Virtual Supply Chain Configuration: Modeling and Decision Making

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ABSTRACT

Manufacturing enterprises have been driven to pursue a global manufacturing strategy that aims to transcend national boundaries to leverage capabilities and resources worldwide. In a global manufacturing supply chain network, a number of business entities are collectively responsible for procurement, fabrication, assembly and distribution activities associated with one or more families of products. Since global manufacturing activities may be dispersed and carried out in diverse locations, coordinated product, process and supply chain decisions have been recognized to be crucial for the successful implementation of multi-site manufacturing supply chain management.

This research proposes a virtual supply chain (VSC) framework for fulfilling individual customized orders in cooperation with worldwide partners through the support of advanced information and communication technologies. The rational of a VSC manifests itself through the configuration of legacy supply chain networks, in which a large number of varieties and their interdependency regarding product families, process platforms and logistics networks are synthesized coherently. VSC configuration entails the instantiation of a generic supply chain network into various specific supply chain variants in accordance with diverse customer requirements.

Systematic and rigorous modeling methodologies are investigated in order to provide support to VSC implementation. A series of formalisms are established to articulate the VSC from an architectural perspective, involving data and information structures, variety configuration, and coordination across different functional areas. A domain-based framework is developed to reveal the coordination issues among product, process and supply chain design. A nested modular approach is developed to model the integration of hierarchical decisions within a VSC. To model the configuration mechanisms within a VSC, the colored Petri net technique is applied, through which dynamic decisions with respect to tradeoffs of various supply chain configuration structures are analyzed consistently.

To shed light on practical validations of the VSC configuration methodology, an advanced information platform is developed based on the multi-agent system infrastructure. It provides an integrated and homogeneous decision making environment for VSC analysis and evaluation. The multi-agent platform supports the entire lifecycle of a VSC, encompassing initiation, formation, operation, cooperation and decommission.

The proposed concepts and methodology have been applied to the management of its global manufacturing supply chain network of an electronic motor manufacturing company located in Finland. The result of case studies, including sensitivity analysis, performance evaluation, and system implementation has demonstrated the feasibility and potential of the virtual supply chain configuration framework.

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CHAPTER 1 INTRODUCTION

This chapter provides an overview of the background leading to this research. Based on discussion of the research motivation, the research problems are identified as virtual supply chain configuration modeling and decision making, which aim to address the new challenge of supply chain management under the global manufacturing and mass customization. The classifications of research objectives and scopes are introduced, which act as the framework for developing the strategies for solution. This chapter concludes with the organization of this dissertation.

1.1 Background

In today's global marketplace, individual firms no longer compete as independent entities, but rather concentrating on their core competencies in the value chain and outsourcing the other functions to supply chain partners (Drucker, 1998; Lambert and Cooper, 2000). A supply chain is referred to as an integrated system which synchronizes a series of inter-related business processes in order to: (i) Acquire raw materials and parts; (ii) Transform these raw materials and parts into finished products; (iii) Distribute and promote these products to either retailers or customers; and (iv) Facilitate information exchange among various business entities (Min and Zhou, 2002). Performance of any entity in a supply chain depends on the performance of others, their willingness and ability to coordinate activities within the supply chain of product fulfillment (Swaminathan, 1996).

Mass customization has emerged as an effective strategy for companies making quick response to fast-changing market requirements. It aims at satisfying individual customer needs while staying near mass production efficiency (Pine, 1993; Christopher, 1995). It recognizes each customer order as an individual and provides each of them with "tailor-made" products (Tseng and Jiao, 1998), while all of the products are derived from a product family with a generic structure.

Under the mass customization and global manufacturing environment, the marketplaces are highly diversified and cannot be served effectively by a single supply chain. Consequently, products and services must be provided to the end customers via tailored supply chain strategies (Childerhouse and Towill, 2000). Fig. 1.1 shows the typical structure of a global manufacturing supply chain network. Such a supply chain network is much more complex than that for the procurement, production and delivery of a simple commodity, not only the volume and complexity of transactions, but also due to its dynamic and heterogeneous manufacturing environments (Gaonkar and Viswanadham, 2001).

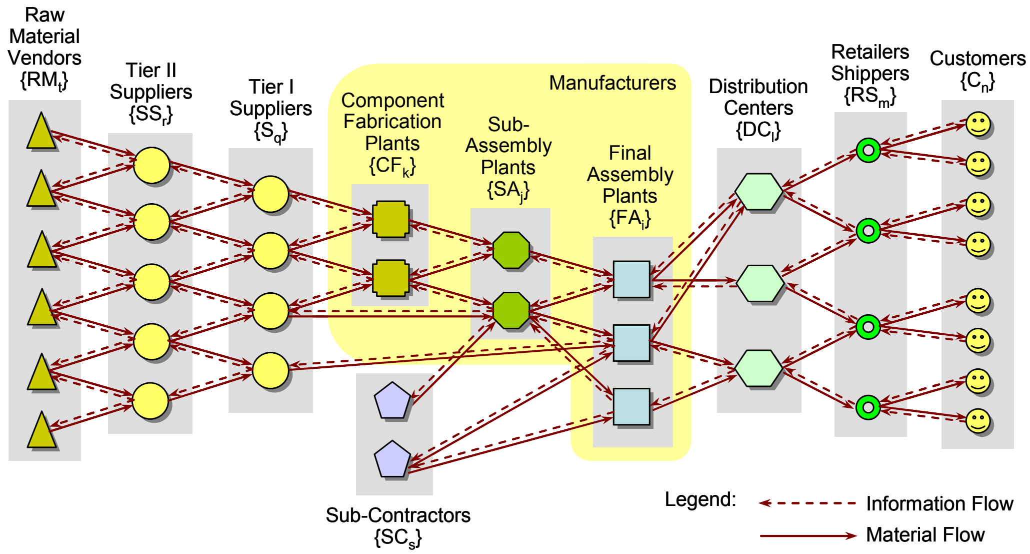


Figure 1.1 Overview of a global manufacturing supply chain network

Over the past decade, a combination of economic, technology and market forces has compelled companies to examine and reinvent their supply chain strategies. To stay competitive, enlightened companies have strived to achieve greater coordination and collaboration among supply chain partners in an approach called “virtual supply chain management (VSCM)” (Gosain *et al*., 2005). It integrates a manufacturer’s operations with those of all of its suppliers and customers and their intermediaries based on the support of advanced Information and Communication Technology (ICT). According to Patterson *et al.* (2003), ICT in SCM refers to a synonym for all those technologies that can be used for managing and controlling supply chain related data, activities and information exchange between organization, such as EDI, XML, ERP, Internet, extranet, electronic B2B, B2C marketplaces, etc. VSCM utilizes information and knowledge as a substitute for inventory, competes on agility and speed, and views partner/customer collaboration as a competitive strategy asset. The successful operation of virtual supply chain network partnerships mandates that every member must be able to share information with trading partners and customers in real-time, preferably without manual intervention, whenever possible.

In fact, ICT has been instrumental in helping actualize the vision of the virtual supply chain. It is the operational backbone of a virtual supply chain network that links suppliers, business partners and customers together as one community. The Internet has brought new business concepts to life, such as e-business. It permits companies to become virtual, i.e., to execute activities such as procurement, order execution, customer service, billing, payment, returns, banking and design optimization by Internet. In addition, the sweeping ERP (Enterprise Resource Planning) system standardization trend has contributed to the practice of SCM by making more hands-on, in-depth control and integration of information possible

(Graham and Hardaker, 2005). New technologies such as Radio Frequency Identification (RFID), Electronic Data Interchange (EDI), mobile agent, accelerate the evolution of supply chain management practices from the mass production era to the mass customization era. The e-business has now emerged as perhaps the most compelling enabler for “virtual supply chain”. The results are much speedy, reliable and lower-cost supply chain operations. Because Internet is open, standard-based and virtually ubiquitous, businesses can gain global visibility across their extended network of trading partners, which helps them respond quickly to fast-changing business conditions.

1.2 Research Motivation

The number of possible configurations for a supply chain network is extremely large due to the huge varieties related to supply chains, including product structures, process operations, network structures and distribution channels. Firstly, each generic supply chain network serves for a product family, which has a number of product variants with different specifications and constituent components. For the same type of materials or components, a set of suppliers with different resources, capabilities, and objectives compete to be included into the supply chain. Secondly, multiple levels of globally distributed suppliers exist in a supply chain network, where suppliers at the lower level provide materials to those consumers at the next higher level and so on throughout the whole network. As each supplier also has its own suppliers and consumers, a supply chain has evolved into a nested network, which could be propagated into an incredibly large and complex system. The complexity is also aggregated by the facts that the companies in a network may also involve in a number of supply chain networks and assume different roles (Sahin and Robinson, 2002).

Due to the inherent complexity in supply chains, it is very difficult to design, configure, and analyze supply chain networks using formal and quantitative approaches. Several leading research, such as Berry *et al*. (1995), Evans *et al*. (1998), Lin and Shaw (1998) and Vernadat (2004), have developed some frameworks and models to analyze the supply chain network from various perspectives. These existing models, however, are either oversimplified or just qualitatively described, and hardly applied to real supply chains. Furthermore, few studies on supply chain configuration consider the impact from other closely linked fields such as product family and process platform. Jiao and Tseng (2004) discussed concurrent enterprising for mass customization and global manufacturing, which aims to align customers, products, processes, and logistics for delivering the increasing product variety with reasonable cost. The challenge in supply chain configuration is to generate an optimal solution of the products, manufacturing processes and supply sources in order to form an effective and efficient supply chain in a simultaneous and integrated manner.

Motivated by the major concerns, including (i) the lack of consideration of explicit variety management mechanisms in current supply chain configuration; and (ii) the impact of product families and process platforms on supply chain structures, this research proposes virtual supply chain configuration to deal with the huge number of varieties in supply chains as well as products and processes**.** It concerns configuring particular supply chains for given new customer orders from a virtual supply chain associated with a product family. The key idea is to configure supply chains from the existing supply elements and proven knowledge attached in a supply chain network while complying with a generic structure. Termed as generic supply chain structure, it is applicable to all possible supply variants in the associated product family. The attempt of configuring supply chains from a common structure is to minimize unnecessary changeovers caused by supply chains planned on the ad hoc basis of the traditional way while taking advantages of logistics similarity and commonality. In other words, such configured supply chains for new orders should be similar with existing supply chain solution. Thus, the economy of scale in production and logistics is realized. In addition, a virtual supply chain should provide a unified structure for accommodating variety management. It is accomplished by unifying various supply data with the associated product and process data into a single entity.

1.3 Research Objectives

The primary objective of this research is to propose a series of modeling formalisms and a supporting information platform for the virtual supply chain configuration and coordination. Specific problem areas related to virtual supply chains are identified as: (i) Absence of rigorous definition and formulation of the virtual supply chain; (ii) Inability in addressing the modeling issues inherent in virtual supply chain; (iii) Failure in capturing the synergy among various virtual supply chain configurations; and (iv) Lack of supporting information platform for virtual supply chain management. Necessary tasks are identified as follows.

(1) Formulation of the virtual supply chain, The first objective of virtual supply chain formulation addresses issues regarding concept definitions, functionalities to be provided and performing approaches to achieve functionalities. The attempt is to provide a basic understanding and overall picture and of virtual supply chain paradigm.

(2) Nested modular modeling for the virtual supply chain. On top of the basic understanding of virtual supply chain concepts, the second objective is modeling the virtual supply chain for integration and coordination. The principle is to modularize

basic elements and processes of the virtual supply chain as building blocks of the system model. Nested system architecture addresses decision granularity issues in a complex supply chain.

(3) CPN modeling formalism for virtual supply chain configuration. The third objective has been identified with an attempt to address the issues regarding modeling virtual supply chain configuration, in terms of dynamic configuration of the generic network entailed in a virtual supply chain. The CPN modeling formalism captures the synergy between various supply chain solutions, including structural correlations and variety instantiation.

(4) An information platform for virtual supply chain management. While the above objectives address issues relevant to virtual supply chain modeling and configuration, it is necessary to build an information platform to support the virtual supply chain management. Each virtual supply chain member is represented by an autonomous and intelligent agent, which cooperates with others to explore the market opportunities.

1.4 Research Scopes

More specific research scopes have been determined in order to fulfill each identified research objective.

1) Define and formulate the virtual supply chain, including:
   - Address fundamental issues of the virtual supply chain such as concepts, characteristics, and strategies for solutions;
   - Design a domain-based reference model for the virtual supply chain, involving customer, product, process and logistics; and

- Formulate the virtual supply chain using the object-oriented technology and set theory.

2) Propose a nested modular approach for modeling the virtual supply chain, including:
   - Identify basic elements, activities and their interdependencies in a supply chain;
   - Use the Petri-net technique to design basic modular nets as building blocks of complex supply chain models;
   - Establish nested supply chain modeling mechanism; and
   - Design deadlock detection and conflict prevention algorithm for the analysis of virtual supply chain models.
3) Design modeling formalisms for virtual supply chain configuration and its evaluation, including:
   - Define the virtual supply chain configuration problem context;
   - Design configuration models for static generic network and dynamic specific solutions;
   - Develop operational models to analyze individualized supply chains; and
   - Illustrate and validate the proposed methods based on practical case studies.
4) Develop an intelligent information platform supporting virtual supply chain configuration, including:
   - Identify the lifecycle of virtual supply chains and establish behavior models;
   - Propose the information platform based on multi-agent technologies;
   - Design agent control mechanisms for integration and coordination of virtual supply chains; and
   - Develop the platform and validate it based on a practical case study.

1.5 Organization of the Dissertation

Fig. 1.2 presents a snapshot of the technological roadmap of this research. It encompasses motivation and significance, problem formulation, modeling methodologies, and validation of the thesis work.

Chapter 1 discusses the general background and states the motivation, objectives and scopes of the research. Chapter 2 provides a comprehensive review of the state-of-the-art research in related fields. The review is organized according to various topics in relation to global manufacturing supply chain network design, including product family development, supply chain network analysis, supply chain modeling approaches, coordinated product, process and logistics decisions, etc.

Chapter 3 discusses some fundamental issues of the virtual supply chain, in terms of concept observations, characteristics, research issues, and responding strategies. A systematic and comprehensive formulation of the VSC based on the object-oriented technology and set theory has been proposed to identify the key elements in relevant fields and their close correlations. It serves as the umbrella for the further rigorous analysis, simulation, and manipulation of the VSC.

Chapter 4 presents a nested modular virtual supply chain modeling approach. Basic supply chain elements and processes, i.e. material inventory, material processing, and material transferring, are encapsulated into a set of objects as the building blocks of virtual supply chain models. The final product and its constituent components are marked as colored tokens transferring in the network. A supply chain network is mapped into a series of cascading nested models that each model takes charge of different supply chain decisions and integrates with other models through a socket mechanism.

Chapter 5 introduces a series of modeling formalisms for the virtual supply chain configuration and evaluation. The structure correlation of a supply chain network is reflected by static representation and dynamic configuration models. The operational model using color Petri-nets is developed to evaluate different configuration solutions from various performance aspects.

Chapter 6 proposes a multi-agent information platform for virtual supply chain configuration. It provides an integrated and homogeneous decision making environment for VSC analysis and evaluation. Each supply chain member is represented by an independent and intelligent agent in the platform. A VSC is coordinated by a particular designed mediator agent, which facilitates information and knowledge sharing, synchronizes the decisions of individual agents and optimizes the overall value of the VSC.

Chapter 7 summarizes the achievements in addressing the research objectives and tasks. A critical assessment is given to highlight the contributions and possible improvements of the thesis work.

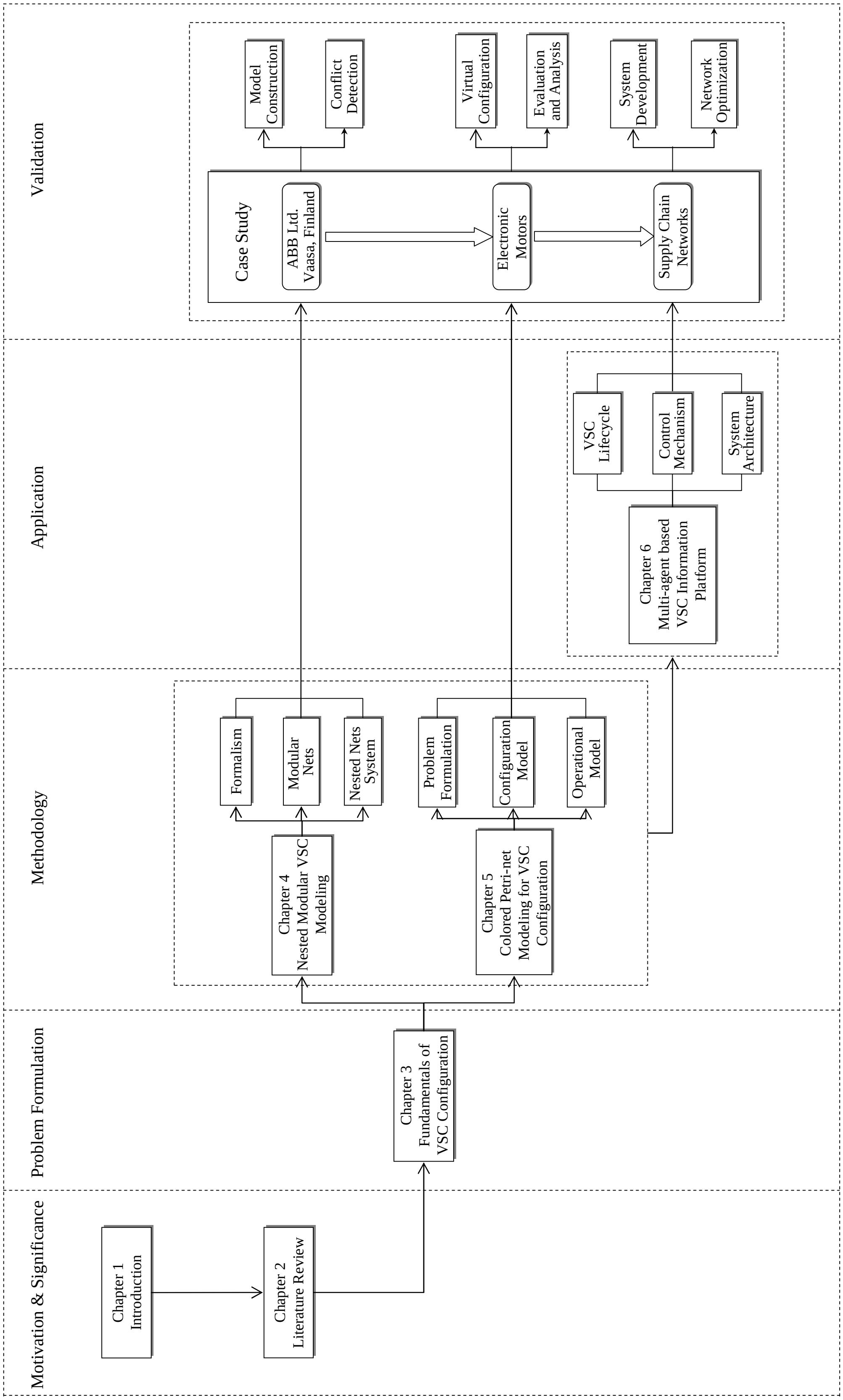


Figure 1.2 Organization of the dissertation

CHAPTER 2 LITERATURE REVIEW

This chapter reviews relevant work addressing supply chain modeling and configuration under mass customization and global manufacturing. The reviewed literature is classified into several broad areas, including product development, supply chain network and supply chain modeling. In each section, the limitations of the research work are pointed out to highlight the significance of the research in this dissertation.

2.1 Product Development under Mass Customization

The globalization and fragmentation of the market is an ongoing and inexorable phenomenon along with the breakdown of outmoded mass market, which raises the concept of mass customization (Stock *et al.*, 1998). Mass customization requires a synthesis between mass production and the production of highly specialized, individualized products (Pontrandolfo *et al.*, 2002). Tseng and Jiao (1998) pointed out that the essence of mass customization lies in maximizing the congruence of the manufacturer’s capabilities with the consideration of customer needs related to target market niches and in timely manner, that is, a manufacturer has to perceive and capture latent market niches and correspondingly develop its technical capabilities to meet diverse customer needs. Their requirement of mass customization lie in three aspects: time to market (quick responsiveness), variety (customization), and economies of scale (mass efficiency). Mass customization appears as an alternative to differentiate companies in a highly competitive and segmented market (Pine, 1993).

2.1.1 Product Family

Although researchers define a product family with different wordings, the consensus is that products in a family have common components, features and subsystems, identical main functions, similar product structures, specific features and components, and secondary functionalities (Javier *et al*., 2000; Farrell and Simpson, 2003; Galan *et al.*, 2007). While the target of a product family is an entire market segment, its product variants (i.e., individualized products) are designed to meet the requirements of each customer in the segment, i.e., segment niches. The challenge of providing customization and variety for the marketplace without losing commonality between customized products can be met with product family concepts (Farrell and Simpson, 2003). Several companies have used product family strategy to successfully design their diverse products such as Sony's Walkman product family (Sanderson and Uzumeri, 1997), Nippondenso's bicycles (Whitney, 1993), and Swatch watches (Ulrich and Eppinger, 1995). As pointed out by Stadzisz and Henrioud (1995), a product family may have its origin in a differentiation process of a base product or in an aggregation process of distinct products. In the first case, the family represents a product series with different technologies and optional parts and functions due to the product evolution and demand for diversity. In the second case, the family represents the standardization of a series of products whose functions and main components are similar. In both cases, the goal is to form a group of products to reduce their variability and, therefore, to decrease investments and production costs.

Product families convey different meanings when viewed from different aspects. Du *et al*. (2002) observed that in practice, different business functions tended to interpret and employ product families in different ways. From the marketing and sales perspective, product families exhibit the company's product line or product portfolio and thus are characterized by various sets of functional features for diverse customer groups (Meyer and Utterback, 2007). The engineering view of product families embodies product technologies and associated manufacturability and is thereby characterized by differences in product structures, design parameters and components. A more comprehensive definition of product families from different disciplines, e.g., customer support, project management, system engineering, can be found in van Vuuren and Halman (2001).

As far as the characteristics of a product family is concerned, McDermott and Stock (1994), and Martin and Ishii (1997) identified commonality; Ulrich and Tung (1991), Pimmler and Eppinger (1994), and Fabrice *et al*. (1997) addressed modularity; Ulrich and Eppinger (1995), and Martin and Ishii (1997) emphasized standardization; Rothwell and Gardiner (1990) focused on robust design; Simpson *et al*. (1997) related changes in form and function to highlight mutability, modularity and robustness, which they suggested are the core characteristics of product families. Chen *et al*. (1994) suggested designing flexible product architectures to enable small product changes to increase product variety.

2.1.2 Product Configuration

Product configuration has been an active research for the past two decades. It can be applied to a wide range of problem domains ranging from computers, telecommunications systems, transportation, modular furniture, custom manufactured materials, industrial products, medical systems and services (Franke, 1998). Product configuration assists in (i) improving inter-firm coordination and reducing the trade-off between product variety and delivery time (Forza and Salvador, 2002); (ii) avoiding time-consuming redesign and manual adaptation (Stumptner, 1997); (iii) lowering product development and production costs (Fleischanderl *et al.*, 1998); and (iv) meeting a wide range of customer requirements and increasing control of production (Magro and Torasso, 2003). The two key features of configuration are (i) the product being configured is assembled from instances of a series of well-defined component types; and (ii) components interact with each other in predefined ways (Stumptner, 1997; Franke, 1998).

Since configuration is synthetic in nature (i.e., the configuration system is expected to produce a new product) (Stumptner, 1997), selecting and arranging parts that satisfy given input specifications form the core of a configuration task. Besides the two subtasks of component selection and arrangement, Brown (1998) also added evaluation of component combination as the third logical subtask. In his evaluation subtask, two tests with respect to component compatibility and goal satisfaction are carried out. During the process of selection and arrangement, no new component types can be created, and the interface of the existing component types cannot be modified. The solution must produce the list of selected components (i.e., part lists of both systems and individual components) as well as the product's structure and topology (Sabin and Weigel, 1998).

Two main characterizations of product configuration formalization are (i) describing the configuration in terms of constraint satisfaction problems (Mittal and Falkenhainer, 1990; Sabin and Freuder, 1996); and (ii) characterizing configuration in terms of logical approaches (e.g., McGuinness and Wright, 1998; Friedrich and Stumptner, 1999; Soininen *et al.*, 2000). While logical approaches to configuration stress the need for an explicit representation of the structural properties of the entities of the domain in terms of specific kinds of relations, constraint satisfaction methods look at configuring products as solving a problem with a number of restrictions

(Magro and Torasso, 2003). Some authors also mentioned the importance in representing the knowledge on a configuration and the restrictions on possible configurations (Robertson and Ulrich, 1998; McGuinness and Wright, 1998).

2.2 Supply Chain Management under Global Manufacturing

The economic and industrial communities worldwide are confronted with the increasing impact of competitive pressures resulting from the globalization of markets and supply chains for product fulfillment. More and more manufacturing enterprises are being driven to pursue a global manufacturing strategy that aims to transcend national boundaries to leverage capabilities and resources worldwide (Pontrandolfo and Okogbaa, 1999). Companies are changing from supplying domestic market with products, via supplying international market through export, to supply worldwide market with local manufacuting (Rudberg and West, 2006). Next generation manufacturing calls for new forms of manufacturing strategies, which are based on global networks of self-organizing and autonomous units (Anderson and Bunce, 2000). These units may be part of a single company located globally, or several companies together to address customers' requirements coherently within extended and virtual enterprises (Bullinger *et al*., 2000). A global supply chain is a worldwide network of suppliers, factories, warehouses, distribution centers, and retailers through which raw material is acquired, transformed, and delivered to customers (Fox *et al*., 2000).

The characteristics of a supply chain network (SCN) are distinguished by physical connections, such as number of tiers, nodes and types of participants, and by operations, objectives (Lin and Shaw, 1998). According to the product characteristic, there exists "lean" (Womack and Jones, 1996) and "agile" (Hiebelar *et al*., 1998) SCN.

Also a “legaile” supply chain was proposed by Naylor *et al*. (1999). Based on structural characteristics, SCNs are divided into dyadic (Ganeshan *et al*., 2001), serial (Kimbrough *et al.*, 2001), divergent (Cachon and Lariviere, 2001), convergent (Cooper *et al*., 1997) and network (Carson and Zhang, 1998). Upon the time horizon, the decisions in the SCNs can be classified into strategic, tactical and operational (Min and Zhou, 2002).

2.2.1 Supply Chain Demand Strategies

An important ingredient of the supply chain is the demand strategy. Any order for a product triggers a series of work processes in the supply chain that have to be completed so that the end customer order is fulfilled. Generally, the following demand management strategies are employed in supply chain management.

Make-to-Stock (MTS): The end customer orders are filled from the stocks of inventory of finished goods that are kept at the supply chain network’s various retail points (Tso *et al*., 2000).

Make-to-Order (MTO): It is the confirmed customer orders that trigger the flow of materials and information in the supply chain (Tian *et al*., 2002). Of the finished goods or component materials, there is very little or no inventory maintained. Important issues include setting due-dates and release dates for orders flowing in the network, scheduling of various orders to minimize the variance or mean of order flow times, effective allocation of resources and order tracing mechanisms for efficient customer response.

Engineering-to-Order (ETO): This strategy places emphasis on the design, which is usually developed after receiving customer requirement and approved by the customer. Consequently, nothing is stocked before the arrival of demand, not even the design (Zuckerman, 2002).

Assemble-to-Order (ATO): Assemble to order involves having the same core assemblies for most products and the ability to vary all other components of the final assembly (Bowersox, 1996).

The markets addressed by MTS companies make production based on forecasts, and try to reduce risk by limiting the product range. MTO companies are prepared to provide many customized products, but start to produce only after receipt of a confirmed customer order. ATO companies position themselves in between MTS and MTO, and address primarily the markets of durable products. With an ATO approach, order lead times are minimized by dividing the value chain into two stages (i.e., a stage of module manufacturer based on forecasts followed by a stage of final assembly of customized products). Risk is minimized by modularizing products and by standardizing modules as much as possible.

MTS, MTO and ATO companies differ essentially by a different position of the decoupling point. A *decoupling point* is defined as a physical point in the value chain of the production system, which separates the investment stage from the realization stage (Beach *et al*., 2000; Chopra and Meindl, 2001). Within the investment stage, operations are executed in response to firm and anticipated demand. Within the realization stage, production is against confirmed customer orders. The decoupling point determines the minimum customer order lead time. A decoupling point must correspond with stocks somewhere in the supply chain, as the result of the fact that forecasts never are perfect (Higgins *et al*., 1996). The position of the decoupling point determines the type of response of a company to its market.

2.2.2 Emerging Issues in Global Supply Chains

Modern manufacturing enterprises are required to continually review their strategies for competing in the ever-changing, ever-expanding global economy. They must constantly restructure and simplify their business and fabrication processes and procedures (Camuffo, 2006). This restructuring frequently involves fundamental decisions regarding those activities which really do need to take place internally, and which can be better done by, and more importantly, in full collaboration with, business partners. In making these decisions, each enterprise must develop a flexible management system to survive in today's competitive market.

More and more, management is deciding in favor of outsourcing both design and fabrication. In some cases, they do not have the capabilities; in others, it is simply a matter of cost. Regardless of the reason, the management of multiple suppliers is becoming critical to an enterprise's success. There are two important keys to achieving that success: a thorough understanding of the business processes and quality practices at these suppliers, and the synchronization material flow and information flow across the chain (Wood *et al.*, 2002).

Global supply chains are more difficult to manage than domestic supply chains. Substantial geographical distances in these global situations not only increase transportation costs, but also complicate decisions because of inventory cost tradeoffs due to increased lead-time in the supply (Wood *et al.*, 2002; MacCarthy and Atthirawong, 2003). Different local cultures, languages, and practices diminish the effectiveness of business processes such as demand forecasting and material planning. Furthermore, global supply chains carry unique risks that influence performance, including variability and uncertainty in currency exchange rates, economic and political instability and changes in the regulatory environment (Stratton and

Warburton, 2006). These difficulties inhibit the degree to which a global supply chain provides a competitive advantage.

The business environment that surrounds the global supply chain is continually changing. First, firms increase their outsourcing to both domestic and global supply chain partners. Second, many firms now strive to integrate decision processes across tiers in the supply chain. The third issue is the broadened definition of supply chain performance. Mission, strategy and objectives can vary considerably based on the value of the product offered to the customer (Keeney, 1994).

Managers find themselves increasingly designing supply chains that include not only corporate but also supplier facilities. Supplier selection decisions change the supply chain structure in fundamental ways, in part because they are based on more broadly defined criteria. Suppliers are typically selected based on the buyer's perception of the supplier's ability to meet quality, quantity, delivery, price and service needs of the firm (Leenders *et al*., 2002). In some cases, purchasing managers consider an even broader set of criteria as defined by the total cost of ownership to include the cost of carrying inventory, repair, training, disposal, etc. (Degraeve and Roodhooft, 1999; Burt *et al*., 2003). Ultimately, purchasing managers summarize these factors so that candidate supplier may be ranked for selection. Supplier contracts also influence the design problem structure with additional factors such as minimum order quantities, restrictions on the number of vendors, geographic preferences, and limitations on supplier capacities (Pan, 1989)

A second emerging issue, the integration of decisions across the supply chain, also influences global supply chain design. Integrating business processes is a best practice in supply chain management that involves coordination decisions across multiple facilities and tiers. In practice, firms engaged in Vendor Managed Inventory

(VMI) and Collaborative Planning, Forecasting, and Replenishment (CPFR) integrate replenishment planning between enterprises by sharing sales and promotion information (Sherman, 1998; Lewis, 1999). Similarly, firms that implement Advanced Planning systems (APS) may integrate production decisions across the supply chain by including supplier inventory and capacity constraints into their scheduling function, striving to avert supply problems before they occur (Rohde, 2000; Bowersox and Closs, 1996). Several authors (Dornier *et al*., 1998; Brush *et al*., 1999) discussed the value and need for integration between facilities in the global supply chain. An integrated, well-coordinated global supply chain is difficult to duplicate and so plays an important role in competitive strategy.

To date, much of the emphasis in supply chain management has been on cost reduction, but performance in real-world supply chains has multiple attributes. As defined in the Supply Chain Operations Reference (SCOR) model, performance measured in terms of reliability, responsiveness, flexibility, cost, and assets (Supply Chain Council, 2003). Additionally, Handfield (1994) mentioned five benefits for companies who choose to source globally—improving quality, meeting schedule requirements, reducing costs, accessing new technologies, and broadening the supply base. For example, throughout the 1990s, a number of firms adopted a quick-response strategy to improve competitiveness (Lowson *et al.*, 1999). Bozarth *et al*. (1998) suggested delivery performance and quality as important measures in global supply chain management. Firms that had previously looked to their international manufacturing sites as a source of low-cost advantage now rely on their global production sites for improved access to customers, suppliers and skilled employees (Ferdows, 1997). Managers who design global supply chains need to align their decisions with the mission, objectives, and strategy of their firms, which is considerably broader in scope than cost reduction.

2.2.3 Supply Chain Configuration

The supply chain design used to be mostly a one-shot problem. Once a supply chain was designed, researchers and practitioners were more interested in means to improve performance given that initial network (Chan and Chan, 2004). However, a single supply chain paradigm will be neither optimal nor efficient under conditions where objectives conflict and requirements are constantly changing. Ideally, the supply chain network should be dynamically configured as per the dictates of the environment (e.g. vendor choice, customer preference, product choice) at any given point in time (Salvador *et al*., 2004).

