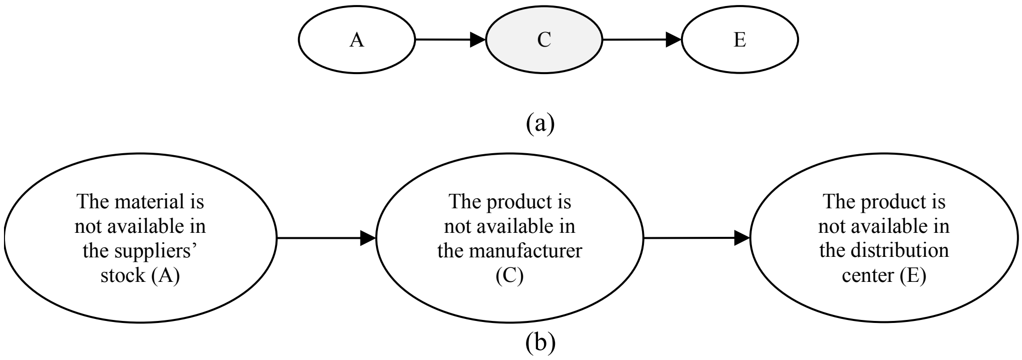


Figure C-19 A serial connection

- If the state of C is known, then knowledge also of the state of E does not change the belief about the possible states of A (and vice versa);

  If we already know that the product is not available from the manufacturer, then knowing that there has been out of stock product in the distribution centre will not provide any new information about status of the material in the supplier's stock.

- If the state of C is not known, then knowledge of the state of E provides information about the possible states of A (and vice versa);

  If we have not observed the product availability from the manufacturer, then knowing that the product is unavailable in the distribution centre will increase the belief that the product is not available from the manufacturer, which in turn will provide some information about the availability of the material in the supplier's stock.

3) Converging connections: Describes a slightly more sophisticated reasoning. The ability to cope with this kind of reasoning is a real asset of Bayesian belief networks. A converging connection is an appropriate graphical model whenever it is believed that A and B are both relevant for C, A is not relevant for B, but does become relevant if the state of C is known. In other words, it is believed that A and B are unconditionally independent but conditionally independent given C. This means that:

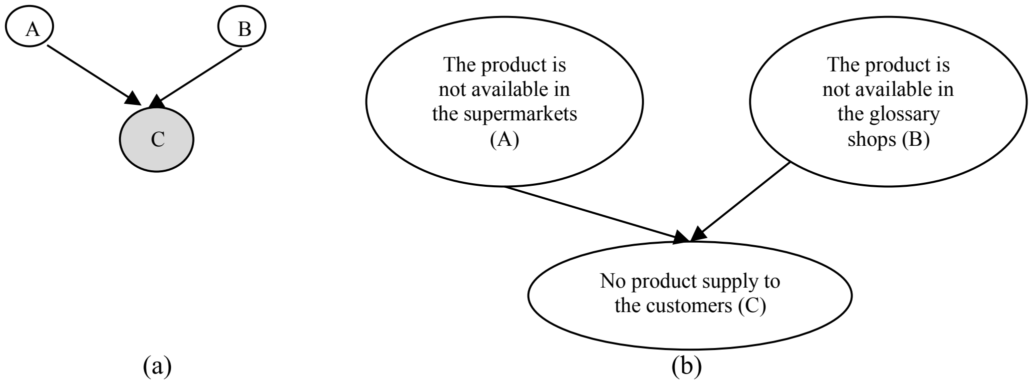


Figure C-20 A converging connection

- If the state of C is known, then knowledge of the state of A provides information about the possible states of B (and vice versa);

  If we know that a customer cannot buy the product, then the information that the product is not available in the supermarket will make us more ready to believe that the product is not available in the glossary shops.

- If the state of C is not known, then the knowledge of the state of A provides no information about the possible state of B (and vice versa): the flow of information is blocked if the state of the middle variable is unknown.

  When we know nothing about customers, then information on whether or not the product is available in the supermarkets will not provide any insight about the availability of the product with the retailers.

2. Eliminating loop

   The link between nodes is connected without a cycle. A *cycle* is said to exist if a node is an ancestor **and** a descendant of itself and a graph is connected if there exists at least one path between every two nodes. The loop destroys the hierarchical form of a graph. The loop can occur in the Causal Map, Risk

Register Map, or other qualitative maps but it should be eliminated under the assumptions of static BBN theory. The feedback loop can be indicated as the dynamic relations between variables over time so part of the loop will be contained in the current time frame and some of links will be associated with the future time frame. Linking between current and future time frames can represent the dynamic relationship of the variables over time, known as Dynamic Bayesian Networks (DBNs). Under the limitation of this course, the Dynamic Bayesian Networks (DBNs) are beyond the scope of the assignment. Students have to define the scope of the current time frame in order to eliminate the effects of the feedback loop.

Example:

