TOWARDS RESILIENT SUPPLY CHAIN NETWORKS

A Thesis Submitted to the College of Graduate Studies and Research

In partial fulfillment of the requirements

For the Degree of Master of Science

In the Department of Mechanical Engineering

University of Saskatchewan

Saskatoon

By

Raja Ram Mohan Roy Muddada

August 2010

Permission to Use

Head of the Department of Mechanical Engineering

University of Saskatchewan

Saskatoon, Saskatchewan (S7N 5A9)

ABSTRACT

In the past decade, events like 9/11 terror attacks, the recent financial crisis and other major crisis has proved that there is strong interaction and interdependency of a supply chain network with its external environments in various channels and thus a need to focus on building resiliency (in short, the ability of the system to recover from damage or disruption) of the entire network system. Although literature has discussed some way of improving resiliency of an individual firm which is a member of the network system, it lacked to capture a holistic view of the supply chain network. Pertaining to this observation, this work proposes to improve resiliency of a supply chain network from a system's perspective rather concentrate on an individual firm. For this purpose, this thesis proposes a conceptual framework to promote early identification and timely information of the disruptions arising in a supply chain network and timely sharing of this information among all the members of the network. The key principle emphasized in this thesis is that recovery from an inevitable disruption has a better possibility if a member of the supply chain network has an early indication or knowledge of the upcoming disruption. A discrete event dynamic system simulation tool called Petri nets is utilized to realize the proposed conceptual framework. Furthermore, the practical benefits and implications of the proposed model and tool are demonstrated with help of two case studies.

This thesis has several contributions to the field of operation management and supply chain. First, a new paradigm for supply chain management to avoid large scale failures such as financial crisis is available to the field, which may be applied by governments or regulatory bodies.

Second, a new framework which allows for a quantitative analysis of failures of an entire supply chain network is available to the field, which is easy to be used. Third, a novel application of Petri nets to this new problem in supply chain management is available.

ACKNOWLEDGEMENTS

I would like to express my heart-felt thanks to Professor W.J. (Chris) Zhang for his esteemed guidance and endless support during this thesis work. I am also grateful to him for the financial support during the master program and the given opportunities to experience several international conferences.

I would also like to express my gratitude to my committee members, Prof. Richard Burton and Prof. FangXiang Wu for their valuable suggestion during my committee meeting.

I thank Forrest Zhang and Shrey Modi for the various brainstorming sessions that helped me solve various issues relating to my thesis. I extend my thanks to all the members of Advance Engineering Design Laboratory group for their priceless suggestions during various seminars. I am also thankful to my roommates and very special friends, Prathamesh Sahay, Hema Sudhakar, Arun Shivakumar, Sougat Mishra, Udhaya Khannan, Kun Zhang, Cam Janzen, Gerry, Shirley and Vinay Kumar for their support and entertainment during my hectic academic work schedules. My special thanks Lily Zhou for lending her computer to run the CPN software and obtain the simulation results.

Last but not the least; I am grateful to my family members for their support and constant belief in me.

DEDICATED TO ERIC CARTMAN

Table of Contents

List of Tables

List of Figures

Chapter 1 Introduction

1.1 Motivation

Over the past few decades, manufacturing strategies have evolved continuously to satisfy the four major attributes of the consumer products namely their (1) Cost, (2) Quality, (3) Usability and (4) Availability (or delivery time). The supply chain management has played a vital role in delivering the complimentary support to achieve the aforementioned attributes. During the 1980's and 1990's, supply chain management was merely treated as a problem of intra-organizational logistical management. Most of the models were solved for the optimal lot size (Adler and Nanda, 1974; Afentakis and Gavish, 1986; Zipkin, 1991; Shinn, 1997), order quantity (Emmett and Lodree, 2007) and architectural decisions to reduce the total channel costs. However, the 9/11 terror attacks, the recent financial crisis and other major crisis have proved that there is interaction and interdependency of the supply chains and a need to focus on building resiliency (in general, the ability of the system to recover from damage or disruption) of the system. On the other hand, factors such as core competency, globalization, improved transportation structure & services, and ever growing information and communication technologies have gradually reframed the supply chains to form strong interacting inter organizational supply chain networks (Lu and Wang, 2008). Amidst these conditions, most organizations are still focused on the vertical integration of various levels of their own supply chain and there was very little consciousness on the interception of different supply chains. Although literature has discussed some ways of improving resiliency of an individual firm it lacked to capture a holistic view of the supply chain network. Pertaining to this condition, this work proposes to improve resiliency of a supply chain network from a system's perspective rather concentrating on an individual firm. In order to pursue this goal, the following research objectives have been laid out in the next section of this chapter.

1.2 Objectives

1: Establish an effective definition for the supply chain network and explore the scope of resiliency in the supply chain network.

2: Develop a framework to have a generic representation that could capture both structural and behavioural elements of a supply chain network.

3: Identify the possible loopholes that compromise resiliency of a supply chain network and their possible solution strategies.

4: Test the feasibility and adapt the aforementioned framework into an operational tool to provide the scope for simulation and prediction of real life scenarios in supply chain network.

1.3 Research Methodology

A research methodology called the systematic review technique is used for the comprehensive coverage and analysis of the related literature. According to (Biolchini et al., 2007), the term 'systematic review' is used to refer to a specific methodology of research, developed in order to gather and evaluate the available evidence pertaining to a focused topic. It represents a secondary study that depends on primary study results to be accomplished. In particular, this methodology will be applied to identify the definition of resiliency with respect to supply chain network and to classify the existing strategies of resiliency in the field of supply chain management. The remaining work will be based on the simulation and demonstration of the conceptual framework built to represent the supply chain network. For this purpose, Petri nets, a discrete event based graphical simulation and formulization tool, is selected as one of the most suitable forms to capture the dynamic behaviour of a supply chain network. To add further validity to the model developed, case-based tests are performed to demonstrate the feasibility and possible benefits of the model proposed in this work.

1.4 Organization of the Thesis

The remainder of this thesis is laid out into five chapters as follows:

Chapter 2: This chapter introduces the basic knowledge about supply chain management, followed by a comprehensive understanding of the term resilience in a general sense. Then, it proceeds to details through the literature review by applying the systematic review technique as mentioned in the section 1.3. This chapter finally converges to the existing research issues in the present supply chain network scenario with respect to resiliency, thus providing necessary directions for further research work. It is to be noted that the literature review regarding the Petri nets and its software are not included in this chapter. They will be discussed along with the application of them in later chapters.

Chapter 3: This chapter builds upon the concepts and principles gathered from the literature review of Chapter 2. A generic conceptual framework for the representation of the supply chain network is developed and the notions required for the same are discussed. The framework centers on the sharing of “economy health status” of each of the member firms with other member firms in a supply chain network. Further, the need and utility of such a framework for resiliency of the supply chain is argued by comparing the supply chain view from an individual firm perspective (which is the contemporary view) with a network (holistic) perspective (which is advocated in this thesis).

Chapter 4: In this chapter, the possible simulation tools for the realization of the framework proposed in Chapter 3 are contemplated and choice of Petri nets is justified. Later, a brief background of Petri nets and its extensions in literature are discussed. The mechanisms needed for the application of the concepts of Petri nets to the proposed framework is illustrated. Further, the Petri net models are realized through a software program (for modeling and simulating Petri nets) called the CPN tools. An introductory section to explain the basic elements and functions of the CPN tools software is also included in this chapter.

Chapter 5: This chapter validates the use of Petri net models proposed in Chapter 4 through their application on two selected case studies.

Chapter 6: The final chapter discusses the contributions, limitations and future work.

Appendix A: This section contains the details of the Petri net simulation tool.

Chapter 2 Background and Literature Review

2.1 Introduction

This chapter introduces the basic knowledge about supply chain management in section 2.2, followed by a comprehensive understanding of the term “resilience” in a general sense. A comprehensive definition of the resilient system in the engineering context is also proposed at the end of this section. Then, the chapter proceeds to two systematic reviews detailed in Section 2.3 and Section 2.4, respectively. The first review (Section 2.3) is regarding the analysis of the term “Supply Chain Network” as referred to in the supply chain literature. The second covers the works focused on resilient supply chains. This chapter finally converges to the existing research issues in the present supply chain network scenario with respect to resiliency, thus providing necessary directions for further research work, a part of which have been defined as the research objectives of the thesis.

2.1.1 Supply Chain Management

In general, a supply chain is group of entities that are involved in a chain of processes concerning the procurement of raw materials or components, their conversion or assembly into a product and delivery of the final product to a customer. Lamming (2000) referred the origins of “supply chain management (SCM)” to the early 1980’s when it only represented the management of materials across functional boundaries within an organization (Oliver and Webber, 1992; Houlihan, 1984) but it was later extended to include “upstream” production chains and “downstream” distribution channels (Womack *et al.*, 1990; Womack and Jones, 1996; Harland and Clark, 1990; Christopher, 1992). The typical definition of the term supply chain management by Bowersox and Closs (1996) is as follows:

> “The supply chain refers to all those activities associated with the transformation and flow of goods and services, including their attendant information flows, from the sources of materials to end users. Management refers to integration of all these activities, both internal and external”.

The activities and components of a traditional supply chain are shown in Figure 2.1.

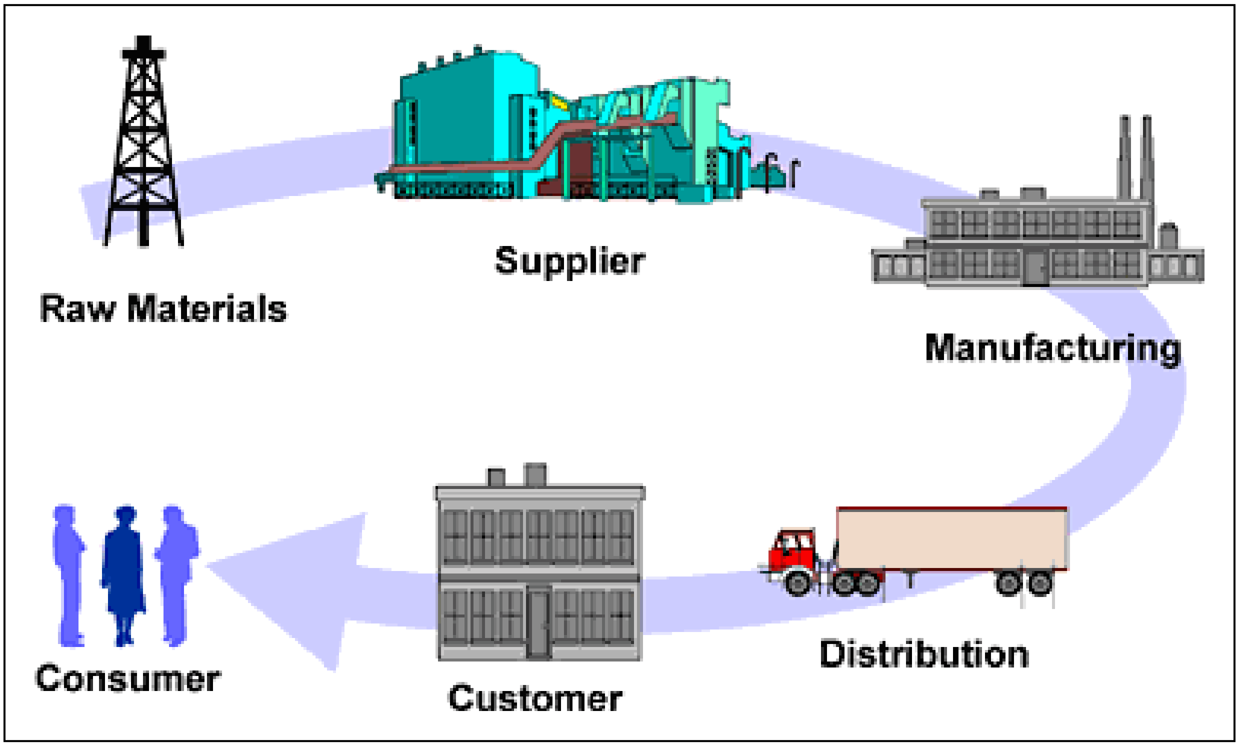


Figure 2.1: Typical supply chain (obtained from website of Weber State University; accessed: June 2010 - http://organizations.weber.edu/sascm/supply_chain.bmp).

Several costs exists in a supply chain such as cost for raw materials, ordering cost, inventory holding cost, transportation costs and production/assemble costs (including the operating costs). Traditionally, supply chain management aims to reduce the sum of these costs by coordinating various activities in the supply chain. At the same time, it also tries to achieve customer satisfaction by improving the delivery time, product quality and availability. For this purpose several strategies have evolved over the history to facilitate these objectives.

1) **Mass customization:** the capability of companies to offer individually tailored products or services on a large scale i.e. combining customization with mass production (Zipkin, 2001).
2) **Lean practices:** Reduction of wastes that are anything without adding value to the supply chain. Several further notions are related to this lean philosophy, such as just in time (JIT), total quality management (TQM), total preventive maintenance (TPM), and human resource management (HRM). (Shah and Ward, 2003). For example, inventory is considered to be one of the non-value adding entities and the appropriate practice of "Just in Time" is adopted. It is noted that "Just in Time" approach aims to reduce the inventory or work in process to zero.
3) **E-commerce and Virtual Organizations:** Some of the modern supply chains enhanced with the power of the Internet and other communication systems embark these new strategies to satisfy the demand of their customers. For more details on E-commerce and Virtual Organizations, the reader is referred to the works of Pego-Guerra (2005), Meyer and Taylor (2000) and Walker (2005).

Supply chain management is a vast topic and involves many other concepts. The above concepts give only the basic ideas that are required for understanding this thesis work.

2.1.2 Resilience

In this section, definitions of resilience as defined in various fields of study are presented. Thereafter, some key characteristics of resilience from these definitions are selected, which will be later used for the systematic review of resiliency in supply chain literature.

(i) Resiliency in Material Science:

Resilience in material science is usually referred to the ability of the material to return to its original shape after temporary deflection. The degree of recovery is measured on the speed of recovery (Nagdi, 1993). The degree of resilience is also measured on the ratio of the energy returned to energy applied to produce the deformation. Higher the ratio, higher is the resilience of the material (Nagdi, 1993). This ratio can be viewed as proportional to the percentage of rebound.

(ii) Human resilience:

A critical review by Luthar et al. (2000) referred resilience as to a dynamic process encompassing positive adaptation within the context of significant adversity. They considered the individuals exposure to significant threat or adversity and positive adaptation despite disruption to the development process.

An interesting distinction between recovery and resilience patterns was made based on the impact of a traumatic event on the normal functioning of the human as shown in Figure 2.2. Figure 2.2 shows that a resilient individual does have major disruptions in normal function during a traumatic event but the effect is mild. Medium level disruptions are absorbed for the recovery pattern which tends to increase first and then reach normal levels ultimately. The other two plots, delayed and chronic are considered to be patterns of non-resilient individuals.

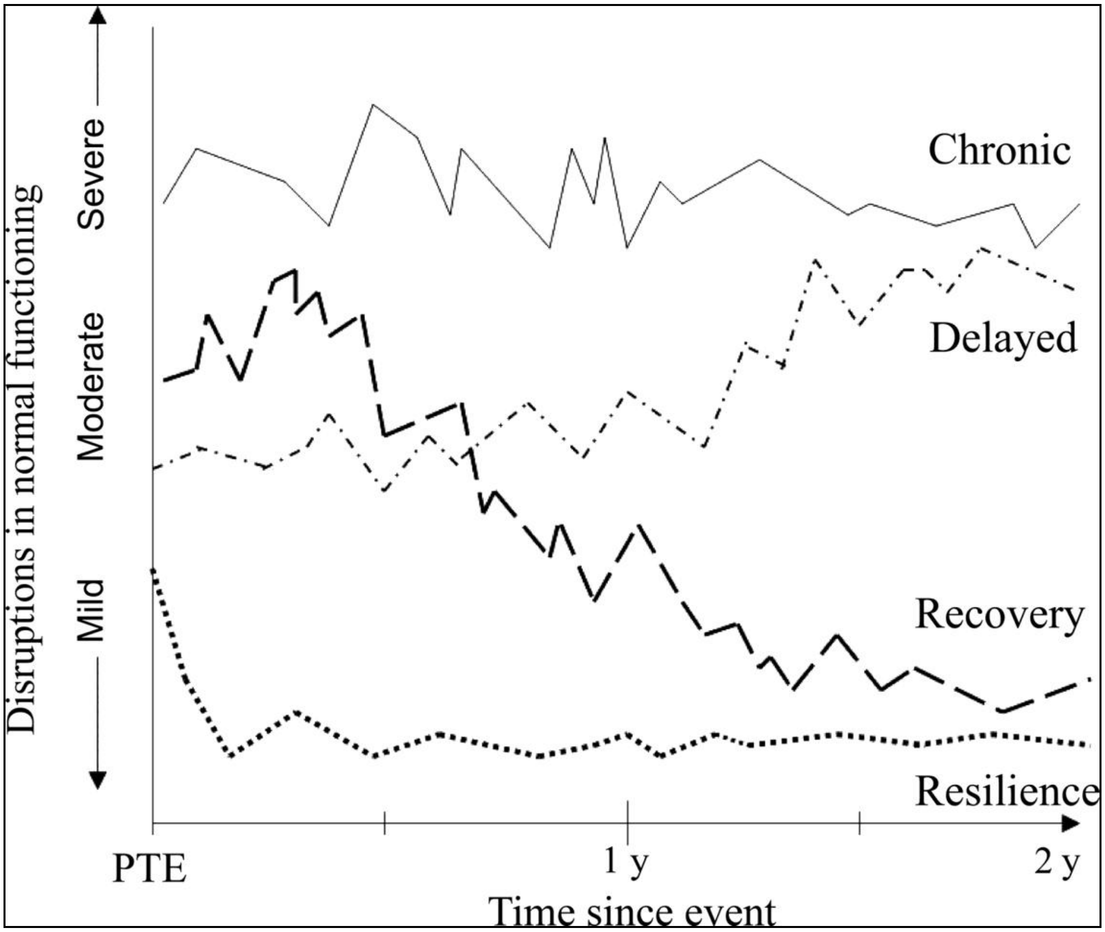


Figure 2.2: Possible human responses after a traumatic event. (Adopted from Bonanno and Mancini (2008)).

(iii) Ecological and Engineering Resilience:

Holling (1996) defines and distinguishes engineering resilience and ecosystem resilience as two different and alternating paradigms. His ideas on these systems are shown in Table 2.1.

Table 2.1: Summary of Engineering Resilience vs. Ecological Resilience (Holling, 1996)

	Engineering Resilience	**Ecological Resilience**
Definition (focus on)	Maintaining the function.	Existence of the function
Attributes (Desired for fail-proof design)	Efficiency, Constancy and Predictability	Persistence, Change, and Unpredictability
Stability	Global optimum or one equilibrium Steady State exists	More than one equilibrium states and systems flips states in case of instabilities.
Measure of Resilience	Resistance to Disturbance, and Speed of Return to equilibrium	The magnitude of disturbance the system can absorb before the system changes its structure and attain a controlled behavior.

In addition to the above work, Gao (2010) proposes a definition for engineering resilience based on the concepts of system function and damage and further distinguishes it from the concepts similar to resilience such as reliability, robustness, repairing, etc.

(iv) Information and communication Resilience:

Laprie (2008) identifies resilience in complex information and computer systems to have the similar notion of ecological resilience as described by Holling (1973). For such system he provides the following definition of resilience as “The persistence of the avoidance of failures that are unacceptably frequent or severe, when facing changes.”

Sterbenz et al. (2010) describes the following two disciplines that serve as basis of network resilience:

a) Challenge tolerance disciplines that deal with the design and engineering of systems that continue to provide service in the face of challenges.
b) Trustworthiness disciplines that describe measurable properties of resilient systems.

The divisions of these disciplines are tabulated in table 2.2.

Table 2.2: Basic disciplines for network resiliency (summarized from the work of Sterbenz et al. (2010))

Challenge tolerance	Fault Tolerance (compensated through Redundancy) Survivability (requires diversity) Disruption tolerance Traffic tolerance (accommodate sudden load)
Trustworthiness	Dependability (availability and reliability) Security (reduce unauthorized access) Perform-ability

(v) Business resilience:

Hamel and Valikangas (2003) referred business resilience as a superior capacity to reinvent a business model before circumstances forces to change. They further proposed the following strategies for business resilience:

1. Anticipation of unexpected failures through close attention to the business environment.
2. Investment in diversity (products or services).
3. Constant exploration of new opportunities.
4. Maintaining the balance between optimization (a pursuit for efficiency) and exploration of new opportunities.

(vi) Generic definition of the resilient system:

The definitions of resilience gathered from various fields are utilized to prescribe the characteristics of a resilient system and build a comprehensive definition for the same. The definition is also translated to a supply chain perspective.

a) Objective: The objective of resilient system should be to survive and maintain function (at least partially) in the course of disruption. In the case of supply chain, survival can be viewed as an equivalent to making profit, while the function of a supply chain is described as to meet the demand with enough supply. Here, survival and function are separated to capture a case where the supply chain meets the demand but the demand is not sufficient to make enough profit for its survival.

b) Anticipation: A resilient system should have continuous anticipation for all kinds of disruptions by paying close attention to the constant changes in its environment and at the same time utilize the knowledge learned from the past disruptive events.

c) Estimation: Have the strong intent to estimate and prioritize the damages that could occur from the anticipated disruptions.

d) Preparation: A resilient system should adopt a suitable resilient strategy or combination of strategies as a preparation for defence from the possible disruptions. Some of the resilient strategies as identified from the above study of resilience in various fields are building diversity, flexibility, redundancy, security and safety measures, collaboration and sharing of resources etc. The strategy selection is system, context and situation dependent. As an extension of the distinction made by Holling (1996) between engineering resilience versus ecological resilience, this article believes that the supply chain systems occupy the intersection of these two paradigms (see Table 2.1) as it not only deals with the social component in the form of interactions with suppliers and customers but also concerns with the engineering values during the production and manufacturing phase.

Combining the above characteristics, a generic definition of resilient system (also applicable to supply chain systems) is derived as follows:

A resilient system is a system with an objective to survive and maintain function even during the course of a disruption, provided with a capability to predict and assess the damage of the possible disruptions, enhanced by strong awareness of its ever changing environment and knowledge of the past events and thereby utilizing resilient strategies for defence against the disruptions.

The proposed definition can be seen as a combination of the definitions of Zhang and Lin (2010) and Hollnagel et al. (2006).

2.2 Supply Chain Network

In this section, the origin of the term “Supply Chain Network” is investigated and its usage in literature is studied. Further, we contemplate the ambiguity in the usage of the term “Supply Chain Network” existing in the literature. This is because the elements of a supply chain are significantly clear; however it is not very vivid how the elements of the supply chain are connected to form a supply chain network. To find answers to the above mentioned issues, systematic review technique is adopted. The steps of the systematic review performed are detailed from subsequent Subsections 2.2.1 to 2.2.5.

2.2.1 Selection of research article data bases

The following two online citation databases have been selected for the study.

1. Science Direct: www.sciencedirect.com.
2. SCOPUS: www.scopus.com

These two data sources comprehensively cover all the major journals and magazines in the fields of supply chain, manufacturing, production, industrial engineering and operations research including journals (e.g., European Journal of Operational Research, International Journal of Production Research, Omega, IEEE, Management Science etc).

2.2.2 Keywords and Search Strategy

The three keywords supply, chain and network are used with the following combinations: ‘supply network’, ‘supply chain’ and ‘network’. The search is directed to all contents including the title of the article, abstract and the keywords in all the relevant journals and magazines. There was no restriction imposed on years of publication. This is done to find out the first use of term “supply chain network”.

The search yielded a huge number of articles and after applying filters in the respective websites Science direct data source search yielded 1027 articles and the distribution of the articles over the years is shown in the following figure. Figure 2.3 shows the number of articles using the term "supply chain network" on the vertical axis and the corresponding year of publication on the horizontal axis.