Research in this field started very early on, with location-allocation problems forming part of the early set of classical operations research problems. Geoffrion and Graves (1974) considered the problem of distribution system layout and DC-customer allocation. It was recognized early on that systematic, optimization-based approaches should be used, and that “common-sense” heuristics might lead to poor solutions (Cohen and Lee, 1985). These early models tended to focus on the logistics aspects. Clearly, much more benefit could be achieved by simultaneously considering the production aspects.

An early example of a production-distribution network optimization study in the process industries is given by Brown *et al*. (1987) who considered the biscuit division of Nabisco. Their model involves the opening or closing of plants, the assignment of facilities to plans and the assignment of production to facilities. The production model is based on the relative product-facility “yields”. A thorough review of the work in this area was presented by Vidal and Goetschalckx (1997). They concluded that features that are not well treated include stochastic elements, accurate descriptions of manufacturing processes (and hence capacity), the international aspects, extended and multi-enterprise networks and solution techniques.

Kallrath (2002) addressed the issue of process and plant representation. He described a tool for simultaneous strategic and operational planning in a multi-site production network, where key decisions include: operation models of equipment in each period, production and supply of products, minor changes to the infrastructure and raw material purchases and contracts. A multi-period model is formulated where equipment may undergo one mode change per period. Sensitivity analyses showed that the key decisions were not too sensitive to demand uncertainty.

Sabri and Beamon (2000) developed a combined strategic-operational design and planning model with two interesting features. A multi-objective optimization procedure is used because of the difficulty of trading off very different types of objectives, and uncertainties in lead times as well as demands are treated. However, the model is dealing steady state rather than dynamic.

Tsiakis *et al*. (2001) showed how demand uncertainty can be introduced in a multi-period model. They argued that the future uncertainties could be captured well through a scenario tree, where each scenario represents a different discrete future outcome. They utilized a multi-purpose production model where flexible production capacity is to be allocated between different productions, and determined the optimal layout and flow allocations of the distribution network.

Most of the above works rely on the concept of fixed “echelons”, i.e. they assume a given fundamental structure for the network in terms of the echelons involved. Thus, a rather rigid structure is imposed on the supply chain and the design procedure focuses on the determination of the number of components in each echelon and the connectivity between components in adjacent echelons. However, changes in the fundamental structure of the network (e.g. the introduction of additional echelons, or the removal or partial bypassing of additional echelons, or the removal or partial bypassing of existing ones) may sometimes lead to economic benefits that far exceed what can be achieved merely by changing the number of components and the connectivity within an existing structure. Tsiakis *et al*. (2001) extended this body of work by developing a general framework that integrates the different components of a supply chain without any prior assumptions as to the fundamental structure of the network.

Decisions in a virtual supply chain can be divided into network structuring, which determines the location, size, and optimal numbers of suppliers, plants, and distributors to be used in the network; partner coordination and cooperation, which identifies information technologies, outsourcing strategy; and information sharing for order management and logistics fulfillment. There are also some operational issues involved in the supply chain decisions. The classification of virtual supply chain decisions is shown in Table 2.1.

Table 2.1 Classification of virtual supply chain decisions

Category	Decision
Network structuring	Location and allocation Number of facilities Number of echelons
Partner coordination and cooperation	ICT technology Outsourcing Information sharing
Operational	Demand management Order replenishment Shipment Service sequence

2.3 Supply Chain Modeling

Considering a broad spectrum of the supply chain concept, there may be various classification schemes to categorize supply chain models. There are five major categories: (1) MIP Deterministic, (2) Stochastic Programming, (3) Heuristic, (4) Simulation-based, (5) ICT-driven. The taxonomy of supply chain models is illustrated in Fig. 2.1.

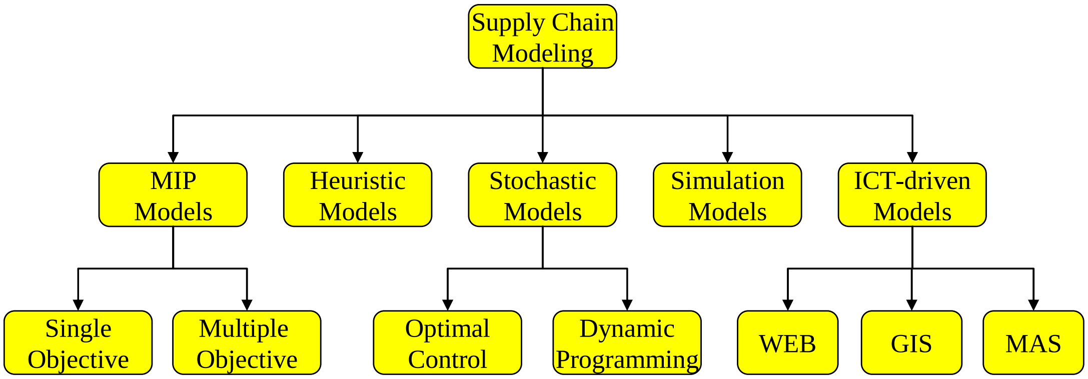


Figure 2.1 Taxonomy of supply chain models

MIP Deterministic Method: Many important supply chain models fall into the MIP (Mixed-Integer Programming) class. This includes most models for vehicle routing and scheduling, facility location and sizing, shipment routing and scheduling, freight consolidation and transportation mode selection. Glover *et al.* (1979) developed a computer-based production, distribution and inventory (PDI) planning system that integrated three supply chain segments comprised of supply, storage/location, and customer demand planning. The core of the PDI system was a network model and diagram that increased the decision maker's insights into supply chain connectivity. Cohen and Lee (1989) developed a mixed-integer, non-linear, value-added chain model that coordinated the supply chain process comprised of sourcing, centralized production planning, and inter-plant transshipment. The model incorporated capacity, demand, and production constraints, but failed to capture risk factors inherent in a global setting.

Arntzen *et al*. (1995) presented a global supply chain model (GSCM) which evaluated global supply chain alternatives involving multiple products and multiple stages. More specifically, GSCM took into account the interdependence of production, inventory and delivery processes to minimize activity days and costs. Ashayeri and Rongen (1997) refined a grid model and the multi-criteria solution method to formulate the DC repositioning strategy based upon the analyses of material flows, DC locations, and throughput items. Although the proposed model and solution method were simple to use, they were confined to single-period and un-capacitated problems. Another multiple objective approach was proposed by Min and Melachrinoudis (1999) to configure multi-echelon supply chain networks connecting material flows among entities.

Stochastic Programming Method: Stochastic programming deals with a class of optimization models and algorithms in which some of the data may be subject to significant uncertainty. Stochastic models take into account uncertain and random elements such as customer demand, lead times, and production fluctuation.

Swaminathan and Tayur (1999) provided stochastic programming models and effective computational procedures to study inventories of common components, the use of vanilla boxes for postponement, and the effect of assembly task sequencing on operational performance. They also utilized the inherent structure of problems to develop computationally efficient algorithms based on sub-gradient methods.

Lee and Billington (1993) attempted to integrate the material flows of marketing, manufacturing, and distribution processes by developing a stochastic program. Their model was designed to determine the material ordering policy, the customer service level for each product, and postponement strategies. Barbarosoglu and Ozgur (1999) developed a robust optimization framework for the problem of supply chain planning in the process industries. Since the standard stochastic programming formulation of the problem does not address the variability of the uncertain recourse costs across the uncertain parameter scenarios, Cachon (1999) extended the stochastic programming formulation to account for robustness of the resource costs through an appropriate variability criterion.

Lowson *et al*. (1999) use a model predictive control framework to understand the dynamic behavior of a consumer goods supply chain. They studied different levels of coordination between the supply and demand entities. They also considered forecasting techniques, particularly for promotional demands. It allows clear conclusions to be drawn regarding promotion and inventory management and the benefits and drawbacks of different degrees of coordination.

Heuristic Method: Heuristic is another important class of methods for generating supply chain alternatives and decisions. A heuristic is simply any intelligent approach that attempts to find good or plausible solutions (Vidal and Goetschalckx, 1997). Generally, mathematical programming methods are used to solve strategic and higher levels of tactical supply chain planning. Tactical and operational models are usually not linear and are much too complex to solve using mathematical programming methods. For this reason, heuristic methods are used in tactical and operational planning level solvers.

Heuristic methods used in supply chain planning and scheduling include the general random search approaches such as simulated annealing (Collier, 1982), genetic algorithms (Cooper, 1997) and TABU algorithms (Fawcett, 1992). Recently, the theory of constraints is also used in supply chain operational planning (Fine *et al*., 2005).

Simulation Method: This is a method by which a comprehensive supply chain model can be analyzed by considering both its strategic and operational elements. This method can be used to study the detailed dynamic operation of a fixed configuration under operational uncertainty, and evaluate expected performance measures for the fixed configuration to a high level of accuracy.

The dynamic nature of supply chains makes the simulation methods necessary for studying the time-varying behavior of supply chains. As suggested by Swaminathan *et al*. (1998), reengineering the supply chain because of business dynamics is becoming a necessity, but it is not an easy task. Although software simulation tools can ease the burden of analysis, it is still a major endeavor. The use of simulation as a vehicle for understanding issues of organizational decision-making has gained considerable attention and momentum in recent years (Feigin *et al*., 1996; Kumar *et al*. 1993; Malone and Benton 1997). Towill *et al*. (1992) used simulation techniques to evaluate effects of various supply chain strategies on demand amplification. Tzafestas and Kapsiotis (1994) utilized a combined analytical/ simulation model to analyze supply chains. Swaminathan *et al*. (1996) utilized a simulation to study the effect of sharing supplier's available-to-promise information.

ICT-driven Model: Information and communication technology (ICT) are considered as the key factors of supply chain modeling, especially in current virtual environment (Wang and Benaroch, 2004). ICT-driven models integrate and coordinate supply chain players on a real-time basis using software so that they can enhance visibility throughout the supply chain. Internet technologies such as Java, XML, CORBA, offer a high connectivity, which are needed for fast and seamless transport of data. The high number of variants and processes leads to higher complexity, especially in information logistics.

Serve *et al.* (2002) discussed the merits of supply-chain and business-to-business (B2B), and the impacts that they have on each other. They employed the concept of B2B marketplaces as the participating units in a supply-chain process in order to enhance the business process. Wang and Benaroch (2004) studied the supply chain coordination in buyer centric B2B electronic market. Castro *et al.* (2007) developed a tool for optimizing purchasing decision in B2B market across the supply chain.

There have been attempts at modeling virtual enterprises using computational techniques. An example of this can be seen in Bernus and Nemes (2004), where they model a supply chain as a set of individual, autonomous, cooperative agents maintaining a set of objectives. Park *et al*. (2005) proposed an agent-based approach (AGORA) for modeling and supporting cooperative work among distributed enterprises. Choi *et al*. (2007) developed a multi-agent framework for the dynamic identification of supply chain partners and the coordinated development, evaluation and manipulation of solutions across the supply chain.

Disney *et al*. (2004) investigated how e-business affects the supply chain dynamics of an enterprise in an attempt to establish e-business enabled supply chain models for quantifying the impact of ICTs. Koh & Kim (2005) modeled a virtual community activity framework, integrating community knowledge sharing into business activities in the form of an e-business model. This proposition attempted to model business activities relationships by limiting itself to statistical analysis of raw electronic interactions. Duffy (2001) attempted to formalize a blueprint of maturity modeling. This model utilized maturity level indicators for each key success driver category to estimate the overall e-business maturity of the enterprise. Wood *et al*. (2002) described a methodology for implementing e-supply chain within the Greek apparel industry. The methodology, based on structured modeling and simulation, examines the potential benefits of a web-based system prior to implementation.

ICT-driven models aim to enhance visibility through an information sharing mechanism linking supply chain partners. Camm *et al*. (1997) combined an integer programming model involving the location of DCs and sourcing of multiple products with a GIS to develop a flexible decision support system. Al-Mashari and Zairi (2000) developed SAP R/3-based ERP architecture and a conceptual diagram in an effort to create value-oriented supply chains that enable a high level of integration and communication among all supply chain processes. Talluri (2000) proposed a goal programming model for an effective acquisition and justification of ICT for a supply chain. The model could be useful in selecting the right ERP system that can consider system acquisition and maintenance costs, flexibility, and compatibility.

Table 2.2 summaries the supply chain modeling literature reviewed in this section. The major decision variables, performance index and modeling types discussed in the papers are different according to the specific problem contexts.

Table 2.2 Literature of supply chain modeling

Authors	Facility Selection	Produciton Scheduling	Inventory	Supplier Selction	Cost	Customer Satisfaction	Lead Time	Model Type
Glover et al. (1979)	√		√		√			Deterministic
Collier (1982)	√	√		√	√		√	Heuristic
Cohen and Lee (1989)		√	√	√	√	√		Deterministic
Fawcett (1992)		√	√		√		√	Heuristic
Towill et al. (1992)	√		√		√	√		Simulation
Lee and Billington (1993)	√		√		√		√	Stochastics
Kumar et al. (1993)		√	√		√	√		Simulation
Tzafestas and Kapsiotis (1994)	√	√		√			√	Simulation
Arntzen et al. (1995)	√	√	√	√	√	√	√	Deterministic
Feigin et al. (1996)		√		√	√			Simulation
Swaminathan et al. (1996)	√		√		√			Simulation
Ashayeri and Rongen (1997)	√		√	√	√	√		Deterministic
Camm et al. (1997)		√	√				√	ICT-driven
Cooper (1997)	√			√	√	√		Heuristic
Malone an dBenton (1997)		√	√		√	√		Simulation
Vidal and Goetschalckx (1997)	√		√	√	√	√		Heuristic
Swaminathan et al. (1998)		√		√	√			Simulation
Richmondw and Peters (1998)	√		√		√		√	ICT-driven
Barbarosoglu and Ozgur (1999)	√	√		√	√	√		Stochastics
Cachon (1999)		√	√	√		√		Stochastics
Min an dMelachrinoudis (1999)	√			√	√			Deterministic
Lowson et al. (1999)		√	√		√		√	Stochastics
Johnston et al. (1999)	√	√			√		√	ICT-driven
Swaminathan and Tayur (1999)			√	√	√	√		Stochastics
Wang and Benaroch (2004)	√			√			√	ICT-driven
Park et al. (2005)		√	√		√			ICT-driven
Choi et al. (2007)	√		√			√		ICT-driven
Castro et al. (2007)		√		√	√			ICT-driven

2.4 The Impact of ICT on SCM

Gunasekaran and Nagi (2004) classified the major components of ICT-eanbled SCM: strategy planning for ICT in SCM, virtual enterprise and SCM, e-business and SCM, infrastructure for ICT in SCM, knowledge and ICT management in SCM, and implementation of ICT in SCM. The role of the ICT in SCM is recognized as critical. ICT is utilized to perform and automate business interactions among supply chain network. These business interactions do not only focus on buying product from suppliers and selling them to customers, but they cover all kinds of collaboration within supply chains, e.g. distribution order forecasting information (Gavirneni, 2006). The purpose of ICT is to increase the added value and to improve the resource utilization and cost efficiency by getting the right products at the right time to the right place. Many research papers have addressed the value of ICT in SCM (Wang and Sang, 2005; Simchi *et al*., 2003, Vickery et al., 2003). For example, Wang and Sang (2005) suggest that ICT in SCM provides reduction of cycle time, reduction of inventories, minimization of bullwhip effect, and improvement of effectiveness of distribution channels. According to Simchi *et al*. (2003), objectives of ICT in SCM are:

- Providing information availability and visibility
- Enabling single point of contact of data
- Allowing decisions based on total supply chain information
- Enabling collaboration with supply chain partners

The most typical role of ICT in SCM is reducing the friction in transactions between supply chain partners through cost-effective information flow (Cross, 2006). Conversely, ICT is more importantly viewed to have a role in supporting the collaboration and coordination of supply chains through information sharing. Third, ICT can be used to provide assistance to managerial decisions (Simchi *et al*., 2003, Swaminathan and Tayur, 2003). It enables the opportunity for demand data and supply capacity data to be visible to all companies within a virtual supply chain. Consequently, companies can be in a position to anticipate demand fluctuations and to respond accordingly. It has given companies even greater tools for tightly orchestrating relationships across the entire supply chain and creating strategic partnerships and operational linkages with a dynamic web of large and small firms spanning all continents (Vickery *et al*., 2003). Internet-enabled shared information helps break down organizational policies and functional fences, helping supply chain alliance members develop a common understanding of the competitive environment.

Using case studies in six Finnish industrial supply chains as data, Grieger (2004) argue that ICT is, alongside specialization and outsourcing, a key precondition for networking of organizations. Williams *et al*. (2002) suggest the electronic SCM combines the structural benefits of SCM with the efficiency benefits of an arms length approach, enabling lower cost through possibilities of selecting from a larger supplier base. Gavirneni (2006) proposed that the value offerings through ICT are electronic communication (speed of communication), electronic brokerage (automated intermediary for resolving market transactions), and electronic integration (coupling of processes). Lim and Palvia (2001) studied 114 US companies and summarized that EDI contributes significantly positively to order cycle time, product availability, distribution flexibility, distribution information and distribution malfunctions. Vickery *et al*. (2003) observed the competence of integrated information systems, supply chain integration, customer service and financial performance from 57 first-tier automotive industry suppliers.

2.5 Coordinated Product, Process and Logistics Decisions

The design of a supply chain has an essential influence on how a manufacturer of complex products organizes and coordinates the stream of innovative products through platform and architectural design strategies via the sourcing, manufacturing and distribution strategies (Mikkola and Skjott-Larsen, 2004). Rungtusanatham and Forza (2005) advocated the coordination of the product, process and supplying chain design decisions. Fine *et al*. (2005) purported to expand traditional concurrent engineering to three dimensions, namely 3D-CE, in terms of product, processes and the supply chain. He argued that all three domains possess certain architectures, and thus simultaneous considering these architectures is the key to accommodate low volume, large variety, and high-speed operations. Jiao and Tseng (2004) discussed concurrent enterprising for mass customization, which aims to align customers, products, processes, and logistics for delivering an increasing product variety with reasonable cost. McKay and Pennington (2001) provided an operational level framework for modeling products, processes and supply chains.

Salvador *et al*. (2002) perhaps is one of the most comprehensive studies dealing with the mutual interactions between product family, productions processes and supply sources. The industry case studies show general guidance for the decision-making processes. Gupta and Krishnan (1999) investigated the reduction in the complexity of a product family through product design by leveraging common characteristics among the products within the family. Based on the concept of ontology-oriented constraint networks, Novak and Eppinger (2001) found statically significant relations between supply chain structures and product architectures for luxury and high performance vehicles.

A series of modeling approaches have been proposed to solve the joint supply chain decision-making problem. Park *et al*. (2000) presented a comprehensive mathematical model for integrated product platform and global supply chain configuration and make experimental simulations to evaluate the result. Huang *et al*. (2005) analyzed the impact of platform products, with and without commonality, on decisions pertaining to supply chain configuration and the consequent performance of the configured supply chain. Kim *et al*. (2002) proposed a mathematical model and a solution algorithm to assist the manufacturer in configuring its supply chain for a mix of multiple products sharing some common raw material and/or component parts. Blackburst *et al*. (2005) developed a decision support modeling methodology, which aims to model dynamic and complex systems, such as supply chains, and the decision-making processes inherent in the operation of the supply chain, product and process decisions.

2.6 Summary

The models and methodologies mentioned in the reviews have focused primarily on the development and analysis of the mathematical model for supply chains to optimize goods, inventories and material flows within the chain (Lee, 1998). In addition, these models are popular because of their abilities to determine the results based on relatively simple mathematical modeling. However, as indicated by Akkermans (1999), the operation management literature has shown non-significant empirical evidence of successful strategic moves towards supply chain management. This is because the researches done on network coordination are mainly on descriptive case studies based on operational context. Very few models in the literature have considered rigorous formulation, integrated modeling and information platforms. It is imperative to shift the management emphasis from aspects of differentiation and specialization to those of integration among functions or facilities; from local performance indicators to goals that at the entire supply chain level; and from the single performance indicator to multi-member objectives.

CHAPTER 3 FUNDAMENTALS OF THE VIRTUAL SUPPLY CHAIN AND ITS CONFIGURATION

This chapter discusses some fundamental issues of the virtual supply chain (VSC) and its configuration, including the concepts, unique characteristics, technique challenges and strategy for solutions. A systematic and comprehensive formulation of the VSC and its configuration has been proposed to identify key elements in multiple fields and their close correlations. It serves as the umbrella for the further rigorous analysis, simulation, and manipulation of the VSC.

3.1 Introduction

Supply chain management has been used as an effective strategy to enhance company's competency for many years. It aims to manage and control a series of inter-related business processes across the value-added chain. With the rapid development of market competition and advanced technologies, a number of new paradigms such as mass customization, global manufacturing, and e-business have emerged and dramatically increased the complexity of supply chain management. The most significant change is the widely spreading varieties along the supply chain. Each node or element might have tens or hundreds options in terms of products, suppliers, logistic channels, etc. Therefore, the traditional supply chain has geared towards the virtual supply chain (VSC) in order to handle the huge number of varieties. A VSC aims to fulfill individual customer order through the cooperation of worldwide suppliers under the support of information and communication technologies.

The VSC distinguishes itself from the traditional concept of a supply chain through its typical features such as virtual, high variety, and cross-discipline.

Firstly, the VSC is *virtual*, which indicates it does not refer to a real or physical supply chain. A VSC entails a generic supply chain network, which could derive to hundreds even thousands of specific supply chains. Huge amount of variety lie in every part of the VSC. Each part or component in the product has a set of capable suppliers to produce it. Each supplier can take different logistic channels to deliver its materials to the upstream consumers. Each logistic channel can operate in different conditions in terms of time, route, cost, size and frequency.

Secondly, the VSC *virtually* exists in the web environment. Recent developments in information and communication technologies offer the promise of connecting suppliers, producers and customers in a seamless integrated network. In such a *virtual* environment, members of the VSC adopt same technologies, such as EDI, XML and agents, to request and exchange information, synchronize decisions and make joint planning and scheduling.

Thirdly, the VSC is *virtual* due to its cross-discipline nature. It spans from *marketing, product, process* and *logistics* four separate disciplines, which have intimate relationships and impact with each other. For example, the objective of a VSC is to fulfill a customer order, which indicates the customer requirements on four disciplines, including cost (*market*), functions and specifications (*product*), quantity and quality (*process*), delivery time and route (*logistics*). Therefore, during the configuration process of a VSC, the supply chain designer should consider how to handle the varieties and satisfy the customer requirements on the four disciplines.

Finally, many researchers adopt numerical methods to represent and analyze supply chain networks. Most mathematic models assume that all the information are available, non-ambiguously and any time. These conditions are hard to be satisfied in the real scenario. It requires long time to collect relevant data, develop suitable models and find efficient solutions. Due to the restricted numerical representing form, the size and structure of the supply chain have to be simplified. In addition, a mathematic model is limited to a specific scenario; the exclusion of uncertainties and the necessity of making strong assumptions make it difficult to accommodate new issues. The VSC model aims to adopt advanced information technologies such as Petri-nets and multi-agent systems to enhance its maintainability and reusability. It provides straightforward graph representation and powerful analysis tools. The modular architecture ensures that the supply chain designer could quickly configure a supply chain by reusing historic solutions.

The VSC is inherently complex due to its high variety in the product, process and supply. Product differentiation inevitably leads to an exponentially increased number of process variations, involving machines, tools, fixtures, setups, cycle times, and labor (Wortmann *et al*., 1997). The demand of large process variations results in the proliferation of supply entities, which in turn compose complex supply chain networks. Nonetheless, the common components and basic structures embedded in the product and process variety inherently enable similarity and thus reusability in the corresponding supply chain network (Martinez *et al*., 2000). Therefore, the key issue in the VSC is to configure product family and supply chain network to take advantage of repetitions. Besides leveraging the cost of delivering variety, exploiting product families around supply chain platforms can reduce development risks by reusing proven elements and knowledge in a supply chain’s activities (Sawhney, 1998). Fig. 3.1 illustrates the relationship between virtual supply chain network and supply chain configuration. There is a generic network, which covers customer needs, product family, process operation, and logistics, while the virtual configuration process is to generate specific supply chain according to the customer needs.

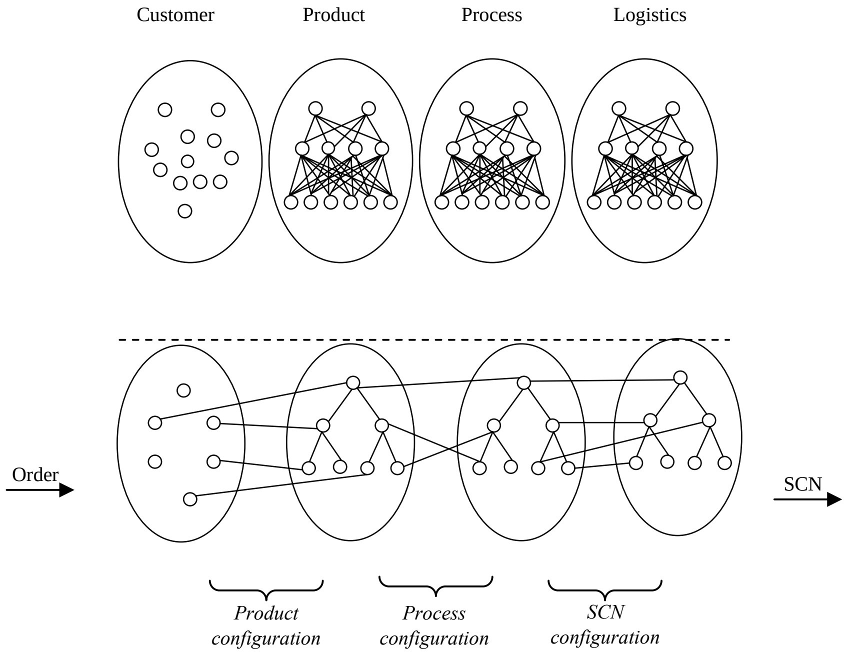


Figure 3.1 Virtual supply chain network and configuration

3.2 Technical Challenges and Strategies for Solution

The VSC entails a conceptual structure and overall logical organizations of producing a family of products. It provides a generic umbrella to capture and utilize commonality, within which each new product fulfillment is instantiated and extended so as to anchor material production and transportation to a common supply chain structure (Martinez *et al.*, 2000). Within the VSC, proper supply elements are selected and arranged to form an optimal supply chain for each individual product in the family. Decisions regarding the configuration of a VSC are deemed very complicated.

The VSC involves a number of research problems from different disciplines and fields. In order to address the key issue of the VSC—variety handling, this dissertation focuses on four fundamental pillars: (i) virtual supply chain framework and formulation, (ii) virtual supply chain modeling, (iii) virtual supply chain configuration decision making, and (iv) supporting intelligent information platform.

The first issue in the VSC deals with a systematic framework and rigorous formulation of the VSC in terms of concepts and functionalities. The framework and formulation lead to a clear understanding of the VSC without any misconception and misinterpretation. It addresses the problem nature of the VSC and paves the way for further investigation of methodologies and solutions. The technical difficulties in formulating a VSC include: (i) Conceptualizing and analyzing the VSC; (ii) Building a reference framework for VSC modeling; and (iii) Formulating key elements, relevant features, behaviors and interacting relationships in the VSC. To satisfy the formulation requirement and meet the technical challenge, the domain-based design theory and object-oriented concept have been adopted in this research to build the framework.

Based on the understanding of concepts and formulation, the VSC modeling issue has been perceived. In order to handle large amount of varieties in multiple domains and multiple-tier structure of a VSC, a nested modular modeling approach based on colored Petri-net technology has been proposed. The suggested solution has approached the construction of supply chain models as the assembly of basic building blocks. A large and complex supply chain network is represented as a series of cascading nested Petri-net models. The technical challenges in the VSC modeling approach lie in: (i) Analyzing the typical structure of the virtual supply chain and identifying basic elements and common behaviors; (ii) Encapsulating the activities and states of a basic supply chain element into a Petri-net node; (iii) Modeling the supply chain into several hierarchical nested models; and (iv) Building the communication mechanism to maintain the consistency of adjacent models.

After the virtual supply chain has been constructed, another important issue is naturally emerged that how to configure the generic structure into a specific solution to meet the individual customer requirement. A series of structure formalisms based on colored Petri nets have been developed to address this issue. They precisely and systematically represent the constituent elements, structure bonds, and behavior mechanism during virtual supply chain configuration. The detailed problems are observed as: (i) Formulation of virtual supply chain configuration; (ii) Modeling of the static generic supply chain structure and dynamic configurations; and (iii) Evaluation of supply chain configurations.

As VSC members are independent and geographically distributed, it is necessary to develop an intelligent information platform to support VSC integration and coordination. A multi-agent platform is proposed to facilitate the handling of the entire lifecycle of a VSC, encompassing its initiation, formation, operation, coordination and decommission. Several technical challenges are identified as: (i) Conceptualizing the lifecycle of an ICT-based VSC; (ii) Behavioral modeling of VSC operation and coordination; and (iii) System development by using multi-agent technology.

3.3 Domain-based VSC Formulation

A critical step in the research of a VSC is to develop a reference framework that can capture the synergy of inter-function and inter-organization within the virtual network with the consideration of solution propagation of the product family and process platform design. Such a reference framework would give some insights to understand the behavior of a virtual supply chain and the effects of product and process decisions on the structures of supply chains.

3.3.1 Product Development Domains

The concept of domain originates from the design theory proposed by Suh (2001). Using it as a guide for systematic product family design, four domains are identified, namely, customer domain, functional domain, physical domain and process domains. Each domain makes its decision independently yet relies on the information transferring from other domains. There exists a series of parameter mappings between domains, which translate the domain decision and knowledge. The customer domain is characterized by a set of customer attributes (CAs), which represent customer needs or final objectives of the design, and trigger downstream design mappings in a cascading manner. These CAs are first translated into functional requirements (FRs) in the functional domain, in which the designer takes into account engineering concerns and elaborates these requirements with limitations or constraints. The physical domain generates design concepts by mapping FRs to design parameters (DPs). The process domain makes use of DPs to develop process variables (PVs), which represent the implementation of the design. The customer, functional, physical and process domains address the customer satisfaction, functionality, technical feasibility, and manufacturability/cost issues associated with the products, respectively (Jiao and Tseng, 1999).

The domain-based framework by Suh (2001) focused on the product family design, in which the input is the customer requirement and the output is the product structure. In this dissertation, this framework is extended into the supply chain field. In a VSC, the input is a customer order, which represents customer needs in terms of functional specifications and transactional requirements including price, volume, delivery time, etc. The output is a specific supply chain network, which determines location of network facility nodes and allocates resources over the infrastructure. The VSC spans from several domains including marketing, product, process and logistics. Complexity arises when these domains amalgamate and interact, which may cause conflicts and contradiction. Therefore, this research applies the domain-based design theory to streamline the complexity of intra-domain, inter-domain relationships within a VSC. With this strategy, major stages of a complex virtual supply chain are represented as particular domains, in which specific characteristics can be established to interpret the semantics of the network relationships.

3.3.2 Domain-based VSC Reference Framework

Different from the product development domains (Suh, 2001) which aim to design a specific product, the VSC domains are established in order to create a supply chain network to satisfy an individualized customer order. Thus, a domain-based VSC reference framework is shown in Fig. 3.2.

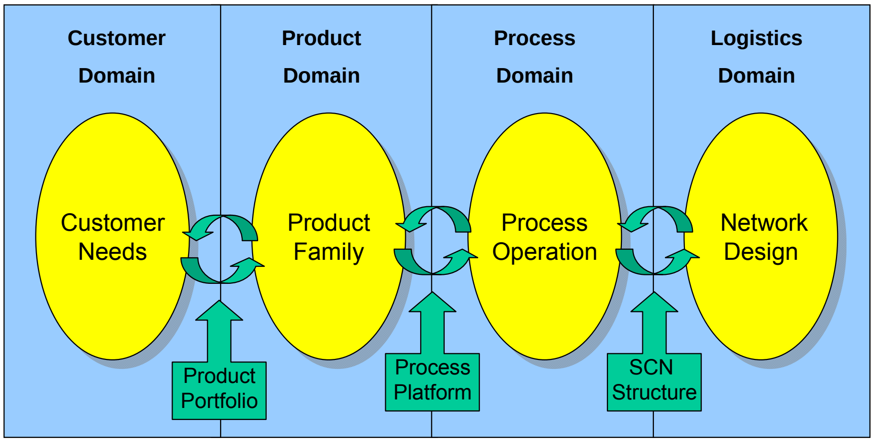


Figure 3.2 Four domains of a VSC

A VSC entails four domains, including a customer domain, a product domain, a process domain and a logistics domain. The customer domain represents customer needs, which specify either product characteristics, i.e. functional specifications and performance requirements, or transactional terms, i.e. price, volume, delivery time, etc. An order in the customer domain is described as a distinctive set of customer needs (CNs). These CNs trigger the configuration processes in downstream domains.

In the product domain, a product family is designed to satisfy the CNs in the upstream customer domain. The component commonality and modularity provide such a possibility that limited components could constitute nearly unlimited products to satisfy various market niches. According to the concrete demand of customers, a generic product structure is tailored into various specific products, which are physical expression of customer requirements. Bill of material (BOM) is used to express the specific product structure. It is the key element of the VSC, where each supplier or manufacturer takes responsibility to produce a certain type of materials in the product BOM, which may be raw materials, components, sub-assemblies or final assemblies.

The process domain is deployed to describe how to decompose the entire production into a series of process operations, which are implemented by either internal assemblies or external suppliers. A number of issues should be taken into consideration in the process domain, including material inventory, production capability, outsourcing price, logistic complexity, etc.

The logistics domain is characterized by the network design module. For each type of material requirements passing from upstream domains, logistics domain should select a suitable entity to provide certain material. For the material produced within the enterprise, the logistics domain should decide the assemblies and delivery routes. For the material to be outsourced, it is necessary to utilize market mechanism to select a capable supplier from a supply base. After all of the material requirements are resolved; the suppliers are selected; the assembly plants are specified; and the distribution channels are determined; a specific supply chain network is established.