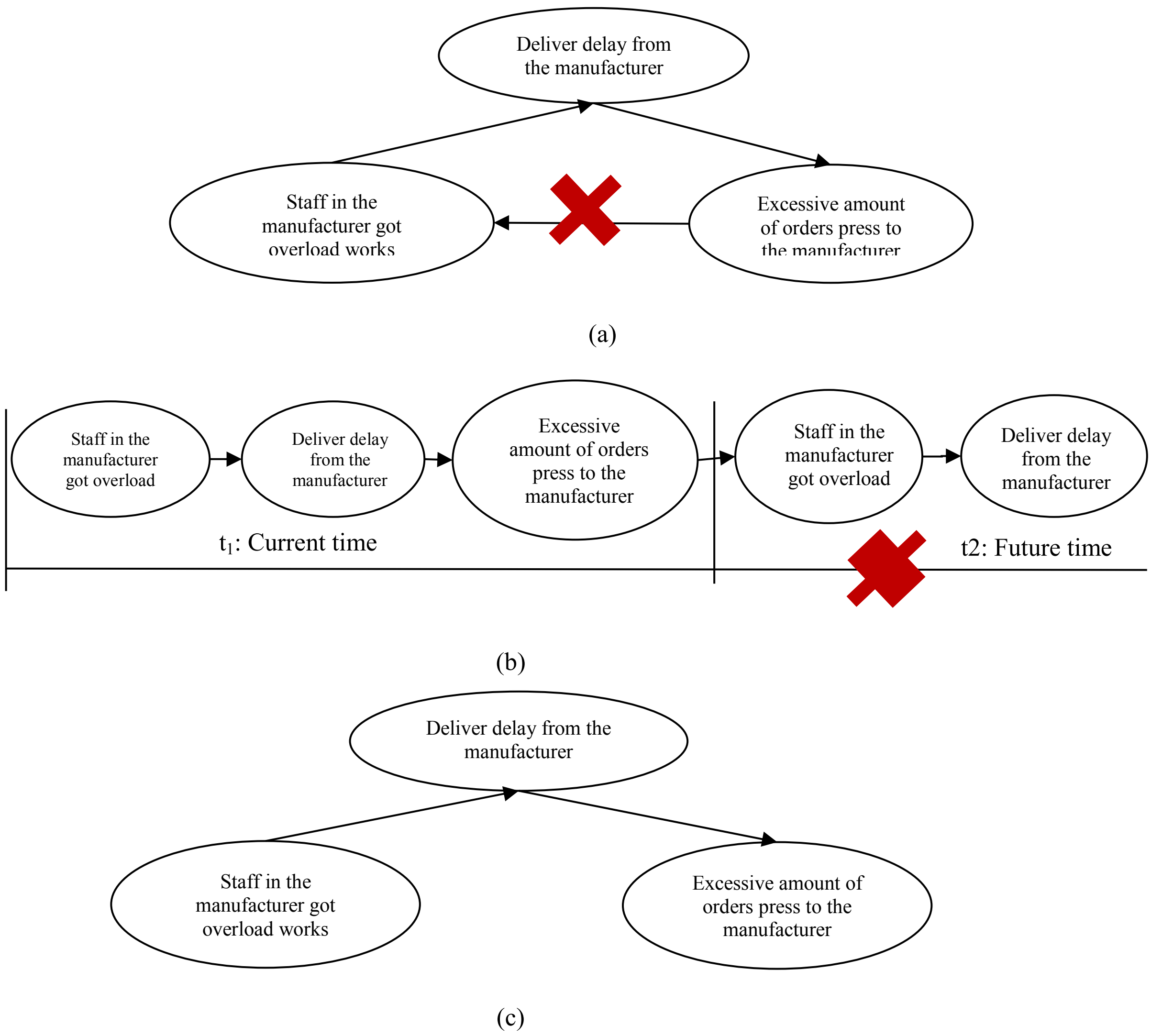
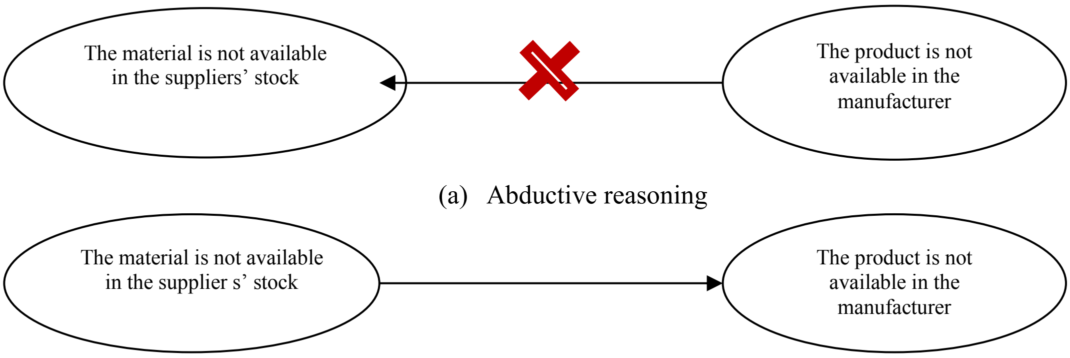


Figure C-21 Disaggregating variables over time

The time frame of this example should be identified by covering one routine order of all customers. For example, if customers have to order once a week, the time frame of this model should be a week.

3. Checking the direction of the link from cause to effect (*deductive reasoning) and* not from effect to cause (*abductive reasoning)*
   The map should represent the logic relation from cause to effect as the same system as all the links should represent the same direction of reasoning. Mixed logic links will be misrepresented and misunderstood and can lead to inaccurate inference later on. The main problem of wrong interpretation of causality is using the wrong causal statement (see the example).

Example: If the product is not available in the distribution centre, then **therefore** the product may not be available in the suppliers' stock does not represent the logic from cause to effect (Figure C-22 (a)). The correct logic link should be represented in the opposite direction (Figure C-22 (b)).



(b) Deductive reasoning

Figure C-22 Distinguishing between abductive reasoning and deductive reasoning

When 2 variables can help to achieve to each other, we adjust the arrow to a one-way arrow by considering the direct relationship.

Example: You may consider that Strategic failure can lead to Supply chain breakdown or Supply chain break down will represent the Strategic failure. The BBN will be used to consider the relationship from cause to effect so the direction of the arrow should point from the Strategic failure to the Supply chain break down.

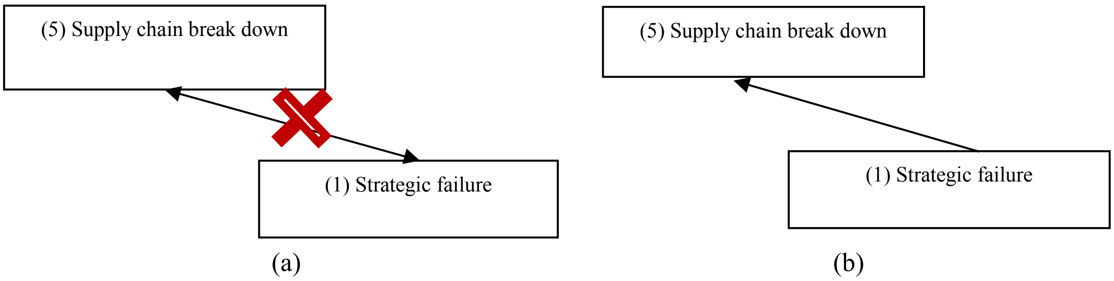


Figure C-23 Changing from two-way arrow to one-way arrow representing cause to effect relationships

4. Including only direct relationships:
   The main reasons for distinguishing direct and indirect cause-effect relations are: Firstly, it can help to understand the nature of the relationships between variables. Secondly, it can reduce the number of redundant links which can increase the complexity of the network representation. Finally it can help to support the analysis of the conditional independencies as the underlying assumptions of the BBN. Therefore, the BBN should represent only the direct relationship and unnecessary indirect links should be deleted.

   Example:

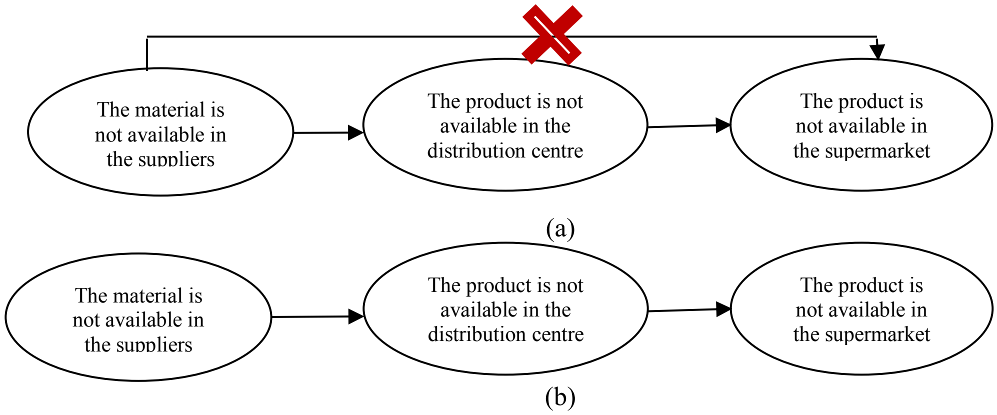


Figure C-24 Distinguishing between indirect and direct relationships

C.6. Manual II: Bayesian Belief Network from Fault Tree

**** This manual mainly contains the same context as manual II: Bayesian Belief Network (BBN) from Causal Map (CM) or Risk Register Map (RRM) (Appendix C.5) but the Section of 'How to develop (qualitative) BBN in SC risk context from Fault Tree (FT)' is adjusted as:*

I. The process of FT extended to a qualitative BBN (was added with the simple process for changing the symbols of FT to BBN as can be shown below.);

II. Define variable description document (see Section II from Appendix C.5, and

*III. Checking BBN assumptions (see Section I from Appendix C.5).****

How to develop (qualitative) BBN in SC risk context from *Fault Tree (FT)*?