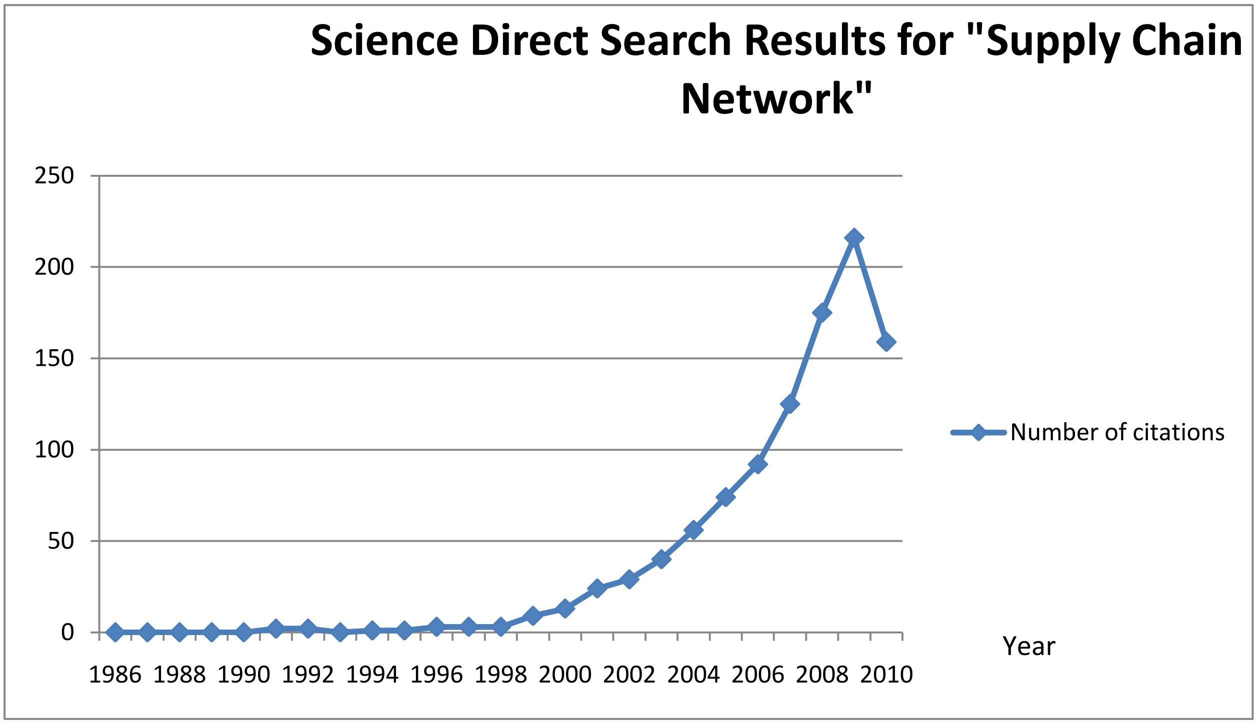


Figure 2.3: Distribution of articles (in ScienceDirect database) using the term "Supply chain Network".

A similar search on the database of SCOPUS showed that 694 articles have used the term 'Supply Chain Network' and distribution of these articles is shown in Figure 2.4.

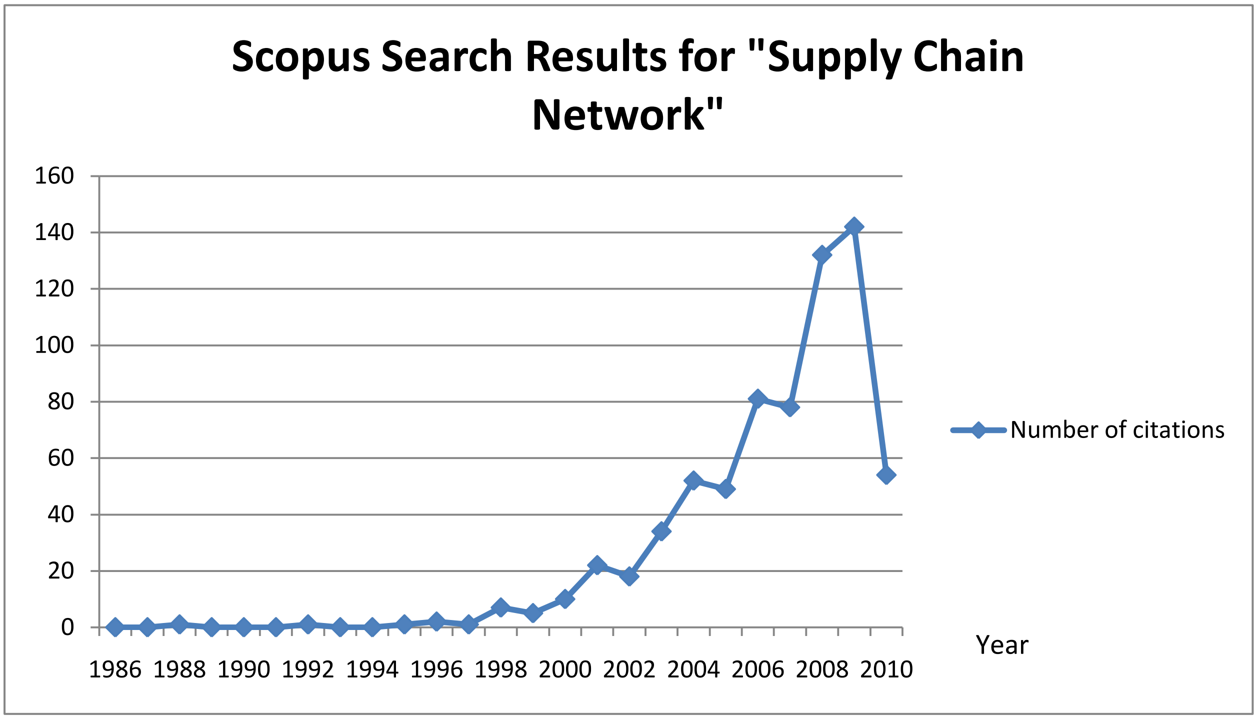


Figure 2.4: Distribution of articles (in SCOPUS database) using the term "Supply chain Network".

The analysis of these graphs is presented in section 2.2.4 later.

2.2.3 Selection criteria and data collection

Since the number of articles found is enormous, only 48 articles were chosen for the analysis based on their relevance to supply chain network and popularity (number of citations received). The articles selection was also uniformly distribution over the years of publications proportional to the number of articles for the respective years.

2.2.4 Analysis

A preliminary analysis was performed on the search results with the help of the plots shown in Figure 2.3 and Figure 2.4, respectively. These plots indicate that the use of term 'supply chain network’ became widely popular in the supply chain literature at the beginning of the years of 1998-1999. Moreover, its usage kept increasing over the years as seen in Figure 2.3 and Figure 2.4, respectively. It is to be noted that the drop in the curves in the last section of the plots is because articles published only till the middle of the year 2010 were considered.

A further analysis was performed through the careful study of the selected 48 articles (listed in Table 2.3). As for the origin of the term ‘supply chain network’ the first among the authors to use this term based on the search above were Billington and Davis (1992), Padillo and Brown (1995), Huchzermeier and Cohen (1996). Correa and Miranda (1998), Chandra (1997), Lin et.al. (1998), Ross et al. (1998), Fu-Renlin and Shaw (1998) Srinvasan and Moon (1999). However, the first comprehensive definition and analysis of supply chain network was not recorded until Fu-Renlin and Shaw (1998). According to them, “A supply chain network (SCN) is a network of autonomous or semi-autonomous business entities involved, through upstream and downstream links, in the different processes and activities that produce goods or services to customers.” Further, they classified supply chain network into three types based on seven attributes. However, such classification has not included the structural information of the network which differentiates different supply chain systems. This is especially important because the increasing usage of the term ‘supply chain network’ combined with no clear definition or classification on its structure might cause some trouble for future researchers to identify relevant literatures. To address this concern, this thesis identified three possible network structures that might have been referred as to supply chain networks by the earlier researchers in this field. These three structures are illustrated as follows:

The first kind of structure contains a tree like structures. In this structure various branches evolve from a single node reaching various parts of the network. This structure is usually seen when the distribution of the products from a single manufacturing unit to various distribution units. All the nodes in the network are in the control of single management. The scope of the study of this kind of networks could be for example planning of distribution activities of products of a single firm at various geographical locations. For the simplicity purpose, hereafter, this type of supply chain structures is referred to as Firm-Centered Supply Chain Networks in this thesis. It is noted that this kind of network has been discussed in Gjerdrum et al. (2001). Figure 2.5 illustrates this type of networks, which is adopted from the paper of Gjerdrum et al. (2001).

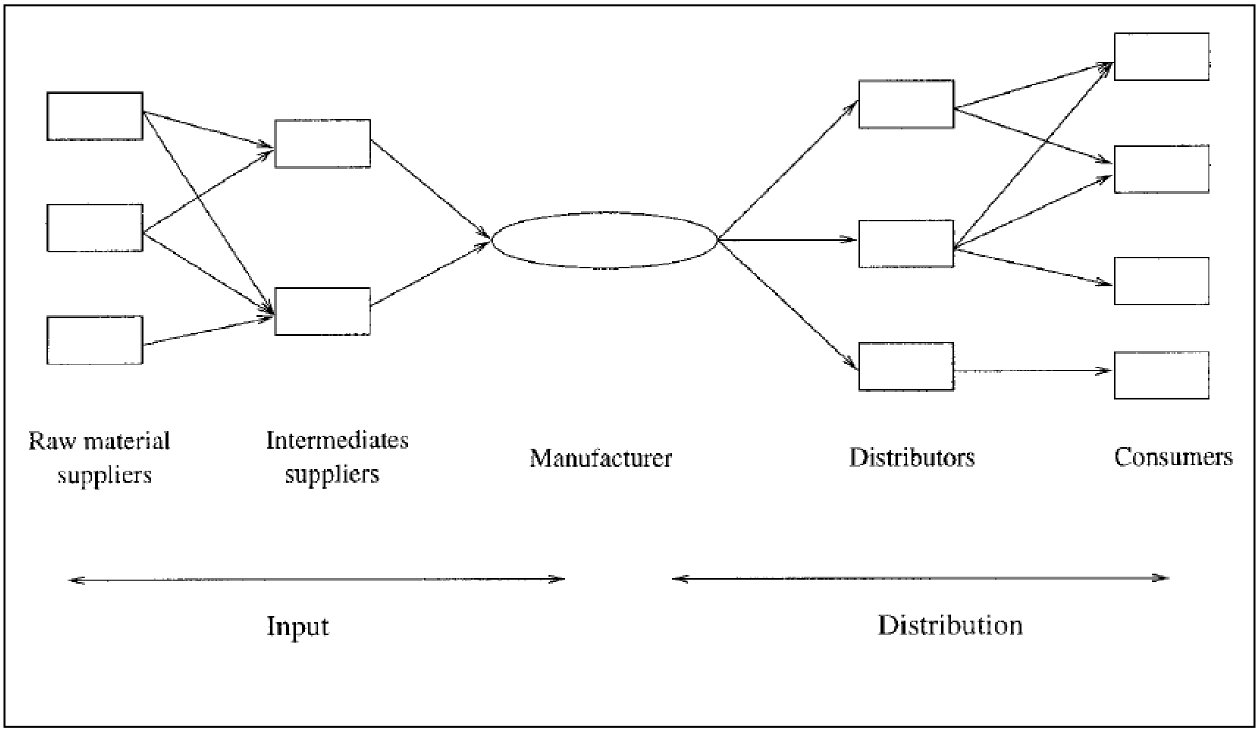


Figure 2.5: Firm-Centered Supply Chain Networks (adapted from Gjerdrum et al. (2001)).

The second kind of supply chain networks is the tier-based network system. In this kind of structure there are multiple instances of different firms at each stage of the supply chain. Such structure is commonly seen when several supply chains exist to have common source nodes (suppliers) and destination (customers) nodes. The nodes in this kind of network are usually independent and not all under the control of a single enterprise. The scope of the study of such networks is usually towards the competition among the members of the same tier level and partner selection strategies. This kind of structure was referred to in the work of Tsiakis et al. (2001), as shown in Figure 2.6.

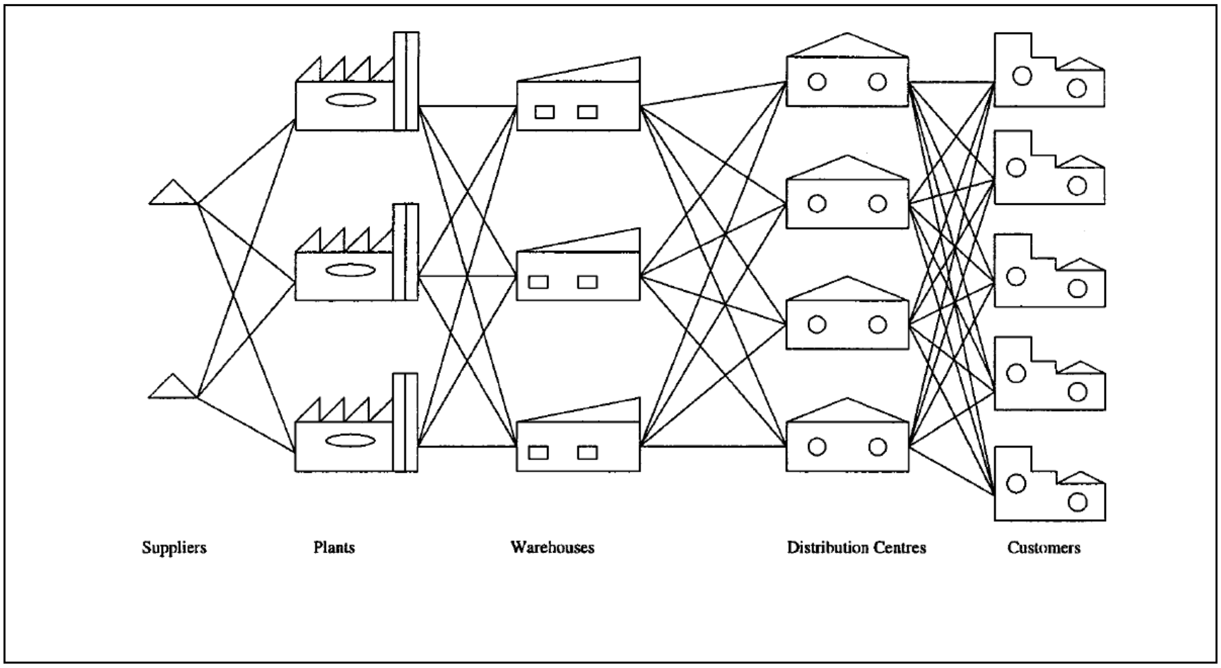


Figure 2.6: Industry Centered Supply Chain Networks (adapted from Tsiakis et al. (2001)).

This kind of networks is centered on a particular industrial sector of products (for example automotive sector). The networks of this kind do not extend their reach beyond their industrial sector.

The last type of structure of supply chain networks this thesis is interested to study is referred to as Inter-industrial Supply Chain Network Structure. Their structure considers a broader range of supply chain networks where the network is not confined just to a single industrial sector; rather it includes the effects of interaction of wide variety of supply chains. According to the author's knowledge, it is believed that this type of networks is important in consideration of the strong interconnection or interdependency of various supply chains in the present day or modern supply chain. For example, the supply chain of wheat in food industry and supply chain of a car in automotive industry might be exceptionally two different things but they might interfere at a common exporting port (e.g., a ship container yard). The scope of the study of this type of networks is to understand the interdependency of a variety of supply chains and their possible indirect effects (sometimes in the form of loops) on each other. Supply chain networks of this type attain the main focus of this thesis and are revisited in the later chapters of this thesis. A theoretical analysis of this kind of networks is done by Dubois et al. (2004). Although they have not used the term 'Supply Chain Network', their representation, as shown in Figure 2.7, does capture some characteristics of this type of supply chains.

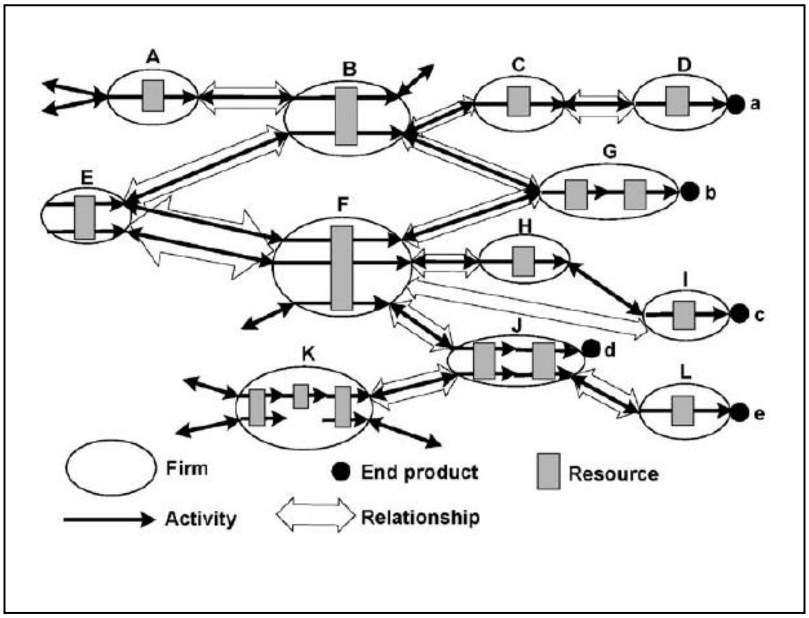


Figure 2.7: Inter-industrial Supply Chain Network (adapted from Dubois et al. (2004)).

The three categories of supply chain networks discussed above are used to classify the 47 selected literatures and are tabulated in Table 2.3.

Table 2.3: Ambiguous usage of term ‘Supply Chain Network’

Firm-Centered Supply Chain Networks
Huchzermeier and Cohen (1996), Zhou et al. (1998), Ross et al. (1998), Dogan and Goetschalckx (1999), Min and Melachrinoudis (1999), Mirhassani et al. (2000), Gjerdrum et.al (2001), Dong and Chen (2001), Raghavan and Viswanadham (2001), Zhou et al. (2002), Dong et al.(2004), Eskigun et al. (2005), Melo et al. (2006), Choi et al. (2006), Liu and Zhou (2007), Dong and Peng (2007), Chiou (2007), Romeijn et al. (2007), Melo et al. (2009),Che et al. (2009).
Industry Centered Supply Chain Networks
Min and Melachrinoudis (1999), Rupp and Ristic (2000), Tsiakis et al. (2001), Nagurney et al. (2002), Cakravastia et al. (2002), Lancioni et al. (2003), Chen et al. (2003), Wathne and Heide (2004), Chen (2004), Dong et al. (2004), Chan and Chan (2004), Jain et.al (2004), Santoso et al. (2005), Altiparmak et al. (2006), Jiao et al. (2006), Patnayakuni et al. (2006), Sha and Che (2006), Ding et al. (2006).
Inter-industrial Supply Chain Networks
Lin and Shaw (1998), Lin et al. (1999), Mirhassani et al. (2000), Cox (2004), Fandel and Stammen (2004), Ranganathan et al. (2004), Beamon and Fernandes (2004), Surana et al. (2005), Sanders (2005), Wuming et al. (2009).

Table 2.3 includes those that use the term ‘supply chain network’ in the literature but use it in an ambiguous manner.

2.2.5 Summary and Discussion of the Review

In summary, the term ‘supply chain network’ has been widely used in the literature. Its usage is ever-growing and so is its ambiguity. Although some classifications of supply chain networks are available in the literature (Lin and Shaw, 1998; Wuming et al., 2009), no clear terminology is available to distinguish the supply chain network structures and their respective scope of purpose. This review suggests three types of supply chain networks based on their structure and scope of purposes; further these are identified with strong informative terminology namely, Firm Centered Supply Chain Networks, Industry Centered Supply Chain Networks and Inter-industrial Supply Chain Network. Some of the prominent works in the field of Supply chain Network are also grouped into the three categories of Supply Chain Networks proposed in Section 2.2.4. It is believed that this classification provides a platform for future researchers to identify and present their works in most relevant sections of the supply chain literature.

2.3 Supply Chain and Resilience

In this section a review of the works relating to the application of resilience in the field of supply chain management is presented. A similar systematic review used in Section 2.2 was adopted for this review. The databases and search methodology remained the same. While the keywords used are shifted to the various combinations of the words Supply chain, Supply chain network, Resilience, Resilient, Resiliency. For the selection criteria, only the works that address resilience and its related issues in supply chains are selected. Besides relevance, the number of citations was also taken into account. As a result, forty three articles are selected for the analysis and the classification is done into four categories. These categories are developed based on the characteristics proposed in the definition of resilient system in Section 2.2. The categories are as follows:

1) **Awareness and anticipation:** Articles that stress on the identification and awareness practices of existing vulnerabilities and upcoming disasters in a supply chain are placed in this category.
2) **Estimation and decision:** The articles that are focused on computation regarding the effect of a disruption or effect of adopting alternative mitigation strategies.
3) **Proactive Defence:** Proactive strategies are ones that are in action even before a disruption takes places.
4) **Reactive Defence:** Reactive strategies are ones that are designed to perform defensive action after a damage or disruption to the system.

Using the above four categories, forty three articles relating to the literature of resilient supply chain are selected and grouped as shown in Table 2.4. If an article is placed in more than one group, it has impact on all the categories in which it is placed.

Table 2.4 Classification of the Resilient Supply Chain

Awareness and Anticipation
Kong and Li (2008), Jianxin (2008), Hammant and Braithwaite(2007), Guojun, and Caihong (2008), Carvalho and Machado (2007), Sheffi (2005), Sheffi and Rice(2005), Klibi (2010), Rice and Caniato (2003),Barnes and Oloruntoba (2005), Craighead (2007).
Estimation
Deleris et al. (2004), Glickman and White (2006), Babich (2006). Babich et al. (2007), Tang and Tomlin (2008), Mitra et al. (2009), Jiang (2009), Yu and Zhao (2008), Bakshi and Kleindorfer (2009), Rice and Caniato (2003), Wagner and Neshat (2009), Sheffi (2005), Sheffi and Rice (2005), Wang et al. (2010), Iakovou et al. (2010), Craighead (2007).
Proactive Defense
Slingo et al. (2005), Glickman and White (2006), Sheffi (2005), Sheffi and Rice(2005), Lodree and Taskin (2009), Sarathy (2006), Carvalho and Machado(2007), Dynes (2008), Mohan (2009), Rice and Caniato (2003), More and Babu (2009), Enyinda and Tolliver (2009), Thun and Hoenig(2009), Alonso et al. (2009), Lara et al. (2009), Thamilarasu, and Sridhar (2008), Roussinov and Chau, (2008), Weber (2010), Barnes and Oloruntoba (2005), Knemeyer et al. (2009), Ratick et al. (2008).
Reactive Defense
Yan et al. (2010), Liu and Ji (2007), Vellema et al. (2006), Boin et al. (2010), Stewart (2009), Thun and Hoenig(2009)

The classification presented in Table 2.4 reveals that the exclusive use of the term ‘resilience’ in supply chain is quite recent (2003-2004). It can also be observed that the supply chain literature suggests more of proactive defence approaches comparative to the reactive approach to achieve resilience in supply chain. However, there is great overlapping of the strategies among various works in the literature. Some of the most prominent strategies were found to be

i) Identification of vulnerabilities
ii) Building Redundancy (Easy but Costly)
iii) Flexibility (cost effective but hard to build)
iv) Planning reconfigurations.
v) Taking high security measure (costs can be reduced through collaboration in maintaining security)

However, the survey revealed that most of the works in resilience of supply chain are theoretical. Besides, the main drawback of the above-mentioned works is that the strategies proposed are at an individual firm level or an enterprise level. The work presented in this thesis builds on the principle that resilience of individual entities does not ensure the resilience of the entire system/network. The recent economic recession presents some good examples of this situation, one among which is the fall of the big three American automobile manufacturers. The fall has significantly affected the component supplies of Japanese car companies, and in such a way, they are negatively affected as well.

Based on the above argument, this thesis confirms the need of a framework and tools to analyze and build resiliency of a supply chain network from a holistic perspective. Further, this justifies the objectives of this thesis, as proposed in Chapter 1. As a first step towards these objectives, a generic conceptual framework for the representation of the holistic supply chain network is developed and the notions required for the network will be discussed in the next chapter.

Chapter 3 Conceptual Framework for Supply Chain Networks

3.1 Introduction

This chapter focuses on definition of a conceptual framework with its emphasis on a holistic view of resilience in a supply chain network. The key argument for the need of such a framework has already been discussed in chapter 2 and in particular is the principle that the resilience of individual entities does not ensure the resilience of an entire system/network. In this thesis, communication (information sharing) among members of a supply chain network is taken as a fundamental concept to promote resiliency in a supply chain network, which is also seen a significant departure of this thesis from many others in literature. Specifically, this thesis focuses on the extraction of information regarding the origin of disruptions and possible propagation of their effects in an entire supply chain network to a certain depth and breadth. The first step towards such a framework is to have a generic representation of a supply chain network which can capture interactions at a level of Inter-industrial Supply Chain Networks (see chapter 2). The choice of this level of description is apparent in the context of a holistic vision as it positions at a higher hierarchical level than the other two types of supply chain networks (i.e., Firm level Supply Chain Networks and Industry centered Supply Chain Networks discussed in chapter 2). Figure 3.1 illustrates that the firm level and industry centered supply chain networks are merely subsets of the Inter-Industrial supply chain networks.