The domain-based reference VSC framework introduces a product-oriented solution to supply chain design. Such representation of the VSC captures the interdependencies among markets, products, processes and logistics. Under the umbrella of the domain framework, all kinds of functionalities like design, process, purchasing are embedded into certain domains. Each domain receives the input from the upstream domain and generates the output to the downstream domain. Important elements and activities of the VSC, e.g. product BOM, process operations, supplier capabilities, and delivery routes are classified into corresponding domains. The synchronization of material requirements in the multi-site manufacturing supply chain is fulfilled through mappings between domains.

3.3.3 VSC Formulation

The VSC aims to address a series of complex supply chain configuration issues, which are characterized as multi-objective, multi-criterion, multi-function and multi-domain. As the VSC manifests itself from various perspectives and forms, a comprehensive and precise formulation is vital to prevent confusion and misunderstanding. Such a formulation provides a sufficiently powerful syntactic model to support rigorous analysis, simulation and manipulation of the VSC.

3.3.3.1 Virtual Supply Chain

Definition 3-1: A virtual supply chain is defined as a tuple: $\Omega = \langle \Lambda, \Pi \rangle$, where Λ is the class of supply chain entities, and Π is the class of flows. A VSC, $\Omega \subset \Lambda \times \Lambda$, contains a set of entities from Λ connected by Π.

Definition 3-2: A supply chain entity class Λ is defined as a 3-tuple: $\Lambda \equiv \langle A, S, D \rangle$, where A is the class of assembly entities, S is the class of supply entities, and D is the class of distribution entities.

A supply chain entity class Λ serves for a product family, including the entities responsible for the material handling, $\Lambda = \{e_i \mid \forall i = 1,...m\}$.

Definition 3-3: A flow class Π is defined as a number of entity precedence, represented as entity pairs, indicating the transferring routes of materials, $\Pi = \{\xi_i \mid \forall i = 1,...m\}$ where $\xi_i = \langle e_a \succ e_b \rangle$.

Definition 3-4: A product family P is described as a tuple: $P = \langle A, \Phi \rangle$, where A is the class of items, and Φ is class of the item BOM structure in the A. $A = \{A_i | \forall i = 1, \cdots, m\}$, each A_i represents an item family; either a part, assembly or final product. The BOM structure is described as $\Phi = \{\phi_i | \forall i = 1, \cdots, n\}$, $\phi_i = \langle c_i \succ c_j, n_{ij} \rangle$.

Definition 3-5: The customer order O includes four types of customer needs, $O \equiv \langle P, C, Q, L \rangle$. The product needs p_i determine the product structure. The supply chain needs describe the entity attributes like cost c_i. The process needs specify the operation parameters, like quantity q_i and lead-time l_i.

Figure 3.3 illustrates the reference model of a VSC, indicating class definitions and their interrelationships. Entity and item in the virtual supply chain context have been defined as classes. The class-member connections between generic supply chains and their variants are formulated in the following section.

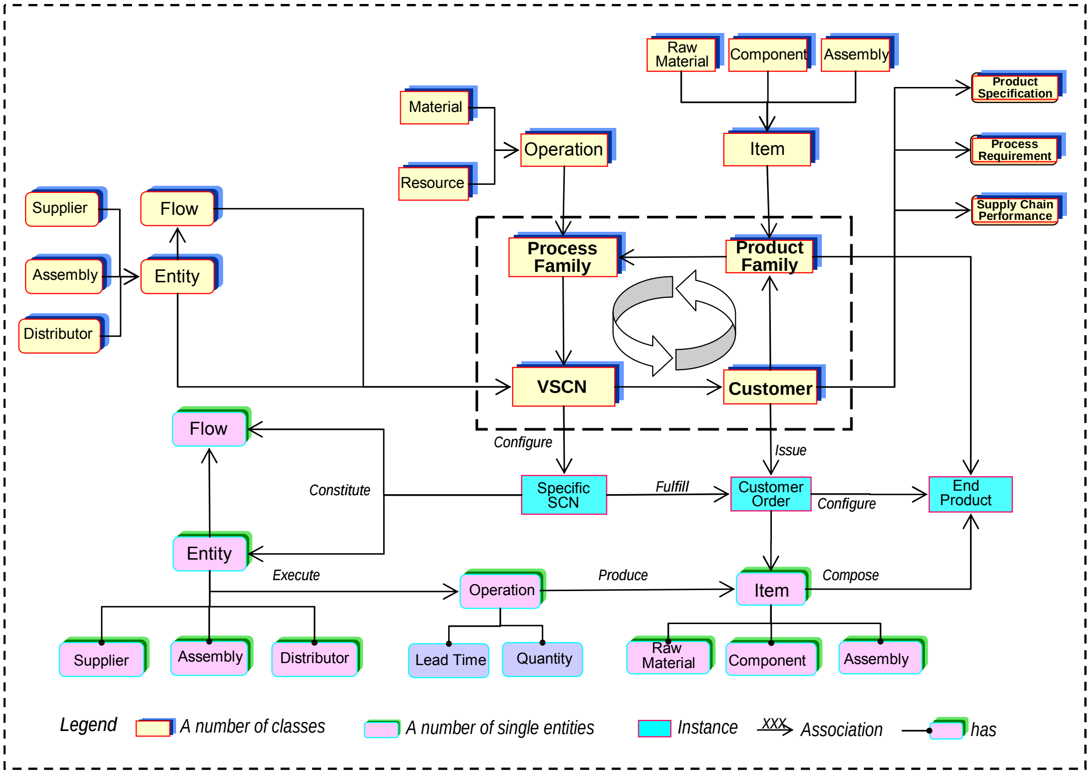


Figure 3.3 VSC reference model

3.3.3.2 Supply Chain Variants

The foundation of generic variety configuration originates from object-oriented modeling. As shown in Fig. 3.3, every object class defined in a VSC can be regarded as a generic item. While every element specific in a supply chain can be looked as an instance of the generic item. The instance of an object encompasses all static properties of the object as well as the dynamic values of these properties. If these generic items are assumed to be analogous to the objects in object-oriented modeling, a concept of variety state should also hold true in playing a similar role in indirect identification of individual variants from generic items.

As a notational convention, the superscript ‘*’ is used within generic variety representation to denote the variant of a generic item, the instance of an object class, or the value of a variety parameter. For an item variant, $c_i^* \in C^*$, where C^* is the set of item variants of item class (i.e., generic component), its variety characteristics are inherited from C.

Definition 3-6: A supply chain variant is an instance of the VSC, defined as a tuple: $\Omega^* = \left\langle \Lambda^*, \Pi^* \right\rangle$, where Λ^* is the set of supply chain entities, and Π^* is the set of material flows.

Definition 3-7: The supply chain entity set $\Lambda^* = \left\langle A^*, S^*, D^* \right\rangle$, where A^* is the set of assembly entities, S^* is the set of supply entities, and D^* is the set of distribution entities.

Definition 3-8: The material flow set Π^* is defined as a number of entity precedence, represented as entity pairs, $\Pi^* = \left\{ \xi_i^* \mid \forall i = 1,...m \right\}$, where $\xi_i^* = \left\langle e_a \succ e_b, c^*, q_{ab} \right\rangle$. ξ_i^* defines the correlations between two entities, including the precedence, transferring material and quantity.

Definition 3-9: A product variant P^* is described as a tuple: $P^* = \left\langle C^*, S^* \right\rangle$, where C^* includes all the constitute items of P^*, and S^* indicates the BOM relations.

3.3.3.3 Virtual Supply Chain Configuration

In the context of mass customization, an individual customer order would lead to a customized product characterized by specific values of a set of variety parameters (Jiao *et al.*, 2000). A supply chain variant supports the fulfillment of customized products through the configuration of corresponding entities and flow. Virtual supply chain configuration adopts such a mechanism of mapping an individualized product to its supply chain, $\Omega^* = \left(\Lambda^*, \Pi^* \right)$, within a VSC. The procedure of VSC configuration consists of the following steps:

(1) Initialization. Given a customer order, it is described as a set of variety parameters and their values: $\left\{\left(f_i, f_i^*\right)|_{i=1,\cdots,L}\right\}$. For a VSC, $\Omega = (\Lambda, \Pi)$, with an established generic structure, a special symbol is assigned as default values to the state of every variety parameter.

(2) Variety state specification. Based on planning or configuration rules, the designer constructs a supply variety grid, which lists all feasible variants of each generic item of a VSC. Each variant is characterized by its variety state. A valid variety state is determined by a feasible combination of relevant variety parameter values. Usually the feasible combinations of variety parameter values are specified by defining, for example, include conditions (Du *et al*., 2001), planning rules (Jiao *et al*., 2000), and configuration constraints (Sanderson and Uzumeri, 1997).

Among many variants of those generic items in a VSC, a few variants that are relevant to the given product are referred to as valid variants identified by their variety states. Through specification of variety states, only those variety parameters relevant to $\left\{f_i |_{\forall i}\right\}$ obtain valid values corresponding to $\left\{f_i^* |_{\forall i}\right\}$.

(3) Instantiation of generic items. Instantiation of generic items is achieved by specifying the states of the relevant variety in accordance with the given product. Valid variants are identified from the supply variety grid by matching their variety states with those valid variety states.

(4) Configuration of supply chain variants. A specific supply chain variant, $\Omega^* = \left(\Lambda^*, \Pi^*\right)$, is constructed by introducing precedence relations to those valid entity variants. An algorithm for deriving a flow variant can be developed based on the BOM structure and decomposed customer orders.

3.4 Case Study

In order to testify the domain-based VSC reference model, the author develops a case of a motor family to represent a real supply chain network. The case comes from an electronic company, which produces a range of motors for worldwide consumers. Most of the motor products are customized with small batch sizes according to the particular project requirement. The motor structure and its supply chain are extracted and simplified as shown in Fig. 3.4. Each circle refers to a supply entity which produces certain material (demonstrated by the content on the left side). The location of the entity is indicated under the circle. The supply chain network serves four market segments with one motor family.

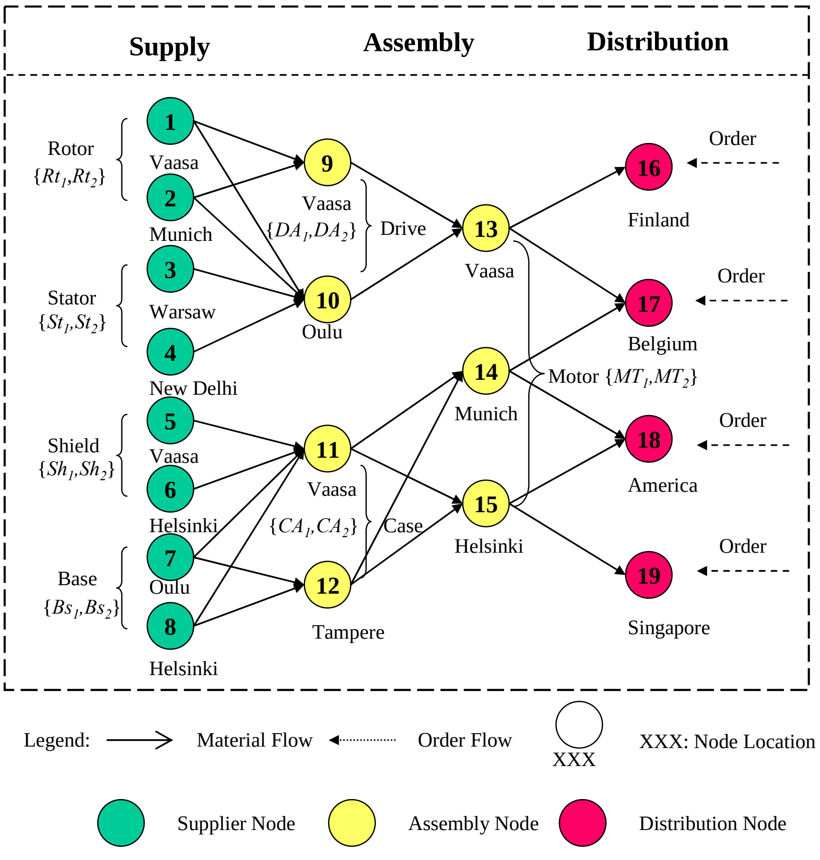


Figure 3.4 The supply chain network of a motor family

Each node in Fig. 3.4 is represented as a supply chain entity e_i. The motor supply chain entity set Λ contains three sub-sets: $\Lambda^S, \Lambda^A, \Lambda^D$. Each sub-set includes a number of entities, which exist in the same horizontal tier of the supply chain. Λ^S is the set of supplier entities which provide raw material or parts to the assemble set Λ^A. The distribution set Λ^D includes the warehouses and retailers, which receive the motor products from Λ^A and deliver motors to final customers.

$$\Lambda^S = \{e_1, e_2, e_3, e_4, e_5, e_6, e_7, e_8\}$$

$$\Lambda^A = \{e_9, e_{10}, e_{11}, e_{12}, e_{13}, e_{14}, e_{15}\}$$

$$\Lambda^D = \{e_{16}, e_{17}, e_{18}, e_{19}\}$$

Item set Γ represents the material transferred along the supply chain. It includes all the raw material, parts, components, assemblies and final products.

$$\begin{aligned} \Gamma_{MT} &= \{Rotor, Stator, Base, Shield, Drive, Case, Motor\} \\ &= \left\{ \begin{array}{l} (Rt_1, Rt_2) \cup (St_1, St_2) \cup (Bs_1, Bs_2) \cup (Sh_1, Sh_2) \cup \\ (DA_1, DA_2) \cup (CA_1, CA_2) \cup (MT_1, MT_2) \end{array} \right\} \end{aligned}$$

BOM structure set Φ represents the structural relations among items in a product family, which can derive to several specific products. It indicates the constituent items and required quantities.

$$\Phi_{MT} = \left\{ \begin{array}{l} (Rt_1 \succ DA_1, 1), (St_1 \succ DA_1, 1), (Bs_1 \succ CA_1, 2), (Sh_1 \succ DA_1, 2), (DA_1 \succ MT_1, 1), \\ (CA_1 \succ MT_1, 1) \cup (Rt_2 \succ DA_2, 1), (St_2 \succ DA_2, 1), (Bs_2 \succ CA_2, 2), (Sh_2 \succ DA_2, 2), \\ (DA_2 \succ MT_2, 1), (CA_2 \succ MT_2, 1) \cup (Rt_1 \succ DA_2, 1), (Bs_1 \succ CA_2, 2), (Sh_1 \succ DA_2, 2), \\ (DA_1 \succ MT_2, 1), \cup (St_2 \succ DA_1, 1), (Bs_2 \succ CA_1, 2), (CA_2 \succ MT_1, 1) \end{array} \right\}$$

The material flow set represents material transferring sequence between entities. It indicates which supplier is capable to provide material to which assembly, and which customer can receive the product from which distributor.

Material flow from supplier to assembly:

$$\begin{aligned}\Pi_{SA} &= \Lambda^S \succ \Lambda^A \\ &= \begin{bmatrix}(e_1 \succ e_9),(e_2 \succ e_9),(e_1 \succ e_{10}),(e_2 \succ e_{10}),(e_3 \succ e_{10}),(e_4 \succ e_{10}), \\ (e_5 \succ e_{11}),(e_6 \succ e_{11}),(e_7 \succ e_{11}),(e_8 \succ e_{11}),(e_7 \succ e_{12}),(e_8 \succ e_{12})\end{bmatrix}\end{aligned}$$

Material flow from assembly to distribution:

$$\begin{aligned}\Pi_{AD} &= \Lambda^A \succ \Lambda^D \\ &= \begin{bmatrix}(e_9 \succ e_{13}),(e_{10} \succ e_{13}),(e_{11} \succ e_{14}),(e_{12} \succ e_{14}),(e_{11} \succ e_{15}),(e_{12} \succ e_{15}), \\ (e_{13} \succ e_{16}),(e_{13} \succ e_{17}),(e_{14} \succ e_{17}),(e_{14} \succ e_{18}),(e_{15} \succ e_{18}),(e_{15} \succ e_{19})\end{bmatrix}\end{aligned}$$

Material flow of the motor supply chain:

$$\begin{aligned}\Pi_{MT} &= \Pi_{SA} \cup \Pi_{AD} \\ &= \left\{\left[\Lambda^S \succ \Lambda^A\right] \cup \left[\Lambda^A \succ \Lambda^D\right]\right\} \\ &= \left\{\begin{matrix}\begin{bmatrix}(e_1 \succ e_9),(e_2 \succ e_9),(e_1 \succ e_{10}),(e_2 \succ e_{10}),(e_3 \succ e_{10}),(e_4 \succ e_{10}), \\ (e_5 \succ e_{11}),(e_6 \succ e_{11}),(e_7 \succ e_{11}),(e_8 \succ e_{11}),(e_7 \succ e_{12}),(e_8 \succ e_{12})\end{bmatrix} \cup \\ \begin{bmatrix}(e_9 \succ e_{13}),(e_{10} \succ e_{13}),(e_{11} \succ e_{14}),(e_{12} \succ e_{14}),(e_{11} \succ e_{15}),(e_{12} \succ e_{15}), \\ (e_{13} \succ e_{16}),(e_{13} \succ e_{17}),(e_{14} \succ e_{17}),(e_{14} \succ e_{18}),(e_{15} \succ e18),(e_{15} \succ e_{19})\end{bmatrix}\end{matrix}\right\}\end{aligned}$$

Under the mass customization environment, each customer order might be different and need a specific supply chain network to satisfy it. An example of the customer order is described as: $O = < p, c, q, l >$

Where $p = (MT_1, DA_1, CA_2, Rt_1, St_1, Bs_2, Sh_1)$

$c = (4500)$

$q = (200)$

$l = (30)$

Here p refers to the product and its constituent items. This item list is the result of product configuration. The original customer requirement might be expressed by this way: (i) high speed rotation, larger than 3000 r/m; (ii) work in the under-water environment; and (iii) low energy consumption. q and l indicates the operational requirements of the products. It is said that the customer needs 200 motors delivered within 30 days. The requirement on the product could be further propagated to materials in the BOM list. c demonstrates the price of a motor is 4500.

Each supply chain entity e_i is capable to produce a particular item c_i at the quantity q_i and lead time l_i. The variables c_i, q_i, and l_i could be viewed as the performance parameters of the entity e_i and determine whether e_i can be selected into the supply chain. All entities involved in the generic motor supply chain network are depicted by relevant performance parameters, which are shown in Table 3.1.

Table 3.1 Entities involved in the motor supply chain network

Entity	**Item**	**Upstream**	**Downstream**	**Quantity**	**Lead Time**	**Cost**	**Inventory**
e_1	Rt_1	NA	e_9 , e_{10}	700	18	900	120
e_2	St_1	NA	e_9 , e_{10}	550	15	1050	100
e_3	St_1	NA	e_{10}	750	22	600	140
e_4	St_2	NA	e_{10}	600	20	550	110
e_5	Sh_1	NA	e_{11}	850	24	400	130
e_6	Sh_2	NA	e_{11}	650	20	480	100
e_7	Bs_1	NA	e_{11} , e_{12}	800	16	450	150
e_8	Bs_2	NA	e_{11} , e_{12}	700	12	650	120
e_9	DA_1	e_1 , e_2	e_{13}	480	25	1200	60
e_{10}	DA_2	e_1 , e_2 , e_3 , e_4	e_{13}	420	20	1000	50
e_{11}	CA_1	e_5 , e_6 , e_7 , e_8	e_{14} , e_{15}	600	22	750	80
e_{12}	CA_2	e_7 , e_8	e_{14} , e_{15}	500	18	900	60
e_{13}	MT_1	e_9 , e_{10}	e_{16} , e_{17}	300	15	2800	40
e_{14}	MT_2	e_{11} , e_{12}	e_{17} , e_{18}	350	20	3200	45
e_{15}	MT_1, MT_2	e_{11} , e_{12}	e_{18} , e_{19}	400	25	3500	50
e_{16}	MT_1	e_{13}	NA	600	10	300	60
e_{17}	MT_1, MT_2	e_{13} , e_{14}	NA	1000	15	420	100
e_{18}	MT_1, MT_2	e_{14} , e_{15}	NA	900	24	480	80
e_{19}	MT_2	e_{15}	NA	550	28	350	45

By summarizing the previous mentioned information, the problem of a VSC configuration for a motor family could be illustrated in Fig. 3.5. The configuration process need go through four domains to determine the variables and values in particular domains. Each domain receives inputs from upstream domains and the output would be sent to downstream domains as their initiatives. The customer order is converted into a set of customer requirements. The product family is tailored into a specific product according to the requirements. Process operations are determined to produce the required materials. Each process is allocated to a capable entity, which in turn becomes a member of the final supply chain configuration.

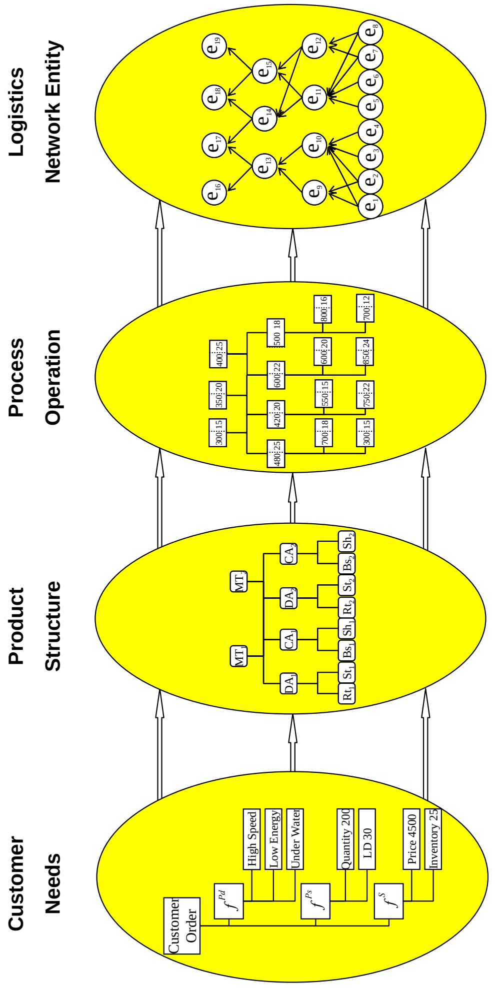


Figure 3.5 Domain mapping of a VSC

3.5 Summary

This chapter proposed the virtual supply chain as a paradigm using information and communication technology (ICT) to address the challenges of mass customization and global manufacturing. First, the “virtual” concept implications are discussed. Typical characteristics of the VSC are identified and illustrated. Subsequently, a domain-based reference model is adopted to build the conceptual framework for the VSC. It reveals the coordination issues among products families, process platforms and logistics networks. A series of precise and rigorous definitions are established to articulate the VSC from an architectural perspective, involving data and information structures, variety configuration, and coordination across different functional areas. Finally, a detailed case study of a motor supply chain network has been investigated.

CHAPTER 4 NESTED MODULAR MODELING FOR THE VIRTUAL SUPPLY CHAIN

This chapter proposes a nested modular approach for the virtual supply chain modeling by using colored Petri-net technology. Basic supply chain elements and processes, i.e. material inventory, material processing, and material transferring, are encapsulated into a series of objects as modular building modules of supply chain models. Final products and relevant constituent components are differentiated as tokens with various colors in the model. A supply chain network is mapped into a series of cascading nested models that each model takes charge of different supply chain decisions and integrates with other models through a socket mechanism. The modular nested model structure facilitates supply chain decision makers to rebuild the network to accommodate varieties in product structures, process operations and logistics channels.

4.1 Petri-net Modeling

The Petri-net technique has been accepted as one of the first concurrent formalism to help solving real time problem due to the ability to model, simulate and control complex flows and processes (Peterson, 1977; Peterson, 1981). Petri nets were first introduced by Petri in the early 1960s (Petri, 1962). Since then, they have been received intensive research and investigation attempting to apply basic Petri net techniques in different problem domains.

As a combination of object-oriented approach and Petri net techniques, the OPNs excel in modeling such systems that are rather large and complex. This is because OPN models are characterized by the encapsulation of physical objects in systems and increased reusability and maintainability of objects in built models (Wang, 1996a; 1996b). Two major elements of an OPN model of a system are objects and message passing relations among interacting objects. The activities and states of an object are also encapsulated in its OPN, thus such object Petri nets are reusable. As a result, the built model of the entire system is more compact, less complex, and consequently more manageable. Differing itself from other Petri nets, a CPN (Zhang, 1989; Jensen, 1992) adds colors to tokens, which in ordinary Petri nets are black. These colors are used to encode different data types and values that are attached to tokens. The presence of colors makes CPNs ideal tools to describe systems that contain many similar (but not identical) interacting components (Jensen, 1992). To accommodate the changes of the system to be modeled, PNs-CS is developed to possess such mechanisms that allow changes to be made to the structures of Petri net models when the system being described changes (Yu *et al.*, 2003). In this way, the changes in the actual system are reflected by the structural changes of the built Petri net models. Li and Lara-Rosano (1999) enhanced the object-oriented colored Petri nets (OOCPNs) with time delay and firing speed to a hybrid-like OOCPN, intending to address the formal modeling of electronic component manufacturing systems, where parts are not processed one by one, but by batch.

In addition to modeling manufacturing systems, Petri nets have been used in software system modeling. For example, Hiraishi (2000) presented a Petri-net based model adopting the classic place/transition nets to mathematically analyze and design multi agent systems. He represented agents using tokens that were place/transition nets also. The developed nested colored object-oriented Petri nets with changeable structures have adopted the same principle as that of the Petri net model of Hiraishi, wherein tokens in the higher-level nets are detailed Petri nets at lower levels. Section 4.2 will give a thorough discussion on the net definitions.

4.2 VSC Net Modeling Formalism

The major issues in virtual supply chain modeling pose some unique requirements on the modeling tool: (i) To accommodate the involved large variety in the way that a concise and easy understandable model can be built; (ii) To handle structure changes so that the built model can be adapted without any difficulties to different configurations; (iii) To address issues concerning the concept selection first, and then granular refinement of these selected concepts until all details have been worked out; and (iv) To deal with multiple constraints at different granularity.

In order to capture all the major issues and solve them accordingly, the modeling formalism of nested colored object-oriented Petri-nets has been developed. The relevant data regarding product items, process elements and manufacturing resources are attached to colored tokens to tackle multiple constraints. Together with Petri-nets, they deal with the large and various varieties involved. Moreover, the concept of net nesting is introduced for coping with granularity issues, such that lower level nets (representing detailed processes) are nested as colored tokens in the higher-level nets. In the modeling formalism, several types of meta nets are defined as the basic building blocks. Each block entails a modular architecture, which could be modified according to the concrete requirements. A meta net ($MNet$) is specified to reflect the basic behaviors of supply chain objects (i.e., material inventory, processing, transferring). A supply net ($SNet$) is defined to reflect a unit which is responsible for providing certain type of raw materials. An assembly net ($ANet$) is introduced to represent the process of producing assemblies and components. Similar to the $SNet$, an $ANet$ denotes the produced assemblies when it is nested in a place of the higher-level Petri nets. A distribution net ($DNet$) is used to represent the processes of delivering materials and products along the supply chain. A supply chain net ($SCNet$) is used to describe the conceptual process of the entire supply chain. While in a system model of supply chain network constructed by using the developed modeling formalism, there may exist a number of $MNets$, $SNets$, $ANets$, and $DNets$, only one $SCNet$ can be found.

4.2.1 Nested Net System

Definition 4-1: A multilevel nested net system is defined as a tuple, $\Omega' = (\Lambda', \Pi')$, where

Ω' is the multilevel nested net system for modeling supply chain network;

Λ' is the supply chain net describing the generic supply chain for a product family; $\Lambda' = (M, S, A, D,)$

Π' indicates the connection between basic supply chain nets; $\Pi' = (PP, SP, \varphi)$

$M = \{m_i\}_{N^M}$ is a finite set of $MNets$, $M = M^1 \cup M^2 \cdots \cup M^O$, where each $M^o = \{m_i^o\}_{N^{M^o}}$, $\forall o \in [1, O]$, is a finite set of $MNets$ representing the behaviors of the objects that are in the same $SNets$ and $ANets$, or $DNets$.

$S = \{S_i\}_{N^S}$ is a finite set of $SNets$, $S = S^1 \cup S^2 \cdots \cup S^P$, where each $S^p = \{s_i^p\}_{N^{S^p}}$, $\forall p \in [1, P]$, is a finite set of $SNets$ nested in such places that are in the same nets at the immediate higher levels.

$A = \{a_i\}_{N^A}$ is a finite set of $ANets$, $A = A^1 \cup A^2 \cdots \cup A^Q$, where each $A^q = \{a_i^q\}_{N^{A^q}}, \forall q \in [1, Q]$ represents the set of $ANets$ that are nested in the same nets at the immediate higher levels.

$PP = \{pp_i\}_{N^{PP}}$ is a finite set of port places representing meta objects in S and A. The messages in the output message places of each pp_i will be sent to the input message places of such meta objects that are connected with those places representing $SNets$ or $ANets$. In other words, the places representing message receiving objects and the places that nest $SNets$ or $ANets$ of port places belong to the same nets.

$SP = \{sp_j\}_{N^{SP}}$ is a finite set of socket places indicating meta objects in A. The input message places of each sp_j will receive messages sent from meta objects of the associated pp_i that belong to the lower level $SNets$ or $ANets$, which are represented by the places connected to sp_i in the same $ANets$ or $DNets$.

$\varphi(pp_i): PP \to SP$ is a port place assignment function. It is defined from PP to SP, so as to establish a binary relationship.

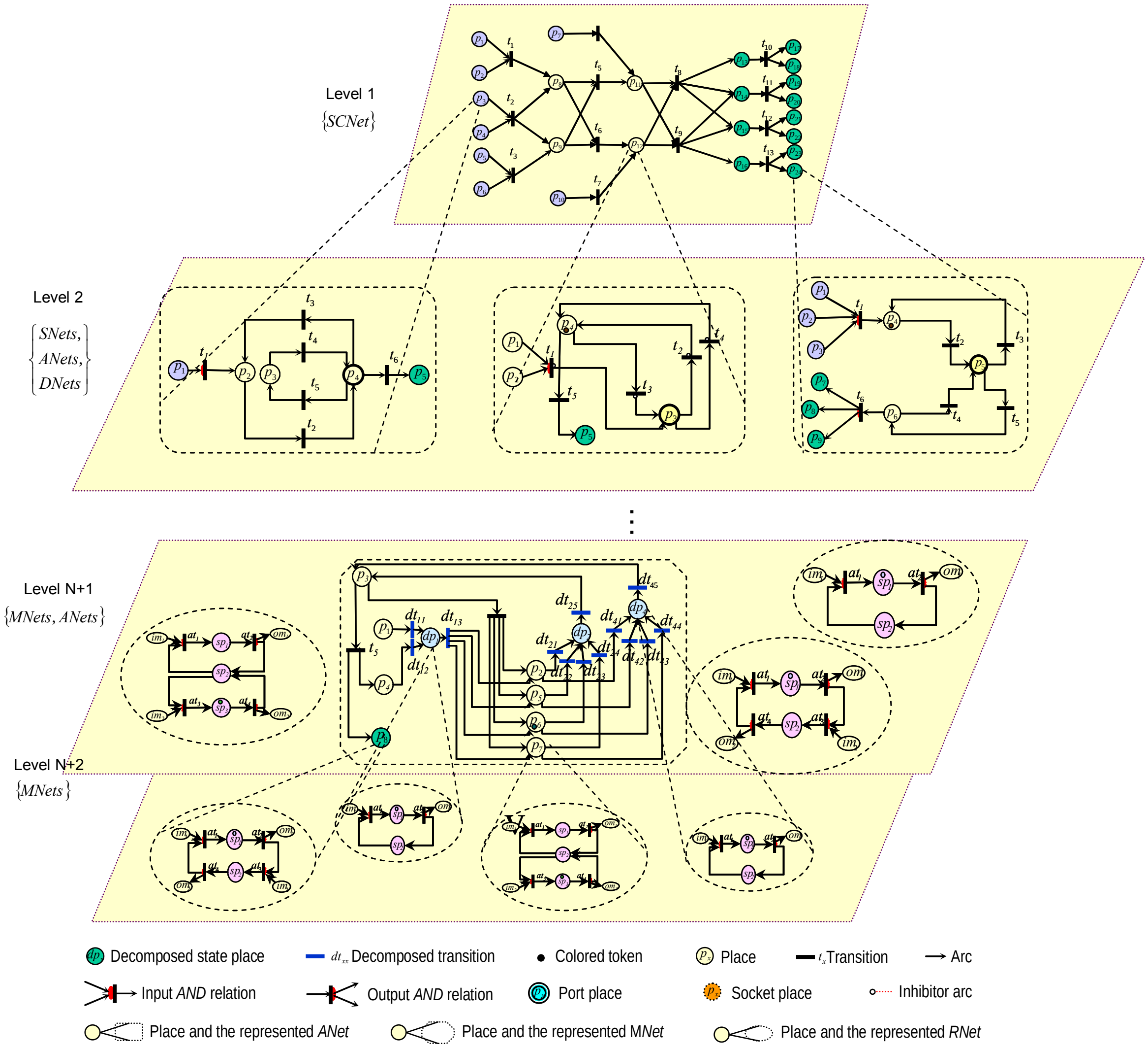


Figure 4.1 An example of nested net systems

Performing as an abstraction mechanism, Ω facilitates the supply chain configuration with right amount of details. Within Ω, the highest level is $SCNet\ \Lambda$, while a number of $SNets$, $ANets$ and $DNets$ are located at the second level. Each of these nets provides more details for the respective places in the $SCNet$. The nets at lower level provide detailed descriptions of the assembly and manufacturing processes nested in the places of the nets at its immediate higher level. A mixture of $SNets$, $ANets$, $DNets$ and $MNets$ can be found at any middle level. Fig. 4.1 demonstrates an N+2 level net system with nested $SNets$, $ANets$, $DNets$, as well as encapsulated *MNets* . Table 4.1 summarizes descriptions of places and transitions of different nets at each level.