In the previous task, each group was assigned different methods in order to identify risks and their relations as an initial map. Fault Tree is developed and can be transformed into qualitative BBN directly. Once participants want to adjust the map, there are several assumptions of qualitative BBN that need to be examined. Furthermore variable and state description document have to develop in parallel and adjusted iteratively with the process of qualitative BBN developing.

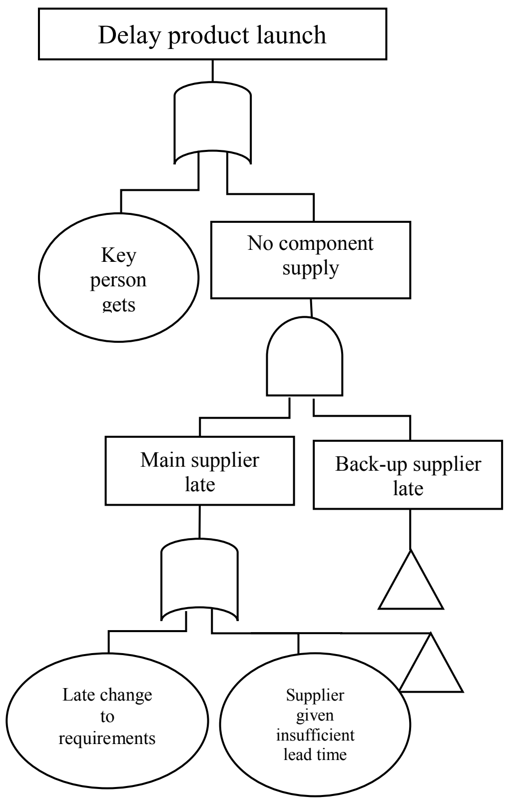


Figure C-25 Full Fault Tree model of Delay product launch example

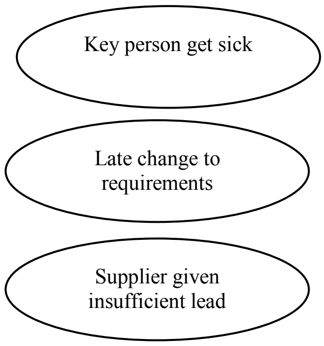
The process of FT extended to a qualitative BBN

Fault Tree (FT) is an intermediate map to develop BBN. The FT of Delay product launch example will be used to show how to modify from FT to qualitative BBN (Figure C-25).

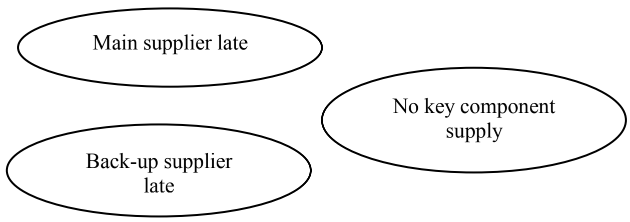
The process for moving from Fault Tree (FT) to Bayesian Belief Networks (BBNs) can be identified as following:

1. Create a root node in BBN from each leaf node of FT

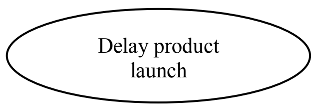
If more leaves of the FT represent the same primary event (i.e. the same component), create just one *Root node* in the BBN.



2. Create a *Corresponding* node in the BBN from each gate of the FT



3. Label the node as the *Fault node or Leaf node* in the BBN from the TOP event of the FT



4. Connect nodes in BBN with arrow from Root node to Corresponding node and to Fault node as events are connected in the FT

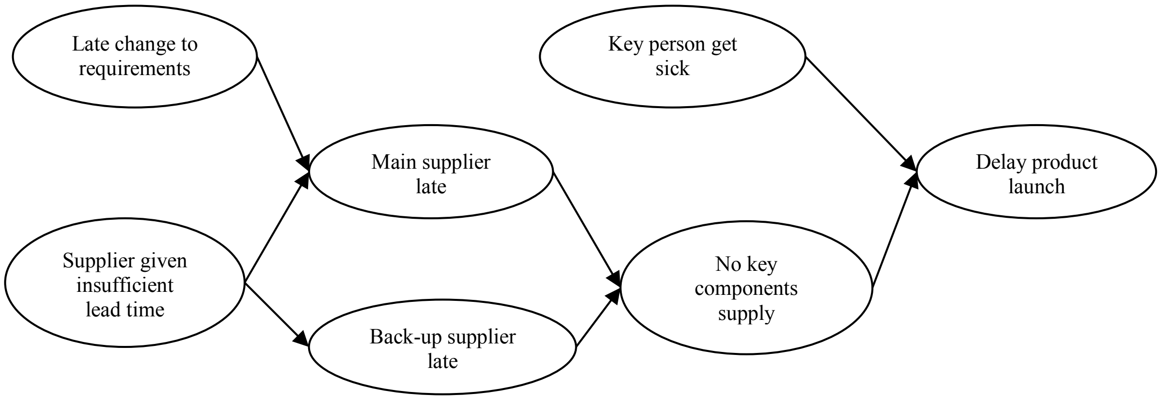


Figure C-26 Qualitative BBN modified from Fault Tree of Delay product launch example

D. Questionnaires Using in Experiment

Questionnaire I: Background knowledge of participants

This questionnaire is a part of PhD research and it will not relate to the assessment of this course. Could you please × in ☐ which you agree or fill the answer in ▭.

1.1. Have you ever had experiences of working in supply chain?

☐ No

☐ Yes (If yes, could you please identify the position of your previous work?)

▭

1.2. Have you ever had experiences of working in risk management?

☐ No

☐ Yes (If yes, could you please identify the position of your previous work?)