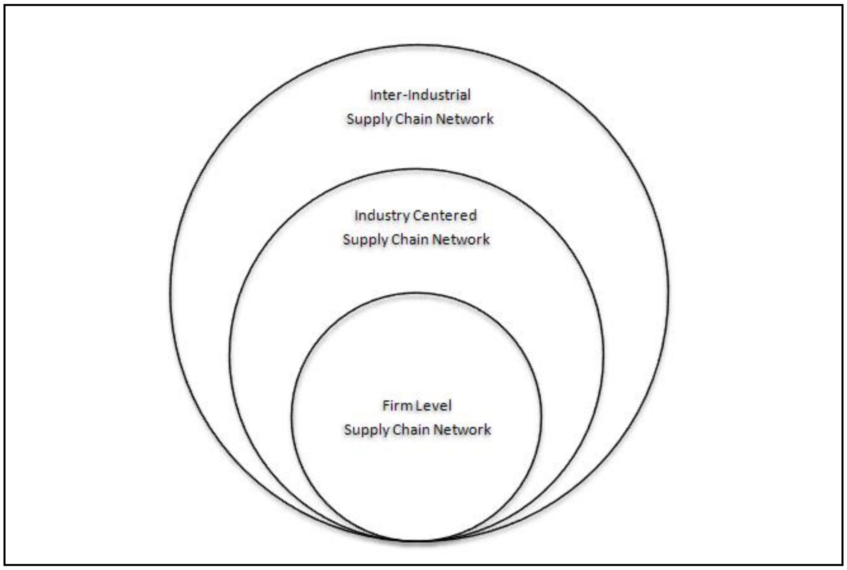


Figure 3.1 Hierarchies of the Supply Chain Networks.

However, the integration of a wide variety (in terms of type of products, services and resources involved) of supply chains into a single framework demands a common attribute (language) to facilitate the detection and communication of effects among supply chains. For this purpose, this thesis work proposes "economic health" of a member in the supply chain network as a common means to detect and measure disruptions, further it is an aggregative attribute of all possible disruptions such as damage to transportation infrastructure (transportation delays), excess inventory, availability of human or machine resources (manufacturing delays), low demand for products, and so on. For simplicity, hereafter, this thesis uses the term "health" to refer to "economic health".

In what follows, Section 3.2 describes the proposed conceptual framework and several relevant notions, including the health of a supply chain network. In Section 3.3, hypothetical examples are employed to illustrate possible applications of the proposed framework to improve resiliency in a supply chain network.

3.2 Conceptual Model

In this section, a conceptual framework is proposed to capture the structure and the behaviour of a supply chain network. At first, the components and flows in a supply chain are identified. A supply chain usually starts with procurement of raw materials through a manufacturing phase and distribution of the materials and it ends with consumption and disposal of a product or service. Various firms (e.g., mining firms, manufacturing firms, transportation service providers, retailers, etc.) are involved to carry out these supply chain functions, and these firms are components of a supply chain. Members of the supply chain can have two types of relationships with other members of the supply chain. One relationship is that a firm is a supplier to other members in the supply chain, and the other relationship is that a firm is a customer to other firms. Here, the supplier firm is used in a general sense, meaning that the thing to be supplied could be material, human or machine resource, knowledge, a service or combinations of any of them (Liu et al., 2006). An existing relationship between any two firms in a supply chain network may have any of the following flows:

1) Physical flows: Flows from the supplier to the consumer firm.
2) Monetary flow: From the consumer firm to the supplier firm.
3) Information flow: Information flow in the form of communications in both directions.

The three flows are supported by various infrastructures. In this thesis, infrastructure is a common front or a supporting interface that is utilized by various firms to enable the aforementioned flows in the network. For example, an infrastructure for the material flow is the transportation system (e.g., roads, rails, seaports, airports, etc) (Wang et al., 2010a; Wang et al., 2010b). A satellite or the internet, telephone lines could be infrastructures for the information flows. Financial institutions such as banks could be kinds of infrastructures that facilitate the money flow in a supply chain network. The infrastructure in a supply chain network cannot be ignored, because many supply chains share the infrastructure for its services and its failure could mean a simultaneous disruption to many supply chains. In the proposed framework, the organization for managing the infrastructure will be regarded as a member in the entire network.

It is proposed that Darwin's theory of survival (Darwin, 1872; Headley, 1909) accounts for the behaviour of each member in a supply chain network. In particular, survival of a firm is linked with its profit gained while it performs its specific supply chain function. Further, the profit is strongly coupled with the primary factors (i.e., supply and demand), generated by its neighbouring suppliers and customers, respectively. In addition to these two factors, availability and efficiency of its internal resources required for conversion of inputs to outputs are also related to the profit. Consequently, failure of a firm in a supply chain network is caused by damage to any of these three (i.e., supply, demand and internal resource) aspects; see also the illustration in figure 3.2. Gunasekaran (2001) has related these three aspects to improving competitiveness and the prospects of survival in an increasing volatile and global business environment, but in his idea, the three are not explicitly related to the profit.

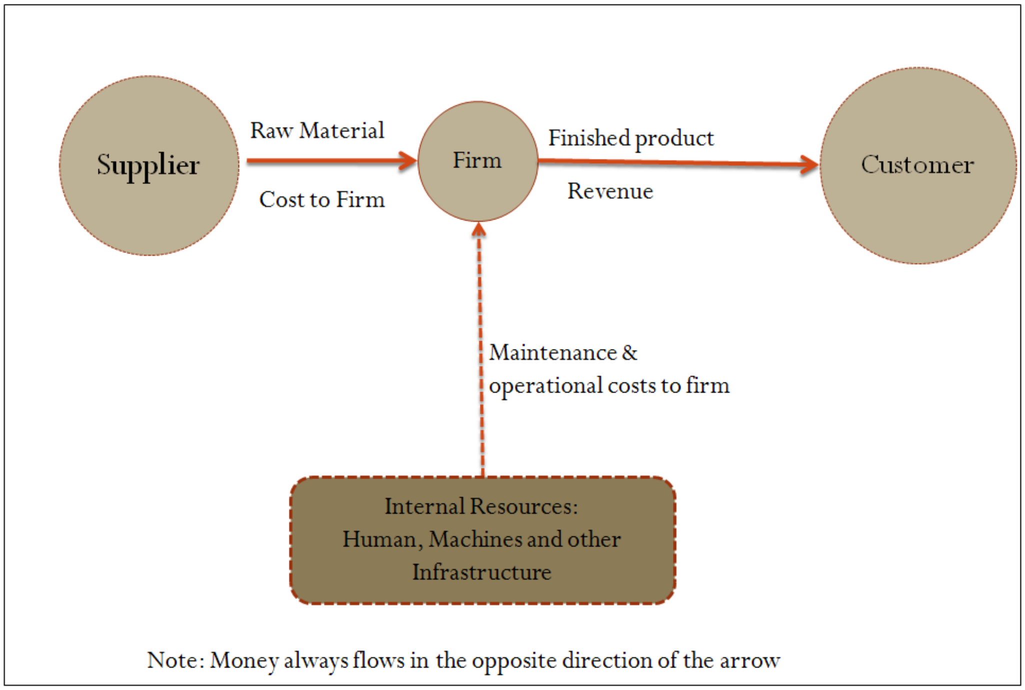


Figure 3.2: Components for survival of a firm.

3.2.1 Notions for representation

This section presents the notions used for the representation of the proposed conceptual framework for a holistic supply chain network. For this purpose, this thesis employs a similar notion in network theory, where a network consists of nodes and arcs connecting the nodes to show existing relationships. In this thesis, nodes in the network represent different firms/organizations in a supply chain network. The firms might be concerned with different functions set (e.g., mining of raw materials, processing, production, assembly, distribution, and consumption), or in some cases a firm may be multifunctional (i.e. carrying out more than one supply chain function). In this thesis, the firm which is multifunctional is also treated as a single node in the network. This is made to promote a simplified holistic view of the supply chain network and the detailed internal structure and process of a firm is not shown in this representation; in other words, a firm in a supply chain network or a node in a network is treated as a black box. However, the health of each firm or node is explicitly represented, and in fact the health information will be supposed to be shared by all the member firms in the network. It is to be noted that the proposed representation takes a graphical form where a node represents a firm, and different states of the health of the firm is represented by different colors.

For determination of the health status of a firm in a supply chain network, a fundamental concept called "break-even analysis" is borrowed from the field of engineering economics (Blank and Tarquin, 2008). A typical break-even analysis consists of two prominent curves, namely total revenue curve and total cost curve, with the quantity of products or services being on the horizontal axis and monetary units on the vertical axis (see Figure 3.3). The intersection of the two curves is noted as the break-even point. The significance of this point is such that it is the point which indicates the minimum quantity of products or services to be sold by a firm to incur no loss or simply to make zero profit.

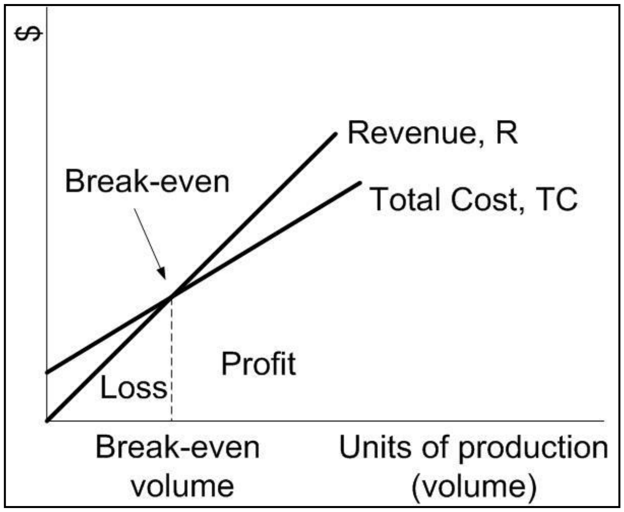


Figure 3.3: Graphical illustration of break-even point (adopted from Blank and Tarquin, 2008).

The above concept is applied to each firm in a supply chain network to determine the health (economic health) of the firm. For the visualization purpose, the plot is divided into the following colored zones (shown in Figure 3.4) to indicate different health levels of a firm:

a) Red zone: This is a loss zone marked by red color, in which the total revenue curve lies below the total cost curve, implying that a firm is in loss and has a poor performance.

b) Green zone: This is a profit zone marked by green color, in which the total revenue curve lies above the total cost curve, implying that a firm has profit and has a healthy business; in other words, sales of a product or a service by the firm comfortably cross the break-even point.

c) Black zone: It is important to note that every firm has a resource capacity constraint in the form of raw materials, human resources or machine resources. The significance of the capacity constraint (indicated by thick grey line) is the maximum quantity of products or services that the firm can generate in a given timeframe and an upper limit of the resources available. Therefore, if the demand generated is beyond the capacity of the firm, there would be an opportunity cost. Opportunity cost is measured as a cost due to loss of customers. This status of a firm is indicated by the black zone as shown in Figure 3.4. This means that the firm should expand its capability of production to stay competitive in the market.

d) In addition to the aforementioned three zones, two additional warning zones are marked in Figure 3.4. The yellow marked zone is a warning zone to indicate that a firm is closely approaching to the red zone of losses and the blue zone indicates the possible overload of the firm due to excess demand.

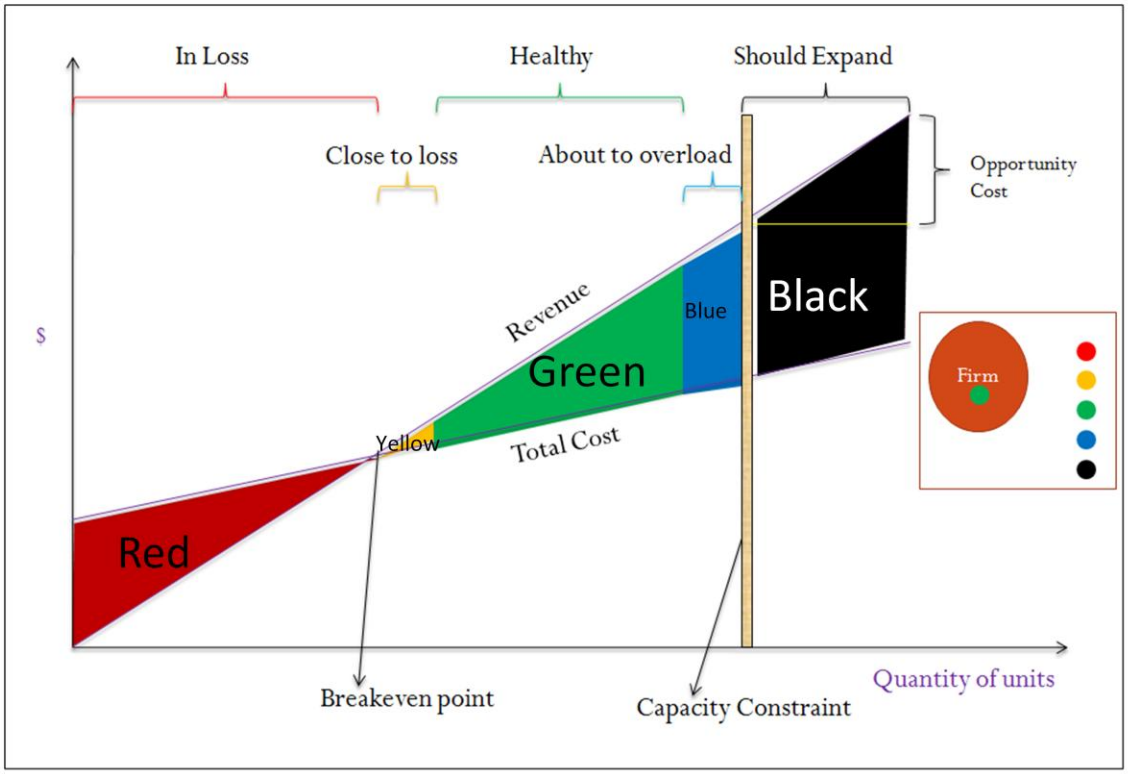


Figure 3.4 Health states of a firm for members of a Supply Chain Network.

Using the notions discussed above, a sample supply chain network is explained using Figure 3.5. The firms are represented by circular nodes connected by arrows with the state of health indicated by a color dot at the center of each node (initially all the firms are show to be in green zone indicating a healthy supply chain network).

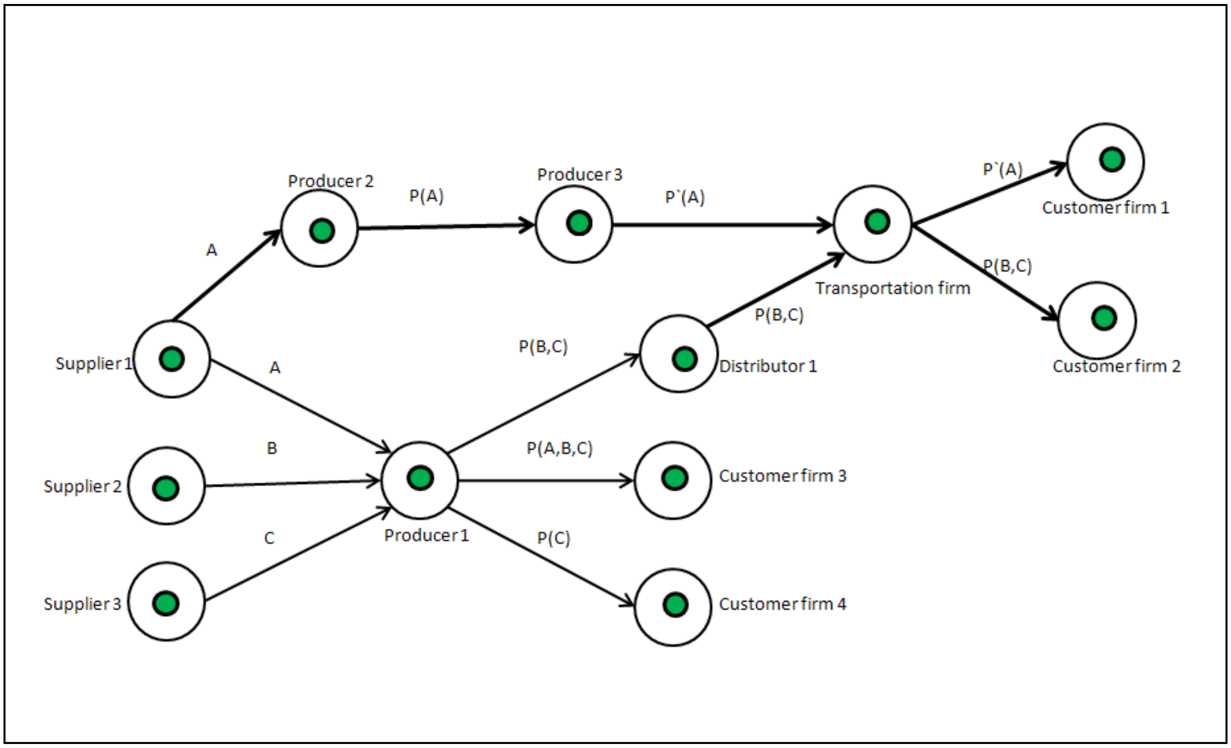


Figure 3.5: Sample of the proposed Supply Chain Network Representation.

Figure 3.5 shows various supply chain network members/firms (e.g., suppliers, production firms, distribution centers, transportation firms, etc) responsible for the flow of four different products. The four products are named after the raw materials (A, B, and C) used for their production. For example, the product made with raw materials B and C is denoted by P (B, C). Also, it is to be noted that products of one firm may become inputs for the product of another firms. For example, the product P (A) from the Producer 2 is used as an input to produce the product P` (A) (i.e. P`(A)=P(P(A)) by Producer 3. Other members in the supply chain network such as transportation firm and distribution center just pass on products to the next stage without any modification to the products. For such firms, inputs and outputs are the same. All the members/nodes in a supply chain network are assumed to be independent in ownership and as mentioned early, the arrow moving away from the node is a source of revenue and the arrow coming towards a node are sources of costs to the firm. For example, considering Producer 1 in Figure 3.5, the incoming arrows indicate the flow of materials A, B, C from the suppliers and are a form of expenditures to the production firm (Producer 1). The arrows indicating the flow of products P(B,C), P(A,B,C) and P(C) originating from the Producer 1 node are sources of its revenue. Further, it may be stated that a disruption in the incoming arrows means a disruption in the supply of materials to the firm (i.e., a probable opportunity cost) and disruption in the outgoing arrows implies disruption at the demand side, hence loss of revenue.

3.3 Application

The above proposed framework can have the following applications:

3.3.1 Detection of disruption and its spread

The early awareness/information regarding the origin and propagation of effects of a disruption contributes to better resiliency of the system. These characteristics give the system or component of a system more time to respond; hence less could be the damage (or further damage) and easier is the recovery of the system. This application is further illustrated through a comparison of the awareness at the firm level (meaning awareness only after the disruption reaches the neighboring nodes) to the global awareness of disruptions over an entire supply chain network. Consider the following hypothetical disruption at the supplier 1 node in the supply chain network shown in Figure 3.5. A series of network diagrams (see Figure 3.6 (a) to (f)) are used to show a possible propagation of this disruption in the supply chain network starting at supplier 1 shown in Figure 3.5. In Figure 3.6(a), the health status of Supplier 1 is indicated by red (i.e. services/products below the breakeven point). The failure of Supplier 1 affects the supply of material “A” to the Producer 1 and Producer 2, respectively, and disables them to produce products P(A,B,C) and

P(A), respectively. These failures are updated in Figure 3.6 (b) where the statuses of Producer 2 and customer firm 3 are changed to red. However, Producer 1 is shown to have a healthy status (green), given the diversity in its product line (i.e. it has the other products P (B, C) and P(C) to generate revenue and do not require material “A”). Figures 3.6(c) and 3.6(d) show the failure of the nodes (Producer 3 and transportation firm) following the disruption in the supply of material A. The failure of Producer 3 follows the failure of Producer 2 since its only product P` (A) uses P (A) as input. As for the transportation firm, its survival is dependent on transportation services provided for both the products P` (A) and P (B, C). However, if a major portion of the revenue is from the transportation service provided to product P` (A), then there exists the possibility of failure of this node due to the failure of Producer 3. The failure of the transportation firm further causes disruption to the distribution center activities and ultimately effect the Producer 1 (see Figure 3.6 (e) and 3.6(f)).

Observing the disruption pattern of the supply chain network in Figure 3.6, the first impact on Producer1 is felt as soon as the Supplier 1 node fails. However, the loss of only one of its product P (A, B, C) does not affect its health status during this event (see Figure 3.6 (b)). Further down the time scale, the disruption propagates through the supply chain of another product P` (A) and effects the distribution center of the product P (B, C) and ultimately effects the health status of the node Producer 1(see Figure 3.6 (b)). Therefore, the failure or the disruption of the Supplier 1 has two effects on Producer 1. The first one is a direct effect and immediate in the form of supply shortage of material “A”. The second effect takes some time to propagate through the supply chain of product P` (A) before reaching the neighboring node (the distribution center) of Producer 1. The early prediction of this indirect effect is possible if and only if Producer 1 has a network level awareness (i.e., knowledge of the various events in the neighboring supply chains before they spread to the neighboring nodes.)

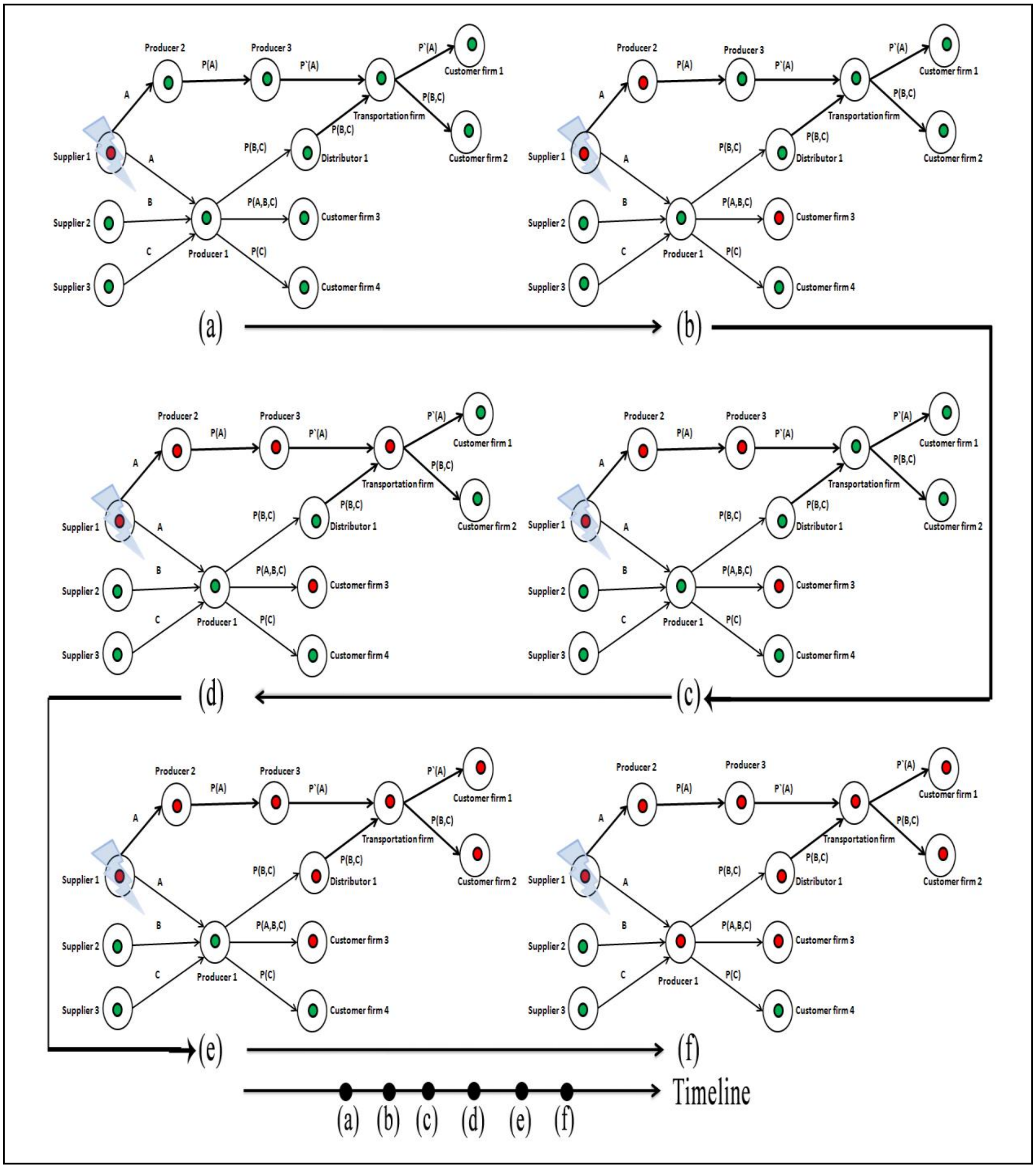


Figure 3.6 Sample disruption sequence in a supply chain network.