Table 4.1 Legends for Level 1 in Fig. 4.1

Place	**Role Description**	**Place**	**Role Description**
$p_1 - p_6$	Raw material suppliers S_1-S_6 & its manufacturing process	$t_1 - t_3$	Transferring transitions from raw material suppliers to component assemblies
p_7	Component suppliers S_7 &its manufacturing process	$t_1 - t_3$	Transferring transitions from component suppliers to product assemblies
$p_8 - p_9$	Component assembly A_1,A_2 & its assembly process	$t_5 - t_6$	Transferring transition from component assemblies to product assemblies
p_{10}	Component suppliers S_{10} &its manufacturing process	$t_8 - t_9$	Transferring transitions from assemblies to distributors
$p_{11} - p_{12}$	Final product assembly A_3, A_4 & its operation	$t_{10} - t_{13}$	Transferring transition from distributors to retailers
$p_{13} - p_{16}$	Distributors D_1-D_4		
$p_{17} - p_{24}$	Retailers R_1-R_8		

Table 4.2 Legends for Level 2 in Fig. 4.1

SNet	**Role Description**	***ANet***	**Role Description**	***DNet***	**Role Description**
p_1	Input buffer in a part's *SNet*	$p_1 - p_2$	Components c_1, c_2 & their *SNet*	$p_1 - p_3$	Product P_1 & its *ANet*
p_2	Raw material inventory in a part's *SNet*	p_3	Assembly machine &its operation in a *ANet*	p_4	Input inventory buffer of a *DNet*
p_3	WIP inventory in a part's *SNet*	p_4	Inventory buffer in a product's *ANet*	p_5	Material handler of a *DNet*
p_4	A machining machine &its machining operation	p_5	Output buffer in a product's *ANet*	p_6	Output inventory buffer of a *DNet*
p_5	Output buffer in a part *SNet*			$p_7 - p_9$	Customers of a *DNet*
t_1	Material transferring into a *SNet*	t_1	Parts transferring from a *SNet* to an *ANet*	t_1	Products transferring from an *ANet* to a *DNet*
$t_2 - t_3$	Transferring between a machine & its raw material inventory	$t_2 - t_4$	Transferring transactions between a machine & its inventory	$t_2 - t_3$	Transferring transactions between material handler & input inventory buffer
$t_4 - t_5$	Transferring transactions between a machine & its WIP inventory	t_5	Material transferring out from an *ANet*	$t_4 - t_5$	Transferring transactions between material handler & output inventory buffer
t_6	Material transferring out from a *SNet*			t_6	Product transferring out from a *DNet*

Table 4.3 Legends for Level N+1 in Fig. 4.1

Place	Role Description	Place	Role Description
p_1	Raw material inventory	p_8	Output inventory buffer
p_2	A machining machine & its machining operation	dp_1	Decomposed state place of the transition t_1
p_3	A transferring place	dp_2	Decomposed state place of the transition t_2
p_4	WIP inventory buffer	dp_4	Decomposed state place of the transition t_4
p_5	A machining machine & its machining operation	$dt_{11/12/13}$	Decomposed transitions of t_1
p_6	A machining machine & its machining operation	$dt_{21/22/23/24/25}$	Decomposed transitions of t_2
p_7	A machining machine & its machining operation	$dt_{41/42/43/44/45}$	Decomposed transitions of t_4

Message exchange among objects between two nets at adjacent levels is implemented through the port places at the lower level nets and the socket places at the higher level nets. Fig. 4.2 illustrates such a mechanism. When a token representing a part is produced in the *SNet* at level i+1, which is nested in place p_2 in the *ANet* at level i, it is loaded into the output buffer represented by place p_6. Then a token with the same color appears in place p_2 in the *ANet* at level i. Meanwhile, a message requesting machine setup from the output buffer p_6 in the nested *SNet* is sent to the place p_3, representing an assembly machine, in the *ANet* at level i.

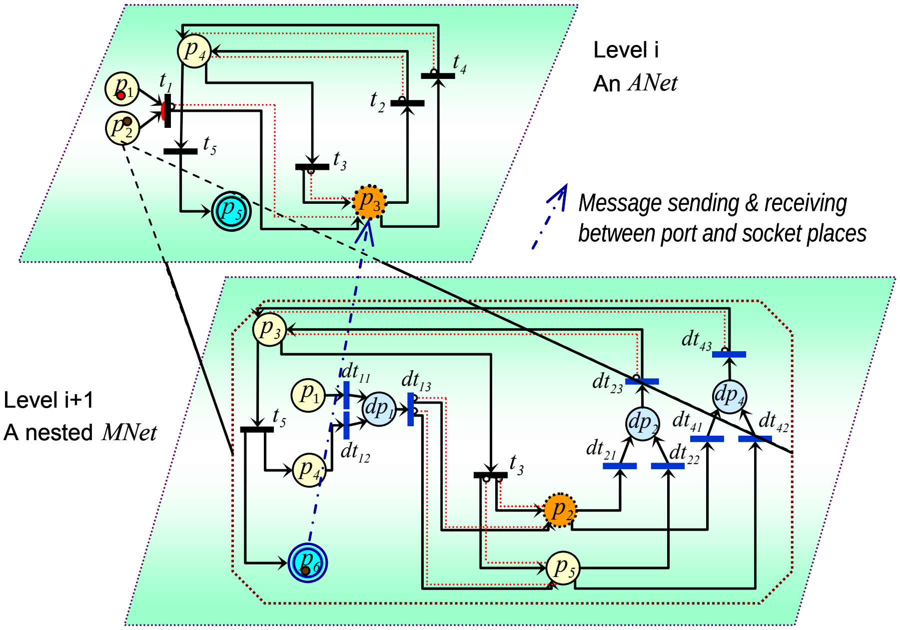


Figure 4.2 Communication between nets through port and socket places

4.2.2 Net Definition

4.2.2.1 Meta Net

A supply chain integrates and controls a series of material-related activities and information. For large and complex system models, analysis of them becomes very difficult, if not impossible. However, for each unit or object in the system, analysis is much easier because it has much smaller number of states and activities with a simpler structure. The basic elements and activities of a supply chain are material transferring, material processing and material inventory. The complex activities executed in the supply chain, such as supplying, assembling, warehousing, are the combination of basic elements. Each of the basic elements performs certain functionality that is achieved through the internal events, and thus can be modeled as OPNs from an object-oriented perspective.

Definition 4-2: A meta net is defined as a tuple, $MNet = \left(G^{OPN},\, \omega\right)$, where $MNet$ is a meta net which includes three types of basic nets, $MNet \equiv INet \cup PNet \cup TNet$. Here $INet$ represents a type of inventory buffer, including raw materials, work-in-processes and final products. $PNet$ refers to processing machines, such as tooling or assembling machines. $TNet$ stands for material transferring handlers, e.g. vehicle, ship and airplane.

G^{OPN} is a structure of OPN, $G^{OPN} = \left(SP, IM, OM, AT, C^{SP}, C^{IM}, C^{OM}, C^{AT}, I^{id}, O^{id}\right)$;

$SP = \{sp_i\}_{N^{SP}}$ is a finite set of state places; $IM = \{im_k\}_{N^{IM}}$ is a finite set of input message places; $OM = \{om_l\}_{N^{OM}}$ is a finite set of output message places; and $AT = \{at_j\}_{N^{AT}}$ is a finite set of activity transitions;

$C^{SP}(i) = \left\{c_j^{sp_i}\right\}_{N^{sp_i}}$ is a set of colored tokens associated with a state place sp_i;

$C^{IM}(k) = \left\{c_j^{im_k}\right\}_{N^{im_k}}$ is a set of colored tokens associated with an input message place im_k;

$C^{OM}(l) = \left\{c_j^{om_l}\right\}_{N^{om_l}}$ is a set of colored tokens associated with an output message place om_l;

$C^{AT}(j) = \left\{c_i^{at_j}\right\}_{N^{at_j}}$ is a set of colored tokens associated with an activity transition at_j;

$I^{id}\left(SP,\, AT/c^{at_j}\right): C^{SP} \times C^{AT} \to C^{SP} \cup \phi$ is an input identity function for arcs that connect state places SP or input message places IM to activity transitions AT with a firing colored token, $c^{at_j} \in C^{AT}(j), \exists j \in \left[1,\, N^{AT}\right]$;

$O^{id}\left(SP,\ AT/c^{at_j}\right): C^{SP} \times C^{AT} \rightarrow C^{SP} \cup \phi$ is an output identity function for arcs that connects activity transitions AT with a firing colored token, c^{at_j}, to state places SP or output message places OM;

$\omega : \left(SP \rightarrow M^{C^{SP}}, IM \rightarrow M^{C^{IM}}, OM \rightarrow M^{C^{OM}}\right)$ is a marking function, such that $\omega(SP) = M^{C^{SP}}, \omega(IM) = M^{C^{IM}}, \omega(OM) = M^{C^{OM}}$, where $M^{C^{SP}}$, $M^{C^{IM}}$ and $M^{C^{OM}}$ are the families of all multi-sets over C^{SP}, C^{IM} and C^{OM}, respectively.

The set of state places, $\{sp_i\}_{N^{SP}}$, specifies all possible states that an object may possess. As shown in Fig. 4.3 and Table 4.4, a processing machine has 3 states, namely idle, setting up and processing. A material transferring handler possesses 2 states, i.e., idle, transferring materials between buffers and machines. All types of inventory buffers assume two states: idle vs. occupied. The buffer could be used to store raw materials, WIPs and finished products.

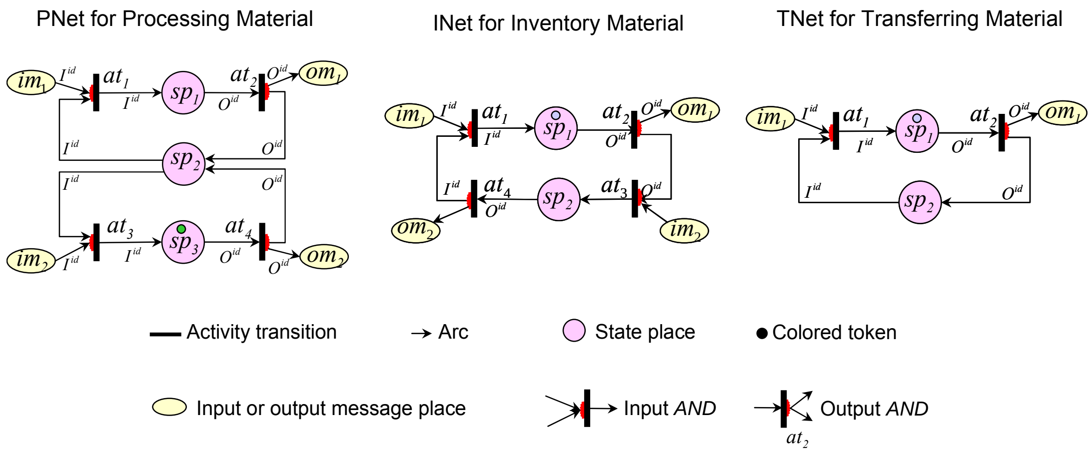


Figure 4.3 States and activities of MNet objects

To enable communication among objects, input message places IM and output message places OM are defined as the interface for objects to send and receive messages (i.e. tokens). For example, in Fig. 4.3, im_1 of the $INet$ for an inventory buffer is used for receiving those messages sent by machines or entities with request for storing materials. om_1 holds the messages to notify other objects about the completion of materials loading. AT describes all activities that a meta object can execute. Input identity functions $I^{id}\left(SP, AT/c^{at_j}\right)$ and $I^{id}\left(IM, AT/c^{at_j}\right)$ specify the set of pre-conditions for enabling AT with a colored token, c^{at_j}, whilst output identity functions $O^{id}\left(SP, AT/c^{at_j}\right)$ and $O^{id}\left(OM, AT/c^{at_j}\right)$ regulate the set of post-conditions of the firing of AT. ω represents the marking of the object after transition firing.

Table 4.4 Legends in Fig. 4.3

Place	***PNet***	***INet***	***TNet***
im_1	A request for setting up	A message of material ready coming	A request of materials for transferring materials
im_2	A request for loading materials	A message of buffer occupied	
om_1	A message of completing setup	A message of material ready going	A message of materials transferring completion
om_2	A message of completing materials processing	A message of buffer idle	
sp_1	Setting up	Inventory buffer occupied	Materials transferring
sp_2	Idle	Inventory buffer idle	Idle and capacity available
sp_3	Processing materials		
at_1	Start setting up	Start loading materials	Start transferring
at_2	End setting up	End loading materials	End transferring
at_3	Start processing materials	Start unloading materials	
at_4	End materials processing	End unloading materials	

The dynamic behavior of a meta object is characterized by the set of state places, $\{sp_i\}_{N^{SP}}$, and the set of activity transitions, $\{at_j\}_{N^{AT}}$. Only when the connected input state place sp_i and message place im_k hold the colored tokens as specified by the input identity functions, i.e., $\omega(sp_i) \geq I^{id}\left(sp_i, at_j / c^{at_j}\right)$ and $\omega(im_k) \geq I^{id}\left(im_k, at_j / c^{at_j}\right)$, can an activity of at_j be carried out, that is, activity transition at_j is activated. The firing of at_j results in the removal of tokens from the set of input places as specified by the input identity functions and the addition of colored tokens to the set of connected output places as specified in the output identify functions.

To accommodate process variations, e.g. adding or removing resources, or changing the execution order of two machining or non-machining operations, the OPNs with changeable structures (OPNs-cs) in Jiang *et al*. (1999) is adopted to define the net structure $G^{OPNs-cs}$ of a $MNet$. The set of places, $\{p_i\}_{N^P}$, are defined for the set of meta objects. Each place p_i carries out either a machining operation or transferring operation. Therefore, the set of colored tokens, $\{c_j^{p_i}\}_{N^{p_i}}$, associated with each place p_i are used to represent the operations, the employed meta objects, as well as the corresponding product items.

Furthermore, the set of transitions $\{t_j\}_{N^T}$ specifies the starting or ending of the relevant operations. The colored token of each transition t_j is defined exactly the same as that of its input place. The input and output transform functions specify the type and number of colored tokens to be removed/added from/to the relevant input and output places. In other words, each transition t_j, colored token set $\{c_i^{t_j}\}_{N^{t_j}}$, and the associated input and output transform functions determine the message passing relationship between two places, p_a and p_b, in accordance with the flow of a part's manufacturing process. If a transition, t_j, is to be activated with respect to a firing colored token, c^{t_j}, each of its input place p_i must contain colored tokens, the type and number of which should be greater or equal to the one specified by the input transform function, e.g. $\mu(p_i) \geq I(p_i, t_j / c^{t_j})$, $p_i \in {}^\circ t_j$.

4.2.2.2 Supply Net

Definition 4-3: A supply net is defined as a tuple, $SNet = (G^{OPNs-cs}, \mu)$, where $SNet$ represents a supplier that provides certain material.

$G^{OPNs-cs}$ is a system of OPNs, $G^{OPNs-cs} = (P, T, C^P, C^T, I, O)$, where

$P = \{p_i\}_{N^P}$ is a finite set of places, representing the set of meta objects involved in the supplier entity;

$T = \{t_j\}_{N^T}$ is a finite set of transitions, where T_1 is a set of input OR relation transition (e.g. transitions with input arcs bearing OR relations), and T_2 is a set of ordinary transitions;

$C^P(i) = \{c_j^{p_i}\}_{N^{p_i}}$ is a finite set of colored tokens associated with a place p_i;

$C^T(j) = \{c_i^{t_j}\}_{N^{t_j}}$ is a finite set of colored tokens associated with a transition t_j;

$I(p_i, t_j / c^{t_j}) : C^P(i) \times C^T(j) \rightarrow C^P(i) \cup \phi$ is an input transform function for an arc (p_i, t_j), $\forall p_i \in {}^\circ t_j$. It connects a place to a transition with a firing colored token c^{t_j};

$O(p_i, t_j / c^{t_j}) : C^P(i) \times C^T(j) \rightarrow C^P(i) \cup \phi$ is an output transform function for an arc (p_i, t_j), $\forall p_i \in t_j^\circ$. It connects a transition with a firing colored token c^{t_j} to a place;

$\mu : P \rightarrow M^{C^P}$ is a marking function, $\mu(P) = M^{C^P}$, where M^{C^P} is the family of all multi-sets over C^P.

The basic activities or events of a supplier are material transferring, material processing and material inventory. Therefore, a supply net is the combination of meta nets, which are $PNet$, $TNet$, and $INet$. Fig. 4.4 shows an example of a supply net which consists of a $TNet$ and a $PNet$. Firstly, the raw material is transferred into the supply net through a $TNet$. Then it will go through steps such as machine set-up, machining processes. The produced part is the output of the $PNet$. Finally, the parts are transferred to the succeeding $SNet$ or $ANet$. Based on the diversified operational environments, the $SNets$ differ in the role, function and position of its meta nets. For example, one $SNet$ might adopts three $PNets$ in a sequential manner without storing the materials in an $INet$. Another $SNet$ might employs several $INets$ and $TNets$ to separate the $PNets$, in order to provide good customization service.

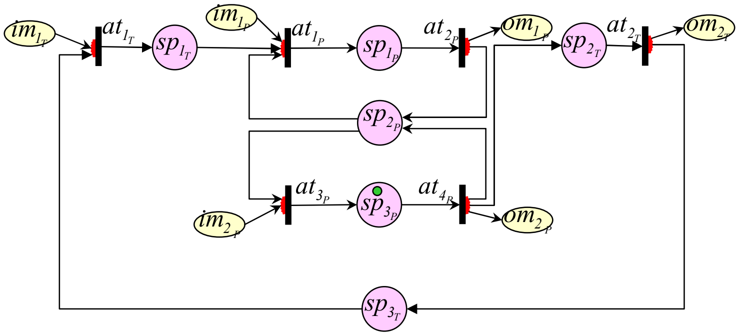


Figure 4.4 An example of supply nets

4.2.2.3 Assembly Net

Definition 4-4: An assembly net is defined as a tuple, $ANet = \left(G^{OPNs-cs}, \mu\right)$, where $ANet$ represents an assembly entity that provides a component, subassembly or assembly.

$G^{OPNs-cs}$ is a system of OPNs, $G^{OPNs-cs} = \left(P, T, C^P, C^T, I, O\right)$, where T, C^T, I, O, and μ carry the same meaning as that for $SNet$.

P is a finite set of places, $\{p_i\}_{N^P}$, $P = P^1 \cup P^2$, where $P^1 = \{p_i^1\}_{N^{P^1}}$ is a set of places corresponding to $SNets$ and/or lower level $ANets$ of child assemblies;

$P^2 = \{p_i^2\}_{N^{P^2}}$ is a set of places representing the meta objects; and $P^1 \cap P^2 = \phi$, $N^{P^1} + N^{P^2} = N^P$.

C^P is a finite set of colored tokens associated with all places, $C^P = C^{P^1} \cup C^{P^2}$, where each $C^{P^1}(i) = \{c_j^{p_i^1}\}_{N^{IFp_i^1}}$ is a set of colored tokens associated with a place p_i^1, indicating the set of part or assembly variants of a family produced by the nested $SNet$ or $ANet$ at the lower level; and $C^{P^2}(j) = \{c_i^{p_j^2}\}_{N^{p_j^2}}$ is a set of colored tokens associated with a meta object p_j^2.

The $ANet$ is defined to represent the processes of producing a family of assemblies. Changes to component items that form assembly variants cause variations in the corresponding assembly processes. To deal with such process changes, the structural change handling mechanism is introduced to the $ANet$. Unlike those places in a $SNet$, the places in an $ANet$ may not be always related to the meta objects. Rather, they are also defined for the child parts and child assemblies produced by the $SNets$ or $ANets$. If a place p_i is defined for $MNets$ or $ANets$ at a lower level, the set of colored tokens, $\{c_j^{p_i^1}\}_{N^{IFp_i^1}}$, are specified to indicate the set of similar item variants (either parts or assemblies), which are produced by the processes nested in the places. If it represents a meta object, the set of colored tokens are assigned according to the process flow of the assembly and used to indicate the assembly operations or non-assembly operations along with the associated meta objects. Fig. 4.5 gives an example of an assembly net.

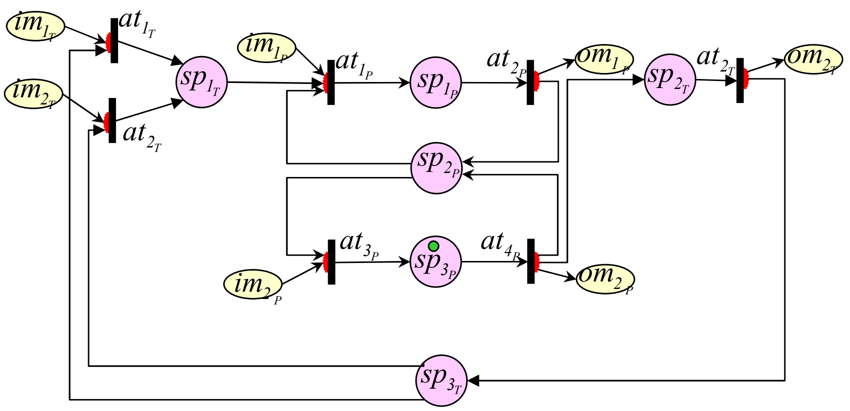


Figure 4.5 An example of assembly nets

4.2.2.4 Distribution Net

Definition 4-5: A distribution net is defined as a tuple, $DNet = \left(G^{OPNs-cs}, \mu\right)$, where $DNet$ represents a distribution entity of the supply chain. $G^{OPNs-cs} = \left(P, T, C^P, C^T, I, O\right)$, where T, C^T, I, O, and μ carry the same meaning as that for $SNet$.

P is a finite set of places, $\{p_i\}_{N^P}$, $P = P^1 \cup P^2$, where $P^1 = \{p_i^1\}_{N^{P^1}}$ is a set of places corresponding to lower level $DNets$; $P^2 = \{p_i^2\}_{N^{P^2}}$ is a set of places representing the meta transferring objects and inventory objects; and $P^1 \cap P^2 = \phi$, $N^{P^1} + N^{P^2} = N^P$.

C^P is a finite set of colored tokens associated with all places, $C^P = C^{P^1} \cup C^{P^2}$, where each $C^{P^1}(i) = \left\{c_j^{p_i^1}\right\}_{N^{IFp_i^1}}$ is a set of colored tokens associated with a place p_i^1, indicating the set of part or assembly variants of a family produced by the nested $SNet$ or $ANet$ at the lower level; and $C^{P^2}(j) = \left\{c_i^{p_j^2}\right\}_{N^{p_j^2}}$ is a set of colored tokens associated with a meta object p_j^2.

A $DNet$ is defined to represent the processes of distributing the materials along the supply chain. It ranges from suppliers to manufacturers, from manufacturers to warehouses, and from warehouses to retailers or customers. Since customer requirements are always changing, the distribution network of a supply chain is not fixed. The structural change handling mechanism is introduced to the $DNet$. As shown in Fig. 4.6, the $DNet$ has three inputs which represents the material sources of $ANets$ or $DNets$. It has three outputs, which connect to other $DNets$.

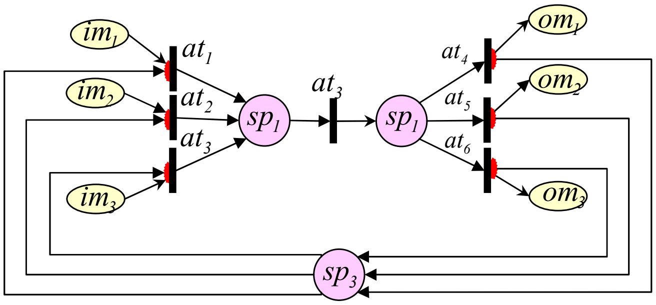


Figure 4.6 An example of distribution nets

4.2.2.5 Supply Chain Net

Definition 4-6: A supply chain net is defined as a tuple, $SCNet = \left(G^{OPNs-cs}, \mu\right)$, where $SCNet$ represents a supply chain network of producing a family of end products and delivering it to customers.

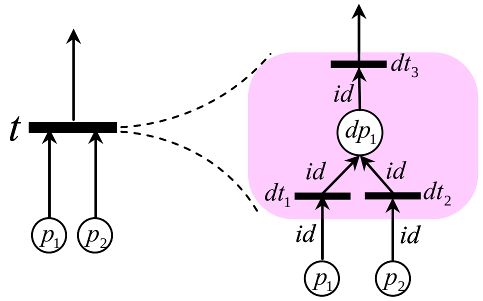
$G^{OPNs-cs}$ is a system of OPNs, $G^{OPNs-cs} = \left(P, T, C^P, C^T, I, O\right)$, where T, C^T, I, O, and μ carry the same meaning as that for $SNet$.

$P = \{p_i\}_{N^P}$ is a finite set of places, $P = P^S \cup P^A \cup P^D$, where $P^S = \{p_i^S\}_{N^{P^S}}$ is a set of places corresponding to $SNets$; $P^A = \{p_i^A\}_{N^{P^A}}$ is a set of places representing $ANets$; $P^D = \{p_i^D\}_{N^{P^D}}$ is a set of places indicating $DNet$; and $P^S \cap P^A \cap P^D = \phi$, $N^{P^S} + N^{P^A} + N^{P^D} = N^{P^{SC}}$.

C^P is a finite set of colored tokens associated with all places, $C^P = C^{P^S} \cup C^{P^A} \cup C^{P^D}$, where each $C^{P^S}(i) = \left\{c_j^{p_i^S}\right\}_{N^{PFp_i^S}}$ is a set of colored tokens associated with a place, p_i^S, and indicates the set of similar part variants produced by the represented $SNet$; $C^{P^A}(i) = \left\{c_j^{p_i^A}\right\}_{N^{AFp_i^A}}$ is a set of colored tokens associated with a place, p_i^A, and indicates the set of assembly variants produced by the represented $ANet$; and $C^{P^D}(i) = \left\{c_j^{p_i^D}\right\}_{N^{p_i^D}}$ is the set of colored tokens associated a place, p_i^D, and indicates the set of end product variants delivered by the represented $DNet$.

A $SCNet$ is defined for the abstract processes of producing a family of products. Similar to an $ANet$, the structural change handling mechanism is employed in $SCNet$ to handle the variations. The places in a $SCNet$ are specified to represent either meta objects carrying out certain operations, or $SNets$ manufacturing parts, or $ANets$ producing assemblies. If a place p_i is defined for a $SNet$ or $ANet$, the set of colored tokens, $\left\{c_j^{p_i^S}\right\}_{N^{PFp_i^S}}$ or $\left\{c_j^{p_i^A}\right\}_{N^{AFp_i^A}}$, are specified to indicate the set of part or assembly variants in a family. If a place p_i is specified to represent a meta object, the set of colored tokens are used to indicate the operations carried out by the objects.

To specify firing conditions for transitions with respect to firing colored tokens, each of these transitions, e.g. t_1 in a $SNet$, $ANet$ or $SCNet$, is decomposed into several input transitions, along with a state place and an output transition. As shown in Fig. 4.7, the decomposed input and output transform functions as well as the state place are assigned with the same colored tokens as those associated with the input places of the original transition.



Identity function
$$id \rightarrow \begin{cases} I\left(p_i, dt_j / c^{t_j}\right) = c^{t_j} \\ O\left(p_i, dt_j / c^{t_j}\right) = c^{t_j} \end{cases}$$

Figure 4.7 Transition decomposition

For a single meta object, whose number is one, there may have more than one input arc. Therefore, conflict may occur when multiple objects or sub-processes require a single object to perform multiple operations at the same time. To maintain a 1-bounded property and the safeness of an object place, inhibitor arcs, $Inh\left(p_i, t_j\right), \forall t_j \in {}^{\circ}p_i$, are introduced to these objects (Wang and Wu, 1998). The inhibitor arcs of a resource object are drawn from the set of input transitions to the single object. Different from those general input arcs, inhibitor arcs are indicated as dotted line with circles at the transition ends. If $Inh\left(p_i, t_j\right) = 1$, it implies that no operation request can be passed to the object represented by the place p_i unless the object is not occupied, that is, there is no token in the place.

4.3 Case Study

The modeling formalism is tested using an industrial case of motor production. Fig. 4.8 shows the generic supply chain network of two types of motors, MT_1 and MT_2. For illustration simplicity, only main parts and assemblies are reflected in the supply chain network. As shown in Fig. 4.8, the generic supply chain network of motors is divided into three parts: supply, assembly and distribution. Each node has several alternative options, which represent independent organizations with unique competency. The CPN formalism is adopted to graphically and symbolically represent a supply chain net, which is further decomposed to supply nets, assembly nets and distribution nets.

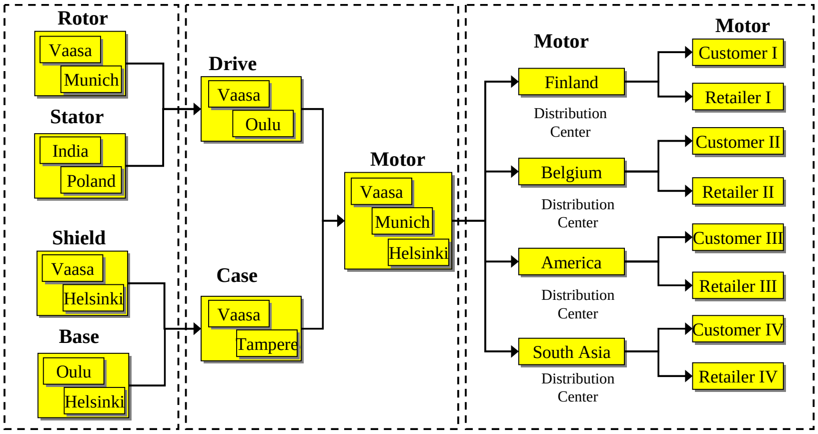


Figure 4.8 The generic supply chain network of motor products

4.3.1 Specification of a *SCNet*

In accordance with specifications of the product structure and supply entities at the first level of the supply chain network, two conceptual supply chains are determined for MT_1 and MT_2, respectively. A conceptual supply chain reflects the material flow of a number of items (parts and/or assemblies) rather than the detailed processes of manufacturing a part. Both the two supply chains share the same network structure, whereas the configurations of supply chain are determined by the specification of two products. The *SCNet* for the motor products is shown in Fig. 4.9. The relevant material flows for MT_1 and MT_2 are detailed in Table 4.5.

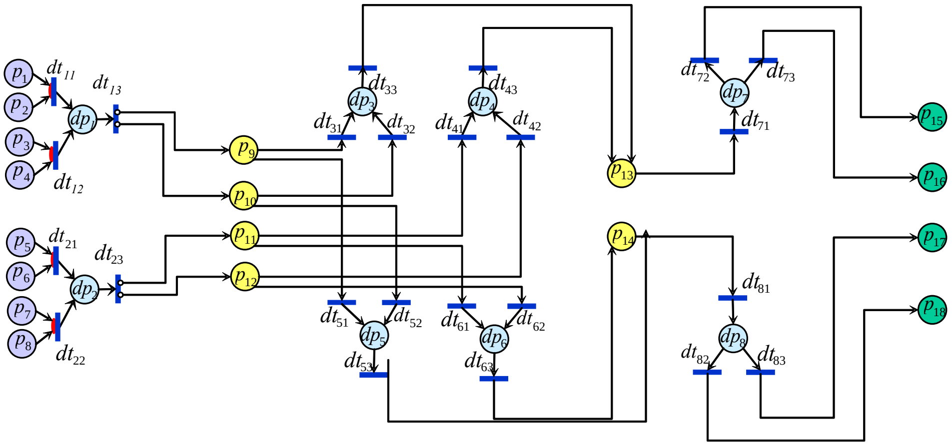


Figure 4.9 The *SCNet* for motor products

Table 4.5 Material flow of MT_1 and MT_2

Process flow of MT_1			**Process flow of** MT_2		
Operations	**Resource (process)/Place**	**Colored Token**	**Operations**	**Resource (process)/ Place**	**Colored Token**
Part Rt_1 is fabricated	Manufacturing processes p_1 , p_2	Rt_1	Part Rt_2 is fabricated	Manufacturing processes p_1 , p_2	Rt_2
Part St_1 is fabricated	Manufacturing processes p_3 , p_4	St_1	Part St_2 is fabricated	Manufacturing processes p_3 , p_4	St_2
Part Sh_1 is fabricated	Manufacturing processes p_5 , p_6	Rt_1	Part Sh_2 is fabricated	Manufacturing processes p_5 , p_6	Sh_2
Part Bs_1 is fabricated	Manufacturing processes p_7 , p_8	Bs_1	Part Bs_2 is fabricated	Manufacturing processes p_7 , p_8	Bs_2
Assembly DA_1 is produced	Assembly processes p_9 , p_{10}	DA_1	Assembly DA_2 is produced	Assembly processes p_9 , p_{10}	DA_2
Assembly CA_1 is produced	Assembly processes p_{11} , p_{12}	CA_1	Assembly CA_2 is produced	Assembly processes p_{11} , p_{12}	CA_2
Product MT_1 is produced	Assembly process p_{13}	$MT_1.0$	Product MT_2 is produced	Assembly process p_{14}	$MT_2.0$
Product MT_1 is distributed	Transferring process t_7	$MT_1.0$	Product MT_2 is transferred	Transferring process t_8	$MT_2.0$
Product MT_1 is stored	Distribution center p_{15}	$MT_1.1$	Product MT_2 is stored	Distribution center p_{16}	$MT_2.1$

The $SCNet$ is constructed according to the material flows of the configured supply chain network. The places representing entities, operations and meta objects, with their relevant colored tokens, are shown in Table 4.6. In Fig. 4.9, dt_{xx} and dp_{xx} denote the decomposed transitions and state places of transitions, $t_1 - t_8$. The colored token in places indicates that one part or product has been produced. To deal with supply chain entity changes, e.g. removal of supplier p_3 from MT_1 production process, the structural change mechanism is enacted to modify input/output transform functions through the message sending and receiving relations in the $SCNet$.