▭

1.3. Have you ever used BBN, Causal Map, Fault Tree, Risk Register, or Risk Register Map techniques?

☐ No ☐ Yes

Evaluation of the case study text information

There are 5 scales that will be used to ask you to evaluate your perception in particular criteria. The definition of the 5 scales can be seen below:

1: Very difficult/Very unclear
2: Difficult/Unclear
3: Moderate/Normal
4: Easy/Clear
5: Very easy/Very clear

Questions	1	2	3	4	5
Q1.1 How can you get insight into understanding of the risks in the case study from the case study information? (Page 6-12 in Workbook)	☐	☐	☐	☐	☐
Q1.2 How transparent is the risk *problem* that you can see from the given case study information or how difficult to communicate with other stakeholders in the supply chain to get aware of the effects of risk events to entire SC from the given case study information? (Page 6-12 in Workbook)	☐	☐	☐	☐	☐

Questionnaire II: Evaluation for initial map (CM/FT/RRM)

This questionnaire is a part of PhD research and it will not be related to any assessments of this course. Could you please × in ☐ where you agree with each statement in terms of your experience to develop the initial map.

Questions	1	2	3	4	5
Outcome					
Q2.1. How can you get an insight into understanding of the risks in the case study from the initial map (task 1)?	☐ Very unclear	☐ Unclear	☐ Moderate	☐ Clear	☐ Very clear
Q2.2. How transparent is the initial map to use to communicate with other stakeholders in the supply chain to become aware of the effects of risk events to entire SC?	☐ Very unclear	☐ Unclear	☐ Moderate	☐ Clear	☐ Very clear
Q2.3. If there are new risk events such as flooding or earthquake listed, how difficult is it to include or update those risks into the initial map?	☐ Very difficult	☐ Difficult	☐ Normal	☐ Easy	☐ Very easy
Q2.4. How complex is the initial map structure in terms of number of related risk events and links?	☐ Very complex	☐ Complex	☐ Normal	☐ Simple	☐ Very simple
Q2.5. How can the initial map cover possible risks in the case study? (Completeness)	☐ Almost none	☐ Minor	☐ Half	☐ Major	☐ All
Q2.6. How can other people who are not related to developing the initial model can understand all variables as the model developer would like to elicit without missing interpretation (Robustness)?	☐ Very unclear	☐ Unclear	☐ Moderate	☐ Clear	☐ Very clear
Process					
Q2.7. How much effort do you need to develop the initial map?	☐ Too much effort	☐ A lot of effort	☐ Moderate	☐ Little effort	☐ Very little effort
Q2.8. How difficult is the process to structure the initial map?	☐ Very difficult	☐ Difficult	☐ Normal	☐ Easy	☐ Very easy
Q2.9. How difficult is it to deal with arguments or disagreements that occurred during brainstorming to developing the initial map?	☐ Very difficult	☐ Difficult	☐ Normal	☐ Easy	☐ Very easy
Q2.10. How confident are you to apply the same process (Manual I) with other case studies?	☐ Very less confident	☐ Less confident	☐ Normal	☐ Confident	☐ Very confident
Team learning					
Q2.11. How do you share your personal insights with your group?	☐ Not at all	☐ A little	☐ Moderate	☐ More than average	☐ A lot
Q2.12. How do you try to understand one another's viewpoints?	☐ Not at all	☐ A little	☐ Moderate	☐ More than average	☐ A lot
Q2.13. How do you feel valued and appreciated by one another?	☐ Not at all	☐ A little	☐ Moderate	☐ Appreciated	☐ Very Appreciated

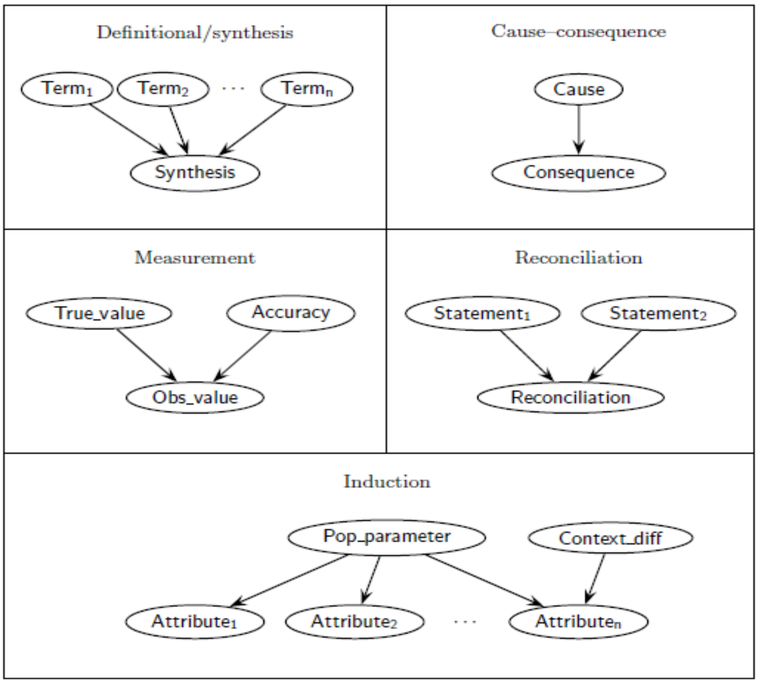
Questionnaire III: Evaluation for Qualitative BBN

This questionnaire is a part of PhD research and it will not be related to any assessments of this course. Could you please × in ☐ where you agree with each statement in terms of your experience to modify the initial map to the qualitative BBN.

Questions	1	2	3	4	5
Outcome					
Q3.1. How can you get an insight into understanding of the risks in the case study from the qualitative BBN (task 2)?	☐ Very unclear	☐ Unclear	☐ Moderate	☐ Clear	☐ Very clear
Q3.2. How transparent is the qualitative BBN to use to communicate with other stakeholders in the supply chain to become aware of the effects of risk events to entire SC?	☐ Very unclear	☐ Unclear	☐ Moderate	☐ Clear	☐ Very clear
Q3.3. If there are new risk events such as flooding or earthquake listed, how difficult is it to include or update those risks into the qualitative BBN?	☐ Very difficult	☐ Difficult	☐ Normal	☐ Easy	☐ Very easy
Q3.4. How complex is the qualitative BBN structure in terms of number of related risk events and links?	☐ Very complex	☐ Complex	☐ Normal	☐ Simple	☐ Very simple
Q3.5. How can the qualitative BBN cover possible risks in the case study? (Completeness)	☐ Almost none	☐ Minor	☐ Half	☐ Major	☐ All
Q3.6. How can other people who are not related to developing the qualitative BBN can understand all variables as the model developer would like to elicit without missing interpretation (Robustness)?	☐ Very unclear	☐ Unclear	☐ Moderate	☐ Clear	☐ Very clear
Process					
Q3.7. How much effort do you need to develop the qualitative BBN?	☐ Too much effort	☐ A lot of effort	☐ Moderate	☐ Little effort	☐ Very little effort
Q3.8. How difficult is the process to structure the qualitative BBN?	☐ Very difficult	☐ Difficult	☐ Normal	☐ Easy	☐ Very easy
Q3.9. How difficult is it to deal with arguments or disagreements that occurred during brainstorming to developing the qualitative BBN?	☐ Very difficult	☐ Difficult	☐ Normal	☐ Easy	☐ Very easy
Q3.10. How confident are you to apply the same process (Manual II) with other case studies?	☐ Very less confident	☐ Less confident	☐ Normal	☐ Confident	☐ Very confident
Team learning					
Q3.11. How do you share your personal insights with your group to modify the initial map to the qualitative BBN?	☐ Not at all	☐ A little	☐ Moderate	☐ More than average	☐ A lot
Q3.12. How do you try to understand one another's viewpoints to modify the initial map to the qualitative BBN?	☐ Not at all	☐ A little	☐ Moderate	☐ More than average	☐ A lot
Q3.13. How do you feel valued and appreciated by one another with your group to modify the initial map to the qualitative BBN?	☐ Not at all	☐ A little	☐ Moderate	☐ Appreciated	☐ Very Appreciated