The above proposed framework can facilitate the visualization of the origin and the spread of a disruption hence the global awareness. However, the challenge remains as how to obtain and update the health information of nodes dynamically so that their effects are automatically displayed with time. This thesis provides the following formal representation for calculating the health of a node in supply chain network.

- 'I' is a set of all inputs to a node and denoted by $I = \{I_1, I_2, \ldots, I_n\}$, where n is the total number of inputs to a node.
- 'P' is a set of all products or services that generate revenues to the node and denoted by $P = \{P_1, P_2, P_3 \ldots, P_m\}$, where m is the total number of products or services that generate revenues to the node.
- Mapping set 'M' is the set containing information of the mapping of the outputs (the products) with their respective inputs (raw materials). Therefore, for every P_i there exists a mapping set M_i where 'i' varies from 1 to m and M_i is a subset or equal to I.
- For example, for Producer 1 in the above network has three inputs A, B, C ($n = 3$) and three output products ($m = 3$).
  - Input set for Producer 1 node can be written as $I = \{A, B, C\}$.
  - Output set for Producer 1 node can be written as $P = \{P(M_1), P(M_2), P(M_3)\}$.
  - The mapping set for Producer 1 can be written as $M = \{M_1, M_2, M_3\}$, where $M_1 = \{B, C\}$, $M_2 = \{A, B, C\}$ and $M_3 = \{C\}$.
- Finally, Health of a node(H) is the difference of the revenue from the output set P and expenditure on the input set I and the production costs i.e.,

$$H = \sum_{i=1}^{m} \mathrm{Re}venue(P(M_i)) - \sum_{j=1}^{n} I_j - \text{production costs} \tag{3.1}$$

Hence, the health of a firm is determined by the condition of the active inputs and outputs. Failure of any of the neighbouring nodes can change the health state of the node. The mapping set defined above implicitly quantifies the supply and demand disruptions. That is, when the product is not sold, the revenue generated by the product will be zero. Similarly, when there is a disruption to at the supply side, the revenue from the corresponding products are updated accordingly.

3.3.2 Recovery module

The additional application of the proposed framework is to facilitate (through information sharing) the possible flow of redundant resources from a resource rich member in the network to a needy member with resource deficit caused by a disruption. This collaboration by sharing redundant resources promotes mutual benefits to all the members involved in a network, besides fixing a disruption before it transmits to other parts of a network. It is known that redundancy can improve resilience but it causes inefficiency in the system. This inefficiency can be reduced through collaboration of various components in the system through sharing of redundant resources. This thesis proposes the need of a module to promote such a sharing of resources of the firms in the modern supply chain network. In addition, the above proposed conceptual framework for the representation of supply chain network, along with the health status of the nodes, lays down the foundation for the formation of such a module (i.e. the global awareness through publishing of the information of redundant resources of healthy firms can mitigate the identified disruptions arising in the network). The sample of a recovery module for resiliency in a network is shown in Figure 3.7. Figure 3.7 shows two firms A and B of a supply chain network, where status of firm A to be red and status of Firm B to have the healthy green status. The recovery module collects information of the required resources of firm A and matches with the information of the redundant resources available from firm B and initiates a negotiation for possible collaboration of the two firms for their mutual benefits. Although the proposed module is based on a simple principle, the realization of such a module has practical difficulties, which will be discussed in the last chapter of this thesis.

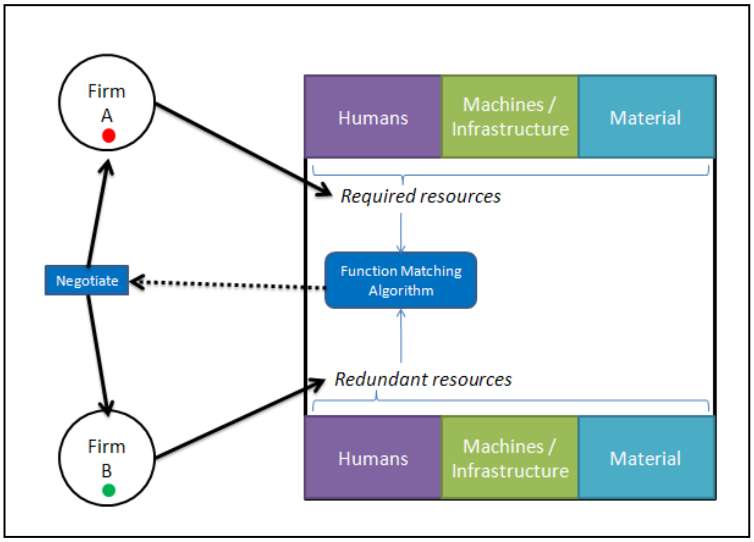


Figure 3.7: Recovery module for sharing of redundant resources.

3.4 Summary

This chapter described a new conceptual framework for a holistic view of the supply chain network with its application to improve resiliency of the (entire) supply chain network. The primary objective of the framework was on the development of a tool for prediction of disruptions and their propagation in over an entire supply chain network. This objective has been shown achievable. The application of the break-even theory in engineering economics works very well to implement the concept of economic health of a firm and sharing of the firm's health information over the entire supply chain network. The concept of redundant resources among firms in a supply chain network is promising.

There is a need to have a computational system to analyze the behavior of a supply chain network based on the proposed framework. This will be discussed in the next chapter.

Chapter 4 Application of Petri Nets to Supply Chain Networks

4.1 Introduction

This chapter presents a proposed means or tool to realize the formal representation and simulation of the operation of a supply chain network in accordance with the proposed framework presented in Chapter 3. For this propose, this thesis looks at some of the widely used simulation programs in the supply chain literature. Kleijnen and Smits (2003) distinguished four types of simulation, and they are summarized as follows:

1) Spreadsheet Simulation: Used for the implementation of manufacturing resource planning (MRP). However, such simulations remain to be too simple and unrealistic according to (Powell,1997; Plane, 1997; Kleijnen and Smits, 2003). The spread sheet simulations also lack the graphical view of the system.
2) System Dynamics: It uses the concepts of flows and stocks to capture behaviours of the systems. Developed by Forrester (1961), System Dynamics is used to demonstrate the bullwhip effect in the supply chain by considering the gaps between the actual and the target inventories. The drawback of System dynamics is that it still only gives qualitative insights and does not provide exact quantitative forecasts (Kleijnen and Smits, 2003).
3) Discrete-event dynamic system simulation: These simulations are more detailed and can provide details of individual events, hence quantification. Further, these simulations can capture uncertainties prevalent in the supply chain management (Law and Kelton, 2000;

Kleijnen and Smits, 2003). Discrete-event dynamic system simulation is widely used in computer based supply chain management systems such as Enterprise resource planning (ERP) / Material requirements planning (MRP) (Vollmann et al., 2003; Kleijnen and Smits, 2003).

4) Business games: These games are more focused on the simulation of human behaviour, specifically the decision makers in the supply chain. Kleijnen and Smits further classified these games into two types (a) Strategic games (Simchi-Levi et al., 2000); Sodhi, 2001) and (b) Operational games (Kleijnen and Smits, 2003). These simulation games are used for training and education of the participants of the supply chain (Kleijnen and Smits, 2003).

In the view of the conceptual model proposed in Chapter 3 and based on the aforementioned analysis by Kleijnen and Smits (2003), a discrete event dynamic system simulation tool called Petri nets is proposed for the purpose of a formal representation and simulation of the concepts proposed in Chapter 3. Besides, this decision is also based on the inherent properties of Petri nets such as graphical visualization, formulization with quantification, provision for tools for analysis of system behaviour, modelling of uncertainty and non determinism, and a wide use of Petri nets in supply chain management (Zhang et al. 2009) and work flow management (Salimifard and Wright, 2001) in the literature.

The remaining portion of this chapter is arranged as follows: Section 4.2 introduces the concept of Petri nets and some of its extensions useful for this thesis. Further, it proceeds to show how the Petri nets and its extension can be used to model the typical activities of a supply chain. In Section 4.3, two levels of Petri nets are built to comprise the formulization of the conceptual framework proposed in Chapter 3. The first level is to capture the generic behaviour of each of the members in a supply chain network and the second level is at a higher level to capture the interactions among the members in a supply chain network. The second level aggregates the Petri nets built in the first level. Section 4.4 concludes the chapter.

4.2 Background and Literature review

4.2.1 Classical Petri nets

Classical Petri nets also sometimes referred to as basic Petri nets were first introduced by Carl Adam Petri through his PhD dissertation. There are four major elements in classical Petri net modelling namely places, transition, arc and tokens (Murata, 1989).

1) Places (p): These are type of nodes in the Petri net. Places in the Petri net are denoted by circles. Places represent events, conditions or resources in modelling.
2) Transitions (t): These are the second type of nodes in the Petri net. These are drawn by rectangular boxes or bars. Transitions are used to represent events, transformation processes, etc.
3) Tokens: A token is represented as a dot. Tokens are used to show the presence of physical objects or informational object and can also act as indicators of state or a condition of place. The number of tokens at a place is used to find the state of Petri net. The state of Petri net also called as marking is represented by the distribution of tokens over places. The marking of a Petri net is vector, and length of the vector is equal to the number of places in the Petri net.
4) Arcs: Arcs are directed arrows connecting two different types of nodes in the Petri net (i.e. places and transitions). Arcs cannot be used to connect any two places or two

transitions. Arcs are labelled with weights (positive integers), where the integer is interpreted as equivalent number of arcs.

Figure 4.1 shows a sample Petri net to illustrate the elements of the Petri net.

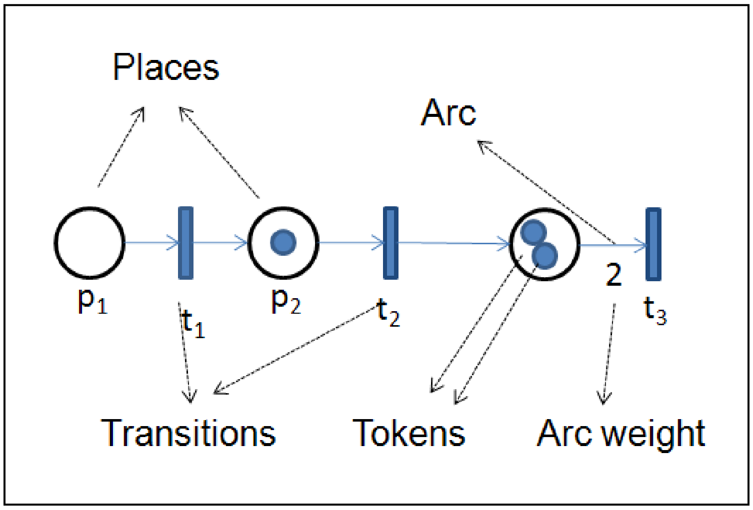


Figure 4.1: Elements of a Petri net.

The formal definition of Petri nets as given in (Murata, 1989) is as follows:

A Petri net is a 5-tuple, PN= (P, T, F, W, M_0) where:

P = {p_1, p_2,…, p_m} is a finite set of places,

T = {t_1,t_2,…,t_n} is a finite set of transitions,

$F \subseteq (P \times T) \cup (T \times P)$ is a set of arcs (flow relations),

$W: F \rightarrow \{1,2,3, \ldots\}$ is a weight function,

$M_0: P \rightarrow \{0,1,2,3, \ldots\}$ is the initial marking,

$P \cap T = \phi \text{ and } P \cup T \neq \phi.$

A Petri net structure N = (P, T, F, W) without any specific initial marking is denoted by N.

A Petri net with a given initial marking is denoted by (N, M_0).

To capture the dynamics of systems and promote the analysis of the systems, tokens in the Petri net flow from places to places through firing of transitions. Firing of a transition of Petri net can be thought as an occurrence of event. Firing of a transition is only possible when it is enabled (meaning conditions required for an event to occur are satisfied). In Petri nets, a transition is only enabled when the number of tokens in all input places of a transition is greater than or equal to the weights of their respective arcs directed towards the transition. The firing of a transition removes tokens (with the number equal to the weights on their respective arcs) from the input places of the fired transition and puts tokens (with the number equal to the weights on their outgoing arcs) in the respective outgoing places. In Figure 4.2, the transitions t_1 and t_4 are not enabled and t_3 and t_4 are enabled.

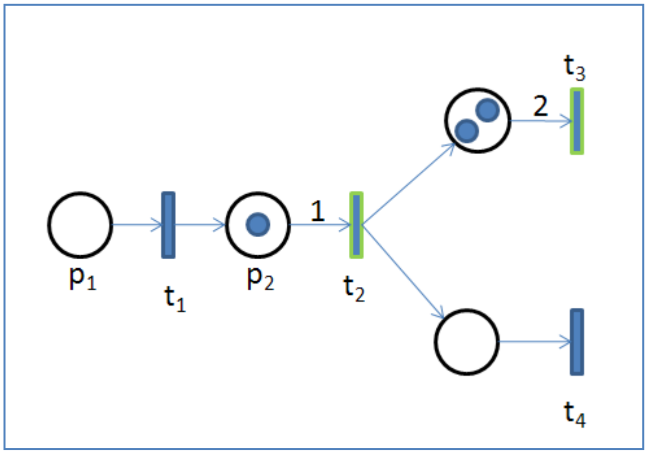


Figure 4.2: Demonstration of enabled transitions.

Although basic Petri nets, classified as low level Petri nets (Vasilis et.al , 1998), they have been successfully implemented in many applications such as performance evaluation and communication protocols (the reader is directed to Murata(1989) for a complete list of applications), some drawbacks of the basic Petri Nets have been addressed in the literature, and many extensions have been proposed to improve the basic Petri nets, resulting in various extensions. Common drawbacks of the low level Petri nets or basic Petri nets are listed as follows:

1) Inability to distinguish the tokens, hence lacking simultaneous representation of various objects and their attributes.
2) Complex structures and lack of compactness.
3) Lack of control over firing of the transition and do not capture time aspect.

Following these backlogs many extensions have been made to Petri nets. The evolution of these Petri nets is well described by (He and Murata, 2005), and they classified the evolution of Petri Nets into the following four generations:

1) Low Level Petri nets (First generation): for modeling system control (Reisig, 1985):
2) High Level Petri nets (Second Generation): for describing both system data and control (Jensen and Rozenberg, 1991).
3) Hierarchical Petri nets (Third-generation): for abstracting system structures (He and Lee, 1991; He, 1996; Jensen, 1992).
4) Object-oriented Petri nets (Fourth-generation): for supporting modern system development approaches (Agha, 2001).

There are some other developments aiming to reduce the complexity of Petri nets, e.g., Zhang et al. (2000), He (2008), etc. In work of Zhang et al. (2000), a generic or template Petri nets is proposed, which is related to individual applications. In He (2008), the function-behaviour-structure concept (Lin and Zhang, 2004; Zhang et al., 2005) is applied to Petri Nets, leading to three related Petri nets: the principle Petri net, structure Petri net, behaviour Petri net.

The comparison of some of these extensions is well described by Vasilis et al. (1998) based on various criteria. For the purpose of the current work, this thesis only discuss three extensions of Petri net, which are considered to be sufficient for developing a tool to implement the proposed framework of Chapter 3.

4.2.2 Extensions of Petri net

Coloured Petri nets (Jensen, 1981, 1990, 1995):

The major contribution of this extension is that it allows distinguishing the tokens (using colours) in a place and allows asserting attributes to the objects. Hence, they carry a more descriptive power than the classical Petri nets. Having one place to carry different types of tokens drastically reduces the number of places in the Petri net and thus the structural complexity of the net. The use of coloured Petri nets in this work is demonstrated through a sample Petri net shown in Figure 4.3, which consists of two places named “Products ordered” and “Orders accepted”. The former place carries two tokens of different colours representing two orders of different products (namely Product A and Product B). Besides, attributes such as order number can be asserted to the tokens as shown in Figure 4.3. There are two variables in the Petri namely ‘x’ and ‘i'. ‘x’ carries the information of the product name and ’i' is an integer that carries information about the order number. An order for a product received is denoted by a coloured token in place named

"Product orders" and these order are accepted (event taking place) the tokens are moved to the place named "Accepted orders". Hence, from Figure 4.3, it can be observed that coloured Petri nets has the provision to distinguish the tokens and additional information can be carried by the tokens through the net.

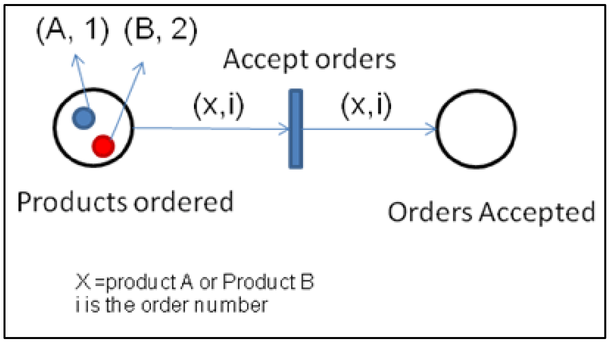


Figure 4.3: Differentiating tokens using Coloured Petri Nets.

Apart from this coloured Petri nets are embedded with the capability to express selection of firing of transitions based on pre-specified conditions and further controlling the removal of the number and type of tokens from the input places and putting the resultant tokens in output places. Jensen (1983 and 1986) proposes arc expressions and guards that could be used for this purpose. These capabilities of the coloured Petri nets are later demonstrated in the later sections of this chapter.

Timed Petri nets:

"In timed Petri nets, each transition takes a 'real time' to fire; i.e., there is a 'firing time' associated with each transition of a net which determines the duration of transition's firings" (Zuberek and Kubiak, 1999). Time Petri nets facilitate to have the information of time in the Petri net models. This enhances the capability to obtain performance measures related to time such as waiting times, delays, throughput times and other efficiencies (Jensen, 2007). To incorporate time in the Petri nets, Jensen (2007) introduced the concept of time stamp through the software called Coloured Petri net tools. The time stamp tells us the time at which the token is ready to be used; i.e., the time at which it can be removed from the place by an occurring transition (Jensen, 2007). Besides, it gives the user the power to model transitions that take place periodically. For example, suppose the employees of a manufacturing company are paid monthly salaries and the flow of money occurs once in a month (i.e. the event of payment). This can be modelled using the timed Petri net, as shown in Figure 4.4.

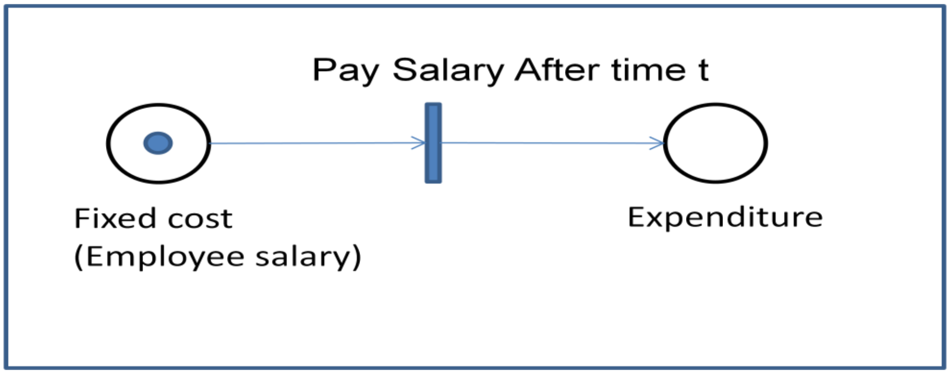


Figure 4.4 Use of Timed Petri net to model periodic events.

Hierarchical Petri nets:

Hierarchical Petri nets are introduced to solve the complexity problem in the Petri nets. The two different mechanisms (Wang and Wei, 2009) proposed in literature for the building of hierarchy in the Petri nets are:

1. Transition refinement and
2. Subnet abstraction

The technique of transition refinement is used for the top-down system development processes, where a transition is substituted with a subnet containing the detailed tasks of the transition in the Petri net (Wang and Wei, 2009). In contrast to this, subnet abstraction is used for bottom-up system development process, where a set of tasks are removed in the form of subnet and replaced by a single transition (Wang and Wei, 2009). Humber et al. (1991) demonstrated how coloured Petri nets can be extended to exhibit the property of hierarchy. The hierarchy in Coloured Petri nets can be achieved in by one of the following methods:

a) Substitution Transitions: The details of the substitution transition are stored in a separate page called the subpage, to offer a simple view of the primary Petri net. The substitution transition called the super node and the page containing this transition is called the super page with respects their subpage.
b) Substitution Places: This method is similar to the substitution of transition except that places are used for substitution instead of transitions.
c) Invocation transitions: In this method, the transitions are not substitutions. Hence, they can concurrently operate with other page instances in the model.
d) Place fusion: Conceptually folding of set of places in the Petri net into a single place.
e) Transition fusion: Conceptually folding of set of transitions in the Petri net into a single transition.

The use of hierarchical Petri nets and their role in the representation of a supply chain network is illustrated in the next section.

4.3 Petri nets for a Supply Chain Network

In this section, the concepts of Petri nets introduced in Section 4.2 will be used to realize the conceptual framework of a supply chain network proposed in Chapter 3. It is noted that the proposed conceptual framework has two levels. The first level is an overall view to display the health statuses of all firms in a supply chain network. To capture and represent information and knowledge at this level, a Petri net called primary Petri net is constructed. The second level is the health of each of the members in the supply chain network, represented by a dot on the node of a supply chain network. To capture this semantics, a notion called “subnet” in Petri net is proposed herein. A subnet of a firm is a Petri net used to evaluate the status of the firm and to feed the primary Petri net with the information of each of the members in a supply chain network. This idea can be implemented with hierarchical Petri nets discussed in the previous section. Furthermore, with the hierarchical Petri nets, the primary Petri net can be constructed in one of the following alternatives:

Alternative 1:

Places in the primary Petri net are used to represent firms, and their status is identified by the tokens present in these places. The tokens are fed by the subnets, associated with each of the firms. Figure 4.5 shows four firms A, B, C, D, represented by places (circular nodes), and each of them is connected with their respective subnets to update their status. This alternative is best when the number of firms (equivalent to the number of places in Petri net) in a supply chain network is not too large. Although the Petri net works for a large number of places, the trade-off would be taken in terms of visual clarity (i.e., the more number of nodes, the less is the visual clarity of the Petri net).

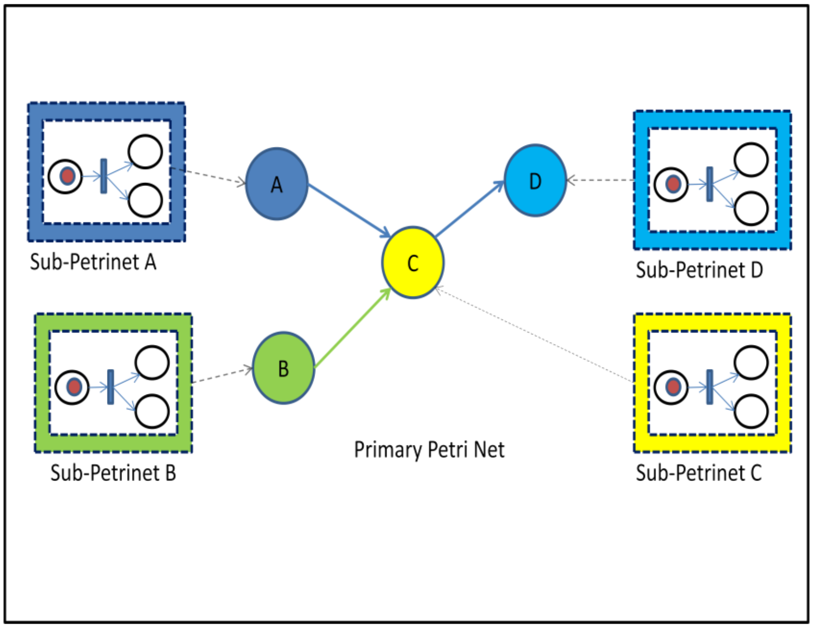


Figure 4.5: (Alternative 1) Hierarchical Petri nets for representing a supply chain network.

Alternative 2:

Tokens in the primary Petri net are used to represent firms and the places are used to represent the state of health of the firms. Using this representation, the number of places in the Petri net is reduced, and only the number of instances in these places will increase with the number of members in the Petri net. This alternative is illustrated using Figure 4.6. Figure 4.6 shows three health states of the firms, represented with three places, namely losses, profitable, and the overloaded. The firms A, B, C and D are shown in the form of tokens existing in different places in the primary Petri net. A dummy Place is used to collect information from the subnets and to update the states of the firms.