Table 4.6 shows the detailed list of colored tokens assigned to the places and transitions (including those decomposed transitions and state places), as well as input and output transform functions. Generalizing the two variant cases to the motor family, the colored tokens assigned to places and transactions indicate all the family members that are produced by the nested supply chains.

Table 4.6 Descriptions of the $SCNet$ in Fig. 4.9

Place	Colored Token	Transition	Colored Token	Input Arc	Input Function	Output Arc	Output Function
p_1, p_2	$\{Rt_1, Rt_2\}$	t_1 $(dt_{11}, dt_{12}, dt_{13})$	$\{Rt_1, Rt_2, St_1, St_2\}$	$(p_1, t_1)(p_2, t_1)$	$\{Rt_1St_1, Rt_2St_2\}$	(dp_1, dt_{13})	$\{Rt_1, Rt_2, St_1, St_2\}$
p_3, p_4	$\{St_1, St_2\}$			$(p_3, t_1)(p_4, t_1)$	$\{Rt_1St_1, Rt_2St_2\}$		
p_5, p_6	$\{Sh_1, Sh_2\}$	t_2 $(dt_{11}, dt_{12}, dt_{13})$	$\{Sh_1, Sh_2, Bs_1, Bs_2\}$	$(p_5, t_2)(p_6, t_2)$	$\{Sh_1Bs_1, Sh_2Bs_2\}$	(dp_2, dt_{23})	$\{Sh_1, Sh_2, Bs_1, Bs_2\}$
p_7, p_8	$\{Bs_1, Bs_2\}$			$(p_7, t_2)(p_8, t_2)$	$\{Sh_1Bs_1, Sh_2Bs_2\}$		
p_9	$\{DA_1, DA_2\}$	t_3	$\{DA_1, DA_2\}$	$(p_9, t_3)(p_9, t_5)$	$\{DA_1CA_1, DA_2CA_2\}$	(dp_3, dt_{33})	$\{DA_1CA_1, DA_2CA_2\}$
p_{10}	$\{DA_2\}$	t_4	$\{CA_1, CA_2\}$	$(p_{10}, t_3)(p_{10}, t_5)$	$\{DA_2CA_2\}$	(dp_4, dt_{43})	
p_{11}	$\{CA_1, CA_2\}$	t_5	$\{DA_1, DA_2\}$	$(p_{11}, t_4)(p_{11}, t_6)$	$\{DA_1CA_1, DA_2CA_2\}$	(dp_5, dt_{53})	$\{DA_1CA_1, DA_2CA_2\}$
p_{12}	$\{CA_2\}$	t_6	$\{CA_1, CA_2\}$	$(p_{12}, t_4)(p_{12}, t_6)$	$\{CA_2DA_2\}$	(dp_6, dt_{63})	
p_{13}	$\{MT_1.0\}$	t_7	$\{MT_1.0\}$	(p_{13}, t_7)	$\{MT_1.0\}$	$(dp_{72}, p_{15})(dp_{73}, dt_{16})$	$\{MT_1.1\}$
p_{14}	$\{MT_2.0\}$	t_8	$\{MT_2.0\}$	(p_{14}, t_8)	$\{MT_2.0\}$	$(dp_{82}, p_{17})(dp_{83}, dt_{18})$	$\{MT_2.1\}$

4.3.2 *SNet* for a Part Family

Fig. 4.10 illustrates the *SNet* for a part family, consisting of two variants, Rt_1 and Rt_2. Their respective manufacturing processes are configured as shown in Table 4.7, where colored tokens are specified to represent both the operations and employed manufacturing resources.

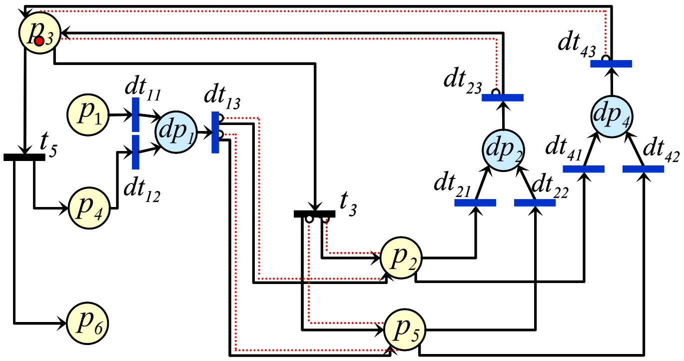


Figure 4.10 The *SNet* for part variants Rt_1 and Rt_2

Table 4.7 Process flow and colored tokens for part variants Rt_1 and Rt_2

Process flow of Rt_1			**Process flow of Rt_2**		
Operations	**Resource/Place**	**Colored Token**	**Operations**	**Resource/Place**	**Colored Token**
Staying in buffer	Input buffer/ p_1	$Rt_1 \cdot 0$	Staying in buffer	Input buffer/ p_1	$Rt_2 \cdot 0$
RtM_1 setting up	RtM_1 / p_2	$Rt_1 \cdot 1$	RtM_2 setting up	RtM_2 / p_5	$Rt_2 \cdot 1$
Being transferred	Material handler/ p_3	$Rt_1 \cdot 2$	Being transferred	Material handler/ p_3	$Rt_2 \cdot 2$
Being machined	RtM_1 / p_2	$Rt_1 \cdot 3$	Being machined	RtM_2 / p_5	$Rt_2 \cdot 3$
Being transferred	Material handler/ p_3	$Rt_1 \cdot 4$	Being transferred	Material handler/ p_3	$Rt_2 \cdot 4$
Staying in buffer	WIP buffer/ p_4	$Rt_1 \cdot 5$	Staying in buffer	WIP buffer/ p_4	$Rt_2 \cdot 5$
RtM_2 setting up	RtM_2 / p_5	$Rt_1 \cdot 6$	RtM_1 setting up	RtM_1 / p_2	$Rt_2 \cdot 6$
Being transferred	Material handler/ p_3	$Rt_1 \cdot 7$	Being transferred	Material handler/ p_3	$Rt_2 \cdot 7$
Being machined	RtM_2 / p_5	$Rt_1 \cdot 8$	Being machined	RtM_1 / p_2	$Rt_2 \cdot 8$
Being transferred	Material handler/ p_3	$Rt_1 \cdot 9$	Being transferred	Material handler/ p_3	$Rt_2 \cdot 9$
Staying in buffer	Output buffer/ p_6	Rt_1	Staying in buffer	Output buffer/ p_6	Rt_2

Table 4.8 summarizes specifications of all the places, transitions, colored tokens, input and output arcs and transform functions defined for the $SNet$. The colored tokens are assigned to different places, thus differentiating specific operations related to individual part variants of the family.

Table 4.8 Colored tokens, input and output transform functions for the $SNet$

Place	Colored Token	Transition	Colored Token	Input Arc	Input Arc Function	Output Arc	Output Arc Function
p_1	$\{Rt_1\cdot 0, Rt_2\cdot 0\}$	dt_{11}	$\{Rt_1\cdot 0, Rt_2\cdot 0\}$	(p_1, dt_{11})	$\{Rt_1\cdot 0, Rt_2\cdot 0\}$	(dp_1, dt_{11})	$\{Rt_1\cdot 0, Rt_2\cdot 0\}$
p_2	$\{Rt_1\cdot 1, Rt_1\cdot 3, Rt_2\cdot 6, Rt_2\cdot 8\}$	dt_{12}	$\{Rt_1\cdot 5, Rt_2\cdot 5\}$	(p_4, dt_{12})	$\{Rt_1\cdot 5, Rt_2\cdot 5\}$	(dp_1, dt_{12})	$\{Rt_1\cdot 5, Rt_2\cdot 5\}$
		dt_{13}	$\{Rt_1\cdot 0, Rt_1\cdot 5, Rt_2\cdot 0, Rt_2\cdot 5\}$	(dp_1, dt_{13})	$\{Rt_1\cdot 0, Rt_1\cdot 5, Rt_2\cdot 0, Rt_2\cdot 5\}$	(p_2, dt_{13})	$\{Rt_1\cdot 1, Rt_2\cdot 6\}$
						(p_5, dt_{13})	$\{Rt_1\cdot 6, Rt_2\cdot 1\}$
p_3	$\{Rt_1\cdot 2, Rt_1\cdot 4, Rt_1\cdot 7, Rt_1\cdot 9, Rt_2\cdot 2, Rt_2\cdot 4, Rt_2\cdot 7, Rt_2\cdot 9\}$	dt_{21}	$\{Rt_1\cdot 1, Rt_2\cdot 6\}$	(p_2, dt_{21})	$\{Rt_1\cdot 1, Rt_2\cdot 6\}$	(dp_2, dt_{21})	$\{Rt_1\cdot 6, Rt_2\cdot 1\}$
p_4	$\{Rt_1\cdot 5, Rt_2\cdot 5\}$	dt_{22}	$\{Rt_1\cdot 6, Rt_2\cdot 1\}$	(p_5, dt_{22})	$\{Rt_1\cdot 6, Rt_2\cdot 1\}$	(dp_2, dt_{22})	$\{Rt_1\cdot 6, Rt_2\cdot 1\}$
		dt_{23}	$\{Rt_1\cdot 1, Rt_1\cdot 6, Rt_2\cdot 1, Rt_2\cdot 6\}$	(dp_2, dt_{23})	$\{Rt_1\cdot 1, Rt_1\cdot 6, Rt_2\cdot 1, Rt_2\cdot 6\}$	(p_3, dt_{23})	$\{Rt_1\cdot 1, Rt_1\cdot 6, Rt_2\cdot 1, Rt_2\cdot 6\}$
p_5	$\{Rt_1\cdot 6, Rt_1\cdot 8, Rt_2\cdot 1, Rt_2\cdot 3\}$	t_3	$\{Rt_1\cdot 2, Rt_1\cdot 7, Rt_2\cdot 2, Rt_2\cdot 7\}$	(p_3, t_3)	$\{Rt_1\cdot 2, Rt_1\cdot 7, Rt_2\cdot 2, Rt_2\cdot 7\}$	(p_2, t_3)	$\{Rt_1\cdot 3, Rt_2\cdot 8\}$
						(p_5, t_3)	$\{Rt_1\cdot 8, Rt_2\cdot 3\}$
p_6	$\{Rt_1, Rt_2\}$	dt_{41}	$\{Rt_1\cdot 3, Rt_2\cdot 8\}$	(p_2, dt_{41})	$\{Rt_1\cdot 3, Rt_2\cdot 8\}$	(dp_4, dt_{41})	$\{Rt_1\cdot 3, Rt_2\cdot 8\}$
dp_1	$\{Rt_1\cdot 0, Rt_1\cdot 5, Rt_2\cdot 0, Rt_2\cdot 5\}$	dt_{42}	$\{Rt_1\cdot 8, Rt_2\cdot 3\}$	(p_5, dt_{42})	$\{Rt_1\cdot 8, Rt_2\cdot 3\}$	(dp_4, dt_{42})	$\{Rt_1\cdot 8, Rt_2\cdot 3\}$
dp_2	$\{Rt_1\cdot 1, Rt_1\cdot 6, Rt_2\cdot 1, Rt_2\cdot 6\}$	dt_{43}	$\{Rt_1\cdot 3, Rt_1\cdot 8, Rt_2\cdot 3, Rt_2\cdot 8\}$	(dp_4, dt_{43})	$\{Rt_1\cdot 3, Rt_1\cdot 8, Rt_2\cdot 3, Rt_2\cdot 8\}$	(p_3, dt_{43})	$\{Rt_1\cdot 4, Rt_1\cdot 9, Rt_2\cdot 4, Rt_2\cdot 9\}$
dp_4	$\{Rt_1\cdot 3, Rt_1\cdot 8, Rt_2\cdot 3, Rt_2\cdot 8\}$	t_5	$\{Rt_1\cdot 4, Rt_1\cdot 9, Rt_2\cdot 4, Rt_2\cdot 9\}$	(p_3, t_5)	$\{Rt_1\cdot 4, Rt_1\cdot 9, Rt_2\cdot 4, Rt_2\cdot 9\}$	(p_4, t_5)	$\{Rt_1\cdot 5, Rt_2\cdot 5\}$
						(p_6, t_5)	$\{Rt_1, Rt_2\}$

4.3.3 *ANet* for an Assembly Family

As shown in Fig. 4.11, the $ANet$ for assembly variants, MT_1 and MT_2, is constructed according to the configured conceptual process flows in Table 4.9. The colored tokens in relation to the respective manufacturing resources and the performed operations are shown in Table 4.9. The mechanism for handling process changes is adopted in the $ANet$ to describe the fact, that assembly machine MTM_1 is required for producing MT_1, but not for MT_2. Table 4.10 summarizes specifications of all the places, transitions, colored tokens, input and output arcs and transform functions defined for the $ANet$. Places p_1 , p_2 and p_6 represent the respective assembly processes of three families: AAs, BAs and FAs. Tokens are specified for each of the places, denoting specific assembly variants of a family.

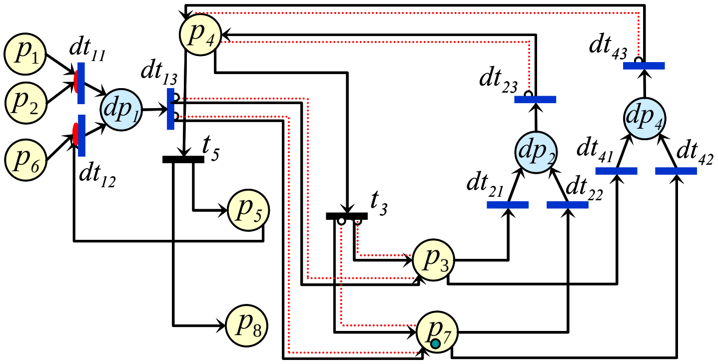


Figure 4.11 Process flows for assembly variants MT_1 and MT_2

Table 4.9 The $ANet$ for assembly variants MT_1 and MT_2

Process flow of MT_1			**Process flow of** MT_2		
Operation	**Resource (or process)/Place**	**Colored Token**	**Operation**	**Resource (or process)/Place**	**Colored Token**
Assembly DA_1 is produced	Assembly process p_1	DA_1	Assembly DA_2 is produced	Assembly process p_1	DA_2
Assembly CA_1 is produced	Assembly process p_2	CA_1	Assembly CA_2 is produced	Assembly process p_2	CA_2
MTM_1 setting up	MTM_1 / p_3	$MT_1 \cdot 0$	MTM_1 setting up	MTM_1 / p_3	$MT_2 \cdot 0$
Being transferred	Material handler p_4	$MT_1 \cdot 1$	Being transferred	Material handler p_4	$MT_2 \cdot 1$
Being assembled	AIM_1 / p_3	$MT_1 \cdot 2$	Being assembled	MTM_1 / p_3	$MT_2 \cdot 2$
Being transferred	Material handler p_4	$MT_1 \cdot 3$	Being transferred	Material handler p_4	$MT_2 \cdot 3$
Staying in buffer	WIP buffer/ p_5	$MT_1 \cdot 4$	Staying in buffer	Output buffer p_8	MT_2
Accessory is prepared	Delivery process p_6	AC			
MTM_2 setting up	MTM_2 / p_7	$MT_1 \cdot 5$			
Being transferred	Material handler p_4	$MT_1 \cdot 6$			
Being assembled	MTM_2 / p_7	$MT_1 \cdot 7$			
Being transferred	Material handler p_4	$MT_1 \cdot 8$			
Staying in buffer	Output buffer p_8	MT_1			

Table 4.10 Colored tokens, input and output transform functions for the *ANet*

Place	Colored Token	Transition	Colored Token	Input Arc	Input Function	Output Arc	Output Function
p_1	$\{DA_1, DA_2\}$	dt_{11}	$\{DA_1CA_1, DA_2CA_2\}$	(p_1, dt_{11})	$\{DA_1CA_1, DA_2CA_2\}$	(dp_1, dt_{11})	$\{DA_1CA_1, DA_2CA_2\}$
p_2	$\{CA_1, CA_2\}$			(p_2, dt_{11})	$\{DA_1CA_1, DA_2CA_2\}$		
p_3	$\left\{\begin{matrix} MT_1 \cdot 0, MT_1 \cdot 2, \\ MT_2 \cdot 0, MT_2 \cdot 2 \end{matrix}\right\}$	dt_{12}	$\{MT_1 \cdot 4AC\}$	(p_5, dt_{12})	$\{MT_1 \cdot 4AC\}$	(dp_1, dt_{12})	$\{MT_1 \cdot 4AC\}$
				(p_6, dt_{12})	$\{MT_1 \cdot 4AC\}$		
p_4	$\left\{\begin{matrix} MT_1 \cdot 1, MT_1 \cdot 3, \\ MT_2 \cdot 1, MT_2 \cdot 3, \\ MT_1 \cdot 6, MT_1 \cdot 8 \end{matrix}\right\}$	dt_{13}	$\left\{\begin{matrix} MT_1 \cdot 4AC, \\ DA_1CA_1, DA_2CA_2 \end{matrix}\right\}$	(dp_1, dt_{13})	$\left\{\begin{matrix} MT_1 \cdot 4AC, \\ DA_1CA_1, DA_2CA_2 \end{matrix}\right\}$	(p_3, dt_{13})	$\{MT_1 \cdot 0, MT_2 \cdot 0\}$
						(p_7, dt_{13})	$\{MT_1 \cdot 5\}$
p_5	$\{MT_1 \cdot 4\}$	dt_{21}	$\{MT_1 \cdot 0, MT_2 \cdot 0\}$	(p_3, dt_{21})	$\{MT_1 \cdot 0, MT_2 \cdot 0\}$	(dp_2, dt_{21})	$\{MT_1 \cdot 0, MT_2 \cdot 0\}$
p_6	$\{AC_1\}$	dt_{22}	$\{MT_1 \cdot 5\}$	(p_7, dt_{22})	$\{MT_1 \cdot 5\}$	(dp_2, dt_{22})	$\{MT_1 \cdot 5\}$
p_7	$\{MT_1 \cdot 5, MT_1 \cdot 7\}$	dt_{23}	$\{MT_1 \cdot 0, MT_2 \cdot 0, MT_1 \cdot 5\}$	(dp_2, dt_{23})	$\{MT_1 \cdot 0, MT_2 \cdot 0, MT_1 \cdot 5\}$	(p_4, dt_{23})	$\{MT_1 \cdot 0, MT_2 \cdot 0, MT_1 \cdot 5\}$
p_8	$\{MT_1, MT_2\}$	t_3	$\{MT_1 \cdot 1, MT_2 \cdot 1, MT_1 \cdot 6\}$	(p_4, t_3)	$\{MT_1 \cdot 1, MT_2 \cdot 1, MT_1 \cdot 6\}$	(p_3, t_3)	$\{MT_1 \cdot 2, MT_2 \cdot 2\}$
dp_1	$\left\{\begin{matrix} MT_1 \cdot 4AC_1, \\ DA_1CA_1, DA_2CA_2 \end{matrix}\right\}$					(p_7, t_3)	$\{MT_1 \cdot 7\}$
		dt_{41}	$\{MT_1 \cdot 2, MT_2 \cdot 2\}$	(p_3, dt_{41})	$\{MT_1 \cdot 2, MT_2 \cdot 2\}$	(dp_4, dt_{41})	$\{MT_1 \cdot 2, MT_2 \cdot 2\}$
dp_2	$\left\{\begin{matrix} MT_2 \cdot 0, \\ MT_1 \cdot 0, MT_1 \cdot 5 \end{matrix}\right\}$	dt_{42}	$\{MT_1 \cdot 7\}$	(p_7, dt_{42})	$\{MT_1 \cdot 7\}$	(dp_4, dt_{42})	$\{MT_1 \cdot 7\}$
		dt_{43}	$\{MT_1 \cdot 2, MT_2 \cdot 2, MT_1 \cdot 7\}$	(dp_4, dt_{43})	$\{MT_1 \cdot 2, MT_2 \cdot 2, MT_1 \cdot 7\}$	(p_4, dt_{43})	$\{MT_1 \cdot 2, MT_2 \cdot 2, MT_1 \cdot 7\}$
dp_4	$\left\{\begin{matrix} MT_2 \cdot 2, \\ MT_1 \cdot 2, MT_1 \cdot 7 \end{matrix}\right\}$	t_5	$\{MT_1 \cdot 3, MT_2 \cdot 3, MT_1 \cdot 8\}$	(p_4, t_5)	$\{MT_1 \cdot 3, MT_2 \cdot 3, MT_1 \cdot 8\}$	(p_5, t_5)	$\{MT_1 \cdot 4\}$
						(p_8, t_5)	$\{MT_1, MT_2\}$

4.3.4 *DNet* for a Distribution Channel

In each VSC, there are three types of basic elements to constitute a complete network, namely supplier, distributor, and customer. Each of the basic elements performs certain functionality that is achieved through the internal events, and thus can be modeled as OPNs from an object-oriented perspective. It is very important to understand the roles played and resource used by the distributor.

Fig. 4.12 illustrates the distribution channel *DNet* for the motor family, in which final products are transferring from one place to another place. The places represent supply entities, consumers, input buffers, output buffers and material transferring facilities; where colored tokens represent certain products. The distribution flows of MT_1 and MT_2 are shown in Table 4.11. Table 4.12 describes colored tokens and functions of the *DNet*.

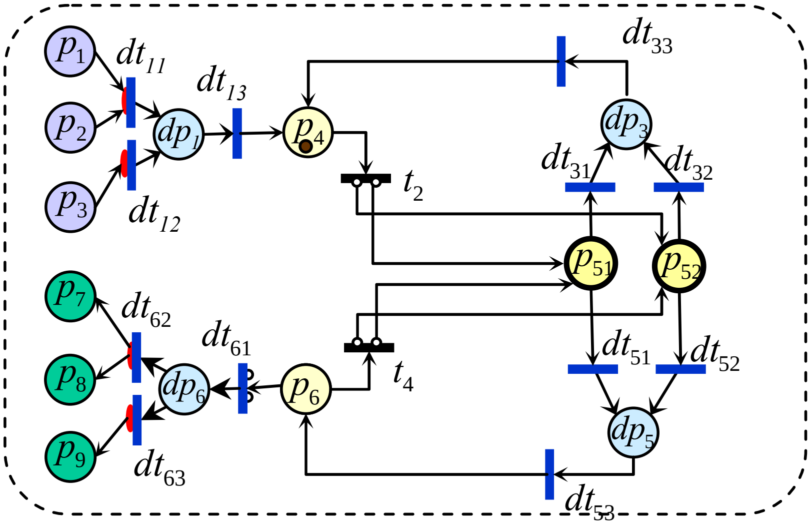


Figure 4.12 The DNet for motors

Table 4.11 Distribution flow of MT_1 and MT_2

Material flow of MT_1			**Material flow of MT_2**		
Operations	**Resource (or process)/Place**	**Colored Token**	**Operations**	**Resource (or process)/Place**	**Colored Token**
Product MT_1 is produced	Assembly process p_1	$MT_1.0$	Product MT_2 is produced	Assembly process p_3	$MT_2.0$
Product MT_1 is produced	Assembly process p_2	$MT_1.0$			
MT_1 is storing in input buffer	Input inventory buffer p_4	$MT_1.1$	MT_2 is storing in inventory buffer	Input inventory buffer p_4	$MT_2.1$
MT_1 is transferring inside the DC	Material handling facility p_{51}	$MT_1.2$	MT_2 is transferring inside the DC	Material handling facility p_{51}	$MT_2.2$
MT_1 is transferring inside the DC	Material handling facility p_{52}	$MT_1.2$	MT_2 is transferring inside the DC	Material handling facility p_{52}	$MT_2.2$
MT_1 is storing in output buffer	Output inventory buffer p_6	$MT_1.3$	MT_2 is storing in output buffer	Output inventory buffer p_6	$MT_2.3$
Product MT_1 is consumed	Retailer p_7	$MT_1.4$	Product MT_2 is consumed	Retailer p_7	$MT_2.4$
Product MT_1 is consumed	Retailer p_8	$MT_1.4$			

Table 4.12 Colored tokens, input and output transform functions for the *DNet*

Place	**Colored Token**	**Transition**	**Colored Token**	**Input Arc**	**Input Transform Function**	**Output Arc**	**Output Transform Function**
p_1, p_2	$\{MT_1.0\}$	dt_{11}, dt_{12}	$\{MT_1.0\}$	$(p_1, t_1)(p_2, t_1)$	$\{Rt_1St_1, Rt_2St_2\}$	(dp_1, dt_{13})	$\{Rt_1, Rt_2, St_1, St_2\}$
p_3	$\{MT_2.0\}$	dt_{13}	$\{MT_2.0\}$	$(p_3, t_1)(p_4, t_1)$	$\{Rt_1St_1, Rt_2St_2\}$		
p_4	$\{MT_1.1, MT_2.1\}$	t_2 $(dt_{11}, dt_{12}, dt_{13})$	$\{Sh_1, Sh_2, Bs_1, Bs_2\}$	$(p_5, t_2)(p_6, t_2)$	$\{Sh_1Bs_1, Sh_2Bs_2\}$	(dp_2, dt_{23})	$\{Sh_1, Sh_2, Bs_1, Bs_2\}$
p_{51}	$\{MT_1.2, MT_2.2\}$			$(p_7, t_2)(p_8, t_2)$	$\{Sh_1Bs_1, Sh_2Bs_2\}$		
p_{52}	$\{MT_1.2, MT_2.2\}$	t_3	$\{DA_1, DA_2\}$	$(p_9, t_3)(p_9, t_5)$	$\{DA_1CA_1, DA_2CA_2\}$	(dp_3, dt_{33})	$\{DA_1CA_1, DA_2CA_2\}$
p_6	$\{MT_1.3, MT_2.3\}$	t_4	$\{CA_1, CA_2\}$	$(p_{10}, t_3)(p_{10}, t_5)$	$\{DA_2CA_2\}$	(dp_4, dt_{43})	
p_7, p_8	$\{MT_1.4\}$	t_5	$\{DA_1, DA_2\}$	$(p_{11}, t_4)(p_{11}, t_6)$	$\{DA_1CA_1, DA_2CA_2\}$	(dp_5, dt_{53})	$\{DA_1CA_1, DA_2CA_2\}$
p_9	$\{MT_2.4\}$	t_6	$\{CA_1, CA_2\}$	$(p_{12}, t_4)(p_{12}, t_6)$	$\{CA_2DA_2\}$	(dp_6, dt_{63})	
p_{13}	$\{MT_1.0\}$	t_7	$\{MT_1.0\}$	(p_{13}, t_7)	$\{MT_1.0\}$	$(dp_{72}, p_{15})(dp_{73}, dt_{16})$	$\{MT_1.1\}$
p_{14}	$\{MT_2.0\}$	t_8	$\{MT_2.0\}$	(p_{14}, t_8)	$\{MT_2.0\}$	$(dp_{82}, p_{17})(dp_{83}, dt_{18})$	$\{MT_2.1\}$

4.3.5 Nested Net System Model

In accordance with the specified product hierarchies, a number of $SNets$, $ANets$ and $DNets$ are constructed for all the parts, assemblies and meta resources contained in the supply chain system. The supply chain system model is constructed based on net nesting, as shown in Fig. 4.13. For illustrative simplicity, not all the $SNets$, $ANets$ and $DNets$ are shown in the figure.

Upon completion of producing a particular item, the objects represented by port places start to send messages to the objects represented by socket places. For example, when one DA_1 is produced in the $ANet$ at level 2 and loaded into output buffer p_8 (also a port place), a message requesting machine setup from p_8 is sent to socket place p_3 (representing machine WcM_1) within the $MNet$. Meanwhile, place p_2 (nesting the $ANet$) holds the same colored token as that of DA_1. The inhibitor arcs are then applied to those single resource objects, for example, machine WcM_1 (p_3) and the material handler (p_4) within the $PNet$.

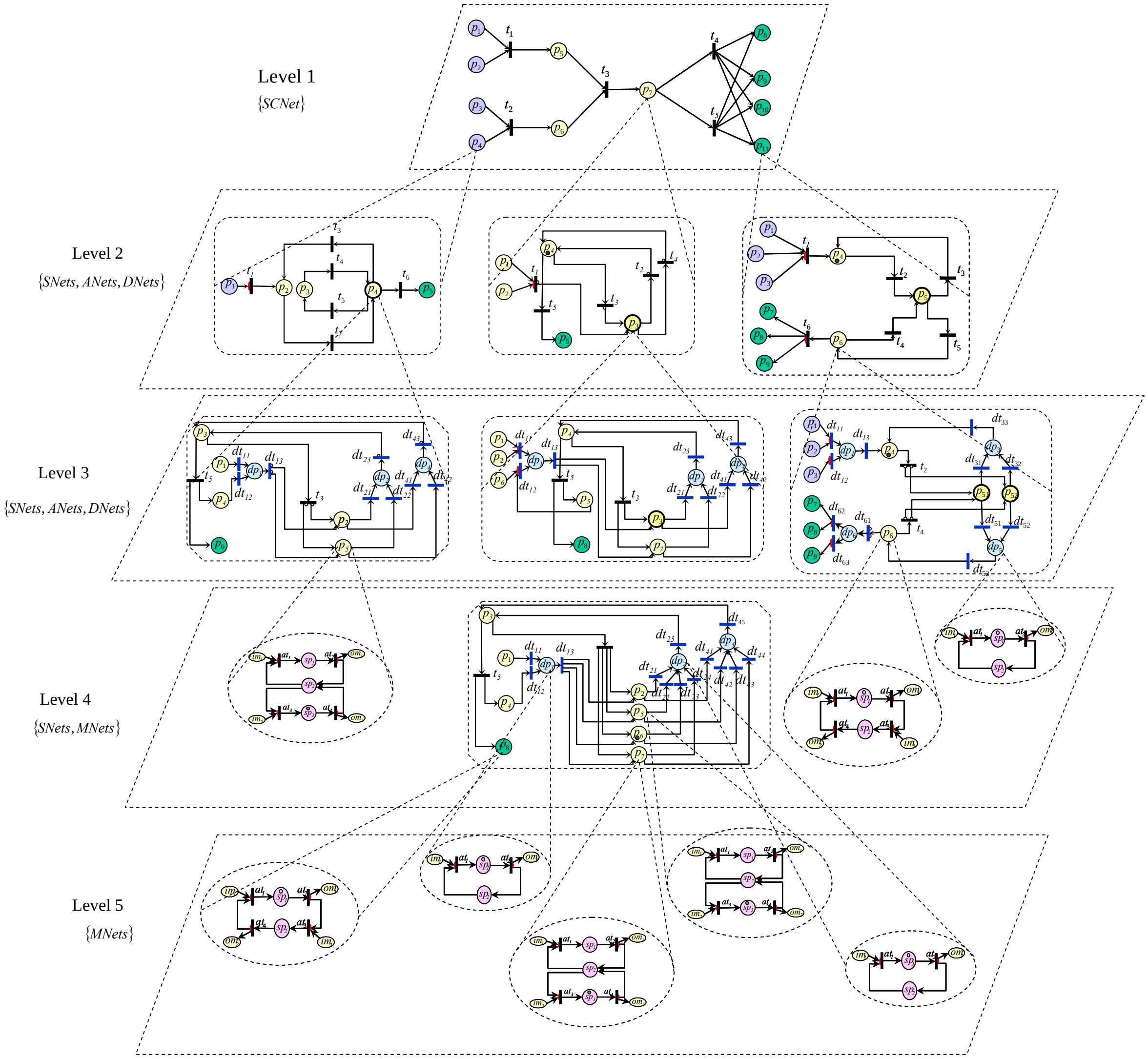


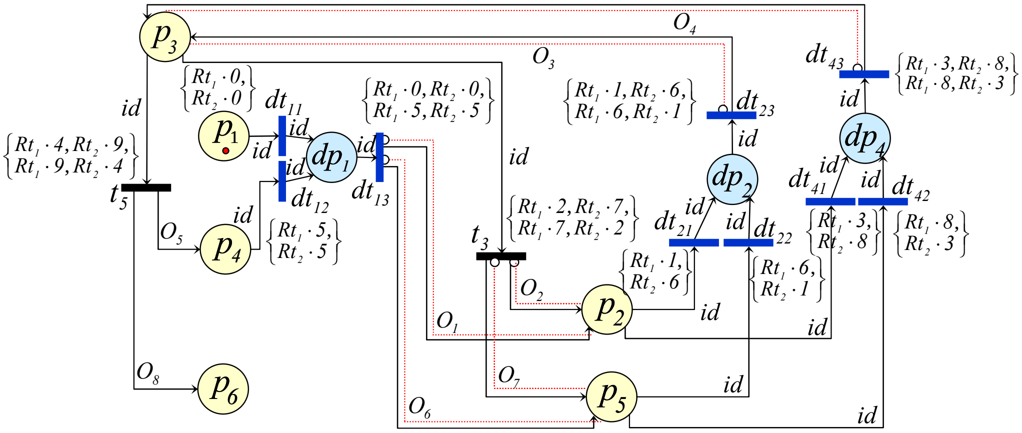
Figure 4.13 The nested net system model for MT_1 and MT_2

4.4 System Analysis and Evaluation

Deadlock detection and conflict prevention are widely adopted as performance indicators for testing a built system model (Wang, 1996; Wang and Wu, 1998). This section adopts these criteria for performance evaluation of the nested net system model. The analysis focuses on the $SNet$ for parts Rt_1 and Rt_2.