E. Understanding Model Structure in the Large-scale Network

The BBN structure can be constructed manually. The identification of probability network structure is not as simple as it might be using a normal qualitative graph (Kjaerulff and Madsen, 2008). Therefore, modellers need to understand the structured approach to network structure identification in order to ground a basic knowledge, particularly in the large-scale BBN. Neil et al. (2000) proposed the following idioms as an approach to eliciting the BBN structure in order to support the building of the BBNs, see Figure E-1. Suggestions for selecting the correct idiom were provided by Kjaerulff and Mansen (2008), as shown by Figure E-2.



Source: Kjaerulff and Madsen, 2008; Neil et al., 2000

Figure E-1 Types of model structure (idioms)

1. Definitional/synthesis

This idiom aims to structure the BBN by linking many variables into one variable such as defining in deterministic or uncertain definition or function from different terms. This idiom is the same as the **divorcing technique** (Appendix F.1) used to reduce the number of condition probability.

2. Cause-consequence

This idiom aims to structure the BBN model in the casual process as the relationship between cause and effect variables. It can sometimes represent the prediction from input(s) to output(s).

3. Measurement

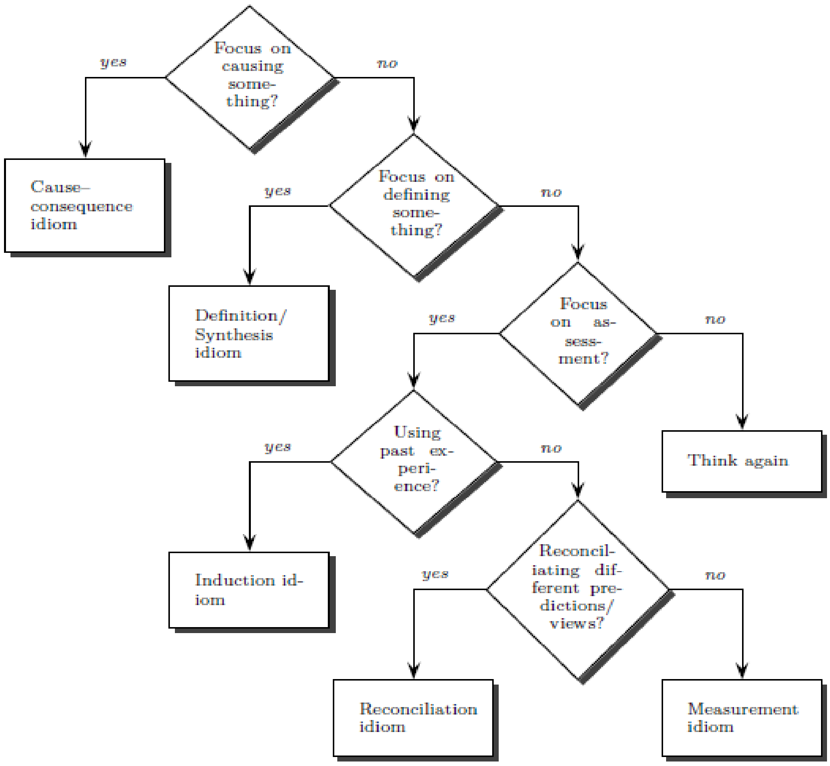
This idiom can represent the uncertain of accuracy via measurement, so the value of the model can be compared with the actual value to measure accuracy from historical data. One variable can represent an estimator of other variables.

4. Reconciliation

This idiom can represent the competitive statements that arise from different sources or methods of information.

5. Induction

Induction is the model process of statistical inference from a series of similar entities to a future or unobserved entity with similar attribute, but there is no reasoning in terms of cause and effect.



Source: Kjaerulff and Madsen, 2008; Neil et al., 2000

Figure E-2 Flowchart of criteria to choose the right idiom

F. Techniques to Reduce Burdens of Eliciting Probability in Large and Complex Networks

Since the scope of BBN implanting in SC risk should be large and complex, the barriers of dealing with the expert knowledge during model quantification can be the main practical concerns. When the size of network is large and the complexity of the relationship will make the CPTs huge, it may be beyond human capability to provide good quality input information.

The CPT is used to capture the level of impact from particular causes on an effect variable or to show the level of uncertainty relationship between parent variables on a child variable. It is clear that the number of required inputs for a CPT depends on the number of its cause or parent variables. For example, when an effect variable that has 3 states is linked from *n* parent variables and each parent variable has 2 states, the CPT of the effect variable will require 3×2^n probabilities (Korb and Nicholson, 2004). Therefore the required probabilities to be assessed should be increased exponentially in numbers of its parents. The larger and more complex networks are, the lower the possibility to implement BBN in the real practical environment.

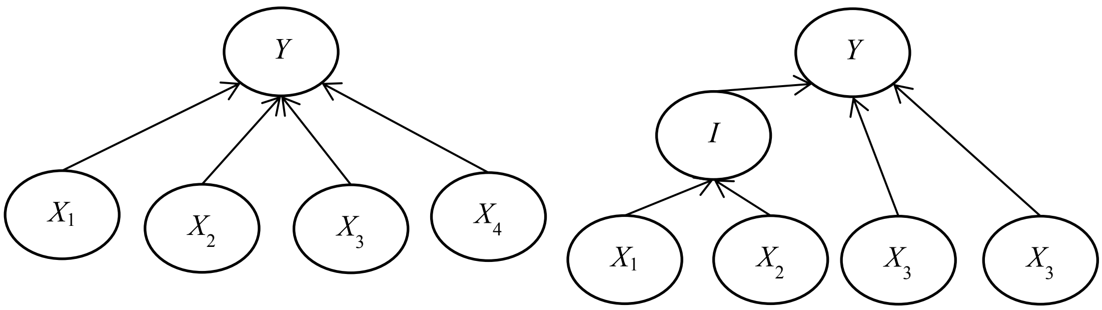
Many studies in advanced approximation techniques have been developed to solve this difficulty of larger and complex network implementation by using high level skills in mathematics or using continuous variables (Veerle M H Coupé et al., 1999; Fenton et al., 2007 ect.). These techniques also require special software or specific programming sort code. On the other hand, several techniques have been developed to support quantifying a CPT for a discrete variable, such as transforming pair-wise comparison scales rather than eliciting in a probability format (Chin et al., 2009; Monti and Carenini, 2000; Renooij, 2001), or sensitivity analysis by Coupé et al. (1999). However, these techniques require considerable computational effort and time consuming.