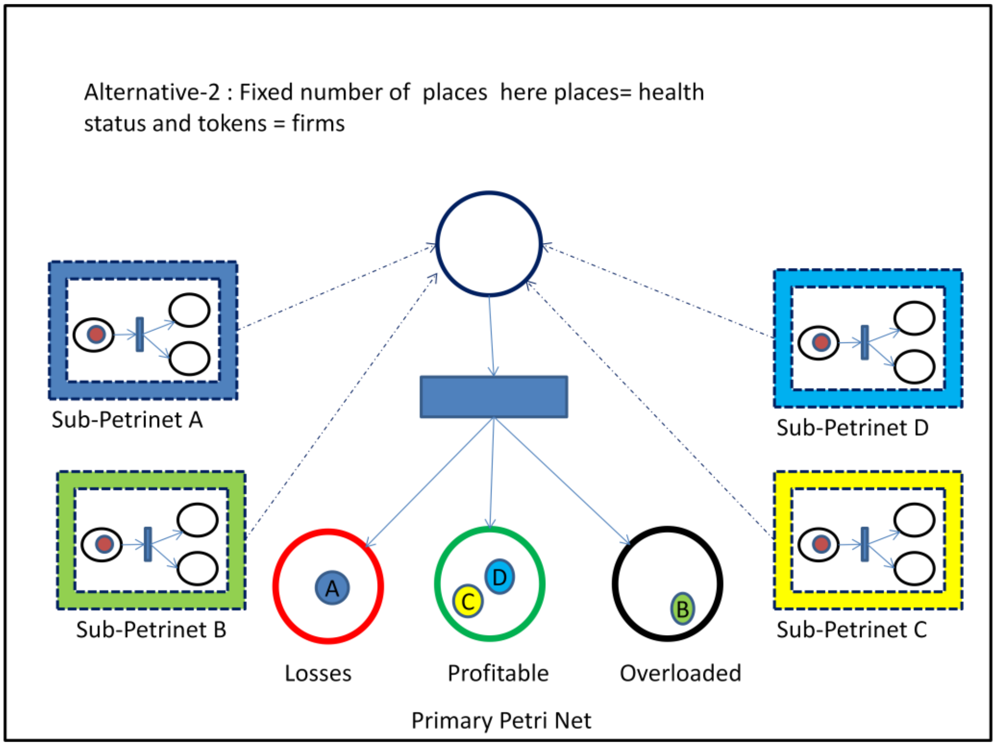


Figure 4.6: (Alternative 2) Hierarchical Petri nets for representing a supply chain network.

Following the construction of the primary Petri net, the reminder of this section will focus on the construction of the subnets for members in a supply chain network. For this purpose, the typical operations of members in a supply chain network are identified. A classification is made among the participating firms of the supply chain network based on their types of operations. The first type is the manufacturing (i.e., gathering components for a product and assembling them), and the other is the service firm (which either transfers the input to the consecutive member in the supply chain or offers support such as transportation arrangement, legal documentation, and so on). Although the operations performed are different in nature, a general work flow might be assumed for all the firms. The general work flow for a supply chain network member defined in this thesis is as follows:

a) Receive Orders: The firm receives orders from its customers for some product or service.

b) Acceptance of Orders: The firm accepts the orders if it has the capacity to either produce the product or offer the service.

c) Inventory check and process: The accepted orders are checked for inventory (i.e., the possibility of immediate fulfillment of the order). If a product is available in the inventory, it could be shipped immediately or an order is made for its production. During its production if a component required for its production is not available, an order is made for the component from its respective supplier. In case of some service firms, the term inventory might not make much sense but the procurement of various tasks (example, gathering information) for the process of the order can be thought as the components required for the completion of the order. If information is readily available, the firm is said to have the inventory of the information.

d) Production/Service: Once all the components of the product and the required human and machine resources are available, the production takes places and the final product is shipped to its customer or customer is served with the service requested.

The general processes in a firm described above are presented in form of a flow chart shown in Figure 4.7.

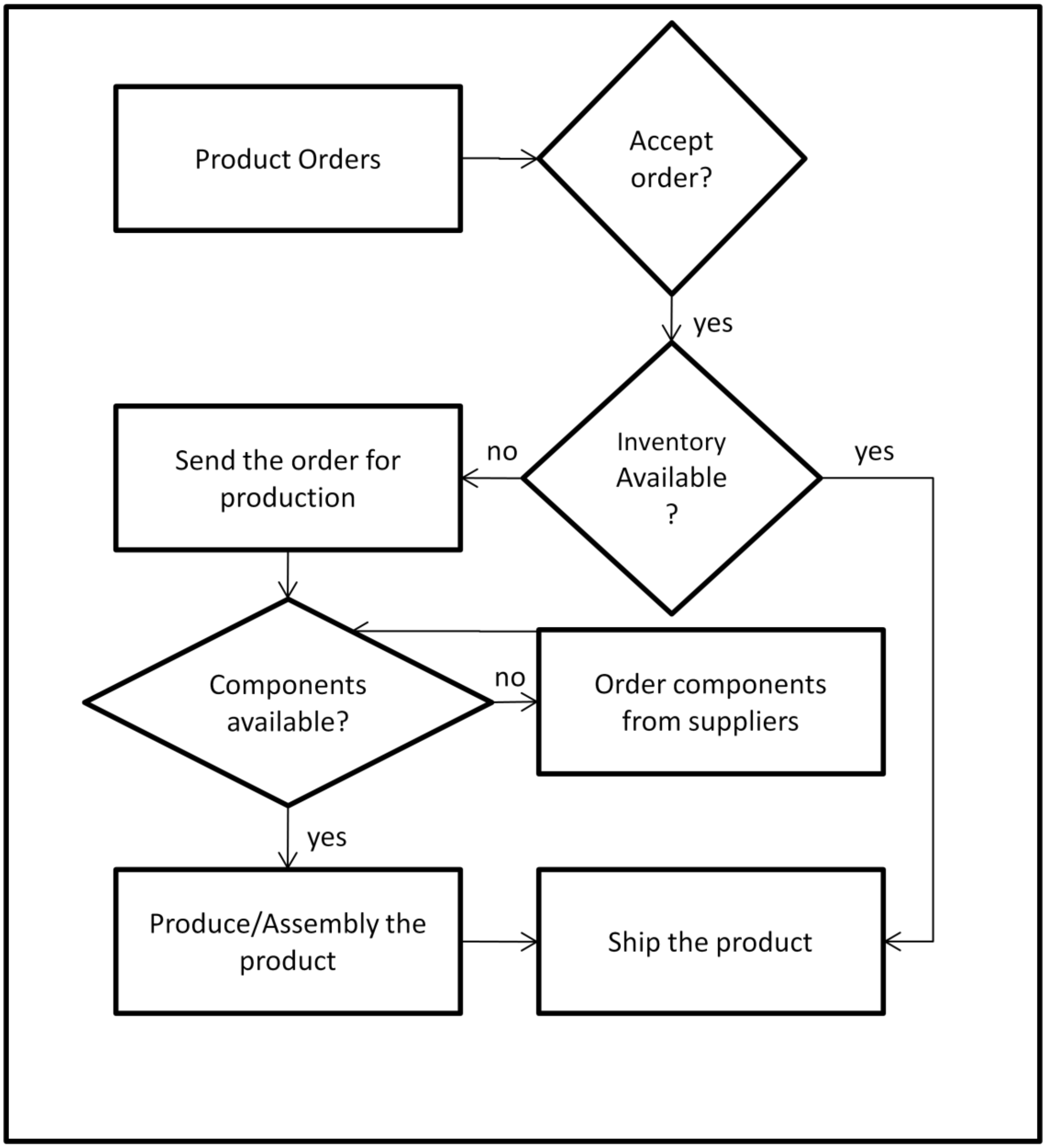
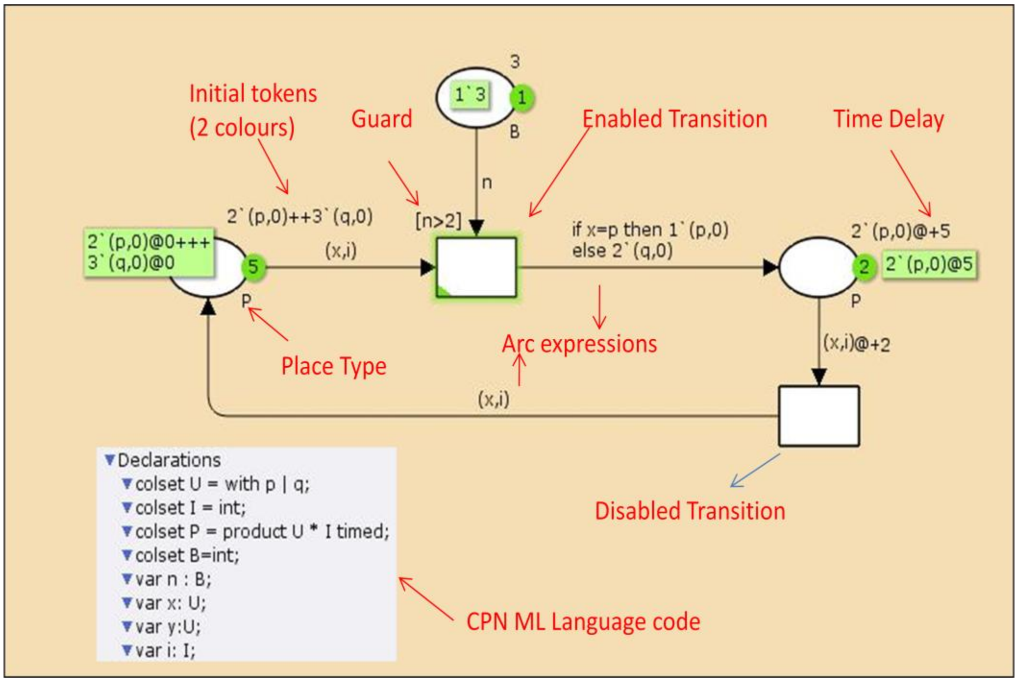


Figure 4.7: General flow of processes of an individual firm in a supply chain.

Considering the processes of firm discussed above, a sub-Petri net that could capture these processes is constructed. This construction is performed in view of the features available in the open source coloured Petri net software called the CPN tools. First, the features available in this software are explained before constructing the Petri net for the member in a supply chain network. CPN Tools is a widespread tool for editing, simulating and analysing coloured Petri nets. This software is designed and maintained by Department of Computer Science University of Aarhus, Denmark. CPN tools offer all the features and extensions of Petri nets discussed earlier in this thesis; hence it is chosen for this work. Some of the basic elements of the software interface that are used in this work are illustrated using a sample Petri net as shown FFigure 4.8.



```
▼Declarations
  ▼colset U = with p | q;
  ▼colset I = int;
  ▼colset P = product U * I timed;
  ▼colset B=int;
  ▼var n : B;
  ▼var x: U;
  ▼var y:U;
  ▼var i: I;
```

Figure 4.8: Basic features and notions of CPN tools.

The oval shaped components in Figure 4.8 are the places in the Petri net and the rectangular structures represent the transitions. Each of the places in the Petri net is declared by their type and the type is indicated at the right bottom. For example the place shown in Figure 4.8 is of type P. The information about the type of tokens a P-type place can contain is declared in a separate console of the CPN software and is written in a special language called the CPN ML language. For example, the declaration P is a product of two color-sets U and I where U can be either of color ‘p’ or color ‘q’ and I is an integer. The declaration contains the description of variables such that ‘x’ represents either of the colors ‘p’ or ‘q’ of the colour set U. An initial number of tokens in a place can be specified on its top right hand corner of the place. For example in Figure 4.8, the left most place of type P is initiated with two (p, 0) coloured tokens and three (q, 0) type coloured tokens and the number 5 in the green bubble indicates the total number of tokens in the place.

Arc expressions are used to specify the type and number of tokens to be removed from the place and the type and number of tokens to be placed in output place. Further, control statements can be used as arc expressions to control the flow of token numbers. For example, the control statement in Figure 4.8 shows that if the input to the transition is a p coloured token i.e. x=p), one token of the similar colour is placed in the output place or else two tokens of q coloured are placed in the output place of the transition. In addition, to the control provided by the arc expressions, CPN tools provide an extra feature called the guard that could place additional constraints on the firing of transition. If the guard evaluates to be true only, a transition is enabled given all other arc conditions satisfied. In the above example, the guard is true if the value of n is greater than 2, since the value of n is 3, the transition is enabled. The enabled transitions are highlighted by green glowing shade while disabled transitions remain without any shade. Time is added to Petri net by declaring the place type with the command timed in the declaration console. Time delays can be added using “@ + time delay expression” to the tokens at the places. In Figure 4.8, a time delay of 5 is added to the tokens in the rightmost corner place. This means that these tokens will only be available for the transition at 5 time units from the start of the simulation because of this the transition following this place is not enabled as shown in Figure 4.8. It is to be noted that the snapshot is taken at start of simulation, hence time=0 units.

In addition to the initial time delays stamps of the tokens, time delay expressions can also be added to the arc expression. For example, a time delay of 2 units is added to the input arc of right bottom transition in Figure 4.8. This means that every token flow through this arc incurs an additional time delay of two units.

The features available in the CPN tools are used to form a generic Petri net for the processes of a supply chain firm. Without loss of generality, a Petri net for a firm to produce two different products (extendable to any number of products) is constructed. The Petri net also considers that two products (say Product X and Product Y) utilize two different components Component A and Component B supplied by external suppliers. Further, the number of components used in making of a product is varied; i.e. Product X requires two quantities of component A and one quantity of component B, while Product Y requires three quantities of component A and two quantities of component B.

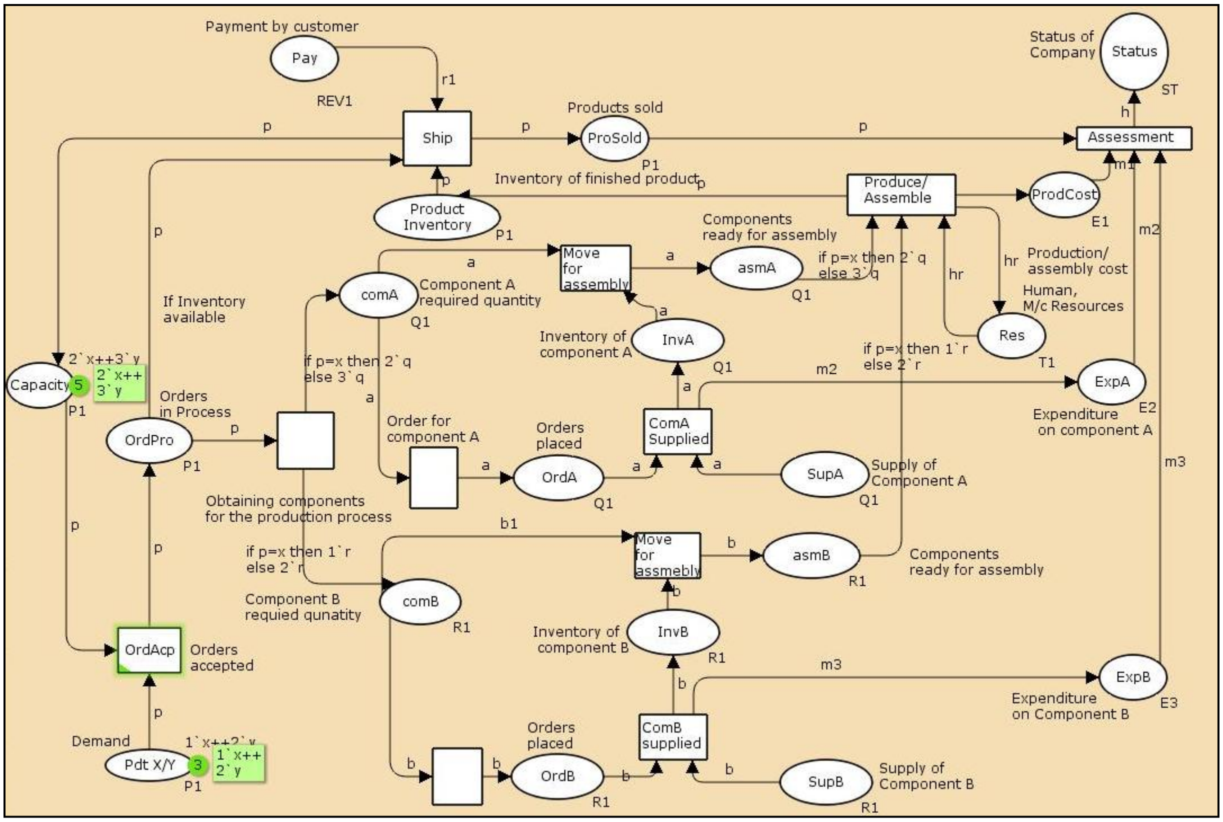


Figure 4.9: Petri net for the member in a supply chain network.

Demand for product X or product Y is generated in the place named “Demand” as shown in Figure 4.9. The initial tokens present in this place show the demand is for one of product X and 2 products of Y. The transition “Orders accepted” is enabled as there exist tokens in the place “Capacity” representing the capacity(say production capacity) of the firm to accept orders. Once the order is accepted orders move to “Order in process” state and a token is also removed from the capacity of the firm. Here if the inventory is available the product is shipped (transition ship is fired) or else the component is moved for the production process. Depending on the product ordered, the required numbers of tokens (components of a product) are placed in places ComA representing the quantity of Component A required and ComB denoting for Component B. If the components are available in their respective inventories places InvA and InvB then they are moved for the assembly or the production of product else orders are placed for the components. The inventories are refilled as the components are supplied from the supplier places SupA and SupB. When all the components required for the production of the product are in position, the assembly takes place moved to inventory which is further moved to shipment. After each shipment is made the capacity of the firm is increased by one token thus maintaining the orders that can be accepted. The expenditures made through the procurement of components A and B are stored in places ExpA and ExpB, respectively. The production cost and the revenue made by the firm directed towards assessment transition and the status of the company are determined. This status information is sent to the primary Petri net as explained at the beginning of this section.

4.4 Summary

This chapter presented a tool to implement the conceptual framework of the supply chain network proposed in Chapter 3. This tool is based on Petri nets. The primary Petri net tailored in this chapter facilitates to view the supply chain network at a holistic level and can be used to monitor the change of states of the firms in a supply chain network. The subnets of the individual firms maintain the statistics of the firm’s material supply, capacity of production, inventory levels, throughput time, production costs and product revenues and perform the dynamic updating of the firm’s health in the network. Embedding these Petri nets with time and simulating a disruption at one firm, propagation of the disruption can be observed in the primary network. This simulation will help a firm to release the possible effect of the disruption in the supply chain network and the time for the effect to propagate to it. The next chapter of this thesis takes up to demonstrate similar simulations with several case studies related to the supply chain network.

Chapter 5 Case Studies and Applications

5.1 Introduction

It is evident that supply chain networks play a major role in society. They act as a backbone in supporting the economics of various communities throughout their span. A supply chain network not only supports the supply of commodities and services but also provides the economic sustainability to society in the form of jobs. Given this strong connection of it with well being of a community, the collapse of a supply chain network (or even a portion of it) could be a devastating effect on the lives of the people who depend on it for living. Hence, it should be of government's interest to regulate the structure and behaviour of the supply chain network to avoid such failure. Although government intervention has been noticed in the recent past in lieu of financial crisis at the first instance, such intervention is only after the considerable damage taking place in the supply chain system. The bail-out package from the US government during the 2008 financial crisis has clearly indicated that government's intervention can be categorized as being mostly reactive (taking a necessary action after considerable damage has occurred) as opposed to being proactive (taking a necessary action before considerable damage is predicted).

The framework proposed in this thesis aims to serve as a supporting tool for governments or other public interest organizations responsible for well being of a supply chain network. In the remainder of this thesis, the term 'Regulatory Body' is used to refer to such an organization (either appointed by a government or chosen by members of a supply chain network) which acts as a vigilante of the supply chain network. The main responsibility of such regulatory body is to collect the information of the statuses of members of a supply chain network, analyze possible and occurring disruptions, and provide early indication of possible spreads of disruptions to relevant members of the supply chain network. This would help members of the network, who would be affected due to disruptions in the network, to prepare ahead of time. In other words, regulatory body is the committee that monitors and maintains the framework proposed in this thesis.

This thesis work also assumes that members in a supply chain network share their health status and information of disruptions with a regulatory body. This chapter will demonstrate how the proposed framework (predictive in nature) could be implemented to foresee the danger of collapse of an entire supply chain network with help of a sample case study. The first case study relates to the supply chain network centered around the American automobile manufacturing industry, specific to the recent bankruptcy of the American big three companies and its effects on society. It is to be noted that the case study is built from reading newspaper articles and blogs which are placed separately in the reference section at the end of this thesis.

5.2 Case Study: 'Big Three' Automobile Manufacturers in the United States.

In the year 2008, the three major American automobile manufacturers (General Motors, Ford and Chrysler) =had to request $50 billion dollars from the US government as part of the bailout package. The three companies gradually recovered with this support from the government and market forces further arising due to the recent call-backs of vehicles by their Japanese competitor, Toyota.

The roots of the crisis did not take place overnight. Some of the causes of the crisis of the Big-Three companies are: production of fuel inefficient vehicles; shift of focus on the pick truck business in anticipation of larger profit margins regardless of the fuel price sensitivity and climate changes. In contrast, the Japanese car manufacturers, who focused on producing fuel efficient cars, captured most car markets during this time.

In the supply chain literature, only a few studies have considered the interdependency of the Japanese car companies and the American car companies through their common supplier base. Only during the big three crisis did this interdependency come to picture. Honda, the Japanese automobile giant, had requested the United States government to support the American ‘big three’ to avoid the spreading of the disruptions to the healthy manufactures of the automobile industry. The problems of the ‘big three’ were only viewed as some competitive advantage during the period 2000-2007, and the common supplier base interdependency was overlooked.

The interdependency between the competitors is the common supplier to these companies. Both the American and Japanese labels have the same supplier base. If the supplier base gets affected due to the troubles of the American automobile companies, the suppliers in the common supplier base would not be able to supply materials to the Japanese companies and thus this would result in a problem for the Japanese companies while initially the problem only occurred to the American “Big Three”. A major impact was felt on the community as well. Hundreds of thousands of jobs were lost due to the direct and indirect effect of the collapse of the American ‘Big Three’ companies. This further had a catastrophic impact on the economic activities in other businesses (e.g., retail, etc).

The solution principle to such a problem is to find a way to predict these effects in the automobile supply chain and to prepare for it, which has been presented in Chapter 3. In Chapter 4, such a solution principle was further described in detail, which has led to a tool for regulatory body to take proactive actions in time. In the following, the use of this tool for the “Big Three” problem will be presented. To demonstrate the use of the tool, a supply chain network is to be constructed. Recreating the automobile supply chain network is out of the scope of this thesis as such a network is extremely widespread, involves a huge number of members and demands a considerable amount of effort on data collection and processing. So, a hypothetical case is constructed in this study. An additional assumption is made that each member of the network will keep regulatory body informed of their statuses.

With the hypothetical case, this thesis will show how the information generated by the Petri net model proposed in this thesis can be used to predict and avoid collapses that occurred in the aforementioned case of the ‘Big Three’. The case assumes a supply chain network structure with two leading automobile manufacturers (Company A and Company B) participating in the proposed framework who depend on common suppliers (Supplier 1 for component 1 and Supplier 2 for component 2). The representation of the network is shown in Figure 5.1.

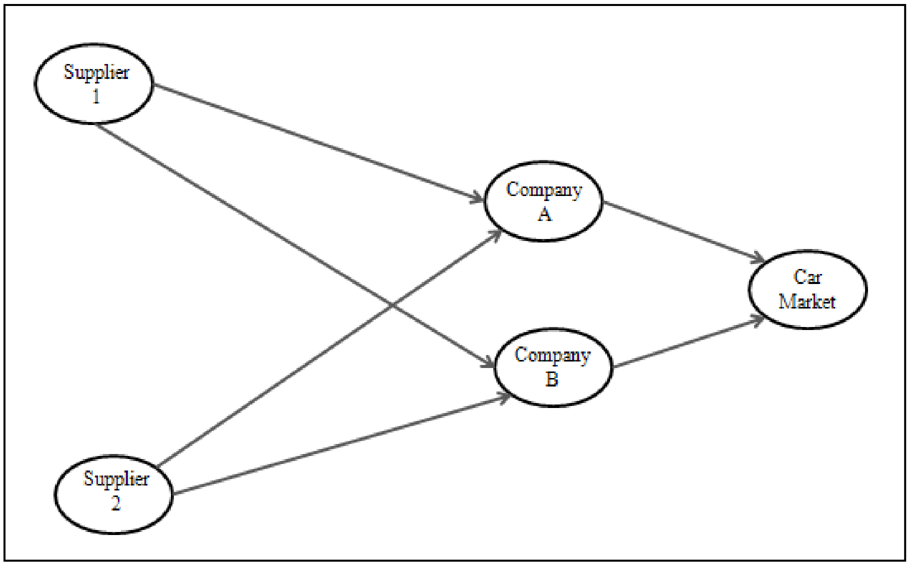


Figure 5.1 Conceptual representation of an automobile supply chain network example.