Generally, there are two types of input conflict and one type of output conflict (Wang, 1996). Type I input conflicts involve more than one output transition to be connected to one output place. Type II conflicts involve two or more than two input places to be connected to one transition via an OR relation. Whenever a transition possesses more than one output place that is connected through an OR relation, an output conflict may occur.

Fig. 4.14 shows the *SNet* for part family Rt. It does not contain type I input conflict, as all of them are removed by transition decomposition. A type II input conflict may occur at places p_2 and p_5, since both of them are connected to two output transitions. An output conflict may occur at transitions dt_{13}, t_3 and t_5, since all of them exhibit two output places with OR relations. Through assignment of colored tokens to places and transitions in conjunction with input and output transform functions, the decisions regarding which transition to fire and which place to add tokens can be determined according to the colors. Therefore, output conflicts are resolved by assigning different colors.



$$O_1=\begin{cases}O(p_2,dt_{13}/Rt_1\cdot 0)=Rt_1\cdot 1\\O(p_2,dt_{13}/Rt_2\cdot 5)=Rt_2\cdot 6\end{cases}\qquad O_2=\begin{cases}O(p_2,t_3/Rt_1\cdot 2)=Rt_1\cdot 3\\O(p_5,t_3/Rt_2\cdot 7)=Rt_2\cdot 8\end{cases}\qquad O_3=\begin{cases}O(p_3,dt_{23}/Rt_1\cdot 1)=Rt_1\cdot 2\\O(p_3,dt_{23}/Rt_1\cdot 6)=Rt_1\cdot 7\\O(p_3,dt_{23}/Rt_2\cdot 1)=Rt_2\cdot 2\\O(p_3,dt_{23}/Rt_2\cdot 6)=Rt_2\cdot 7\end{cases}$$

$$O_5=\begin{cases}O(p_4,t_5/Rt_1\cdot 4)=Rt_1\cdot 5\\O(p_4,t_5/Rt_2\cdot 4)=Rt_2\cdot 5\end{cases}\qquad O_6=\begin{cases}O(p_5,dt_{13}/Rt_2\cdot 0)=Rt_2\cdot 1\\O(p_5,dt_{13}/Rt_1\cdot 5)=Rt_1\cdot 6\end{cases}$$

$$O_4=\begin{cases}O(p_3,dt_{43}/Rt_1\cdot 3)=Rt_1\cdot 4\\O(p_3,dt_{43}/Rt_1\cdot 8)=Rt_1\cdot 9\\O(p_3,dt_{43}/Rt_2\cdot 3)=Rt_2\cdot 4\\O(p_3,dt_{43}/Rt_2\cdot 8)=Rt_2\cdot 9\end{cases}$$

$$O_7=\begin{cases}O(p_5,t_3/Rt_1\cdot 7)=Rt_1\cdot 8\\O(p_5,t_3/Rt_2\cdot 2)=Rt_2\cdot 3\end{cases}\qquad O_8=\begin{cases}O(p_6,t_5/Rt_1\cdot 9)=Rt_1\\O(p_6,t_5/Rt_2\cdot 9)=Rt_2\end{cases}$$

Figure 4.14 The *SNet* for two part variants

The deadlock detection algorithm in Wang and Wu (1998) is applied to the $SNet$ in Fig. 4.14, as elaborated below.

(1) The initial state is set as that raw materials of two parts are in the input buffer. The goal state is set as that both parts are produced and transferred into the output buffer. The initial marking M_0 and the goal state marking M_g become the following,

$$\begin{aligned} M_0 &= (\mu(p_1), \mu(p_2), \mu(p_3), \mu(p_4), \mu(p_5), \mu(p_6), \mu(dp_1), \mu(dp_2), \mu(dp_4)) \\ &= (Rt_1 \cdot 0 + Rt_2 \cdot 0, 0, 0, 0, 0, 0, 0, 0, 0) \end{aligned},$$

$$M_g = (0, 0, 0, 0, 0, Rt_1 + Rt_2, 0, 0, 0).$$

(2) Construct an incidence matrix, W, such that,

$W^+ = [w_{ij}^+]_{mxn}$, where $w_{ij}^+ = O(p_i, t_j / c^{t_j})$, $\forall i \in [1, m]$, $j \in [1, n]$; and

$W^- = [w_{ij}^-]_{mxn}$, where $w_{ij}^- = I(p_i, t_j / c^{t_j})$, $\forall i \in [1, m]$, $j \in [1, n]$.

Set $m = 9$ (the total number of places in the $SNet$) and $n = 11$ (the total number of transitions in the $SNet$). Then,

$$W^+ = \begin{array}{c} \begin{array}{ccccccccccc} dt_{11} & dt_{12} & dt_{13} & dt_{21} & dt_{22} & dt_{23} & t_3 & dt_{41} & dt_{42} & dt_{43} & t_5 \end{array} \\ \left[\begin{array}{ccccccccccc} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & O_1 & 0 & 0 & 0 & O_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & O_3 & 0 & 0 & 0 & O_4 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & O_5 \\ 0 & 0 & O_6 & 0 & 0 & 0 & O_7 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & O_8 \\ id & id & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & id & id & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & id & id & 0 & 0 \end{array}\right] \end{array} \begin{array}{c} \\ p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \\ p_6 \\ dp_1 \\ dp_2 \\ dp_3 \end{array}$$

$$W^- = \begin{bmatrix} id & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & id & 0 & 0 & 0 & id & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & id & 0 & 0 & 0 & id \\ 0 & id & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & id & 0 & 0 & 0 & id & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & id & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & id & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & id & 0 \end{bmatrix}$$

$$W = W^{+} - W^{-} = \begin{bmatrix} -id & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & O_1 & -id & 0 & 0 & O_2 & -id & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & O_3 & -id & 0 & 0 & O_4 & -id \\ 0 & -id & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & O_5 \\ 0 & 0 & O_6 & 0 & -id & 0 & O_7 & 0 & -id & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & O_8 \\ id & id & -id & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & id & id & -id & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & id & id & -id & 0 \end{bmatrix}.$$

(3) At the initial marking M_0 (i.e. k=0), the set of enabled transitions, $T_{enable-0}$, are related to their firing colored tokens c^{t_j}, that is, $T_{enable-0} = \{dt_{11}/Rt_1 \cdot 0, dt_{11}/Rt_2 \cdot 0\}$.

(4) Transition $dt_{11}/Rt_1 \cdot 0$ is selected to fire.

(5) The characteristic vector $\overline{S_k}$ of a firing sequence S is set to have entry c^{t_j} for the transition selected to fire. The other transitions are set to 0. Hence,

$$\begin{aligned} \overline{S_0} &= \left(dt_{11}, dt_{12}, dt_{13}, dt_{21}, dt_{22}, dt_{23}, t_0, dt_{41}, dt_{42}, dt_{43}, dt_5\right)^{-1} \\ &= \left(Rt_1 \cdot 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0\right)^{-1} \end{aligned}.$$

(6) The following state marking, $M_{k+1} = M_{0+1} = M_1$, after firing the transition $dt_{11}/Wt_1 \cdot 0$ is computed according to $M^{-1}_{k+1} = M^{-1}_k + W\overline{S_k}$. Thereby, $M_1 = \left(Rt_2 \cdot 0, 0, 0, 0, 0, 0, Rt_1 \cdot 0, 0, 0\right)$. As $M_1 \neq M_g$, k is set to be k+1 (i.e., k=0+1=1). Then go to step (3).

As for marking M_1, it is true that $T_{enable-1} = \{dt_{13}/Rt_1 \cdot 0, dt_{11}/Rt_2 \cdot 0\}$. Thus transition $dt_{11}/Rt_2 \cdot 0$ is selected to fire. Then $\overline{S_1} = \left(Rt_2 \cdot 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0\right)^{-1}$. Therefore $M_{k+1} = M_2$ is computed as $M_2 = \left(0, 0, 0, 0, 0, 0, Rt_1 \cdot 0 + Rt_2 \cdot 0, 0, 0\right)$. Since $M_2 \neq M_g$, k is set to 2. Go to step (3).

Since $T_{enable-2} = \{dt_{13}/Rt_1 \cdot 0, dt_{13}/Rt_2 \cdot 0\}$, $dt_{13}/Rt_1 \cdot 0$ is selected to fire. As a result, $\overline{S_2} = \left(0, 0, Rt_1 \cdot 0, 0, 0, 0, 0, 0, 0, 0, 0\right)^{-1}$, and thus M_3 is computed as

$M_3^{-1} = M_2^{-1} + W\overline{S_2}$. According to the output functions of the $SNet$, it can infer that $O_6(Rt_1 \cdot 0) = 0$ and $O_1(Rt_1 \cdot 0) = Rt_1 \cdot 1$. Considering the input identity function defined for the $SNet$, it has $-id(Rt_1 \cdot 0) = -Rt_1 \cdot 0$. Furthermore,

$$M_3^{-1} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ Rt_1 \cdot 0 + Rt_2 \cdot 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} -id & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & O_1 & -id & 0 & 0 & O_2 & -id & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & O_3 & -id & 0 & 0 & O_4 & -id \\ 0 & -id & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & O_5 \\ 0 & 0 & O_6 & 0 & -id & 0 & O_7 & 0 & -id & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & O_8 \\ id & id & -id & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & id & id & -id & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & id & id & -id & 0 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ Rt_1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$= \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ Rt_1 \cdot 0 + Rt_2 \cdot 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ O_1(Rt_1 \cdot 0) \\ 0 \\ 0 \\ O_6(Rt_1 \cdot 0) \\ 0 \\ -id(Rt_1 \cdot 0) \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ Rt_1 \cdot 0 + Rt_2 \cdot 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ Rt_1 \cdot 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ -Rt_1 \cdot 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ Rt_1 \cdot 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ Rt_2 \cdot 0 \\ 0 \\ 0 \end{bmatrix}$$

Since $M_3 \neq M_g$, the deadlock detection process is continued. Upon completion, the deadlock analysis reaches a final goal marking, $M_g = (0, 0, 0, 0, 0, Rt_1 + Rt_2, 0, 0, 0)$. Fig. 4.15 shows an example of feasible sequence that leads to the final goal state. Accordingly, it concludes that the $SNet$ for Rt_1 and Rt_2 is live and deadlock free.

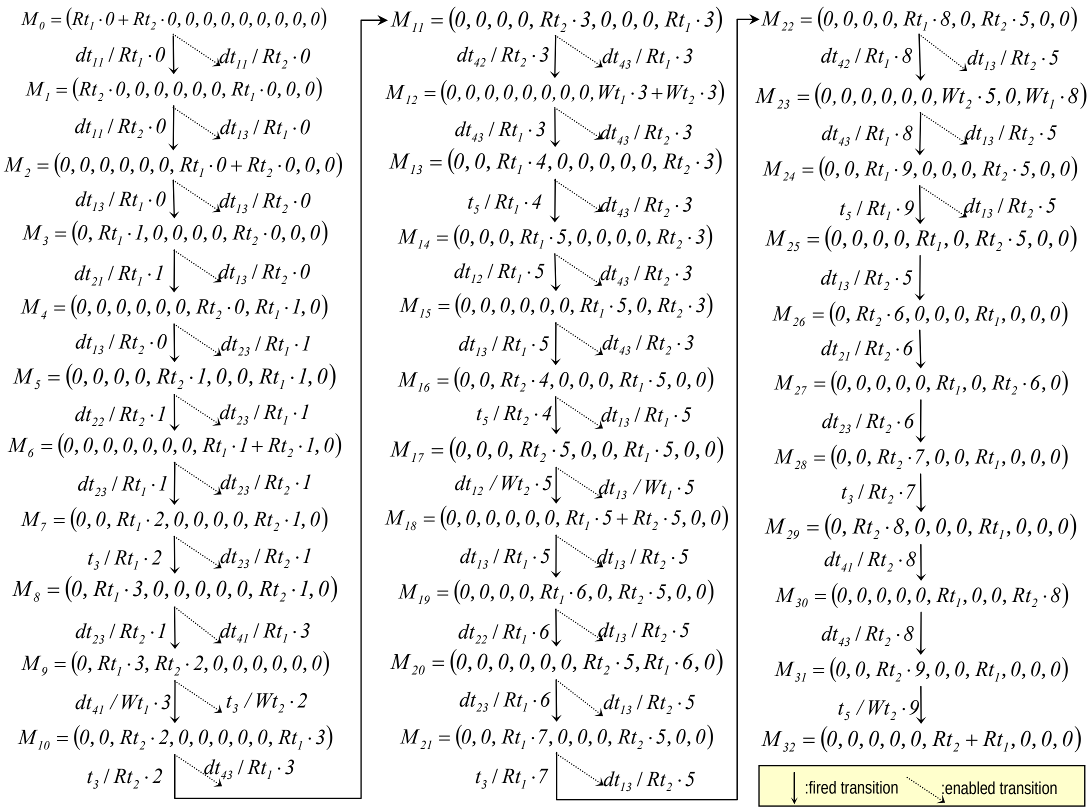


Figure 4.15 Feasible firing sequences leading to the goal marking

4.5 Summary

This chapter addressed the virtual supply chain modeling issue through the development of a series of nested modular formalism of colored object-oriented Petri nets. The relevant data regarding product items, process elements and manufacturing resources are attached to colored tokens to tackle multiple constraints. Together with Petri-nets, they deal with the large and various varieties involved. Moreover, the concept of net nesting is introduced for coping with granularity issues, such that lower level nets are nested as colored tokens in the higher-level nets. A supply chain net (*SCNet*) is built to describe the conceptual process of the entire supply chain, including a number of *MNets* , *SNets* , *ANets* , and *DNets* . The results of the validation case not only clarified the process of supply chain modeling but also demonstrated the correctness of the system model through conflict analysis.

CHAPTER 5 COLORED PETRI-NET MODELING FOR VIRTUAL SUPPLY CHAIN CONFIGURATION

This chapter introduces an integrated structure modeling and analysis formalism for virtual supply chain configuration. To model the configuration mechanisms within a VSC, the colored Petri-net technique is applied, through which dynamic decisions with respect to tradeoffs of various supply chain configurations are analyzed consistently. The static generic supply chain network and dynamic configurations are explicitly expressed and formalized as CPN models by using gates and colored tokens. Performances of various configurations are analyzed and evaluated through operational models. The linchpin of modeling supply chain configuration lies in the coordination of product, process and logistics decisions in relation to a variety of customer orders.

5.1 Problem Description

Each supply chain represents a configuration of business entities as well as the parts and processes that they provide for generating a final product (Casati *et al.*, 2001). Among these supply chain elements (e.g., parts, manufacturing processes, products, logistics, customers), there exist complex and heterogeneous relationships representing dependencies among the elements. A collection of elements and the correlations between them comprises a supply chain configuration.

Supply chain configuration is inherently complex due to the dynamic, decentralized and distributed characteristics of a supply chain network. Each node in such a network often includes several alternative options, which are autonomous organizations with unique resources, capabilities, objectives, and competencies. Configuring a supply chain not only requires to decide alternative suppliers, delivery modes and inventory levels, but also to specify manufacturing processes such as operations sequence, lead times, setups, and manufacturing resources (Huang *et al.*, 2005). Due to the constant flux of changes in current increasingly competitive global environment, there are many uncertain or random events in the supply chain, e.g., customer demand variations, delivery time alternations, production fluctuations. A number of supply chain configurations that can deliver a customer order can be obtained from a generic supply chain network according to particular customer requirements and specific operational environments.

In order to address the challenge of designing effective supply configurations that integrate platform product decisions, manufacturing process decisions, and supply sourcing decisions, one crucial issue is to identify the key elements and relationships among marketing, product, process and logistics domains. The objective is to develop a formal supply chain configuration methodology to provide unambiguous representation of the involved information and operations so that the mechanism for supporting supply chain configuration can be defined.

To shed light on the entities and their correlations in the supply chain network, some definitions are given below.

Definition 5-1: A customer order set $O = \left[O_i^*\right]_n$ is a set of orders that are placed by end customers. Each O_i^* is defined as a 4-tuple: $O_i^* = \left\langle P_i^*, C_i^*, Q_i^*, L_i^* \right\rangle$, where P_i^*, C_i^*, Q_i^*, and L_i^* represent the ordered product, the quoted total cost, the required quantity, and the lead time of delivering P_i^*, respectively.

Definition 5-2: A VSC aims to fulfill order $O^{''}$ and is defined as a tuple: $\Omega^{''}=\left\langle \Lambda^{''},\Pi^{''}\right\rangle$, where $\Lambda^{''}=\left[E_e^*\right]_E$ is the entity set involved in $\Lambda^{''}$, and $\Pi^{''}$ is the flow set. $\Pi^{''}=F^I\cup F^M$, $F^I\cap F^M=\Phi$, where F^I and F^M are the information flow and material flow across $\Lambda^{''}$, respectively.

Definition 5-3: In a VSC $\Omega^{''}$, four types of entities are observed, i.e., $\Lambda^{''}=E^M\cup E^A\cup E^C\cup E^R$, $E^M\cap E^A\cap E^C\cap E^R=\varPhi$ where E^M, E^A, E^C, and E^R are four sets of final manufacturers, assembly suppliers, component suppliers, and raw material suppliers, respectively.

Definition 5-4: Each $F_f^*, \forall f=1,\cdots,F$ in $\Pi^{''}$ defines a precedence correlation between entities in $\Lambda^{''}$, such that $F_f^*=\left(E_a^*, E_b^*\right)\in\left\{\Lambda\times\Lambda\right\}$.

If $F_f^*=\left(E_a^*, E_b^*\right)\in F^M$, then E_a^* is an upstream entity and provides material items to E_b^*; If $F_f^*=\left(E_a^*, E_b^*\right)\in F^I$, then E_a^* is a downstream entity and launches the order information to E_b^*.

Definition 5-5: Each E_i^* is described by a set of attributes, i.e., $E_i^*=\left[A_{ij}^*\right]_{E\times A}$. An $A_{ij}^*, \forall j=\left[1,A\right]$ is defined as a 4-tuple: $A_{ij}^*=\left\langle I_{ij}^*, C_{ij}^*, Q_{ij}^*, L_{ij}^*\right\rangle$, where I_{ij}^*, L_{ij}^*, C_{ij}^*, and Q_{ij}^* represents an item that E_i^* can offer, be it a finished product, an assembly, a component, or a raw material, the lead time and total cost of delivering I_{ij}^*, and the production capacity (or the required quantity) of I_{ij}^*.

The total cost C_{ij}^* is an aggregation of three type costs, including the transportation cost (i.e., cost incurred in transporting I_{ij}^* to the order placer), the production cost and the inventory cost of I_{ij}^*. Further, both the inventory and production costs rely upon the adopted process and design of the item I_{ij}^*.

According to the product structure of P_i^* in O_i^{c*}, a set of internal orders $O^s = O^A \cup O^C \cup O^R$ is placed by entities in S to their upstream entities. O^A, O^C and O^R are three sets of assembly orders, component orders and raw material orders, respectively. The selection of upstream entities to fulfill the internal orders is based on the attributes of entities. Fig. 5.1 shows the constituent elements and their correlations inherent in a VSC.

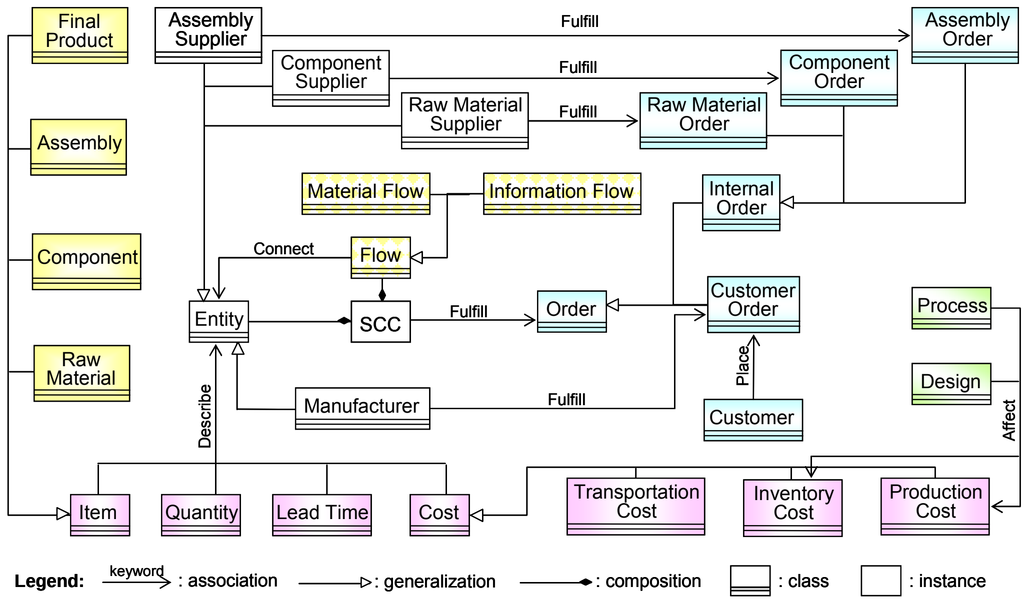


Figure 5.1 VSC basic elements and correlations

5.2 CPN Modeling Formalism

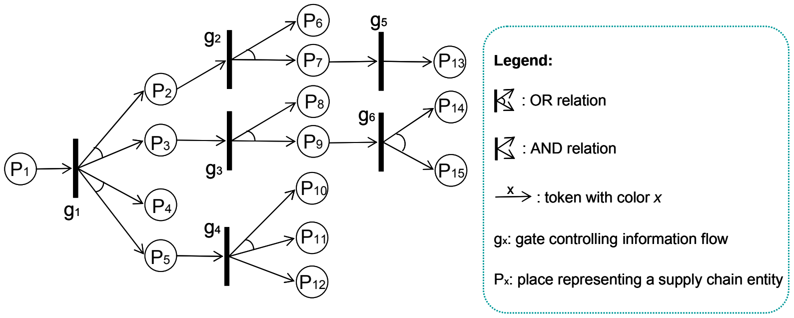
In the OO technique, each object is a generic concept representing a class, and thus contains all descriptive data of its member instances. By selecting certain data, the generic object is instantiated and a specific member is obtained. When the real system changes, the necessary generic objects in the system model, which is built by applying OO technique, are instantiated to the set of desired object instances according to given information. To reduce the complexity of the built system model by reusing model components, i.e., generic objects, OO concepts are incorporated into the proposed CPN modeling formalism. Different customer orders may require different supply chain entities, which in turn leads to varieties in supply chains. To accommodate the configuration changes caused by adding or removing entities in the system model, the change handling mechanism in Jiang *et al.* (1999b) is also adopted in the CPN modeling formalism.

According to Wang (1996a; 1996b), the OPN of a physical object has a number of input message places, output message places, activity transactions, state places, and arcs among places and transactions. The dynamic behavior of a physical object is characterized by the state places and activity transactions. The communication between two objects is accomplished by sending and receiving messages.

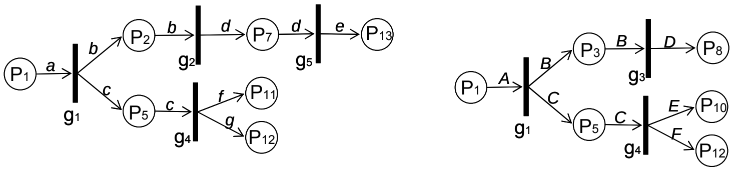
A CPN model of a supply chain consists of a set of places (P_s) and gates (g_s). Each gate connects with two places. A place is an object denoting a supply chain entity. Thus, a place may represent a final manufacturer, an assembly supplier, a component supplier or a raw material supplier. In manufacturing practice, it is common that an entity produces a variety of items, be they are products, assemblies, components, or raw materials. Therefore, in a CPN model a number of colored tokens are assigned to each place. Each token represents a particular item that can be produced by the place, and thus relates to an order placed by a downstream entity. Further, a token records information pertaining to the item, such as the quantity, cost and lead time. The cost requirement includes the transportation cost, inventory cost and production cost. As both the inventory and production costs are determined by the design and process of the item, all changes in product, process and logistics need be taken into account. Consequently, modeling configuring supply chains using CPN formalism can assist supply chain entities in making decisions about product, process and logistics design and supplier selection. A place object is generic in the sense that it can be instantiated to a particular instance with respect to a certain colored token. There are two implications. First, for an end customer order, only these places possessing colored tokens that can match with the colored tokens representing the end customer order will be instantiated. Second, after the instantiation, each place is represented by one of the colored tokens that are assigned to them.

A gate represents a transaction and carries out certain function. It decomposes a product item placed in the order by a downstream entity into child items. The orders of these child items will be placed to the proper upstream entities. Since different items are represented by different tokens, a gate defines the change of colored tokens. These tokens flow from the input arcs of a transaction to the output arcs. Thus, transactions control the forward information (and the backwards material) flows in the configuration models.

Figure 5.2 shows examples of CPN models of configuring supply chains for different customer orders. The model in Figure 5.2(a) reflects the supply chain network of a final manufacturer represented by the place P_1. It includes all the potential suppliers in the supplier base of the manufacturer. Among such suppliers that provide same items, for example, P_6 and P_7, one supplier will be selected into the supply chain for a particular customer order. Each end customer order is described by the ordered product (P), the ordered quantity (Q), the total cost (C), and the allowed delivery time (L).



a. CPNs model of a SCN



b. A SCC with respect to a customer order O1

c. A SCC with respect to a customer order O2

Figure 5.2 Principles of CPN model of supply chain configurations

For example, a token with color a (or token a) is assigned to a customer order $O_1 = (FP_1, C_1, Q_1, L_1)$. A specific supply chain from the supply chain network is configured for this order, as shown in Fig. 5.2(b). The product FP_1 is formed by two assemblies, $A_1^{fp_1}$ and $A_2^{fp_1}$. Accordingly, the gate g_1 decomposes FP_1 and generates two new tokens for the two subassemblies, $\left(A_1^{fp_1}, CA_1^{fp_1}, QA_1^{fp_1}, LA_1^{fp_1}\right)$ with color b and $\left(A_2^{fp_1}, CA_2^{fp_1}, QA_2^{fp_1}, LA_2^{fp_1}\right)$ with color c. The two new tokens convey the delivery requirements of the two assemblies, including cost, quantity and lead time. The requirements are transformed from the order information and the product structure of FP_1. Two assembly suppliers, P_2 and P_5, that can satisfy the assembly order requirements are selected. It indicates that among all the colored tokens assigned to P_2 (or P_5), one has color b (or c). Therefore, at this configuration, P_2 and P_5 are represented by token b and token c, respectively. Other upstream component and raw material suppliers are specified in the same way. Fig. 5.2(c) shows a supply chain for another customer order $O_2 = (FP_2, C_2, Q_2, L_2)$ with color A. For illustrative simplicity, only the colors of the tokens are shown in Fig. 5.2. The detail information of tokens and their colors are given in Table 5.1.

Table 5.1 Tokens and colors in Fig. 5.2

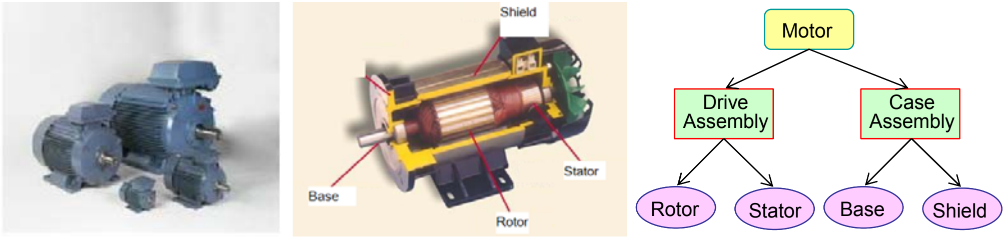
Tokens and Colors in Figure 5.2(b)		**Tokens and Colors in Figure 5.2(c)**	
Tokens	**Colors**	**Tokens**	**Colors**
(FP_1, C_1, Q_1, L_1)	a	(FP_2, C_2, Q_2, L_2)	A
$(A_1^{fp_1}, CA_1^{fp_1}, QA_1^{fp_1}, LA_1^{fp_1})$	b	$(A_1^{fp_2}, CA_1^{fp_2}, QA_1^{fp_2}, LA_1^{fp_2})$	B
$(A_2^{fp_1}, CA_2^{fp_1}, QA_2^{fp_1}, LA_2^{fp_1})$	c	$(A_2^{fp_2}, CA_2^{fp_2}, QA_2^{fp_2}, LA_2^{fp_2})$	C
$(C_1^{fp_1a_1}, CC_1^{fp_1a_1}, QC_1^{fp_1a_1}, LC_1^{fp_1a_1})$	d	$(C_1^{fp_2a_1}, CC_1^{fp_2a_1}, QC_1^{fp_2a_1}, LC_1^{fp_2a_1})$	D
$(R_1^{a_1c_1}, CR_1^{a_1c_1}, QR_1^{a_1c_1}, LR_1^{a_1c_1})$	e	$(C_1^{fp_2a_2}, CC_1^{fp_2a_2}, QC_1^{fp_2a_2}, LC_1^{fp_2a_2})$	E
$(C_1^{fp_1a_2}, CC_1^{fp_1a_2}, QC_1^{fp_1a_2}, LC_1^{fp_1a_2})$	f	$(C_2^{fp_2a_2}, CC_2^{fp_2a_2}, QC_2^{fp_2a_2}, LC_2^{fp_2a_2})$	F
$(C_2^{fp_1a_2}, CC_2^{fp_1a_2}, QC_2^{fp_1a_2}, LC_2^{fp_1a_2})$	g		

The differences in FP_1 and FP_2 results in the selection of different suppliers and thus the different configurations of supply chains. To fulfill O_2, P_3 instead of P_2 is selected to deliver an assembly order $(A_1^{fp2}, CA_1^{fp2}, QA_1^{fp2}, LA_1^{fp2})$. Further upstream component and raw material suppliers are also changed, as shown in Fig. 5.2 (c). The adoption of the change handling mechanism accommodates such configuration variations in the built system models.

5.3 The Supply Chain Network of ABC Ltd.

Headquartered in Finland, ABC Ltd. (disguised name) is a multinational company. It provides a high variety of electrical motors with a wide output power range from 1 KW to 3000 KW. Each year ABC fulfills around 12000 orders. The total number of motor types in these orders is over 800. In turn, a large number of material items (including raw materials, components and assemblies) are required. ABC Ltd. maintains a large supplier base for all potential suppliers with an attempt to ease configuring supply chains for different customer orders. Nevertheless, the diverse motors, the various resulted raw materials, components and assemblies, the dispersed location of suppliers, and the different capabilities of suppliers, complicate supplier selection and material procurement.

Fig. 5.3 shows some motors that ABC has offered. For illustrative simplicity, the author limits the relevant motor items to four major modules, including Base (Bs), Rotor (Rt), Stator (St), and Shield (Sh). Further, one Bs and one Sh form a Case Assembly (CA); one Rt and one St form a Drive Assembly (DA), as shown in Fig. 5.3(c).



a. Motor variants

b. Main parts of motors

c. Product structure of a motor

Figure 5.3 Motor variants, main parts and product structure

Figure 5.4 shows ABC's typical supply chain network. Each node corresponds to suppliers that can provide certain material item. For instance, DAs can be provided by either the supplier at Vaasa, Finland or the one at Oulu, Finland. The final motors can be assembled at Vaasa (Finland), Munich (Germany) or Helsinki (Finland). Each supplier has its own capability to produce the required material items at certain volume and cost. Only such suppliers that satisfy the requirements in terms of cost, quantity and lead time of ordered items are selected to fulfill the end customer orders.

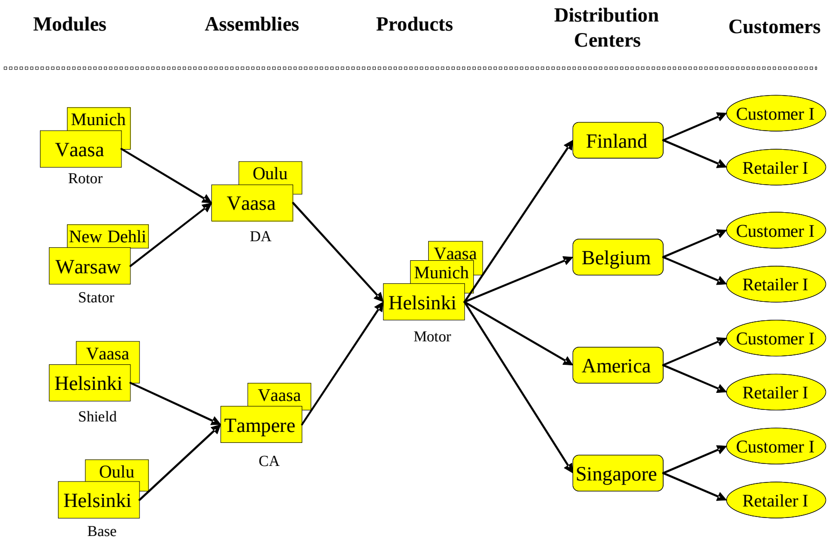


Figure 5.4 The supply chain network of ABC Ltd.

5.4 Modeling Virtual Supply Chain Configuration

CPN modeling formalism in virtual supply chain configuration involves the construction of three types of systems models: including (i) A static CPN representation model of a manufacturer’s supply chain network; (ii) A dynamic CPN model of a supply chain configuration; and (iii) A changed dynamic CPN model of another supply chain configuration. Thus, index *k* is introduced to indicate the number of times that the system has been configured. The assumption is that each order is placed for different motors. Table 5.2 gives a list of nomenclature involved in the example.