It is believed by author/researcher that effectively managing risks at the operation level should lead to improved understanding by the experts, by not just using a *black box model*. Therefore, the parent divorcing and Noisy-OR techniques are selected to reduce the effort of probability elicitation, while allowing the experts to maintain ownership of their model.

F.1. Parent Divorcing Technique

The parent divorcing technique has been suggested to reduce the number of labor tasks of probability quantification (Cain, 2001; Kjaerulff and Madsen, 2008; Nasir et al., 2003). This technique is used to adjust the structure of the graph by adding intermediate variables as a new layer to which grouping parent variables are linked. However, the parent divorcing technique can be implemented when the relations between parents can be expressed as a binary operation, such as 'AND' ($\cap$), 'OR' ($\cup$), 'MIN', 'MAX', '+', '-', and so on. In general, the basic idea of this technique is to partition a pair of parent variables into a set of different configurations.

Example: The variable Y has four parent variables which are X_1, X_2, X_3, X_4 (see Figure F-1(a)). The variable I is introduced to be an intermediate variable which is assumed as X_1, X_2 and Y. After applying the parent divorcing technique, Y becomes a parent of I, X_3 and X_4. The structure of the new map can be seen in Figure F-1(b).



(a) Original direct parents of Y (b) Implementing Divorcing technique

Figure F-1 Example of implementing divorcing technique

If the Variable Y is the binary operation $Y = X_1 \cup X_2 \cup X_3 \cup X_4$, then the intermediate variable (I) can capture $I = X_1 \cup X_2$. It is found that Y in either Figure F-1 (a) or (b) are equivalent. This can be explained by the equation below.

Since
$$\begin{aligned} Y &= X_1 \cup X_2 \cup X_3 \cup X_4 \\ &= (X_1 \cup X_2) \cup X_3 \cup X_4 \\ &= I \cup X_3 \cup X_4 \end{aligned}$$

The usefulness of this technique is to keep the same meaning of the map but reduce the size of the CPT. If the variables X_1, X_2, X_3, X_4 can take 2 states each and variable *Y* can take 3 states, according to the structure in Figure F-1 (a), the size of CPT for *Y* variable is $3 \times 2^4 = 48$. On the other hand, there are only two possible states of variable I, represented by $X_1 \cup X_2$. Thus, the size of variable Y with the divorcing technique is $3 \times 2^3 = 24$ with an added CPT of *I* = $2 \times 2^2 = 8$. Therefore the size of the CPTs required to be input has been reduced from 48 to 32. If there are more parents in the model, this technique can reduce the size of the CPT significantly.

F.2. CPT Approximation: Noisy-OR

Noisy-OR was introduced by Pearl (1988). It is restricted to the discrete variable and does not require an adjustment of the structure of the network or the use of binary operations. Therefore, by implementing this technique we can still maintain the model structure that was agreed upon with the users. However, Noisy-OR model is developed under *the Boolean independence* of causal influence model, which is the extension of a deterministic OR operation (e.g. FT) (Langseth and Portinale, 2007). Therefore, the Noisy-OR model is limited to binary-state variables.

When an effect variable is influenced by many cause variables, the CPT quantification will required a lot of input probability numbers. The following paragraphs explain how the Noisy-OR model can aid to reduce the demand of input numbers and compare it to the normal method.

Let *E* be the common child variable or the main effect variable, which can be presented as the top event or Noisy-OR gate (see Figure F-2).

$C_1,...,C_i,...,C_n$ or $\mathbf{C}$ are the parent variables and they are referred to as cause variables.

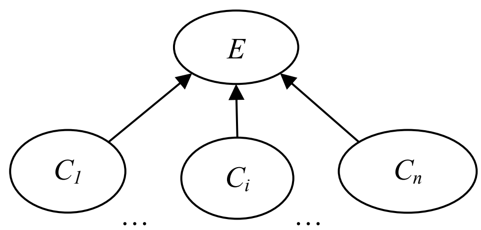


Figure F-2 General network structure of an effect variable with *n* root cause variables

Noisy-OR is known as an approximation technique. The theory of Noisy-OR is explained by Pearl (1988), but this explanation will not be detailed in this thesis.. The term 'Noisy' refers to *"the possibility that some causes fail to produce the effect event when they are present"* (Diaz and Druzdzel, 2007). Therefore, if C_i is the only parent that is true, E will be true if and only if the inhibitor associated with C_i remains inactive. The required conditional probability for the CPT of variable E is:

$$\mathrm{P}(\mathrm{E} = \mathrm{t}|C_i = t) = P(E = t|C_1 = f, C_2 = f, ..., C_i = t, ..., C_n = f) = 1 - q_i$$

Or
$$P(E = f|C_i = t) = q_i$$

Or
$$\mathrm{P}(E|\mathbf{C}) = \begin{cases} \prod_{i \in I(C=true)} q_i & \text{if } E = \mathit{fault} \\ 1 - \prod_{i \in I(C=true)} q_i & \text{if } E = \mathit{true} \end{cases} \quad \text{(F-1)}$$

Example F-1 The simple example is defined for two cause (parent) variables with two simple states (see Figure F-3).

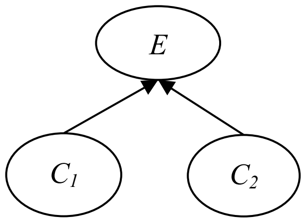


Figure F-3 Example of a network of an effect variable with two root cause variables

How the Noisy-OR can reduce number of demanded input probability numbers for a CPT will be compared.

a. *CPT quantification by normal method*

Generally, the CPT of an effect variable can be quantified by considering particular states of the defined parent variables. There are four probability numbers to be elicited in order to complete this CPT. This is shown in Table F-1.

Table F-1 Example of CPT for Normal technique with two parents

$P(E \mid C_1, C_2)$				
C_1	*true*		*false*	
C_2	*true*	*false*	*true*	*false*
true	$p_{C_1=t,C_2=t}$	$p_{C_1=t,C_2=f}$	$p_{C_1=f,C_2=t}$	$p_{C_1=f,C_2=f}$
false	$1-p_{C_1=t,C_2=t}$	$1-p_{C_1=t,C_2=f}$	$1-p_{C_1=f,C_2=t}$	$1-p_{C_1=f,C_2=f}$
Total	1	1	1	1

b. *CPT quantification by Noisy-OR*

Based on eq. (F-1), the simple example is presented as a CPT in Table F-2.