Figure 5.1 shows those relations between various members of the supply chain network representing the conceptual framework. Although the number of nodes/firms in the network is limited to four in this example, it can be extended for any number of nodes given the generic nature of the proposed framework. The data assumed for the case is illustrated in Table 5.1. Table 5.2 and Table 5.3 present the evaluation criteria used in the case of Figure 5.1. In Table 5.2 only two levels (Good and Bad) are used to describe the performance measures of the members in the supply chain network, however with additional conditions, more levels of description (like Worse, Moderately Bad, Very Good, etc) can also be incorporated. The evaluation criteria for the performance and health of the members in the network can also be customized for each individual firm. The Remark column in the tables helps to understand the attributes and other evaluation criteria assumed for the supply chain network.

Table 5.1 Data selected for the automobile supply chain network shown in Figure 5.1.

Attribute	**Company A**	**Company B**	**Remark**
Time Interval T (hrs)	300hrs	300hrs	Time interval means that for every 300hrs (approx. 2weeks) the health status of the members (Company A, Company B, Supplier1 and Supplier 2) of the supply chain network is updated. This time is adjustable by the "Regulatory Body" of supply chain network.
Maximum Production / Capacity (100 cars/T)	15	25	This attribute refers that Company A can produce a maximum of 1500 cars during the time period T=300hrs; and Company B can produce a maximum of 2500 cars.
Production time / 100 cars	16 to 20 hrs	15 to 18 hrs	The production time is a time range assumed for producing a batch of 100 cars.
Maximum Internal Resource availability / Cycle	400 hours	500 hours	Internal Resource relates to human and machine resources of the firm. This maximum resource availability is achieved with no major breakdown of machines or absence of employees.
Production Plan (100 cars/T)	Random function 5 to 15	Random function 5 to 25	At the start of cycle the companies have a production plan based on demand forecast to produce certain number of products.

	(Initial value set to 10)	(Initial value set to 20)	Each company has their own strategy (or a mathematical function) to come up with this number. For simulation purpose, this example assumes a random function for the production plan.
Demand in the market (100cars/T)	Random function 5 to 20 (Initial value set to 11)	Random function 5 to 30 (Initial value set to 16)	This is the demand forecast of the actual sales of the cars in the market. The demand generated by the market would further translate to the suppliers in the form of orders made by Companies A &B.
Initial Inventory (100 cars)	2	4	For the simulation, the initial inventories were assumed to be 200 and 400 cars for the companies A and B respectively.
Delay in the supply of component 1 (from Supplier 1)	1A=5 hrs	1B=2hrs	This is the time taken for the companies to receive the order of the components from their respective suppliers. The notion 1A is used to indicate the time that Supplier 1 takes to supply (component 1) to Company A.
Delay in the supply of component 2 (from Supplier 2)	Random function 2A=1 to 4 hrs	Random function 2B=1 to 4 hrs	
Suppliers	First Come,	First Come,	This means that the suppliers have no special

Preference	first serve.	first serves.	preferences for their customers (Company A and B) and the orders are served based on first-come–first-served basis.

Table 5.2 Evaluation criteria for key Supply Chain Performance Measures.

Performance Measure	**Evaluation criteria of the performance measure**		**Remark**
	Company A	**Company B**	
Utilization (of production capacity) (j_1) (100 cars)	Good if $j_1 < 4$ else Bad	Good if $j_1 < 8$ else Bad	It is the difference between the maximum production capacity and the actual production in a given time period. E.g. If a car manufacturing company makes only 300 cars when it has the capability of making 500 cars then j1= (500-300)/100=2.
Unsatisfied demand (j_2) (100 cars)	Good if $j_2 < 2$ or else Bad	Good if $j_2 < 3$ or else Bad	This figure denotes the lost sales irrespective of the cause.
Inventory level (j_3) (100 cars)	Good if $j_3 < 3$ or else Bad	Good if $j_3 < 4$ or else Bad	Inventory level at the end of each cycle (T=300hrs).
Products sold (j_4) (100 cars)	Good if $j_4 > 10$ or else Bad	Good if $j_4 > 16$ or else Bad	Products sold during the time interval (T)
Relationship with	Good if $j_5 > 7$ or else Bad	Good if $j_5 > 10$ or else Bad	This measures the relationship between the supplier and

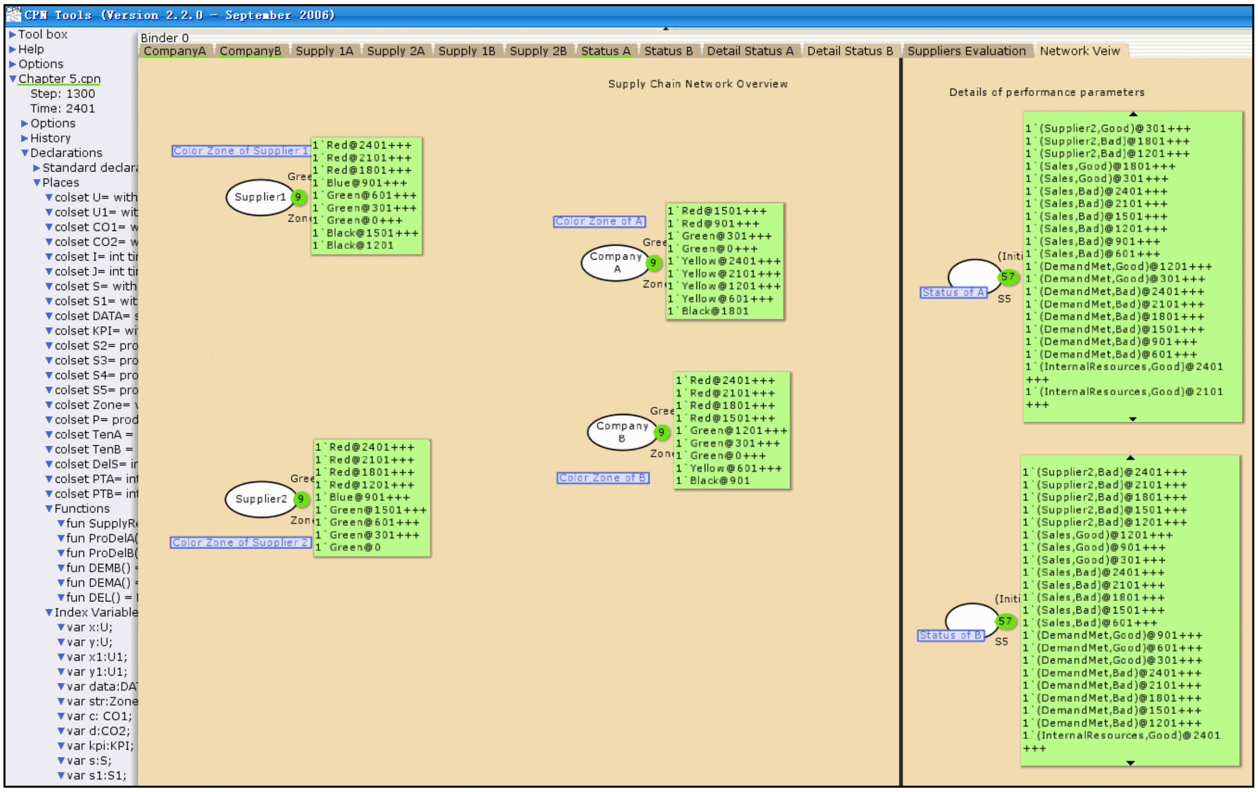
Supplier 1 (j_5)			companies. The quantity of supplies flowing between a company and a supplier is used for this measure for a given time period.
Relationship with Supplier 2 (j_6)	Good if $j_6 > 4$ or else Bad	Good if $j_6 > 12$ or else Bad	
Operating time saved (i)	Good if $i > 100$ or else Bad	Good if $i > 200$ or else Bad	This measures the efficiency and the availability of the internal resources. This is obtained by subtracting the operational time used from the maximum resource time availability.

Table 5.3 Criteria for determining the health status (Color Zone) of the supply chain network members.

Status	Red	Yellow	Green	Blue	Black	Break-even and Max capacity
Company A	Sales≤ 500	500<Sales ≤900	900<Sales ≤1200	1200<Sales ≤1400	Sales≥ 1400	500 1400
Company B	Sales≤ 800	800<Sales ≤1000	1000<Sales ≤1600	1600<Sales ≤2000	Sales≥ 2000	800 2000
Supplier 1	TCS1≤ 1500	1500< TCS1 ≤2000	2000<TCS1 ≤3000	3000<TCS1 ≤4000	TCS1≥ 4000	1500 4000
Supplier 2	TCS2≤ 1500	1500<TCS2 ≤2000	2000<TCS2 ≤3000	3000<TCS2 ≤4000	TCS2≥ 4000	1500 4000
Note: TCS1 stands for Total Components Supplied by Supplier 1 during the time interval. TCS2 stands for Total Components Supplied by Supplier 2 during the time interval.						

The data specified in the above table is used to construct the Petri net model using the Color Petri Net software called the CPN Tools (Version 2.2.0-September 2006). The result of the simulation is illustrated with a screen shot shown in Figure 5.2. On the left side of the grey-shaded area contains the file name ‘Chapter 5.cpn’ and also shows that the screen shot was taken after ‘1300 steps’ (transitions fired) and the clock run for ‘2401 units’ (here ‘units’ is hours). In the same column, a partial view of the declarations is made for the network. The declarations are made in ML language tailored for CPN Tools (Appendix A). The screenshot presented in Figure 5.2

contains Binder 0 with various pages/tabs. These tabs contain Petri nets that capture different aspects of the supply chain network. The purpose of each tab and their respective Petri nets are presented in Table 5.4. The screen shots of all the Petri net tabs are presented in Appendix A for completeness and a file (in .cpn format) of this model is included in the CD attached with this thesis.



```
1`Red@2401+++
1`Red@2101+++
1`Red@1801+++
1`Blue@901+++
1`Green@601+++
1`Green@301+++
1`Green@0+++
1`Black@1501+++
1`Black@1201
```

```
1`Red@1501+++
1`Red@901+++
1`Green@301+++
1`Green@0+++
1`Yellow@2401+++
1`Yellow@2101+++
1`Yellow@1201+++
1`Yellow@601+++
1`Black@1801
```

```
1`Red@2401+++
1`Red@2101+++
1`Red@1801+++
1`Red@1501+++
1`Green@1201+++
1`Green@301+++
1`Green@0+++
1`Yellow@601+++
1`Black@901
```

```
1`Red@2401+++
1`Red@2101+++
1`Red@1801+++
1`Red@1201+++
1`Blue@901+++
1`Green@1501+++
1`Green@601+++
1`Green@301+++
1`Green@0
```

```
1`(Supplier2,Good)@301+++
1`(Supplier2,Bad)@1801+++
1`(Supplier2,Bad)@1201+++
1`(Sales,Good)@1801+++
1`(Sales,Good)@301+++
1`(Sales,Bad)@2401+++
1`(Sales,Bad)@2101+++
1`(Sales,Bad)@1501+++
1`(Sales,Bad)@1201+++
1`(Sales,Bad)@901+++
1`(Sales,Bad)@601+++
1`(DemandMet,Good)@1201+++
1`(DemandMet,Good)@301+++
1`(DemandMet,Bad)@2401+++
1`(DemandMet,Bad)@2101+++
1`(DemandMet,Bad)@1801+++
1`(DemandMet,Bad)@1501+++
1`(DemandMet,Bad)@901+++
1`(DemandMet,Bad)@601+++
1`(InternalResources,Good)@2401
+++
1`(InternalResources,Good)@2101
+++
```

```
1`(Supplier2,Bad)@2401+++
1`(Supplier2,Bad)@2101+++
1`(Supplier2,Bad)@1801+++
1`(Supplier2,Bad)@1501+++
1`(Supplier2,Bad)@1201+++
1`(Sales,Good)@1201+++
1`(Sales,Good)@901+++
1`(Sales,Good)@301+++
1`(Sales,Bad)@2401+++
1`(Sales,Bad)@2101+++
1`(Sales,Bad)@1801+++
1`(Sales,Bad)@1501+++
1`(Sales,Bad)@601+++
1`(DemandMet,Good)@901+++
1`(DemandMet,Good)@601+++
1`(DemandMet,Good)@301+++
1`(DemandMet,Bad)@2401+++
1`(DemandMet,Bad)@2101+++
1`(DemandMet,Bad)@1801+++
1`(DemandMet,Bad)@1501+++
1`(DemandMet,Bad)@1201+++
1`(InternalResources,Good)@2401
+++
```

Figure 5.2: Petri net model of a sample run of an automotive industry example.

Table 5.4 Pages of the Petri net model of an automobile supply chain network.

Tab/ Page Name	**Purpose**	**Pages with immediate Hierarchy.**
Company A	Contains the Petri net to capture the supply chain activity of Company A.	Supply 1A, Supply 2A, Status A.
Company B	Contains the Petri net to capture the supply chain activity of Company B.	Supply 1B, Supply 2B, Status B.
Supply 1A	Contains the Petri net to capture all the supply from Supplier 1 to Company A.	Company A, Suppliers Evaluation.
Supply 2A	Contains the Petri net to capture all the supply from Supplier 2 to Company A.	Company A, Suppliers Evaluation.
Supply 1B	Contains the Petri net to capture all the supply from Supplier 1 to Company B.	Company B, Suppliers Evaluation.
Supply 2B	Contains the Petri net to capture all the supply from Supplier 2 to Company B.	Company B, Suppliers Evaluation.
Status A	Contains a Petri net that gathers all the performance measures data (see table 5.2) of a Company at the end of every time cycle(T) and sends the same data to Detail Status page for the evaluation of the performance measures and the assignment of Health Status(Color zone). This Petri net also updates the Company Petri net	Company A, Detail Status A.
Status B		Company B, Detail

	with the production plan, demand, resources available for the next time interval.	Status B.
Detail Status A	Contains a Petri Net to evaluate the performance measures using the criteria specified in table 5.2 and table 5.3. The evaluation information is sent to the Page Network View received from the Status Page.	Status A, Network View.
Detail Status B		Status B, Network View.
Suppliers Evaluation	Aggregates the information of component supplies made by Supplier 1 and Supplier 2. Evaluates their performance using the criteria presented in table 5.3. Also updates the supplies available for the next time interval(T)	Supplier 1, Supplier 2, Network View.
Network View	Network View displays the end result (health status) of all the members in a supply chain network and updates at the end of each time interval.	Detail Status A, Detail Status B, Suppliers Evaluation.

Figure 5.2 only displays the Network view page. It contains six places of two different color sets namely “Zone” and “S5”. The color set of each place is denoted at the right bottom corner of a place. The places tagged with color set “Zone” specifies the health of the firms with colors (Red, Yellow, Green, Blue and Black) as explained in the conceptual framework present in Chapter 3. The places are updated with tokens at the beginning of every time cycle. Each token in color set ‘Zone” maintains two fold information; first is a health status of a firm and then the time at

which the update was performed. Since the cycle time for updating status is assumed to be 300 hours, the status updates occur at 301, 601, 901, and so on. For example, all the members in the network contain a Green token with time stamp 0, indicating that at the start of the simulation; all the members of the supply chain network are in good health. The results of a sample simulation as seen from the screen shot of Figure 5.2 are summarized in Table 5.5.

Table 5.5 Statuses of the firms in a supply chain network during the simulation.

Time	Supplier 1	Supplier 2	Company A	Company B
0 hours	Green	Green	Green	Green
301hours	Green	Green	Green	Green
601 hours	Green	Green	Yellow	Yellow
901 hours	Blue	Blue	Red	Green
1201 hours	Black	Red	Yellow	Green
1501 hours	Black	Green	Red	Red
1801 hours	Red	Red	Black	Red
2101 hrs	Red	Red	Yellow	Red
2401 hrs	Red	Red	Red	Red

The simulation results presented in Table 5.5 demonstrate that the framework not only predicts the failure of the firms (i.e. entering Yellow and Red zones) but also determines in what time period they might fail. Company A witnesses first trouble going close to yellow. The change in the health status of the firms is noticed due to the disruptions in the automobile supply chain network. The disruptions are embedded in the model with random functions (see Table 5.1) for the demand of cars in the market, production plan of a company, and component availability determined at periodic time intervals. For example, in Table 5.1 the demand for the cars produced by company A in the simulation is a random number between 5 to 30 hundreds of cars. Therefore if the demand generated during a time period is close to the random number 5 then the Company A is facing a low demand for its cars in a particular time interval, i.e. disruption at the demand side. However, mere information of the health status and the time of failure of a firm might not be enough for other members in a supply chain network to plan alternative strategies to avoid failure. The nature of disruption is also needed. For this purpose, additional two nodes tagged with the color set named S5 are also displayed in the Network view page. These places contain the details of each of the performance measure recorded at the end of every time cycle for each of the companies. For the demonstration purpose, these details are shown only for company A and company B. The tokens at these places give the information about the performance measure (e.g. Inventory Level), followed by the classification of the performance measure into Good or Bad at the end of each time interval. The sample results obtained for the automobile supply chain network are presented in Table 5.6. Using this table, it is possible to get an idea of what kind of disruption is taking place in a particular member of a supply chain network. For example, for the time interval 901 to 1201 the failure of Company A might be its lost sales (i.e., due to poor demand forecast).

Table 5.6 Evaluation of the supply chain performance measures

	Attributes	301 hrs	601 hrs	901 hrs	1201 hrs	1501 hrs	1801 hrs	2101 hrs	2401 hrs
A	Utilization (of production capacity) (j_1)	Bad	Bad	Good	Bad	Bad	Good	Bad	Bad
B		Good	Good	Good	Bad	Bad	Good	Good	Bad
A	Unsatisfied demand (j_2)	Good	Bad	Bad	Good	Bad	Bad	Bad	Bad
B		Good	Good	Good	Bad	Bad	Bad	Bad	Bad
A	Inventory level (j_3)	Bad	Good	Good	Bad	Bad	Bad	Good	Good
B		Bad	Bad	Bad	Good	Good	Good	Good	Good
A	Products sold (j_4)	Good	Bad	Bad	Bad	Bad	Good	Bad	Bad
B		Good	Bad	Good	Good	Bad	Bad	Bad	Bad
A	Relationship with Supply 1 (j_5)	Good	Bad	Good	Good	Good	Bad	Bad	Bad
B		Good	Good	Good	Good	Bad	Bad	Bad	Bad
A	Relationship with Supply 2 (j_6)	Good	Good	Good	Bad	Good	Bad	Good	Good
B		Good	Good	Good	Bad	Bad	Bad	Bad	Bad
A	Operating time saved (i)	Good	Good	Good	Good	Good	Good	Good	Good
B		Bad	Bad	Good	Good	Good	Good	Good	Good

In short, with the proposed tool, it is possible to detect a threat as early as possible and inform members of the supply chain network to make alternative strategies.

5.4 Conclusion

This chapter presented a case study to showcase the application of the proposed framework to real life scenarios. The Petri nets built for the case study of an automotive supply chain network can be easily modified to suit to any type of supply chain network. The central idea is only to demonstrate how Petri nets can be helpful to achieve the philosophy of resilience proposed in this thesis work i.e. timely sharing of information regarding disruptions among the firms in a supply chain network could imply resilience.

Chapter 6 Conclusion and Recommendations

6.1 Overview

This thesis aims to build resilience in a supply chain network by creating awareness of upcoming disruptions in a network. Since the effect of disruptions in a supply chain network could have a devastating effect on the community that depends on it for living, this study is motivated to prevent such catastrophes. For this purpose, a conceptual framework is developed to promote early identification and timely sharing of information of the disruptions arising in a supply chain network. The key principle emphasized in this thesis is that recovery from an inevitable disruption has a better possibility if a member of supply chain network has an early indication or knowledge of the upcoming disruption. This principle is derived by considering the comprehensive definition of resilience proposed in this thesis. The definition is developed by combining some of selected characteristics of resilience definitions from various fields such as material science, human resilience, engineering resilience, ecological resilience etc. Further, the construction of the conceptual framework and representation of a supply chain network demands a clear definition of supply chain network, as use of the term “Supply Chain Network” has mostly been ambiguous in literature. To address this issue, a classification based on supply chain structural configuration was proposed for various supply chain networks.

A (generic) conceptual framework was proposed to represent supply chain networks. The framework included assignment and monitoring of health levels to each of the members of a supply chain network. The health levels are denoted by five colour zones. These color zones are derived on break-even analysis, a concept borrowed from engineering economy. A disruption to a firm, either from its supplier side, demand side or internally, alters the color zones of a firm. This happens because the color zones are strongly connected with the output of a firm, which is one of the key variables in break-event analysis. Hence, the color zones act as indicators of the disruptions and the spreading of a disruption can be derived over time. The utility of such a framework was demonstrated through its application for early detection of disruptions in a network and building of a 'recovery module' to promote the recovery of a network from a disruption. The recovery module is centered on the principle of sharing redundant resources by members of supply network, in particular from resources rich members to resource deficient firms for the holistic benefit of the entire supply chain network.

To release the conceptual framework a discrete event dynamic system simulation tool called Petri nets was selected. This selection was based on the inherent properties of Petri nets such as graphical visualization, formulization with quantification, provision for standard analysis of system behaviour, modeling of uncertainty and non determinism, and a wide use of Petri nets in supply chain management and work flow management. The usefulness of the extensions of traditional Petri nets was discussed in the context of this thesis. Open source software called the CPN tools was selected for the construction of the Petri net model. Finally, the applicability of the proposed framework and tool to real life scenarios was demonstrated through two case studies.

6.2 Conclusion

The major conclusions obtained throughout this thesis are presented as follows:

1) 9/11 terror attack, the recent financial crisis and other major crisis have proved that there are interactions and interdependencies of supply chains. Due to the strong interconnectivity, a disruption in one supply chain can easily spread to another causing a complete collapse of a supply chain network. This calls for the monitoring of failures and disruptions in a supply chain network. Although disruptions in a supply chain cannot be avoided completely, early detection and prior knowledge of a disruption and its possible spreading could help members of a supply chain to prepare to reduce or even avoid damage. The conceptual framework proposed in this thesis is able to demonstrate its ability to provide such a support to a supply chain network.
2) Translation of disruptions to economic terms provides an effective way to analyze the spreading of disruptions over diverse supply chains. Break-even analysis has proved to act as a generic concept to achieve this translation.
3) Recovery module, an extended application of the conceptual module, can help to improve the efficiency of redundancy resources. This could be achieved by sharing redundant resources among members of a supply chain network. However, feasibility of such a recovery module might trigger a debate over the prosperity of free market dogma against government regulation dogma. (This is further discussed in Section 6.4).
4) Petri net is an effective tool to capture both the structure and behaviour of a supply chain network. Given the generic nature of the Petri net model developed in this thesis, it can be easily adopted for representation of a supply chain network regardless of the diversity (in terms of products, processes, etc) of supply chains involved in a network. Further, the application of the proposed framework to some case studies clearly showcased the need of a regulatory body to monitor the disruptions in a supply chain network. This point is

strongly consistent with the current practice in the financial business sector in the developed nation worldwide.

6.3 Contribution

The following contributions were made in this thesis:

1) A systematic literature review is presented to mitigate the problem of the usage of the term “supply chain network” with no clear definition or classification on its structure. The review has suggested three classifications of Supply Chain Networks based on their structure and scope of purposes; further these are identified with strong informative terminology namely, Firm Centered Supply Chain Networks, Industry Centered Supply Chain Networks and Inter-industrial Supply Chain Network. It is believed that this classification provides a platform for future researchers to identify and present their works in most relevant sections of the supply chain literature.
2) The information-based conceptual framework proposed in this thesis is unique in the supply chain literature for its holistic perspective. It enables to monitor the performance and well being of all members in a supply chain network. Further, it supports the recovery module which mitigates the disruptions in the supply chain network by sharing redundant resources in a network.
3) This thesis also provides a generic Petri net model with illustration of obtaining and sharing information regarding the disruptions arising in a supply chain network. The predictive capability of Petri net model enhances the ability of regulatory body to foresee upcoming disruptions and proactively inform the member of a supply chain network to take necessary actions. This reduces the damage that might be caused by the upcoming disasters.

6.4 Limitations and Future work

There are several limitations with the present thesis, which suggest some further study. They are discussed in the following.