Table 5.2 Nomenclature of the CPN model

S_k	The system CPN model after the k^{th} change
I_k	The total number of objects after the k^{th} change
O_k	The set of physical objects after the k^{th} change, i.e., $O_k = \{o_{ki} \mid \forall i = 1, \cdots I_k\}$
O_k^r	The set of removed objects after the k^{th} change
O_k^a	The set of added objects after the k^{th} change
R_k	The set of message passing relations among objects after the k-th change, i.e., $R_k = \{R_{kij} \mid i, j = 1, \ldots, I_k, i \neq j\}$
R_k^r	The set of removed message passing relations after the k^{th} change
R_k^a	The set of added message passing relations after the k^{th} change
O_{ki}	Message sending object after the k^{th} change
O_{kj}	Message receiving object after the k^{th} change
R_{kij}	Message passing relations between O_{ki} and O_{kj} after the k^{th} change and defined as a four tuple: $R_{kij} = (OA_{kij}, G_{kij}, IA_{kij}, E_{kij})$
OM_{ki}	Output message places of O_{ki}
IM_{kj}	Input message places of O_{kj}
G_{kij}	The set of gates between OM_{ki} of O_{ki} and IM_{kj} of O_{kj} after the k^{th} change
OA_{kij}	The set of output connection arcs from OM_{ki} of O_{ki} to G_{kij}
IA_{kij}	The set of input connection arcs from G_{kij} to IM_{kj} of O_{kj}
E_{kij}	The set of expression functions of connection arcs between OM_{ki} and IM_{kj}, defined as $E_{kij} = \lfloor E_{kij}(OA_{kij}), E_{kij}(IA_{kij}) \rfloor$
E_{kij}^r	The set of removed expression functions after the k^{th} change
E_{kij}^a	The set of added expression functions after the k^{th} change
$E_{kij}(OA_{kij})$	The set of expression functions of OA_{kij}

Table 5.2 Nomenclature of the CPN model (Con't)

$E_{kij}\left(IA_{kij}\right)$	The set of expression functions of IA_{kij}, together with $E_{kij}\left(OA_{kij}\right)$, they determine the number and the color of tokens flowing through OA_{kij} and IA_{kij} for each firing of G_{kij}
$M_{k,0}$	The set of initial markings of system CPN model after the k^{th} change and defined as a tuple: $M_{k,0} = \left(MM_{k,0}, SM_{k,0}\right)$
$MM_{k,0}$	Initial markings of input/output message places of objects after the k^{th} change
$MM^{r}_{k,0}$	Markings of input/output message places of removed objects after the k^{th} change
$MM^{a}_{k,0}$	Markings of input/output message places of added objects after the k^{th} change
$SM_{k,0}$	Initial markings of state places of objects after the k^{th} change
$SM^{r}_{k,0}$	Markings of state places of removed objects after the k^{th} change
$SM^{a}_{k,0}$	Markings of state places of added objects after the k^{th} change
Σ_k	The color set of the system CPN model after the k^{th} change and defined as a tuple: $\Sigma_k = \left(PS_k, RS\right)$
PS_k	The set of product state after the k^{th} change
RS	Resource state with e representing resource available
g	A gate after the k^{th} change
${}^{\bullet}g^{k}$	The set of output message places connected to g after the k^{th} change
$g^{\bullet k}$	The set of input message places connected to g after the k^{th} change
l_i	The number of output message places connected to g
l_o	The number of input message places connected to g
$\vee$	Relationship operator OR
$\wedge$	Relationship operator AND
$\wedge/\vee\begin{pmatrix} x_1, x_2 \\ ,\ldots, x_n \end{pmatrix}$	Logic operation by operators $\vee$ and $\wedge$ over message places $x_1, x_2, \ldots, x_n$, e.g. $x_1 \vee x_2$ means that either x_1 or x_2 is chosen, and $x_1 \wedge x_2$ indicates both x_1 and x_2 are chosen
L_k	The input/output logic relationship function of gates and directs the token flows passing through g from O_{ki} to O_{kj} and is defined as $L_k(g) = \begin{bmatrix} \left\{ {}^{\bullet}g^{k} = \left(om_1, om_2, \cdots, om_{l_i}\right), L_k\left({}^{\bullet}g^{k}\right) = \wedge/\vee\left(om_1, om_2, \cdots, om_{l_i}\right) \right\}, \\ \left\{ g^{\bullet k} = \left(im_1, im_2, \cdots, im_{l_o}\right), L_k\left(g^{\bullet k}\right) = \wedge/\vee\left(im_1, im_2, \cdots, im_{l_o}\right) \right\} \end{bmatrix}$
Note	If k equals to 0, it means there is no change to the system.

5.4.1 Static CPN Model of a Generic Supply Chain Network

A generic supply chain network of a manufacturer contains all its upstream suppliers. While each supplier has its unique competency and is capable to provide certain materials under certain conditions, their inclusion to a particular supply chain configuration depends on the matching of their design and processes of the items ordered by their upstream partners, their manufacturing capabilities of producing the items, their financial performance, as well as their delivery lead times with the items' order requirements, which originate from the requirements of the end customer orders. Their financial performance relates to the costs of transporting the ordered items at the right volumes to the right destinations, the costs of producing the items and inventory.

Attempting to encompass all above aspects that have an impact on the selection of upstream partners, a 4-attribute value pairs, $\{A_i V_{ij}^*\}_{4\times n}$, is used to describe an entity (i.e., an object in the CPN models). The four attributes are item (A_1), quantity (A_2), cost (A_3), and delivery time (A_4). The values of A_1, A_2 and A_4 correspond to the identity of the item, the respective quantity and delivery time that an entity can offer, whilst the values of A_3 include the transportation, production and inventory costs in relation with the values of A_1, A_2 and A_4.

Configuring supply chains from a network requires two steps. In the first configuration step, all possible solutions that can fulfill a customer order will be formed. The performance of each configuration in terms of time and cost is not considered in this step. In the second evaluation step, all the feasible configurations will be evaluated and trade-off between time and cost will be made. Finally, the optimal configuration will be determined based on the evaluation result. The following validation case illustrates that a particular supply chain can be configured without losing generality. It demonstrates how a supply chain configuration responding to a motor order is obtained instead of all the possible configurations, in that they can be generated in the same manner.

Fig. 5.5 shows the static CPN model of a generic supply chain network of the ABC motor Ltd. in Vaasa (VMP). A dummy place (P_{14}) and a dummy gate (g_6) are added into the configuration model to ensure computer execution. Table 5.3 lists all the supply chain objects represented by places in Fig. 5.5. These objects are generic in the sense that each of them offers a variety of items. As a result, each object instance corresponds to a particular item that the entity can deliver. The set of gates, including g_1, g_2, g_3, g_4, g_5, and g_6, indicates the occurrence of certain events and controls the information flows. For example, g_1 not only controls the split of the motor order (the information carried by the token in P_1 is transferred into two tokens for DA and CA), but also passes them to the proper places (either P_2 or P_3, P_4 or P_5). g_2, g_3, g_4, and g_5 have the similar role as that of g_1. The difference is that they are responsible for converting the assembly order into four module orders. P_{14} and g_6 do not hold any practical meaning. They are necessary to guarantee the executing of models in computers.

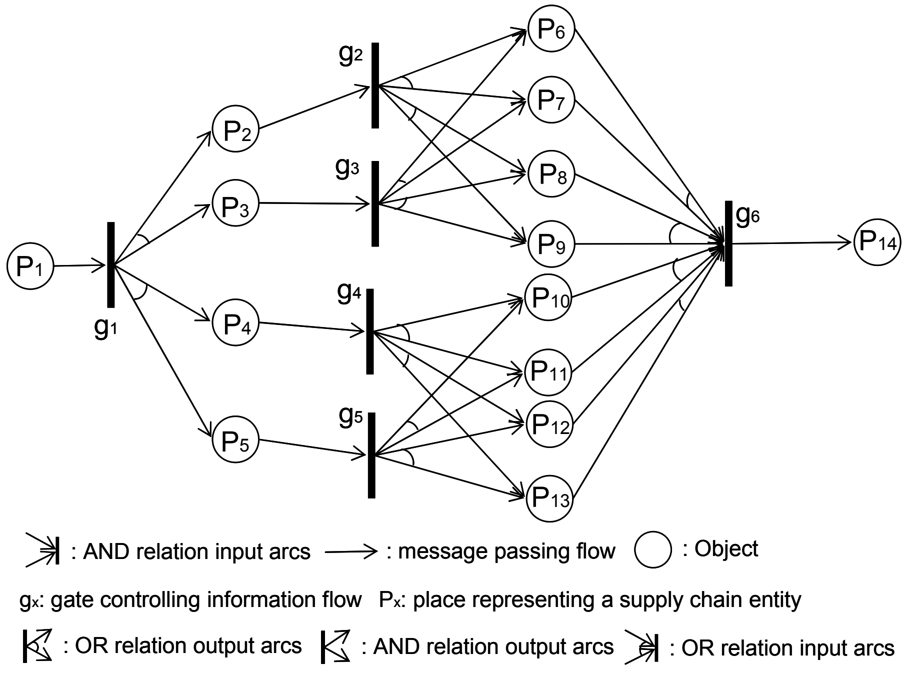


Figure 5.5 The static CPN model of the ABC supply chain network

Table 5.3 Places in the CPN model in Fig. 5.5

Places	**Supply Chain Entities**	**Places**	**Supply Chain Entities**
P_1	Vaasa motor plant (VMP)	P_8	New Dehli stator supplier (NSS)
P_2	Vaasa DA supplier (VDS)	P_9	Warsaw stator supplier (WSS)
P_3	Oulu DA supplier (ODS)	P_{10}	Vaasa shield supplier (VSS)
P_4	Vaasa CA supplier (VCS)	P_{11}	Helsinki shield supplier (HSS)
P_5	Tampere CA supplier (TCS)	P_{12}	Oulu base supplier (OBS)
P_6	Vaasa rotor supplier (VRS)	P_{13}	Helsinki base supplier (HBS)
P_7	Munich rotor supplier (MRS)	P_{14}	Dummy place (DP)

While the static model in Fig. 5.5 conveys all the suppliers' information, their dynamic relationships and all possible information flows in the SCN of VMP are reflected in the dynamic CPN models. It entails the selection of suppliers and the configuration of a supply chain in respond to a customer order. The change handling mechanism is applied to changes in different configurations when constructing the dynamic CPN models.

5.4.2 Dynamic CPN Configuration Model for Order O_1

To fulfill a customer order, $O_1 = \left(A_1V_{11}^*,\, A_2V_{21}^*,\, A_3V_{31}^*,\, A_1V_{41}^*\right) = \left(M_3^*, Q_3^*, C_3^*, L_3^*\right)$ (M_3^* indicates the third type of motors produced in VMP), VMP first decomposes the order into two assembly orders for DA and CA, as well as four module orders for Bs, Rt, St, and Sh. Order decomposition is conducted in the way that the receiving of the decomposed orders contributes to the timely delivery of the motor order O_1. Based on the delivery requirements in the decomposed orders, the qualified suppliers are selected. Fig. 5.6 shows the CPN model of the supply chain configured for fulfilling the order O_1.

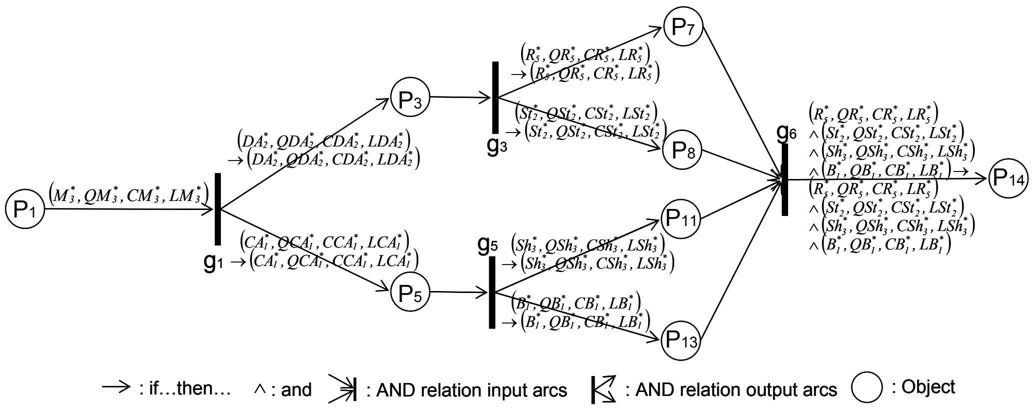


Figure 5.6 The dynamic CPN model for the customer order O_1

The model is formally described as follows.

$$
\begin{aligned}
\Omega_0 &=< \Lambda_0, \Pi_0 > \\
&=< (O_0, C_o) \cup (R_0, M_{0,0}, L_0)
\end{aligned}
$$

(1) $O_0 = \left(VMP,\, ODS,\, TCS,\, MRS,\, NSS,\, HSS,\, HBS,\, DP\right)$

(2) $R_0 = \begin{pmatrix} R_{0VMPODS}, R_{0VMPTCS}, R_{0ODSMRS}, R_{0ODSNSS}, R_{0TCSHSS}, \\ R_{0TCSHBS}, R_{0MRSDP}, R_{0NSSDP}, R_{0HSSDP}, R_{0HBSDP} \end{pmatrix}$

To illustrate the message passing relation between objects, the relation $R_{0VMPODS}$ between VMP and ODS is used as an example. From the model, the following information can be obtained.

$$G_{0VMPODS} = (g_1)$$

$$OA_{0VMPODS} = \left(om^{VMP} - g_1\right)$$

$$IA_{0VMPODS} = \left(g_1 - im^{ODS}\right)$$

$$\begin{aligned} E_{0VMPODS} &= \left[E_{0VMPODS}\left(OA_{0VMPODS}\right), E_{0VMPODS}\left(IA_{0VMPODS}\right)\right] \\ &= \left\{\left[1'\left(M_3^*, Q_3^*, C_3^*, L_3^*\right)\right], \begin{bmatrix} 1'\left(DA_2^*, QDA_2^*, CDA_2^*, LDA_2^*\right) \\ \rightarrow 1'\left(DA_2^*, QDA_2^*, CDA_2^*, LDA_2^*\right) \end{bmatrix}\right\} \end{aligned}$$

Thus,

$$\begin{aligned} R_{0BM_{Sh_1}} &= \left(OA_{0VMPODS}, G_{0VMPODS}, IA_{0VMPODS}, E_{0VMPODS}\right) \\ &= \left\{\begin{matrix} \left(om^{VMP} - g_1\right), \left(g_1\right), \left(g_1 - im^{ODS}\right), \\ \left\{\left[1'\left(M_3^*, Q_3^*, C_3^*, L_3^*\right)\right], \begin{bmatrix} 1'\left(DA_2^*, QDA_2^*, CDA_2^*, LDA_2^*\right) \\ \rightarrow 1'\left(DA_2^*, QDA_2^*, CDA_2^*, LDA_2^*\right) \end{bmatrix}\right\} \end{matrix}\right\} \end{aligned}$$

(3) $\Sigma_0 = \left(PS_0 - RS\right)$ where

$$PS_0 = \begin{bmatrix} \left(M_3^*, Q_3^*, C_3^*, L_3^*\right), \left(DA_2^*, QDA_2^*, CDA_2^*, LDA_2^*\right), \left(CA_1^*, QCA_1^*, CCA_1^*, LCA_1^*\right), \\ \left(R_5^*, QR_5^*, CR_5^*, LR_5^*\right), \left(St_2^*, QSt_2^*, CSt_2^*, LSt_2^*\right), \left(Sh_3^*, QSh_3^*, CSh_3^*, LSh_3^*\right), \\ \left(B_1^*, QB_1^*, CB_1^*, LB_1^*\right), \begin{bmatrix} \left(R_5^*, QR_5^*, CR_5^*, LR_5^*\right) \wedge \left(St_2^*, QSt_2^*, CSt_2^*, LSt_2^*\right) \wedge \\ \left(Sh_3^*, QSh_3^*, CSh_3^*, LSh_3^*\right) \wedge \left(B_1^*, QB_1^*, CB_1^*, LB_1^*\right) \end{bmatrix} \end{bmatrix}$$

and $RS = e$

(4) $G_0 = \left(g_1, g_3, g_5, g_6\right)$

$$L_0\left(g_1\right) = \left[L_0\left({}^{\bullet}g_1\right), L_0\left(g_1^{\bullet}\right)\right] = \left\{\left(om^{VMP}\right), \left[\wedge / \vee \left(im^{ODS}, im^{TCS}\right)\right]\right\} = \left[\left(om^{VMP}\right), \left(im^{ODS} \wedge im^{TCS}\right)\right]$$

Similarly, $L_0(g_3)$, $L_0(g_5)$ and $L_0(g_6)$ are as follows.

$$L_0(g_3) = \left[L_0\left({}^{\bullet}g_3\right), L_0\left(g_3^{\bullet}\right)\right] = \left[\left(om^{ODS}\right), \left(im^{MRS} \wedge im^{NSS}\right)\right]$$

$$L_0(g_5) = \left[L_0\left({}^{\bullet}g_5\right), L_0\left(g_5^{\bullet}\right)\right] = \left[\left(om^{TCS}\right), \left(im^{HSS} \wedge im^{HBS}\right)\right]$$

$$L_0(g_6) = \left[L_0\left({}^{\bullet}g_6\right), L_0\left(g_6^{\bullet}\right)\right] = \left[\left(om^{MRS} \wedge om^{NSS} \wedge om^{HSS} \wedge om^{HBS}\right), \left(im^{DP}\right)\right]$$

Thus,

$$\begin{aligned} L_0(G_0) &= \left[L_0(g_1), L_0(g_3), L_0(g_5), L_0(g_6)\right] \\ &= \left\{ \begin{array}{l} \left[\left(om^{VMP}\right), \left(im^{ODS} \wedge im^{TCS}\right)\right], \left[\left(om^{ODS}\right), \left(im^{MRS} \wedge im^{NSS}\right)\right], \\ \left[\left(om^{TCS}\right), \left(im^{HSS} \wedge im^{HBS}\right)\right], \left[\left(om^{MRS} \wedge om^{NSS} \wedge om^{HSS} \wedge om^{HBS}\right), \left(im^{DP}\right)\right] \end{array} \right\} \end{aligned}$$

(5) $M_{0,0} = \left(MM_{0,0}, SM_{0,0}\right)$

where $MM_{0,0} = \phi$ and

$$\begin{aligned} SM_{0,0} = {} & 1'\left(P_1^{VMP}, e\right) + 1'\left(P_1^{ODS}, e\right) + 1'\left(P_1^{TCS}, e\right) + 1'\left(P_1^{MRS}, e\right) + \\ & 1'\left(P_1^{NSS}, e\right) + 1'\left(P_1^{HSS}, e\right) + 1'\left(P_1^{HBS}, e\right) + 1'\left(P_1^{DP}, e\right) \end{aligned}$$

The information flow in the net model in Fig. 5.6 is described as follows.

$$F_0 = \left[\begin{array}{l} (VMP, ODS), (VMP, TCS), (ODS, MRS), (ODS, NSS), (TCS, HSS), \\ (TCS, HBS), (MRS, DP), (NSS, DP), (HSS, DP), (HBS, DP) \end{array} \right]$$

As shown in the figure, the involved objects include VMP (P_1), ODS (P_3), TCS (P_5), MRS (P_7), NSS (P_8), HSS (P_{11}), HBS (P_{13}), and DP (P_{14}). Order O_1 is decomposed into two assembly orders at g_1. After the firing of g_1, the two tokens that carry the information of two assembly orders are transferred to P_3 and P_5 (representing ODS and TCS). Only such places capable to satisfy the order requirements can receive tokens. The data attached to each token are a particular set of 4-attribute value pairs pertaining to an item. The logic relation function of g_1 specifies the token flow, which goes to the qualified suppliers.

5.4.3 Dynamic CPN Configuration Model for Order O_2

Another customer order $O_2 = \left(A_1V_{12}^*, A_2V_{22}^*, A_3V_{32}^*, A_1V_{42}^*\right) = \left(M_5^*, Q_5^*, C_5^*, L_5^*\right)$ is placed for motor M_5. Current supply chain configuration for O_1 can not fulfill O_2 due to the difference in quantity, cost and delivery date, as well as various design specifications of two motors. Another supply chain is configured, as shown in Fig. 5.7. To fulfill O_2, assembly suppliers represented by P_2 and P_4 rather than P_3 and P_5 are selected; module suppliers represented by P_6, P_9, P_{10}, and P_{12} instead of P_7, P_8, P_{11}, and P_{13} are specified. In relation to the addition of some suppliers and the removal of old ones, message passing relations and logic relationship function of gates should be changed. The following detail illustrates how these changes are handled by describing the system model after configuration.

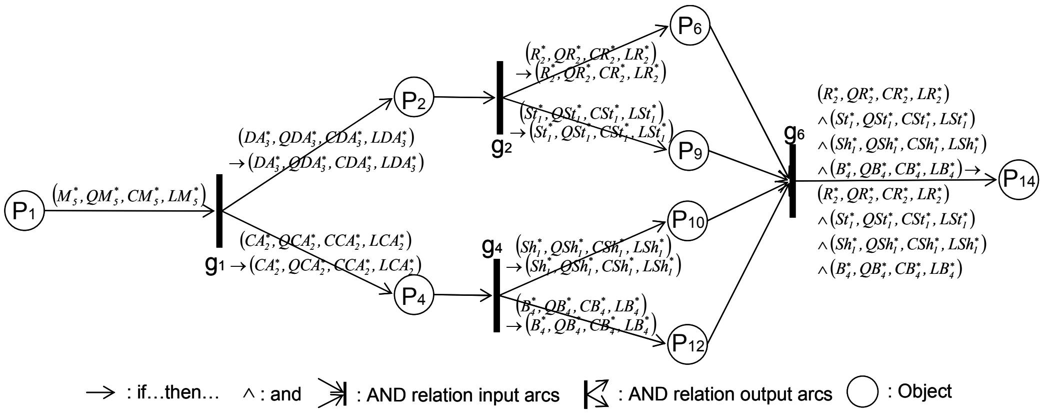


Figure 5.7 The dynamic CPN model for the customer order O_2

Let S_1 denote the CPN model of the system after change, then

$$\begin{aligned}\Omega_1 &= <\Lambda_1, \Pi_1> \\ &= <(O_1, C_1) \cup (R_1, M_{1,0}, L_1)\end{aligned}$$

(1) $O_1 = O_0 - O_0^{\,r} \bigcup O_0^{\,a}$

$$
\begin{aligned}
&= (VMP,\ ODS,\ TCS,\ MRS,\ NSS,\ HSS,\ HBS,\ DP) - \\
&\quad (ODS,\ TCS,\ MRS,\ NSS,\ HSS,\ HBS) \cup (VDS,\ VCS,\ VRS,\ WSS,\ VSS,\ OBS) \\
&= (VMP,\ VDS,\ VCS,\ VRS,\ WSS,\ VSS,\ OBS,\ DP)
\end{aligned}
$$

(2) $R_1 = R_0 - R_0{}^r \bigcup R_0{}^a$

$$
\begin{aligned}
&= R_0 - \begin{pmatrix} R_{0VMPODS}, R_{0VMPTCS}, R_{0ODSMRS}, R_{0ODSNSS}, R_{0TCSHSS}, \\ R_{0TCSHBS}, R_{0MRSDP}, R_{0NSSDP}, R_{0HSSDP}, R_{0HBSDP} \end{pmatrix} \\
&\quad \bigcup \begin{pmatrix} R_{1VMPVDS}, R_{1VMPVCS}, R_{1VDSVRS}, R_{1VDSWSS}, R_{1VCSVSS}, \\ R_{1VCSOBS}, R_{1VRSDP}, R_{1WSSDP}, R_{1VSSDP}, R_{1OBSDP} \end{pmatrix} \\
&= \begin{pmatrix} R_{1VMPVDS}, R_{1VMPVCS}, R_{1VDSVRS}, R_{1VDSWSS}, R_{1VCSVSS}, \\ R_{1VCSOBS}, R_{1VRSDP}, R_{1WSSDP}, R_{1VSSDP}, R_{1OBSDP} \end{pmatrix}
\end{aligned}
$$

For the added message passing relations, $R_{1VMPVDS}$ is taken to explain how the new message passing relationships are generated.

$$OA_{1VMPVDS} = \left(om^{VMP} - g_1\right)$$

$$G_{1VMPVDS} = (g_1)$$

$$IA_{1VMPVDS} = \left(g_1 - im^{VDS}\right)$$

$$
\begin{aligned}
E_{1VMPVDS} &= \left[E_{1VMPVDS}\left(OA_{1VMPVDS}\right), E_{1VMPVDS}\left(IA_{1VMPVDS}\right)\right] \\
&= \left\{ \left[1'\left(M_5^*, Q_5^*, C_5^*, L_5^*\right)\right], \begin{bmatrix} 1'\left(DA_3^*, QDA_3^*, CDA_3^*, LDA_3^*\right) \rightarrow \\ 1'\left(DA_3^*, QDA_3^*, CDA_3^*, LDA_3^*\right) \end{bmatrix} \right\}
\end{aligned}
$$

Then,

$$
\begin{aligned}
R_{1VMPVDS} &= \left(OA_{1VMPVDS}, G_{1VMPVDS}, IA_{1VMPVDS}, E_{1VMPVDS}\right) \\
&= \left\{ \begin{array}{l} \left(om^{VMP} - g_1\right), (g_1), \left(g_1 - im^{VDS}\right), \\ \left\{ \left[1'\left(M_5^*, Q_5^*, C_5^*, L_5^*\right)\right], \begin{bmatrix} 1'\left(DA_3^*, QDA_3^*, CDA_3^*, LDA_3^*\right) \rightarrow \\ 1'\left(DA_3^*, QDA_3^*, CDA_3^*, LDA_3^*\right) \end{bmatrix} \right\} \end{array} \right\}
\end{aligned}
$$

Other added message passing relations can be specified in the similar way.

(3) $\Sigma_1 = \Sigma_0 - \Sigma_0{}^r \bigcup \Sigma_0{}^a = (PS_1, RS)$

where

$$PS_1 = \left\{ \begin{array}{l} \left(M_5^*, Q_5^*, C_5^*, L_5^*\right), \left(DA_3^*, QDA_3^*, CDA_3^*, LDA_3^*\right), \left(CA_2^*, QCA_2^*, CCA_2^*, LCA_2^*\right), \\ \left(R_2^*, QR_2^*, CR_2^*, LR_2^*\right), \left(St_1^*, QSt_1^*, CSt_1^*, LSt_1^*\right), \left(Sh_1^*, QSh_1^*, CSh_1^*, LSh_1^*\right), \\ \left(B_4^*, QB_4^*, CB_4^*, LB_4^*\right), \left[\begin{array}{l} \left(R_2^*, QR_2^*, CR_2^*, LR_2^*\right) \wedge \left(St_1^*, QSt_1^*, CSt_1^*, LSt_1^*\right) \wedge \\ \left(Sh_1^*, QSh_1^*, CSh_1^*, LSh_1^*\right) \wedge \left(B_4^*, QB_4^*, CB_4^*, LB_4^*\right) \end{array} \right] \end{array} \right\}$$

and $RS = e$

(4) $G_1 = \left(g_1, g_2, g_4, g_6\right)$

$$L_1(G_1) = \left\{\left[L_1\left({}^{\bullet}g_1\right), L_1\left(g_1^{\bullet}\right)\right], \left[L_1\left({}^{\bullet}g_2\right), L_1\left(g_2^{\bullet}\right)\right], \left[L_1\left({}^{\bullet}g_4\right), L_1\left(g_4^{\bullet}\right)\right], \left[L_1\left({}^{\bullet}g_6\right), L_1\left(g_6^{\bullet}\right)\right]\right\}$$

The changes to objects, i.e., the change from P_3, P_5, P_7, P_8, P_{11}, and P_{13} to P_2, P_4, P_6, P_9, P_{10}, and P_{12}, result in (i) the changes to the input message places connecting to g_1; and (ii) the changes in output message places connecting to g_6. For illustrative simplicity while without losing generality, g_1 is used to show how to modify the logic relationship functions.

$${}^{\bullet}g_1^0 = \left(om^{VMP}\right)$$

$${}^{\bullet}g_1^{0r} = \Phi$$

$${}^{\bullet}g_1^{0a} = \Phi$$

$${}^{\bullet}g_1^1 = {}^{\bullet}g_1^0 - {}^{\bullet}g_1^{0r} + {}^{\bullet}g_1^{0a} = \left(om^{VMP}\right) - \Phi + \Phi = \left(om^{VMP}\right)$$

$$L_1\left({}^{\bullet}g_1^1\right) = \left(om^{VMP}\right)$$

$$g_1^{\bullet 0} = \left(im^{ODS} \wedge im^{TCS}\right)$$

$$g_1^{\bullet 0r} = \left(im^{ODS} \wedge im^{TCS}\right)$$

$$g_1^{\bullet 0a} = \left(im^{VDS} \wedge im^{VCS}\right)$$

$$\begin{aligned} g_1^{\bullet 1} &= g_1^{\bullet 0} - g_1^{\bullet 0r} + g_1^{\bullet 0a} \\ &= \left(im^{ODS} \wedge im^{TCS}\right) - \left(im^{ODS} \wedge im^{TCS}\right) + \left(im^{VDS} \wedge im^{VCS}\right) \\ &= \left(im^{VDS} \wedge im^{VCS}\right) \end{aligned}$$

$$L_1\left(g\bullet_1^1\right)=\left(im^{VDS}\wedge im^{VCS}\right)$$

Thus,

$$L_1(g_1)=\left[L_1\left(\bullet g_1^1\right),L_1\left(g\bullet_1^1\right)\right]=\left[\left(om^{VMP}\right),\left(im^{VDS}\wedge im^{VCS}\right)\right]$$

$L_1(g_2)$, $L_1(g_4)$ and $L_1(g_6)$ can be generated in the same way.

(5) When the system is at the state that the configuration of a supply chain for O_1 has been completed, the token recorded the information regarding order O_2 has been in place P_1. This state is indicated by the following markings.

$$M_{o,s}=\left(MM_{o,s},SM_{o,s}\right)$$

where $MM_{o,s}=\phi$, and

$$\begin{aligned}SM_{o,s}=&1'\left(P_1^{VMP},e\right)+1'\left(P_1^{ODS},e\right)+1'\left(P_1^{TCS},e\right)+1'\left(P_1^{MRS},e\right)+\\&1'\left(P_1^{NSS},e\right)+1'\left(P_1^{HSS},e\right)+1'\left(P_1^{HBS},e\right)+1'\left(P_1^{DP},e\right)\end{aligned}$$

Thus,

$$\begin{aligned}MM_{1,0}&=MM_{0,s}-MM_{0,s}^{r}+MM_{0,s}^{a}\\&=\Phi-\Phi+1'\,im^{VDS}\left(DA_3^*,QDA_3^*,CDA_3^*,LDA_3^*\right)+1'\,im^{VCS}\left(CA_2^*,QCA_2^*,CCA_2^*,LCA_2^*\right)\\&=1'\,im^{VDS}\left(DA_3^*,QDA_3^*,CDA_3^*,LDA_3^*\right)+1'\,im^{VCS}\left(CA_2^*,QCA_2^*,CCA_2^*,LCA_2^*\right)\end{aligned}$$

$$\begin{aligned}SM_{1,0}&=SM_{0,s}-SM_{0,s}^{r}+SM_{0,s}^{a}\\&=SM_{0,s}-\begin{bmatrix}1'\left(P_1^{ODS},e\right)+1'\left(P_1^{TCS},e\right)+1'\left(P_1^{MRS},e\right)+\\1'\left(P_1^{NSS},e\right)+1'\left(P_1^{HSS},e\right)+1'\left(P_1^{HBS},e\right)\end{bmatrix}+\begin{bmatrix}1'\left(P_1^{VDS},e\right)+1'\left(P_1^{VCS},e\right)+1'\left(P_1^{VRS},e\right)+\\1'\left(P_1^{WSS},e\right)+1'\left(P_1^{VSS},e\right)+1'\left(P_1^{OBS},e\right)\end{bmatrix}\\&=1'\left(P_1^{VMP},e\right)+1'\left(P_1^{VDS},e\right)+1'\left(P_1^{VCS},e\right)+1'\left(P_1^{VRS},e\right)+\\&\quad 1'\left(P_1^{WSS},e\right)+1'\left(P_1^{VSS},e\right)+1'\left(P_1^{OBS},e\right)+1'\left(P_1^{DP},e\right)\end{aligned}$$

Thus,

$$M_{1,0} = \left(MM_{1,0}, SM_{1,0}\right)$$
$$= \left\{ \begin{array}{l} \left[1'im^{VDS}\begin{pmatrix} DA_3^*, QDA_3^*, \\ CDA_3^*, LDA_3^* \end{pmatrix} + 1'im^{VCS}\begin{pmatrix} CA_2^*, QCA_2^*, \\ CCA_2^*, LCA_2^* \end{pmatrix} \right], \\ \left[\begin{array}{l} 1'\left(P_1^{VMP}, e\right) + 1'\left(P_1^{VDS}, e\right) + 1'\left(P_1^{VCS}, e\right) + 1'\left(P_1^{VRS}, e\right) + \\ 1'\left(P_1^{WSS}, e\right) + 1'\left(P_1^{VSS}, e\right) + 1'\left(P_1^{OBS}, e\right) + 1'\left(P_1^{DP}, e\right) \end{array} \right] \end{array} \right\}$$

As shown in Fig. 5.7, the information flow depicted as follows is also changed due to the selection of different suppliers.

$$F_1 = \begin{bmatrix} (VMP, VDS), (VMP, VCS), (VDS, VRS), (VDS, WSS), (VCS, VSS), \\ (VCS, OBS), (VRS, DP), (WSS, DP), (VSS, DP), (OBS, DP) \end{bmatrix}$$

In Fig. 5.7, the tokens corresponding to the two assembly orders are represented as $\left(DA_3^*, QDA_3^*, CDA_3^*, LDA_3^*\right)$ for DA and $\left(CA_2^*, QCA_2^*, CCA_2^*, LCA_2^*\right)$ for CA. Based on the requirements of the two assembly orders, four module orders are generated, including $\left(R_2^*, QR_2^*, CR_2^*, LR_2^*\right)$ for Rt, $\left(St_1^*, QSt_1^*, CSt_1^*, LSt_1^*\right)$ for St, $\left(Sh_1^*, QSh_1^*, CSh_1^*, LSh_1^*\right)$ for Sh, and $\left(B_4^*, QB_4^*, CB_4^*, LB_4^*\right)$ for Bs. Subsequently, 4 suppliers represented by P_6, P_9, P_{10}, and P_{12} are selected. With the presence of 4 orders, g_6 is fired. A new token, $\begin{bmatrix} \left(R_2^*, QR_2^*, CR_2^*, LR_2^*\right) \wedge \left(St_1^*, QSt_1^*, CSt_1^*, LSt_1^*\right) \wedge \\ \left(Sh_1^*, QSh_1^*, CSh_1^*, LSh_1^*\right) \wedge \left(B_4^*, QB_4^*, CB_4^*, LB_4^*\right) \end{bmatrix}$, is generated and flows to P_{14}.