Table F-2 Example of CPT for Noisy-OR with two parents (q_i)

$P(E \mid C_1, C_2)$				
C_1	*True*		*False*	
C_2	*True*	*False*	*True*	*False*
True	$1-q_1 \times q_2$	$1-q_1$	$1-q_2$	0
False	$q_1 \times q_2$	q_1	q_2	1
Total	1	1	1	1

When $p_i = 1-q_i$, the CPT can represent by Figure F-3.

Table F-3 Example of CPT for a Noisy-OR with two parents (p_i)

$P(E \mid C_1, C_2)$				
C_1	*True*		*False*	
C_2	*True*	*False*	*True*	*False*
True	$1-(1-p_1)\times(1-p_2)$	p_1	p_2	0
False	$(1-p_1)\times(1-p_2)$	$1-p_1$	$1-p_2$	1
Total	1	1	1	1

Generally the size of CPT of an effect variable depends on number of its parent variables. The *Independence of causal inference* assumptions implemented by Noisy-OR technique can help to reduce size of the CPT on the effect variable from exponential to linear in the number of parent variables. Referring to Table F-2, only 2 numbers are required: q_1 and q_2 (p_1 and p_2). The other cells can be calculated from these two values. In case of a general chance binary variable with n binary parents, the user has to specify n parameters (without including leak probability) rather than the minimum required 2^n parameters that are exponential to the number of parents. This number can quickly become prohibitive.

Suggestions to develop questions for probability elicitation

We also need to implement Noisy-OR for design questions for eliciting probability number from expert judgement. The choice of questions is influenced by the two different techniques of probability elicitation as described above (that is, the normal and the Noisy-OR method). This is further explained below.

a. *Normal method*

General question format: 'What is the probability that Y is in y state (Y = y) when $X_1 = x_1, X_2 = x_{2, \ldots}, X_n = x_n$?'

when	n	is number of causes of *Y*
	y	is possible states of *Y*
	x_i	is possible states of X_i

b. *Noisy-OR method*

General question format: "What is the probability that Y is present when X_i is present and all other causes of Y that we are considering in the model are absent?" (Zagorecki and Druzdzel, 2004, p. 882)

Since individual variables are defined by two states, it can show present and absent state.

The Noisy-OR method can not only reduce the numbers of inputs but it is also readily available as a function in GeNIe software. Furthermore, it has been proven to provide a good quality approximation. An experiment to compare the CPT given by Apple tree root, implemented by Henrion (1988), disorders the CPT example given by Noisy-OR. Subsequently, Zagorecki and Druzdzel (2006) showed that Noisy-MAX (General form of Noisy-OR) can fit 50% of CPTs of general ALAM, HAILFINDER and HEPAR II examples (which are available in general BBN literature). In addition, they show that fitting Noisy-MAX with the random generated CPTs for 10,000 CPTs simulation is poor. Zagorecki and Druzdzel (2004) used experimental design with 44 graduated students and found that using human experts to provide parameters by using elicitation Noisy-OR parameters can provide better accuracy than eliciting CPT directly. This was done by comparing with parameters generated with a Noisy-OR distribution. However, Noisy-OR only deals with the bivariate-state variable. It also only generates an input number from an approximation technique, rather than using real data. Therefore, the outcomes from the model and results should be interpreted carefully, with the limitations of the approximation technique borne in mind.

G. Model Evaluating Criteria: Synthesis from Literature

Table G-1 Criteria collection for BBN SC risk modelling method evaluation, methodology and the comparison with criteria from literature

Criteria for this thesis *BBN SC risk modelling*	(Chong and Brown, 2000) *Properties for project risk management*	(Revie, 2008) *Evaluation of Bayes linear model*	(Brun et al., 2006) *Value and risk assessment by SNOpAck*	(Tako and Robinson, 2009) *Compare 2 simulation approaches (DES & SD)*	(Salama et al., 2009) *Value of auditing SC*	(Akehurst et al., 2000) *Properties of good decision analytic model*	(McCarl, 1984) *Usefulness of a model*
1. Model technique evaluation							
Mathematically justifiable		Mathematically justifiable defendable				Internal consistency	
Process traceable or transparent		Traceable			Transparent	Transparency	
Adjustable	Modifiable					Reproducibility	
Exploration of uncertainty						Exploration of uncertainty	
Computable	Computable (Result duplicated, transformed etc.)						
2. Outcome Validation							
Model robustness (Sensitivity analysis)		Model is robust (Sensitivity analysis)		Model validity/ Credibility	Quick and Accurate		
Model behaves appropriately (Scenarios analysis)		Model behaves appropriately (Scenario analysis)					Appropriate for model intended use(s)
3. Modelling process and model outcome evaluation							
3.1 In modelling evaluation scope							
Practical							
Simple to use	Easy to use	Simple to use					
Useful				Model usefulness/ result			
• Reaching project aims		Meet the project aims					Whether the model contributes to making better decisions

Criteria for this thesis *BBN SC risk modelling*	(Chong and Brown, 2000) *Properties for project risk management*	(Revie, 2008) *Evaluation of Bayes linear model*	(Brun et al., 2006) *Value and risk assessment by SNOpAck*	(Tako and Robinson, 2009) *Compare 2 simulation approaches (DES & SD)*	(Salama et al., 2009) *Value of auditing SC*	(Akehurst et al., 2000) *Properties of good decision analytic model*	(McCarl, 1984) *Usefulness of a model*
Model understanding				Model understanding			
• Utility of model outcomes		Comparison with the current process		*Communication tool*			Model performs compared to alternative model
- Communicable							
Natural of result				Nature of results			
- Interpretation of results				Interpretation of results		Interpretability	
- Realistic	Realistic			Realistic outputs			
- **Awareness of effects on SC***				Communicable			
• Utility of the modelling process				*Learning tool*			
• Visions of Further Implementation from the BBN SC risk model				*Strategic thinking*			
3.2 Out of the modelling evaluation scope							
Efficiency		Efficient	Effectiveness		Not invasive		
Economical	Economical		Effectiveness				Benefits of improving model usefulness exceed the costs
(Stimulate) Model complexity				Model complexity			
Avoid bias					Avoid bias		
Stimulate consensus building					Stimulate consensus building		
Robustness			(process) Robustness				
Scalable					Scalable		

Note: * is the criterion that proposed for this research which may not mention from the example of literature which was reviewed.

H. Questionnaires Using in Case Study for Modelling Process Evaluation

Questionnaire A: BBN SC risk modelling processes

This questionnaire is a part of the model validation of the hospital medicine SC project. Your response to this questionnaire will be used anonymously in the research evaluation.

There are two main types of questions - close-ended and open-ended questions. In the close-ended question, please indicate by marking × in ☐, the answer with which you agree. 5 scales are used to evaluate your perception in particular criteria. Where indicated, please write your thoughts on particular developing phases of BBN supply chain risk model modelling in the given spaces.