1) Legal Issues and Cooperate Rights: The framework proposed in this thesis is centered on the assumption that firms involved in the supply chain network share information of their statuses and relationships with other members in a network. However, this might not be the case in real situation. Privacy issues may arise that compromise the security and a competitive advantage of some cooperates. This demands a further research to ensure that sensitive information are held only with the regulatory body and only used for the purpose of maintaining health of the overall network structure.
2) False information: The participation of the firms is the key to successful implementation of the purposed framework. The proposed framework is based on an assumption that corporations responsibly share truthful information of all disruptions and their activities. This makes the present model vulnerable to incorporate fraud and unfair manipulation to manoeuvre the dynamics of a supply chain network to its own benefits. Enron scandal (Petrick and Scherer, 2003) and Satyam Computer Services (Heather and Bettina, 2009) scandals provide perfect examples for such possibilities. Given the scope of this thesis, it is not possible to address these issues. The recovery module proposed in this thesis suggests the possible sharing of redundant resources among members of a supply chain to reduce the spreading of damage due to a disruption to other parts of a network. A firm with excess of resources might protest against the sharing of its resources with a resource deficient firm. This will trigger the traditional debate on the extent of regulation on a free

market business world. The Petri net model developed in this thesis is not popular in the corporate culture. Hence, an interface built upon the Petri net model is warranted, which will facilitate the management of the supply chain network. The Petri net based supply chain network model proposed in this thesis is only capable of predicting the upcoming disruptions and the spreading of their effects in a supply chain network. It only acts as a warning mechanism to offer the firms the time and information regarding the disruption to design an alternative strategy, but it doesn't advise on what could be the best optimal strategy. However, a simulation based design can derive the best alternative by testing each of the available alternatives. This would only be practical if the number of alternative strategies is small.

Future studies might also take the direction to combine cause and loop diagrams of System Dynamics to capture more complex attributes such as culture and human behaviour into the supply chain network. This kind of study would have two levels: A system dynamics model at one level abstracting complex attributes such as culture and human reactions and communicating its results with the more quantitative Petri net model at the second level.

References

Adler, G. & Nanda, R. (1974). The Effects of Learning on Optimal Lot Size Determination - Multiple Product Case. *AIIE Transactions*, *6*(1), 21-27.

Afentakis, P. & Gavish, B. (1986). Optimal lot sizing algorithms for complex product structures, *Operations Research*, 34, 237-244.

Altiparmak, F., Gen, M., Lin, L., & Paksoy, T. (2006). A genetic algorithm approach for multi-objective optimization of supply chain networks. *Computers and Industrial Engineering, 51*(1), 196-215.

Beamon, B. M., & Fernandes, C. (2004). Supply-chain network configuration for product recovery. *Production Planning and Control, 15*(3), 270-281.

Billington, C. A., & Davis, T. C. (1992). Manufacturing strategy analysis: Models and practice. *Omega*, *20*(5-6), 587-595.

Blank, L. T., and Tarquin, A.J. (2008). Engineering Economy, 5th Edition, McGraw-Hill, USA.

Bonanno, G. A., & Mancini, A. D. (2008). The human capacity to thrive in the face of potential trauma. *Pediatrics*, *121*(2), 369-375.

Bowersox, D. J., & D. J. Closs. (1996). Logistical Management, the Integrated Supply Chain Process McGraw-Hill, New York.

Cakravastia, A., Toha, I. S., & Nakamura, N. (2002). A two-stage model for the design of supply chain networks. *International Journal of Production Economics*, *80*(3), 231-248.

Chan, F. T. S., & Chan, H. K. (2004). A new model for manufacturing supply chain networks: A multiagent approach. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 218*(4), 443-454.

Chandra, C. (1997). Enterprise architectural framework for supply-chain integration. *Industrial Engineering Research, Conference Proceedings*, 873-878.

Che, Z., Che, Z. H., & Hsu, T. A. (2009). Cooperator selection and industry assignment in supply chain network with line balancing technology. *Expert Systems with Applications, 36*(7), 10381-10387.

Chen, C., & Lee, W. -. (2004). Multi-objective optimization of multi-echelon supply chain networks with uncertain product demands and prices. *Computers and Chemical Engineering, 28*(6-7), 1131-1144.

Chen, C., Wang, B. -., & Lee, W. -. (2003). Multiobjective optimization for a multienterprise supply chain network. *Industrial and Engineering Chemistry Research, 42*(9), 1879-1889.

Chiou, S.(2007). A combinatorial approximation algorithm for supply chain network flow problem. *Applied Mathematics and Computation, 186*(2), 1526-1536.

Choi, J., Lee, H., Heo, S.,& Lee, J. (2006). A mathematical programming for supply chain network design. *International Joint Conference* , 170-174.

Christopher M.G. (1992) Logistics and Supply Chain Management, Pitman, London.

Corrêa, H. L., & De Miranda, N. G. M. (1998). Supply network management in the brazilian automotive industry. *Integrated Manufacturing Systems, 9*(5), 261-271.

Cox, A. (2004). The art of the possible: Relationship management in power regimes and supply chains. *Supply Chain Management, 9*(5), 346-356.

Darwin, C. (1872), The origin of species. London: John Murray.

de Almeida Biolchini, J. C., Mian, P. G., Natali, A. C. C., Conte, T. U., & Travassos, G. H. (2007). Scientific research ontology to support systematic review in software engineering. *Advanced Engineering Informatics, 21*(2), 133-151.

Ding, H., Benyoucef, L., & Xie, X. (2006), A simulation-based multi-objective genetic algorithm approach for networked enterprises optimization, *Engineering Applications of Artificial Intelligence, 19*(6), 609-623.

Dong, M., & Chen, F. F. (2001), Process modeling and analysis of manufacturing supply chain networks using object-oriented petri nets, *Robotics and Computer-Integrated Manufacturing, 17*(1-2), 121-129.

Dong, M., & Peng, Y. (2007), The robustness metrics for supply chain network design, *Shanghai Jiaotong Daxue Xuebao/Journal of Shanghai Jiaotong University, 41*(7), 1092-1096.

Dong, J., Zhang, D., & Nagurney, A. (2004), A supply chain network equilibrium model with random demands, *European Journal of Operational Research, 156*(1), 194-212.

Dogan, K., & Goetschalckx, M. (1999), A primal decomposition method for the integrated design of multi-period production-distribution systems, *IIE Transactions (Institute of Industrial Engineers), 31*(11), 1027-1036.

Dubois, A., Hulthén, K., & Pedersen, A. -. (2004), Supply chains and interdependence: A theoretical analysis, *Journal of Purchasing and Supply Management, 10*(1 SPEC ISS.), 3-9.

Eskigun, E., Uzsoy, R., Preckel, P. V., Beaujon, G., Krishnan, S., & Tew, J. D. (2005), Outbound supply chain network design with mode selection, lead times and capacitated vehicle distribution centers. *European Journal of Operational Research, 165*(1), 182-206.

Fandel, G., & Stammen, M. (2004), A general model for extended strategic supply chain management with emphasis on product life cycles including development and recycling, *International Journal of Production Economics, 89*(3), 293-308.

Gao, F. (2010). The Proposed Resilience Analysis Methodology and Its Application to the Saskwater Pumping Station. University of Saskatchewan, Saskatoon, SK.

Gjerdrum, J., Shah, N., & Papageorgiou, L. G. (2001), A combined optimization and agent-based approach to supply chain modelling and performance assessment, *Production Planning and Control, 12*(1), 81-88.

Gunasekharan, A. (Ed.), (2001), Agile Manufacturing: The 21st Century Competitive Strategy. Elsevier, Amsterdam.

Hadley, A. T. (1909), The influence of Charles Darwin upon historical and political thought, *Psychological Review, 16*(3), 143-151.

Hamel, G., & Valikangas, L. (2003), The quest for resilience, *Harvard Business Review*, September, 52-63.

Harland C.M., & Clark J. (1990), Effectiveness framework for supply chain management, *Computer Integrated Manufacturing Systems*, 3(4) 196-207.

He, Y. (2008). A systematic approach to emergency management for telecommunication systems. M. Sc. Thesis, Department of Mechanical Engineering, University of Saskatchewan.

Heather, T., & Bettina, W., (2009), Satyam Chief Admits Huge Fraud, *The New York Times Business world* (online), Available: http://www.ifp.uiuc.edu/nsfhcs/final_report/toc.html [Accessed July 2010].

Hollnagel, E., Woods, D.D., & Leveson, N. (2006), Resilience engineering: concepts and precepts. Aldershot, UK: Ashgate.

Holling, C. S. (1973), Resilence and stability of ecological systems, *Annual Review of Ecology and Systematics*, 4, 1-23.

Holling, C. S. (1996), Engineering resilience vs. ecological resilience, In *Engineering within Ecological Constraints*, ed. PC Schulze, pp. 31–43. Washington, DC: Natl.

Houlihan J.B. (1984), Supply chain management, Proceedings *of the 19th International Technical Conference*, BPICS, pp.101-10.

Huchzermeier, A., & Cohen, M. A. (1996), Valuing operational flexibility under exchange rate risk, *Operations Research, 44*(1), 100-113.

Jain, V., Tiwari, M. K., & Chan, F. T. S. (2004), Evaluation of the supplier performance using an evolutionary fuzzy-based approach, *Journal of Manufacturing Technology Management, 15*(8), 735-744.

Jiao, J., You, X., & Kumar, A. (2006), An agent-based framework for collaborative negotiation in the global manufacturing supply chain network, *Robotics and Computer-Integrated Manufacturing, 22*(3), 239-255.

Lamming R., Johnsen T., Zheng J., and Harland C. (2000), An initial classification of supply networks, *International Journal of Operations & Production Management*, 20(6), 675– 691.

Lancioni, R. A., Smith, M. F., & Schau, H. J. (2003), Strategic internet application trends in supply chain management, *Industrial Marketing Management, 32*(3), 211-217.

Laprie, J.C. (2008), From dependability to resilience. In: *International Conference on Dependable Systems and Networks (DSN 2008)*, Anchorage, AK, USA, pp. G8–G9.

Lin, F., & Shaw, M. J. (1998), Reengineering the order fulfillment process in supply chain networks, *International Journal of Flexible Manufacturing Systems, 10*(3), 197-229.

Lin, F., Tan, G. W., & Shaw, M. J. (1998), Modeling supply-chain networks by a multi-agent system, *Proceedings of the Hawaii International Conference on System Sciences*, 5, 105-114.

Lin, F., Tan, G. W., & Shaw, M. J. (1999), Multiagent enterprise modeling, *Journal of Organizational Computing and Electronic Commerce, 9*(1), 7-32.

Lin, Y., & Zhang, W. J. (2004). Towards a novel interface design framework: Function-behavior-state paradigm. *International Journal of Human Computer Studies, 61*(3), 259-297.

Liu, X., Tu, Y., Zhang, W., Deters, R., & Chai, C.,(2006), A Generic Architecture of the Networked Critical Infrastructure System: T*hird Conference on Critical Infrastructure*, September 24-27, Old Town Alexandria, USA.

Liu, N., & Zhou, J. (2007), Supply chain network equilibrium model with capacity constraints, *Journal of Southeast University (English Edition), 23*(SUPPL.), 83-88.

Lodree Jr. E. J. (2006), EOQ revisited: The case of unequal and integral order quantities, *International Journal of Production Economics*, 105(2), Scheduling in batch-processing industries and supply chains, 580-590.

Lu, L., & Wang G. (2008), A study on multi-agent supply chain framework based on network economy, *Computers & Industrial Engineering*, 54(2), 288-300.

Luthar, S., Cicchetti, D., & Becker, B. (2000). The construct of resilience: A critical evaluation and guidelines for future work. *Child Development*, *71*(3), 543-562.

Melo, M. T., Nickel, S., & Saldanha Da Gama, F. S. (2006). Dynamic multi-commodity capacitated facility location: A mathematical modeling framework for strategic supply chain planning. *Computers and Operations Research, 33*(1), 181-208.

Melo, M. T., Nickel, S., & Saldanha-da-Gama, F. (2009). Facility location and supply chain management - A review. *European Journal of Operational Research*, *196*(2), 401-412.

Meyer, A., & Taylor, P. (2000). E-commerce - an introduction. *Computing and Control Engineering Journal*, *11*(3), 107-108.

Min, H., & Melachrinoudis, E. (1999). The relocation of a hybrid manufacturing/distribution facility from supply chain perspectives: A case study. *Omega*, *27*(1), 75-85.

Mirhassani, S. A., Lucas, C., Mitra, G., Messina, E., & Poojari, C. A. (2000). Computational solution of capacity planning models under uncertainty. *Parallel Computing*, *26*(5), 511-538.

Nagdi K. (1993) Rubber As Engineering Material: Guideline For Users, Hanser Publisher, Munich.

Nagurney, A., Dong, J., & Zhang, D. (2002). A supply chain network equilibrium model. *Transportation Research Part E: Logistics and Transportation Review, 38*(5), 281-303.

Oliver R.K., & Webber M.D. (1992) Supply chain management: logistics catches up with strategy. In Christopher, M.G (Editor), *Logistics: The Strategic Issues*, Chapman & Hall, London, 63-75.

Padillo, J., Ingalls, R., & Brown, S. (1995), A strategic decision support system for supply network design and management in the semiconductor industry, *Computers and Industrial Engineering*, *29*(1-4), 443-447.

Patnayakuni, R., Rai, A., & Seth, N. (2006), Relational antecedents of information flow integration for supply chain coordination, *Journal of Management Information Systems, 23*(1), 13-49.

Pego-Guerra M. A. (2005), Analysis and design of virtual enterprises, Ph.D dissertation, University of Saskatchewan.

Petrick, J. A., Scherer, R. F. (2003), The Enron Scandal and the Neglect of Management Integrity Capacity, *Mid-American Journal of Business*, 18, 37-50.

Raghavan, N. R. S., & Viswanadham, N. (2001), Generalized queueing network analysis of integrated supply chains, *International Journal of Production Research, 39*(2), 205-224.

Ranganathan, C., Dhaliwal, J. S., & Teo, T. S. H. (2004), Assimilation and diffusion of web technologies in supply-chain management: An examination of key drivers and performance impacts, *International Journal of Electronic Commerce, 9*(1), 127-161.

Romeijn, H. E., Shu, J., & Teo, C. -. (2007), Designing two-echelon supply networks, *European Journal of Operational Research, 178*(2), 449-462.

Ross, A., Venkataramanan, M. A., & Ernstberger, K. W. (1998), Reconfiguring the supply network using current performance data, *Decision Sciences, 29*(3), 707-724.

Rupp, T. M., & Ristic, M. (2000), Fine planning for supply chains in semiconductor manufacture, *Journal of Materials Processing Technology, 107*(1-3), 390-397.

Salimifard, K., & Wright, M. (2001). Petri net-based modelling of workflow systems: An overview. *European Journal of Operational Research*, 134(3), 664-676.

Sanders, N. R. (2005), IT alignment in supply chain relationships: A study of supplier benefits, *Journal of Supply Chain Management, 41*(2), 4-13.

Santoso, T., Ahmed, S., Goetschalckx, M., & Shapiro, A. (2005), A stochastic programming approach for supply chain network design under uncertainty, *European Journal of Operational Research, 167*(1), 96-115.

Sha, D. Y., & Che, Z. H. (2006), Supply chain network design: Partner selection and production/distribution planning using a systematic model, *Journal of the Operational Research Society, 57*(1), 52-62.

Shah, R., & Ward, P. T. (2003), Lean manufacturing: Context, practice bundles, and performance, *Journal of Operations Management, 21*(2), 129-149.

Shinn S. W. (1997), Determining optimal retail price and lot size under day-terms supplier credit, *Computers & Industrial Engineering*, 33(3-4), Selected Papers from the Proceedings of 1996 ICC, 717-720.

Srinivasan M., & Moon Y. B. (1999), A comprehensive clustering algorithm for strategic analysis of supply chain networks, *Computers & Industrial Engineering*, 36(3), 615-633.

Sterbenz, J. P. G., Hutchison, D., Çetinkaya, E. K., Jabbar, A., Rohrer, J. P., Schöller, M., et al. (2010), Resilience and survivability in communication networks: Strategies, principles, and survey of disciplines, *Computer Networks, 54*(8), 1245-1265.

Surana, A., Kumara, S., Greaves, M., & Raghavan, U. N. (2005), Supply-chain networks: A complex adaptive systems perspective, *International Journal of Production Research*, *43*(20), 4235-4265.

Tsiakis, P., Shah, N., & Pantelides, C. C. (2001), Design of multi-echelon supply chain networks under demand uncertainty, *Industrial and Engineering Chemistry Research*, *40*(16), 3585-3604.

Walker, H. (2005), The virtual organisation: A new organisational form? *International Journal of Networking and Virtual Organisations*, *3*(1), 25-41.

Wang, Z., & Wei, D., (2009). Subnet abstract and transition refinement in Petri nets model. *2nd International Workshop on Computer Science and Engineering-WCSE2009*, 2, 418-421.

Wang, J.W., Zhang, W.J., Ip, W.H., (2010). An integrated road construction and resource planning approach to the evacuation of victims from single source to multiple destinations. *IEEE Intelligent Transportation Systems*, 11(2): 277-289.

Wang, J.W., Zhang, W.J., Ip, W.H., (2010), A New Conceptual Model of Service Oriented System. *Enterprise Information Systems*, Submitted.

Wathne, K. H., & Heide, J. B. (2004), Relationship governance in a supply chain network, *Journal of Marketing*, *68*(1), 73-89.

Womack J.P., & Jones D.T. (1996), Lean Thinking: Banish Waste and Create Wealth in your Corporation, Simon & Schuster, New York.

Womack J.P., Jones D.T., & Roos D. (1990), The machine that changed the world, Macmillan, London.

Wuming, L., Pingyang, H., & Fei, G. (2009), Study on system modeling and analyzing of supply chain network, Paper presented at the *IEEE International Conference on Automation and Logistics*, *ICAL 2009*, art. no. 5262715, pp. 1598-1602

Zipkin PH (1991), Computing optimal lot sizes in the economic lot scheduling problem, *Operations Research*, 39(1), 56-63.

Zipkin, P. (2001), The limits of mass customization, *MIT Sloan Management Review, 42*(3), 81-87.

Zhang, W. J., Li, Q., Bi, Z. M., & Zha, X. F. (2000). A generic petri net model for flexible manufacturing systems and its use for FMS control software testing. *International Journal of Production Research, 38*(5), 1109-1131.

Zhang, W.J., & Lin Y. (2010), Principles of Design of Resilient Systems and its Application to Enterprise Information Systems. *Enterprise Information Systems*, 4(2), 99-110.

Zhang, W.J., Lin, Y., and Sinha, Niraj, 2005. On the Function-Behavior-Structure Model for Design. The 2nd CDEN Conference, Alberta, Canada, July 18-20. CD ROM, 8 pages.

Zhang, X., Lu, Q., & Wu, T. (2009). Petri-net based application for supply chain management: An overview. *IEEE International Conference on Industrial Engineering and Engineering Management-IEEM2009,* 1406-1410.

Zhou, G., Min, H., & Gen, M. (2002), The balanced allocation of customers to multiple distribution centers in the supply chain network: A genetic algorithm approach, *Computers and Industrial Engineering*, *43*(1-2), 251-261.

Zhou, G., Min, H., & Gen, M. (2003), A genetic algorithm approach to the bi-criteria allocation of customers to warehouses, *International Journal of Production Economics*, *86*(1), 35-45.

References for case study:

-, Wiki: Effects of the 2008-2010 automotive industry crisis on the United States, *Wapedia* [online]. Available from: http://wapedia.mobi/en/Effects_of_the_2008-2010_automotive_industry_crisis_on_the_United_States

-, American Axle and Manufacturing Holdings (AXL), *wikiinvest* [online]. Available from: http://www.wikinvest.com/wiki/American_Axle_%26_Manufacturing_Holdings_(AXL)

Green J. (2009), Big Three hit the brakes, *Panjiva* [online]. Available from: http://panjiva.com/blog/2009/03/20/big-three-hit-the-brakes

Matt (2008), Trickle down effects of letting U.S automakers go bankrupt, *Business Pundit* [online]. Available from: http://www.businesspundit.com/trickle-down-effects-of-letting-us-automakers-go-bankrupt/

Neff J. (2006), So long, friend: Ford producing the last Taurus next week, *Autoblog* [online]. Available from: http://www.autoblog.com/2006/10/19/so-long-friend-ford-producing-the-last-taurus-next-week/

Ortolani A. (2009), GM suppliers face new cash threat as bankruptcy looms (Update 1), Bloomberg [online]. Available from: http://www.bloomberg.com/apps/news?pid=newsarchive&sid=ax1pfe7GMX6Y

Pope B. (2009), Visteon faces uncertain future as Chrysler, GM falter, *WardsAuto.com* [online]. Available from: http://wardsauto.com/ar/Visteon_uncertain_future_090521/

Priddle A. (2008a), Chevrolet Volt and Aveo, Pontiac G3 among small cars that need big profits - car news, *Car and Driver* [online]. Available from: http://www.caranddriver.com/news/car/08q2/chevrolet_volt_and_aveo_pontiac_g3_among_small_cars_that_need_big_profits-car_news

Priddle A. (2008b), Chrysler ties Toyota for top productivity says 2008 Harbour report - car news, *Car and Driver* [online]. Available from: http://www.caranddriver.com/news/car/08q2/chrysler_ties_toyota_for_top_productivity_says_2008_harbour_report-car_news

Ricciuti A. (2008), Japanese brands building cars in the US fear a collapse of one of the big 3 could serious harm their operations, *World Car Fans* [online]. Available from: http://www.worldcarfans.com/108121615616/japanese-brands-in-us-fear-a-big-3-failure

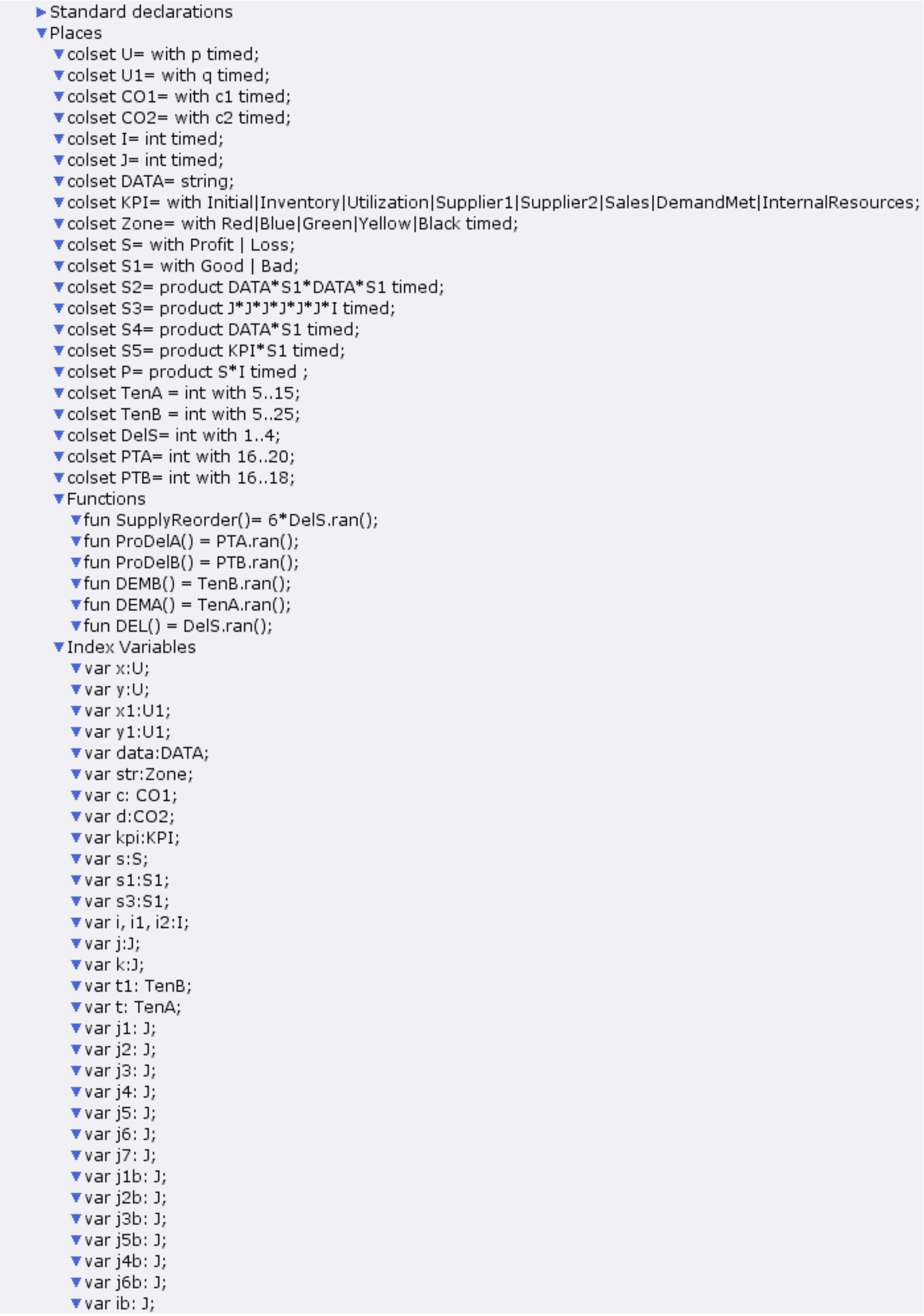
Wailgum T. (2009), Why U.S taxpayers will bail out foreign automotive suppliers, *CIO* [online]. Available from: http://www.cio.com/article/486380/Why_U.S._Taxpayers_Will_Bail_Out_Foreign_Automotive_Suppliers_