Tools					
Questions	**1**	**2**	**3**	**4**	**5**
1.1 How easy/difficult was it to identify adverse events?	**Identify risk events** ☐ Very difficult	☐ Difficult	☐ Normal	☐ Easy	☐ Very easy
1.2 How easy/difficult was it to structure the Causal Map?	**Link as Causal Map** ☐ Very difficult	☐ Difficult	☐ Normal	☐ Easy	☐ Very easy

Please explain:

Tools					
Questions	**1**	**2**	**3**	**4**	**5**
2 How easy/difficult was it to structure consensus model (with workshop I)?	**Agree structure network (Workshop I)** ☐ Very difficult	☐ Difficult	☐ Normal	☐ Easy	☐ Very easy

Please explain:

Tools					
Questions	1	2	3	4	5
3.1 How easy/difficult was it to quantify probability numbers?	***Elicit number of possible events/frequency*** ☐ Very difficult	☐ Difficult	☐ Normal	☐ Easy	☐ Very easy
3.2 Which sets of questions did you confident to answers? (A or B)					

Please explain:

Tools					
Questions	1	2	3	4	5
4.1 Did you feel confident in sharing your perception in Workshop I (discuss and agree the structure of the risk model)?	☐ Very difficult	☐ Difficult	☐ Normal	☐ Easy	☐ Very easy
4.2 Have you gained a better understanding of adverse events from other stakeholders by developing the tool through meeting and discussing with other stakeholders?	☐ Very difficult	☐ Difficult	☐ Normal	☐ Easy	☐ Very easy

Further comments:

☺ Thank you very much for your participation ☺

Questionnaire B: Comparing outcomes between Risk Register and BBN SC risk model

This questionnaire is a part of the model validation of the hospital medicine supply chain project. Your response to this questionnaire will be used anonymously in the research evaluation. The first section would like you to answer questions 1-6 of both Risk Register and BBN part in order to compare outcomes from both techniques. Please indicate, by marking × in ☐, the answer with which you agree. 5 scales are provided to you to evaluate your perception of particular criteria.

Tools	**Risk Register**					**BBN**				
Questions	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
***1**: Can the tool support the stakeholders in their awareness of the effects of adverse events to the entire supply chain?*	***Document or spreadsheets***					***Map***				
	☐ Very difficult	☐ Difficult	☐ Moderate	☐ Easy	☐ Very easy	☐ Very difficult	☐ Difficult	☐ Moderate	☐ Easy	☐ Very easy
***2**: Can the tool aid the discussion with stakeholders to explain the major risks of each stakeholder?*	***Document or spreadsheets***					***Map and variable description***				
	☐ Very unclear	☐ Unclear	☐ Moderate	☐ Clear	☐ Very clear	☐ Very unclear	☐ Unclear	☐ Moderate	☐ Clear	☐ Very clear
***3**: How easy/difficult is it to interpret the numbers of each tool?*	***Rating format***					***Probability format***				
	☐ Very difficult	☐ Difficult	☐ Moderate	☐ Easy	☐ Very easy	☐ Very difficult	☐ Difficult	☐ Moderate	☐ Easy	☐ Very easy
***4**: How can other people who have not been involved in developing the tool (e.g. new staff) understand the outcomes without mis-interpretation?*	***Document or spreadsheets***					***Map and variable description***				
	☐ Very unclear	☐ Unclear	☐ Moderate	☐ Clear	☐ Very clear	☐ Very unclear	☐ Unclear	☐ Moderate	☐ Clear	☐ Very clear
***5**: Can the outcomes of the particular tool represent realistic risks or adverse events in medicine supply chain?*	***Risk rating***					***Adverse event prioritisation***				
	☐ Not at all	☐ A little	☐ Moderate	☐ More than average	☐ A lot	☐ Not at all	☐ A little	☐ Moderate	☐ More than average	☐ A lot
						Risk diagnosis				
						☐ Not at all	☐ A little	☐ Moderate	☐ More than average	☐ A lot
						Scenario analysis				
						☐ Not at all	☐ A little	☐ Moderate	☐ More than average	☐ A lot
***6**: Can the results of analysis help you to better understand the risks in your supply chain? (Understanding)*	***Risk rating***					***Adverse event prioritisation/Risk diagnosis /Scenario analysis***				
	☐ Very unclear	☐ Unclear	☐ Moderate	☐ Clear	☐ Very clear	☐ Very unclear	☐ Unclear	☐ Moderate	☐ Clear	☐ Very clear

I. Timeline of Conducting the Case Study

Table I-1 Time-line of the NHS hospital medicine SC

Activity	Experts (date)
Interview decision maker to define purpose of the model and define NHS GG&C SC (1 interview)	• NHS GG&C Lead pharmacist, Acute Care (12/03/2012)
Interview to define modelling assumptions and confirm with the process map (Flowchart) (1 interview)	• NHS GG&C Lead pharmacist, Acute Care (03/04/2012)
Interview to identify potential adverse events (6 interviews)	• NHS GG&C Lead pharmacist, Acute Care (19/04/2012) • Lead pharmacy technician (MMyM) (08/05/2012) • Pharmacist supplementary prescribing in a neonatal Intensive care unit (29/05/2012) • Senior Pharmacy technician (06/06/2012) • PDC: Senior purchasing officer (09/05/2012) • PDC: Distribution lead technician (14/06/2012)
Workshop to discuss and agree model structure (2 workshop sessions and 1 meeting)	**Workshop 1/1 (02/08/2012)** o NHS GG&C Lead pharmacist, Acute Care o Lead pharmacy technician (MMyM) o Pharmacist supplementary prescribing in a neonatal Intensive care unit o PDC: Senior purchasing officer o Pharmaco-logistics adviser in National Procurement
	Workshop 1/2 (21/08/2012) o NHS GG&C Lead pharmacist, Acute Care o PDC: Senior purchasing officer o PDC: Distribution lead technician
	Meeting (31/10/2012) o Senior pharmacy technician
Interview to quantify model (8 interviews)	• NHS GG&C Lead pharmacist, Acute Care (06/11/2012) • Lead pharmacy technician (MMyM) (12/10/2012) • Senior pharmacy technician (4/10/2012), (31/10/2012) • PDC: Senior purchasing officer (10/10/2012), 05/11/2012) • PDC: Distribution lead technician (10/10/2012), (05/11/2012)

Activity	Experts (date)
Workshop to Validate BBN SC risk model behaviour (1 workshop session and 1 meeting)	**Workshop 2 (15/11/2012)** ○ NHS GG&C Lead pharmacist, Acute Care ○ Lead pharmacy technician (MMyM) ○ Pharmacist supplementary prescribing in a neonatal Intensive care unit ○ Senior pharmacy technician
	Meeting (13/12/2012) ○ PDC: Senior purchasing officer ○ PDC: Distribution lead technician
Interview for model validation with decision maker (1 interview)	• NHS GG&C Lead pharmacist, Acute Care (20/11/2012)
Workshop of the demo session	**Training session (08/01/2013)** ○ NHS GG&C Lead pharmacist, Acute Care ○ Lead pharmacy technician (MMyM) ○ Pharmacist supplementary prescribing in a neonatal Intensive care unit ○ PDC: Senior purchasing officer ○ Senior pharmacy technician