Woodyard C. (2009), The other 'Big 3': Japanese car giants caught in sales skid, too, *USA Today* [online], Available from: http://www.usatoday.com/money/autos/2009-04-02-toyota-honda-nissan_N.htm

Appendix A: Details of the Petri net tool

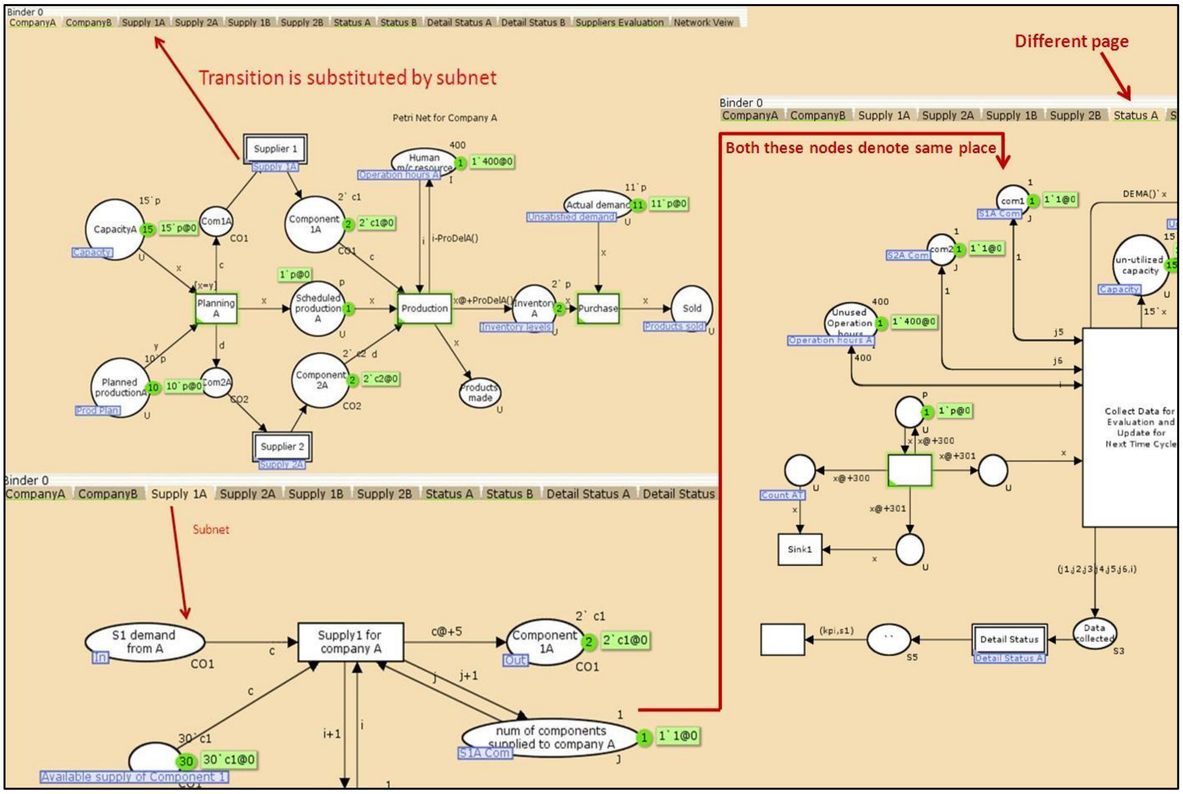
CPN Tools is maintained by the CPN Group at the University of Aarhus, Denmark (http://wiki.daimi.au.dk/cpntools/cpntools.wiki). To use this tool, a licence is needed for installation. Licences are free for academic use.

ML Code for the Petri Net:



```
▶Standard declarations
▼Places
  ▼colset U= with p timed;
  ▼colset U1= with q timed;
  ▼colset CO1= with c1 timed;
  ▼colset CO2= with c2 timed;
  ▼colset I= int timed;
  ▼colset J= int timed;
  ▼colset DATA= string;
  ▼colset KPI= with Initial|Inventory|Utilization|Supplier1|Supplier2|Sales|DemandMet|InternalResources;
  ▼colset Zone= with Red|Blue|Green|Yellow|Black timed;
  ▼colset S= with Profit | Loss;
  ▼colset S1= with Good | Bad;
  ▼colset S2= product DATA*S1*DATA*S1 timed;
  ▼colset S3= product J*J*J*J*J*J*I timed;
  ▼colset S4= product DATA*S1 timed;
  ▼colset S5= product KPI*S1 timed;
  ▼colset P= product S*I timed ;
  ▼colset TenA = int with 5..15;
  ▼colset TenB = int with 5..25;
  ▼colset DelS= int with 1..4;
  ▼colset PTA= int with 16..20;
  ▼colset PTB= int with 16..18;
  ▼Functions
    ▼fun SupplyReorder()= 6*DelS.ran();
    ▼fun ProDelA() = PTA.ran();
    ▼fun ProDelB() = PTB.ran();
    ▼fun DEMB() = TenB.ran();
    ▼fun DEMA() = TenA.ran();
    ▼fun DEL() = DelS.ran();
  ▼Index Variables
    ▼var x:U;
    ▼var y:U;
    ▼var x1:U1;
    ▼var y1:U1;
    ▼var data:DATA;
    ▼var str:Zone;
    ▼var c: CO1;
    ▼var d:CO2;
    ▼var kpi:KPI;
    ▼var s:S;
    ▼var s1:S1;
    ▼var s3:S1;
    ▼var i, i1, i2:I;
    ▼var j:J;
    ▼var k:J;
    ▼var t1: TenB;
    ▼var t: TenA;
    ▼var j1: J;
    ▼var j2: J;
    ▼var j3: J;
    ▼var j4: J;
    ▼var j5: J;
    ▼var j6: J;
    ▼var j7: J;
    ▼var j1b: J;
    ▼var j2b: J;
    ▼var j3b: J;
    ▼var j5b: J;
    ▼var j4b: J;
    ▼var j6b: J;
    ▼var ib: J;
```

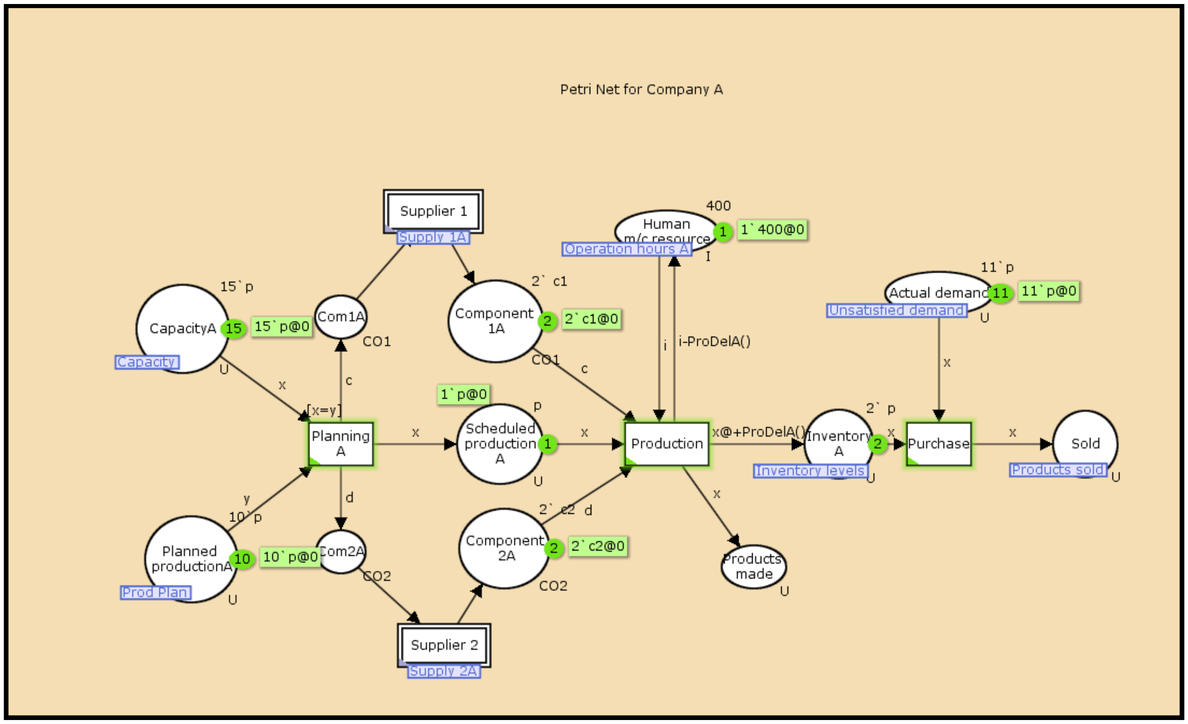
Navigation Notions:



The above figure is used to explain elements tagged with text in blue boxes. These elements are of two types:

1. Substitution Transitions: These are double layered rectangles and act as substitutions for subnets. In the figure, the CompanyA Petri net has substitution transition “Supply 1A”, that means the tokens are sent to the subnet in the tab “Supply 1A”.
2. Fusion of places: Fusion of places is helpful to use the same nodes at different place. For example, in the above figure the nodes with tags “S1A Com” denote the same place in two different pages. The number of components supplied to A is counted in “Supply 1A” page and the same information is simultaneously recorded the “Status A” page which will further to used to calculate the status of Company A.

Petri net for events within Company A:



The user of the software could adjust the following in Petri net for Company A

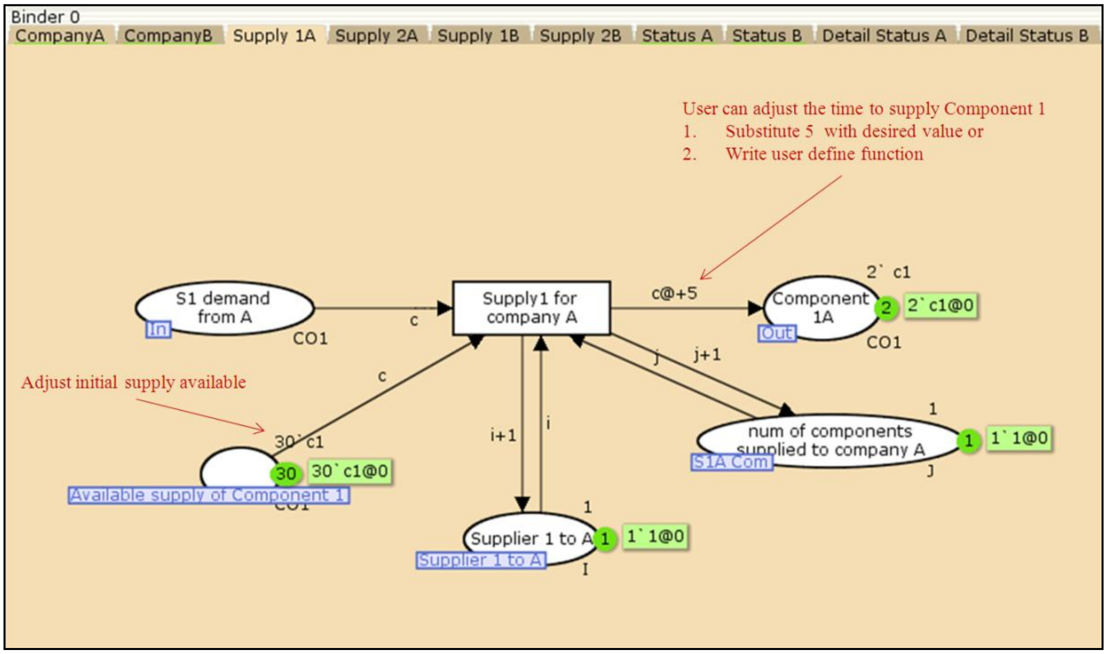
Production Capacity: CapacityA is the production capacity of Company A. In the above net it is set to 15 (1500 cars) for time period 300. This Capacity can be easily adjusted to desired value. For this, the user has to click on 15`p and enter a new value in place of 15.

Other Initial values: Similarly the initial values of the places Component 1A, Component 2A, Inventory A, Actual Demand and Human m/c resources can be adjusted to desired initial values.

Production time of a car: Outgoing arcs of transition "Production" contains the function ProDelA() denoting the time taken to produce 100 cars (1token). In the ML code, ProDelA()= PTA.ran() and colset PTA= int with 16..20, meaning that time to produce 100 cars is between 16 to 20 hours. The user can write its own function or change the values of 16 and 20. Similar modifications can be done for any other functions specified in the ML code.

Similar Changes can be performed for Company B.

Petri net for transactions between Supplier 1 to Company A (similar to Supply 2A, 1B and 2B):

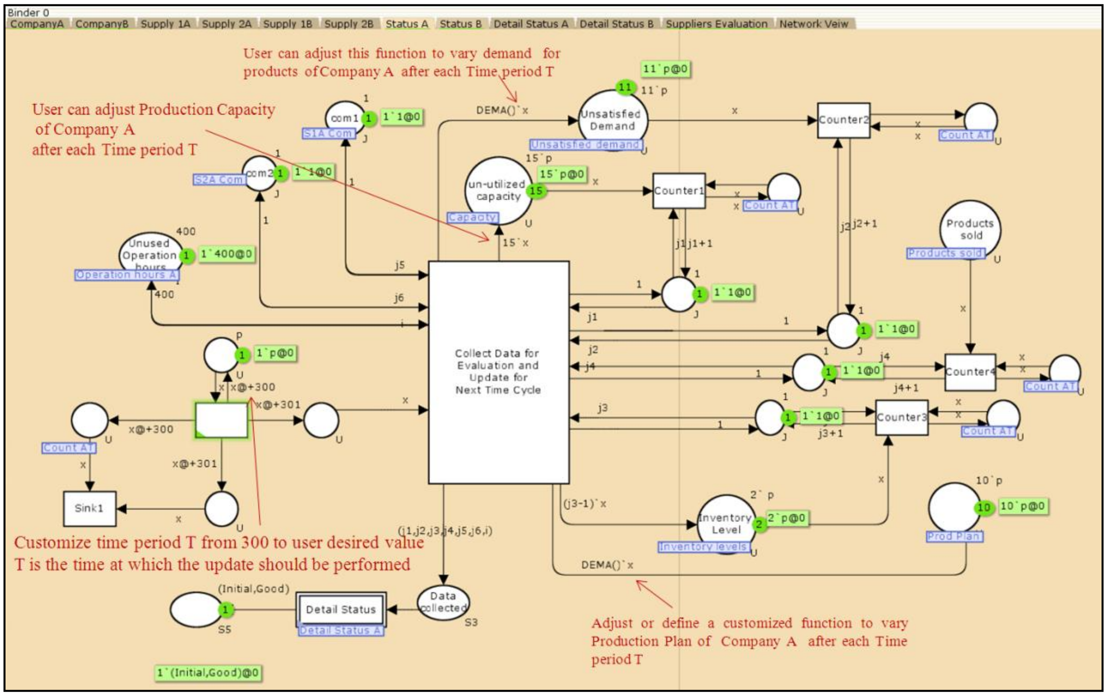


User can adjust the time to supply Component 1

1. Substitute 5 with desired value or
2. Write user define function

Adjust initial supply available

Petri net to collect data and update nodes at end of each time period for Company A:



User can adjust this function to vary demand for products of Company A after each Time period T

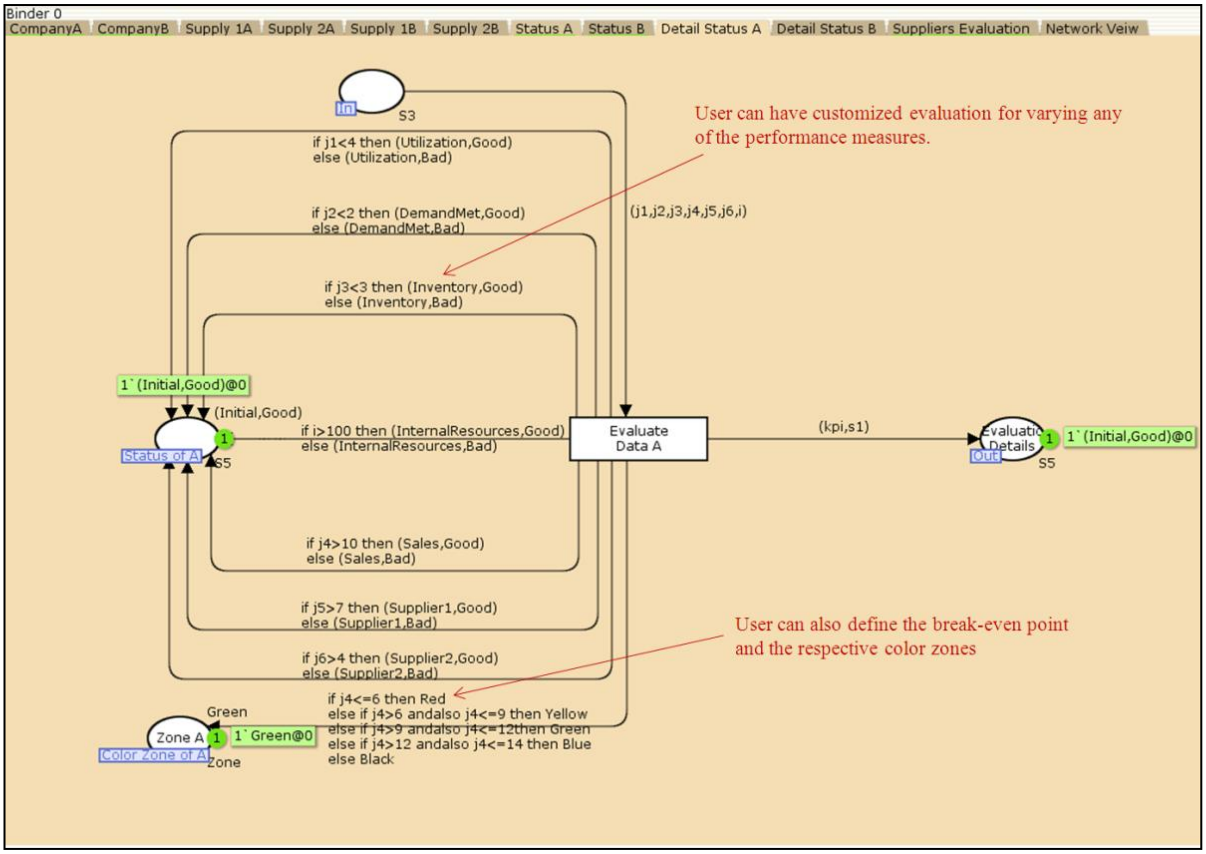
User can adjust Production Capacity of Company A after each Time period T

Customize time period T from 300 to user desired value T is the time at which the update should be performed

Adjust or define a customized function to vary Production Plan of Company A after each Time period T

Note: The data is collected in integer format with help of counter transitions. These are act as accessory elements in the Petri net for counting of tokens and have no relation with supply chain terminology.

Petri net (Detail Status A) to determine the status and the color zone of Company A (similar is used for Company B):

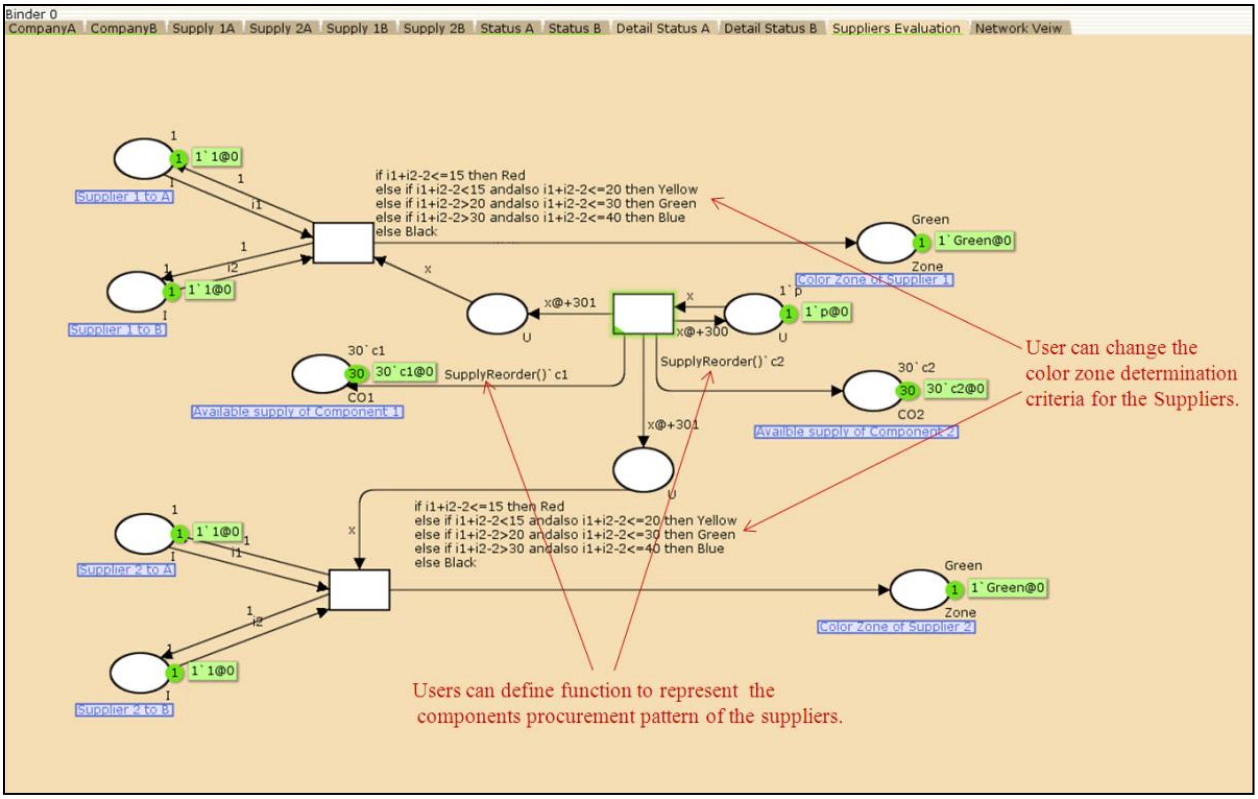


```
(j1,j2,j3,j4,j5,j6,i)

if j1<4 then (Utilization,Good)
else (Utilization,Bad)

if j2<2 then (DemandMet,Good)
else (DemandMet,Bad)

if j3<3 then (Inventory,Good)
else (Inventory,Bad)

(Initial,Good)

if i>100 then (InternalResources,Good)
else (InternalResources,Bad)

(kpi,s1)

if j4>10 then (Sales,Good)
else (Sales,Bad)

if j5>7 then (Supplier1,Good)
else (Supplier1,Bad)

if j6>4 then (Supplier2,Good)
else (Supplier2,Bad)

if j4<=6 then Red
else if j4>6 andalso j4<=9 then Yellow
else if j4>9 andalso j4<=12then Green
else if j4>12 andalso j4<=14 then Blue
else Black
```

User can have customized evaluation for varying any of the performance measures.

User can also define the break-even point and the respective color zones

Petri net to determine color zones of Supplier 1 and Supplier 2:



```
if i1+i2-2<=15 then Red
else if i1+i2-2<15 andalso i1+i2-2<=20 then Yellow
else if i1+i2-2>20 andalso i1+i2-2<=30 then Green
else if i1+i2-2>30 andalso i1+i2-2<=40 then Blue
else Black
```

```
if i1+i2-2<=15 then Red
else if i1+i2-2<15 andalso i1+i2-2<=20 then Yellow
else if i1+i2-2>20 andalso i1+i2-2<=30 then Green
else if i1+i2-2>30 andalso i1+i2-2<=40 then Blue
else Black
```

User can change the color zone determination criteria for the Suppliers.

Users can define function to represent the components procurement pattern of the suppliers.