When the second order O_2 is presented, a new color is assigned to the token in P_1 to indicate order information. Based on the logic function of g_1, two new tokens corresponding to the two new decomposed orders flow to P_2 and P_4 that can deliver the two orders. Consequently, P_3 and P_5 are removed from current system since they cannot be qualified. Similarly, four different module suppliers are determined to fulfill the 4 module orders. Table 5.4 gives the items, orders, assigned colors to tokens that represent orders, and the suppliers that can match with the colors in two models in Fig. 5.6 and 5.7. While the colors influence the enabling of gates, the firing of gates determines the flow of tokens. For example, the generation of the token with color *b’* enables g_2 rather than g_3; the firing of g_1 in relation with the token with color *a’* directs the two tokens with color *b’* and *c’* to P_2 and P_4 rather than P_3 and P_5. The implication is that the descriptive data of P_2 and P_4 can match with the data indicated by color *b’* and *c’*. At the gate g_6, one token with a certain color is generated at the presence of four tokens from the connected four places. For example, the tokens with color *d’*, *e’*, *f’*, and *g’* lead to the generation of a token with color *h’* (the color of the token in the dummy place P_{14}), whilst the compatible color of the set of colors, including *d*, *e*, *f*, and *g*, is *h* (another color of the token in the dummy place P_{14}).

Table 5.4 Details of configuration models in Fig. 5.6 and 5.7

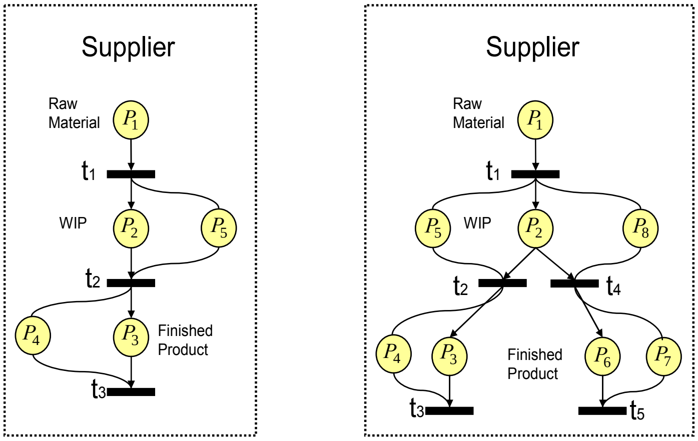
Item	**Order**	**Supplier**	**Color**	**Item**	**Order**	**Supplier**	**Color**
M_3^*	$(M_3^*, Q_3^*, C_3^*, L_3^*)$	VMP	a	M_5^*	$(M_5^*, Q_5^*, C_5^*, L_5^*)$	VMP	a’
DA_2^*	$(DA_2^*, QDA_2^*, CDA_2^*, LDA_2^*)$	ODS	b	DA_3^*	$(DA_3^*, QDA_3^*, CDA_3^*, LDA_3^*)$	VDS	b’
CA_1^*	$(CA_1^*, QCA_1^*, CCA_1^*, LCA_1^*)$	TCS	c	CA_2^*	$(CA_2^*, QCA_2^*, CCA_2^*, LCA_2^*)$	VCS	c’
R_5^*	$(R_5^*, QR_5^*, CR_5^*, LR_5^*)$	MRS	d	R_2^*	$(R_2^*, QR_2^*, CR_2^*, LR_2^*)$	VRS	d’
St_2^*	$(St_2^*, QSt_2^*, CSt_2^*, LSt_2^*)$	NSS	e	St_1^*	$(St_1^*, QSt_1^*, CSt_1^*, LSt_1^*)$	WSS	e’
Sh_3^*	$(Sh_3^*, QSh_3^*, CSh_3^*, LSh_3^*)$	HSS	f	Sh_1^*	$(Sh_1^*, QSh_1^*, CSh_1^*, LSh_1^*)$	VSS	f’
B_1^*	$(B_1^*, QB_1^*, CB_1^*, LB_1^*)$	HBS	g	B_4^*	$(B_4^*, QB_4^*, CB_4^*, LB_4^*)$	OBS	g’

5.5 Evaluation of Virtual Supply Chain Configuration

In order to evaluate different configuration solutions of a generic supply chain network, a further detailed operational model is developed to compare various supply chain configurations from certain performance metrics, e.g. lead time, cost, service level, etc. The operational model serves as the extension of supply chain configuration model. It simulates the concrete process flow along the supply chain to produce the final products for customers. In the configuration model, a supply entity is described as a node attached with attributes and parameters. In the operational model, it is extended to a series of activities and places that facilitate the information flow and decision flow within the entity.

5.5.1 Supply Chain Operational Model

The most basic activities of supply chain entities are material handling, including fabrication and transportation. Fig. 5.8 (a) shows the process of a supplier which produces a part c_1. The place P_1 represents the inventory of raw material. The place P_2 refers to the work-in-process (WIP) inventory in the production. The place P_3 indicates the transportation event from the supplier to manufacturer. Place P_4 and P_5 stand for the constraints of production capacity and transportation capacity of the supplier. Transitions t_1, t_2, t_3 represent the events of production start, production end, and transportation start, respectively. Through the five places P_1, P_2, P_3, P_4, P_5 and three transitions t_1, t_2, t_3, the major activities and states of a supply chain entity are modeled for its operational analysis. One supplier might be able to provide a part family including several types of parts. Fig. 5.8 (b) demonstrates a supplier capable for two types of parts. Transitions t_2 and t_4 receive same raw material from the place P_2, yet produce different parts, c_1 and c_2.The process flows for c_1 and c_2 are: $t_1 \succ t_2 \succ t_3$ and $t_1 \succ t_4 \succ t_5$, respectively. The production and transportation capability for c_1 and c_2 in the same supplier might be different. It would have impact for the entity selection in the supply chain configuration.



(a) Supplier for one material (b) Supplier for two materials

Figure 5.8 Two types of supplier nodes

Fig. 5.9 shows the operational model of the aforementioned motor supply chain in section 5.4. Descriptions of the model are given in Table 5.5 and 5.6, reporting the places and transitions in the configuration, respectively. The operational model adopts a modular object-oriented design approach, that each part, supplier, assembler and manufacturer (represented by the dashed-line boxes with captions $S_{Sh}, S_{Rt}, S_{DA}, S_{CA}, S_{MT}$) is modeled by a sub-net with same structure. The customers are represented by circular places $P_{22}, P_{23}, P_{24}, P_{25}$.

Obviously, the proposed operational model may be generalized for any *n-tier* supply chain network by employing *n* identical sub-nets for each type of partners (component supplier, sub-assembly supplier, manufacturer, warehouse, retailer, and customer). In addition, if the generic supply chain produces *m* parts, then it may be modeled as a *m-tier* subnet.

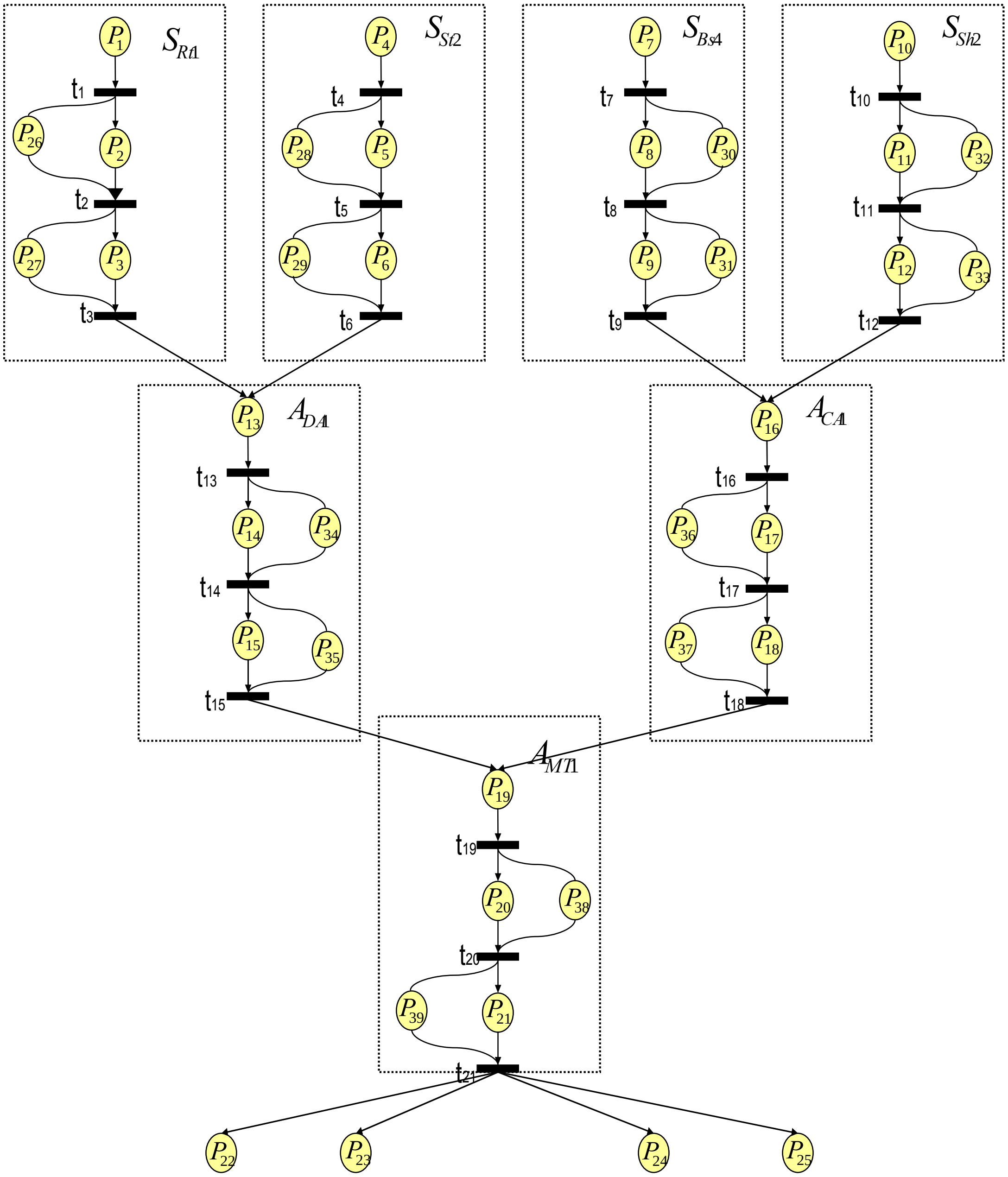


Figure 5.9 Petri-net based supply chain configuration operational model

Table 5.5 Operational model place descriptions

Name	**Description**
P_1	Raw material for production Rt_1 ready in S_{Rt1}
P_2	Work-in-process inventory of Rt_1 in S_{Rt1}
P_3	Final part inventory of Rt_1
P_4	Raw material for production St_1 ready in S_{St2}
P_5	Work-in-process inventory of St_1 in S_{St2}
P_6	Final part inventory of St_1
P_7	Raw material for production Bs_1 ready in S_{Bs4}
P_8	Work-in-process inventory of Bs_1 in S_{Bs4}
P_9	Final part inventory of Bs_1
P_{10}	Raw material for production Sh_1 ready in S_{Sh2}
P_{11}	Work-in-process inventory of Sh_1 in S_{Sh2}
P_{12}	Final part inventory of Sh_1
P_{13}	Part Rt_1 and St_1 for production of DA_1 ready in A_{DA1}
P_{14}	Work-in-process inventory of DA_1 in A_{DA1}
P_{15}	Final assembly inventory of DA_1
P_{16}	Part Bs_1 and Sh_1 for production of CA_1 ready in A_{CA1}
P_{17}	Work-in-process inventory of CA_1 in A_{CA1}
P_{18}	Final assembly inventory of CA_1
P_{19}	Assembly DA_1 and CA_1 for production of MT_1 ready in A_{MT1}
P_{20}	Work-in-process inventory of MT_1 in A_{MT1}
P_{21}	Final product inventory of MT_1
P_{22}	Warehouse I
P_{23}	Warehouse II
P_{24}	Customer I
P_{25}	Customer II
P_{26}	Production capacity of Rt_1 in S_{Rt1}
P_{27}	Transportation capacity of Rt_1 from S_{Rt1} to A_{DA1}
P_{28}	Production capacity of St_1 in S_{St2}
P_{29}	Transportation capacity of St_1 from S_{St2} to A_{DA1}
P_{30}	Production capacity of Bs_1 in S_{Bs4}
P_{31}	Transportation capacity of Bs_1 from S_{Bs4} to A_{CA1}
P_{32}	Production capacity of Sh_1 in S_{Sh2}
P_{33}	Transportation capacity of from S_{Sh2} to A_{CA1}
P_{34}	Production capacity of DA_1 in A_{DA1}
P_{35}	Transportation capacity of CA_1 from A_{CA1} to A_{MT1}
P_{36}	Production capacity of CA_1 in A_{CA1}
P_{37}	Transportation capacity of CA_1 from A_{CA1} to A_{MT1}
P_{38}	Production capacity of MT_1
P_{39}	Transportation capacity of MT_1

Table 5.6 Transitions and parameters in the operational model

Entity	**Transition**	**Description**	**Lead Time**	**Prod. Cost**	**Setup Cost**	**Trans. Cost**	**Inventory Cost**
S_{Rt1}	t$_1$	Start production of Rt_1 in S_{Rt1} for A_{CA1}	18	0	10	0	**2**
	t$_2$	End production of Rt_1 in S_{Rt1} for A_{CA1}	18	160	0	0	**5**
	t$_3$	Transportation of Rt_1 from S_{Rt1} to A_{CA1}	4	0	0	350	**8**
S_{St2}	t$_4$	Start production of St_1 in S_{St2} for A_{CA1}	15	0	15	0	**3**
	t$_5$	End production of St_1 in S_{St2} for A_{CA1}	15	150	0	0	**6**
	t$_6$	Transportation of St_1 from S_{St2} to A_{CA1}	5	0	0	400	**9**
S_{Bs4}	t$_7$	Start production of Bs_1 in S_{Bs4} for A_{DA1}	10	0	8	0	**4**
	t$_8$	End production of Bs_1 in S_{Bs4} for A_{DA1}	10	60	0	0	**6**
	t$_9$	Transportation of Bs_1 from S_{Bs4} to A_{DA1}	4	0	0	300	**8**
S_{Sh2}	t$_{10}$	Start production of Sh_1 in S_{Sh2} for A_{DA1}	13	0	10	0	**2**
	t$_{11}$	End production of Sh_1 in S_{Sh2} for A_{DA1}	13	90	0	0	**4**
	t$_{12}$	Transportation of Sh_1 from S_{Sh2} to A_{DA1}	4	0	0	250	**6**
A_{DA1}	t$_{13}$	Start production of CA_1 in A_{CA1} for A_{MT1}	15	0	12	0	**6**
	t$_{14}$	End production of CA_1 in A_{CA1} for A_{MT1}	15	360	0	0	**8**
	t$_{15}$	Transportation of CA_1 from A_{CA1} to A_{MT1}	7	0	0	500	**10**
A_{CA1}	t$_{16}$	Start production of DA_1 in A_{DA1} for A_{MT1}	14	0	15	0	**5**
	t$_{17}$	End production of DA_1 in A_{DA1} for A_{MT1}	14	320	0	0	**7**
	t$_{18}$	Transportation of DA_1 from A_{DA1} to A_{MT1}	7	0	0	450	**12**
A_{MT1}	t$_{19}$	Start production of MT_1	22	0	20	0	**6**
	t$_{20}$	End production of MT_1	22	450	0	0	**8**
	t$_{21}$	**Transportation of** MT_1	**10**	**0**	**0**	**600**	**13**

It is assumed that each token in the operational model represents a job lot, aiming to produce a batch of components or products. The capacities of each supply entity in the supply chain are shown in Table 5.6. The entire procedure of the operational model is running for 6 months. Table 5.6 reports the lead time associated with each transition. It is used as the firing time of a transition. For example, considering the transition t_2 modeling the end of production Rt_1 in S_{Rt1} for A_{CA1}, the maximum production capacity of Rt_1 in S_{Rt1} is 200 units. The firing time associated to the transition t_2 is 3 days. The firing times of transitions t_1, t_4, t_7, t_{10} are set to zero, which means the raw material for the production is immediately available. In order to avoid the situation that the component suppliers start production always at their maximum capacity, the start of raw material processing is modeled by transitions with non-zero firing times.

The last four columns of Table 5.6 report the cost related to the whole process, including processing cost, set-up cost for the machine and plants, transportation cost from one entity to another entity, inventory cost for raw material, WIP and finished product. Under the support of Petri-net embedded mathematic functions, it is easy to calculate the entire cost occurred in the supply chain. Supply managers could selectively analyze certain type of costs to make corresponding improvement. For example, the inventory cost on WIP of the sub-assembly can be extracted out to examine whether it is too high. As shown in Table 5.6, for the production transitions, e.g. t_1 and t_2, a production cost 160$ occurs during the firing of these two transitions. The firing of transition t_3 would cost the supplier 350$ to transfer part Rt_1 from supplier S_{Rt1} to assembler A_{CA1}. The cost structure could be further customized for specific supply chain configuration. For example, some companies need differentiate normal time production cost and extra time production cost.

5.5.2 CPN Simulation

To support supply chain configuration evaluation, the operational model is further empowered with Petri net simulation. The Petri NET Simulator 2.0 (http://petrinet.bigeneric.com) is adopted in the case. An example of Petri net simulation model is shown in Fig. 5.10. The number of tokens in each place is presented as a function of time. The stochastic arrival of tokens in P_9 (reflecting the random arrival of customer order) affects the generation of tokens in P_8 in a linear trend. The delivery times set for each suppliers also influence the generation of tokens in P_8.

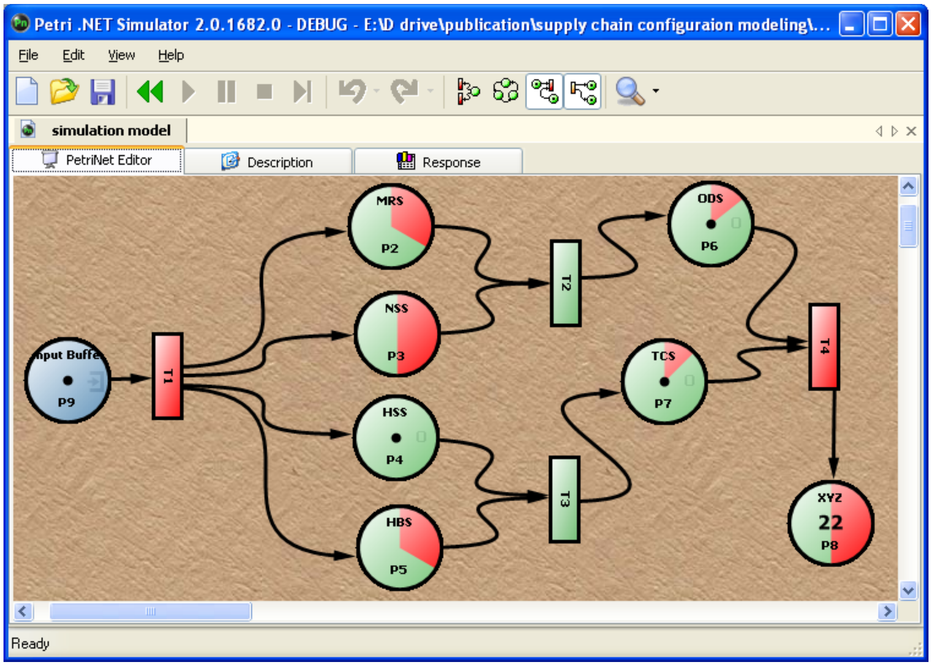


Figure 5.10 Petri-net based simulation supply chain configuration model

The considered performance indices of supply chain configurations are: (i) The overall production volume of final products, MT_1 and MT_2; (ii) The lead time of the entire network; and (iii) The overall cost, i.e. the sum of the production, fixed, transportation and inventory cost.

The configuration models are simulated in four scenarios. Scenario 1 adopts the configuration model to produce MT_1 with shortest lead time. Scenario 2 employs the configuration model to produce MT_1 with lowest cost. Scenario 3 uses the configuration model to produce MT_2 with shortest lead time. Scenario 4 takes the mixed configuration models to produce MT_1 and MT_2. As shown in Table 5.7, the four scenarios serve for customer orders, O_1 and O_2.

Table 5.7 Configured supply chains for O_1 and O_2

Order	**Supply Chain**	**Supplier**	**Product Item**	**Item Order**
O_1	$S_1^{O_1}$	VMP	M_3^*	$(M_3^*, Q_3^*, C_3^*, L_3^*)$
		ODS	DA_2^*	$(DA_2^*, QDA_2^*, CDA_2^*, LDA_2^*)$
		TCS	CA_1^*	$(CA_1^*, QCA_1^*, CCA_1^*, LCA_1^*)$
		MRS	R_5^*	$(R_5^*, QR_5^*, CR_5^*, LR_5^*)$
		NSS	St_2^*	$(St_2^*, QSt_2^*, CSt_2^*, LSt_2^*)$
		HSS	Sh_3^*	$(Sh_3^*, QSh_3^*, CSh_3^*, LSh_3^*)$
		HBS	B_1^*	$(B_1^*, QB_1^*, CB_1^*, LB_1^*)$
	$S_2^{O_1}$	VMP	M_3^*	$(M_3^*, Q_3^*, C_3^*, L_3^*)$
		ODS	DA_2^*	$(DA_2^*, QDA_2^*, CDA_2^*, LDA_2^*)$
		VCS	CA_1^{1*}	$(CA_1^{1*}, QCA_1^{1*}, CCA_1^{1*}, LCA_1^{1*})$
		MRS	R_5^*	$(R_5^*, QR_5^*, CR_5^*, LR_5^*)$
		NSS	St_2^*	$(St_2^*, QSt_2^*, CSt_2^*, LSt_2^*)$
		HSS	Sh_3^*	$(Sh_3^*, QSh_3^*, CSh_3^*, LSh_3^*)$
		OBS	B_1^{1*}	$(B_1^{1*}, QB_1^{1*}, CB_1^{1*}, LB_1^{1*})$
O_2	$S_1^{O_2}$	VMP	M_5^*	$(M_5^*, Q_5^*, C_5^*, L_5^*)$
		VDS	DA_3^*	$(DA_3^*, QDA_3^*, CDA_3^*, LDA_3^*)$
		VCS	CA_2^*	$(CA_2^*, QCA_2^*, CCA_2^*, LCA_2^*)$
		VRS	R_2^*	$(R_2^*, QR_2^*, CR_2^*, LR_2^*)$
		WSS	St_1^*	$(St_1^*, QSt_1^*, CSt_1^*, LSt_1^*)$
		VSS	Sh_1^*	$(Sh_1^*, QSh_1^*, CSh_1^*, LSh_1^*)$
		OBS	B_4^*	$(B_4^*, QB_4^*, CB_4^*, LB_4^*)$
	$S_2^{O_2}$	VMP	M_5^*	$(M_5^*, Q_5^*, C_5^*, L_5^*)$
		VDS	DA_3^*	$(DA_3^*, QDA_3^*, CDA_3^*, LDA_3^*)$
		TCS	CA_2^{1*}	$(CA_2^{1*}, QCA_2^{1*}, CCA_2^{1*}, LCA_2^{1*})$

		VRS	R_2^*	$(R_2^*, QR_2^*, CR_2^*, LR_2^*)$
		WSS	St_1^*	$(St_1^*, QSt_1^*, CSt_1^*, LSt_1^*)$
		VSS	Sh_1^*	$(Sh_1^*, QSh_1^*, CSh_1^*, LSh_1^*)$
		HBS	B_4^{1*}	$(B_4^{1*}, QB_4^{1*}, CB_4^{1*}, LB_4^{1*})$

Fig. 5.11 shows the simulation result in terms of time cost in the first scenario. The horizontal axis represents time while vertical axis refers to unit numbers. The overall productions of two supply chain configuration models in the four scenarios are depicted in Fig. 5.12, including the amount of final products and total lead time. As both product volume and lead time in the vertical axis are counted by unit, in order to have a more straightforward comparison of different supply chain scenarios, the author puts different performance indicators with the same measure magnitude into the same figure. As shown in the figure, scenario 2 is the most productive one, followed by scenario 3 and 1, which exhibit similar production capacities.

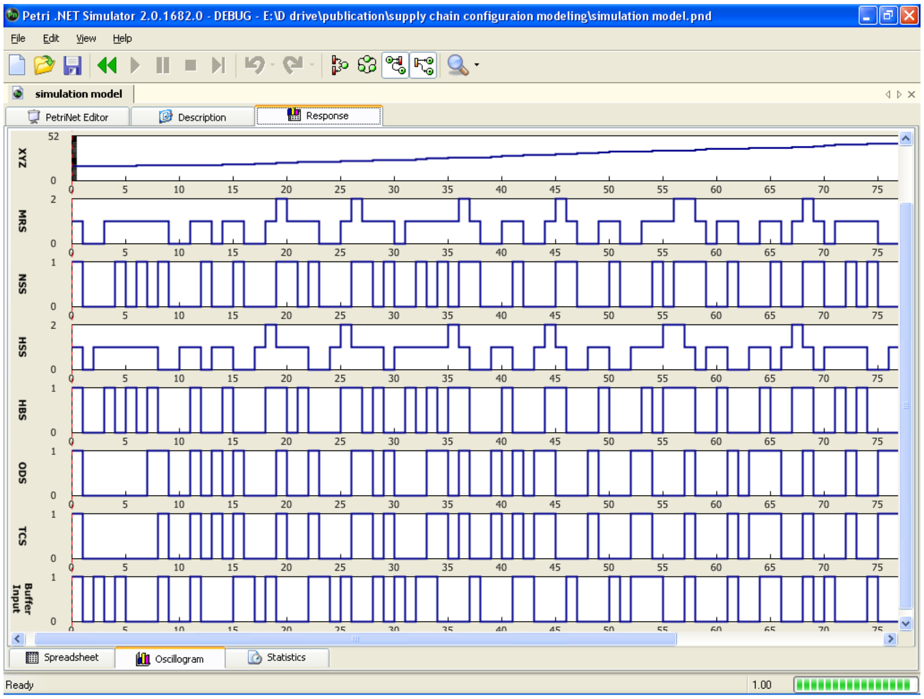


Figure 5.11 Simulation result of the first scenario

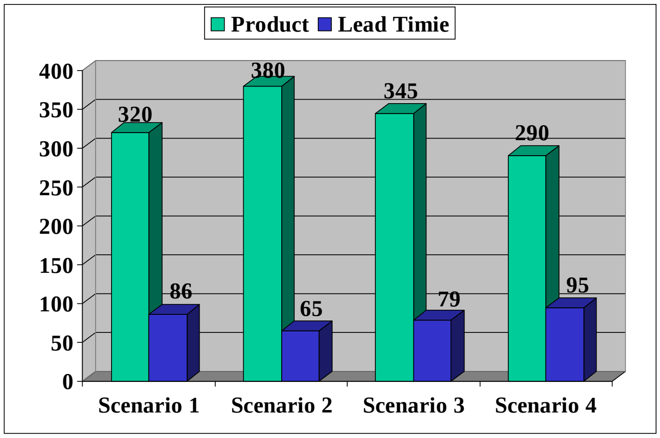


Figure 5.12 Performance indices of four configuration scenarios

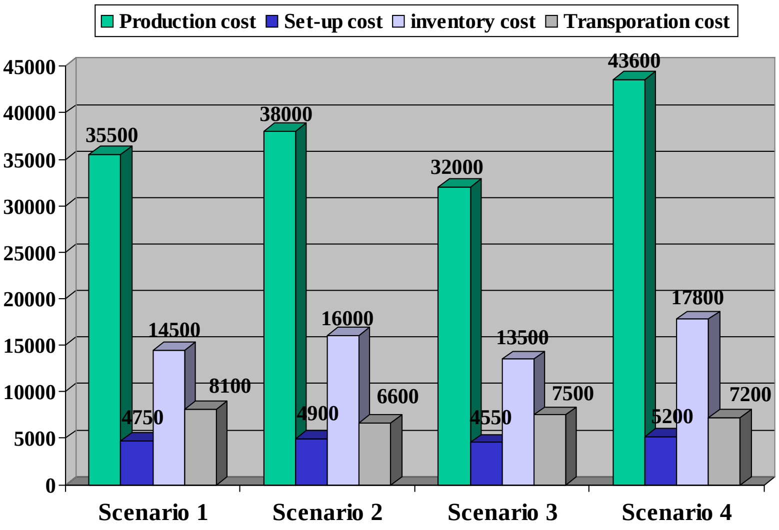


Figure 5.13 Cost comparison of four configuration scenarios

The overall costs of different configuration scenarios are reported in Fig. 5.13. The vertical axis lists four performance measures with the same magnitude: production cost, set-up cost, inventory cost and transportation cost. This figure shows that the production costs are comparable in all configurations. With regards to the transportation cost, scenario 3 and 4 exhibit higher numbers than scenario 2. Scenario 1 is characterized by lowest transportation cost. Indeed, the more complex supply chain configuration requires the higher amount of logistic cost, which may be justified by the increase of orders delivering to the consumer. The highest inventory cost occurs in scenario 4. In fact, scenario 4 requires larger stocks than other cases, as it does not benefit from the exchange of parts and products between partners belonging to different tiers.

As it can be seen from Fig. 5.12 and 5.13, each configuration scenario has its strength and drawback in terms of productivity, lead time and cost. The scenario 2 shows an overall better performance by joint consideration of performance measures, such as productivity and entire cost.

5.6 Discussion

CPN is a powerful tool that provides many analysis and simulation functionalities, which can be suitable for VSC modeling and configuration. Some of the main qualities of CPN are:

- CPN has a graphical representation. The graphical form is intuitively very appealing. It is extremely easy to understand and grasp - even for people who are not very familiar with the details of CPN.
- CPN has well-defined semantics, which unambiguously defines the behavior of each net. The presence of the semantics makes it possible to implement simulators for CPNs, and it forms the foundation for the formal analysis methods.
- CPN integrates the description of control and synchronization with the description of data manipulation. This means that on a single sheet of paper it can be seen what the environment, enabling conditions and effects of an action are. Many other graphical description languages work with graphs, which only describe the environment of an action, while the detailed behavior is specified separately (often by means of unstructured prose).

- CPN has computer tools supporting their drawing, simulation and formal analysis. This makes it possible to handle larger nets without drowning into details and without making trivial calculation errors.

Chapter 5 describes how different supply chain scenarios can be modeled and analyzed by CPN tools. The CPN approach permits the functions of forming customer orders and delivery to be defined in an easy and fast way, which is not possible by using the modeling tools known to the authors. According to the results, the simulations can measure different performances: reactions of participants to sudden changes in customer demands, changes in supply level in a time, surplus of inventory goods, the costs of SC participants and the entire SC, etc. It has been shown that it is possible to form a PN model of a supply chain, which allows easy experimenting with different scenarios.

However, there also are certain limitations. For example, CPN has very few, although powerful, primitives. The definition of CPNs is rather complex and it builds upon concepts which are different from many other programming languages. This means that it is relatively difficult to learn to use CPNs. Also, CPNs have a semantics which builds upon interleaving, instead of true concurrency. In an interleaving semantics, it is impossible to have two actions in the same step, and thus concurrency only means that the actions can occur after each other, in any order. A true concurrency semantics is easier to work with, because it is closer to the way human beings think about concurrent actions.

As a future direction, CPN should be used in VSC modeling for three different - but closely related purposes. First of all, a CPN model is a description of the modeled supply chain, and it can be used as a specification or as a presentation. By creating a model, we can investigate a new system before we construct it. This is an obvious advantage, in particular for systems where design errors may jeopardize security or be expensive to correct. Secondly, the behavior of a CPN model can be analyzed, either by means of simulation (which is equivalent to program execution and program debugging), or by means of more formal analysis methods (which are equivalent to program verification). Finally, it should be understood that the process of creating the description and performing the analysis usually gives the modeler a dramatically improved understanding of the modeled system, and it is often the case that this is more valid than the description and the analysis results themselves.

5.7 Summary

This chapter introduces a modeling formalism based on colored PNs for virtual supply chain configuration, with consideration of joint product, process and logistics design. It represents the configuration and operation of a supply chain as an abstracted network, where the supply entity is modeled as a net node attached with attributes and related parameters. It is able to shed light on the implications of joint product, process and logistics decision making, which assists companies in predicting the performance of the configured supply chains. This is accomplished by incorporating OO technique and a mechanism to handle structural changes in colored PNs. While the colored tokens and the OPNs collaboratively address the large number of suppliers and the various product items that they can produce, the change handling mechanism deals with the different structures of the configured supply chains. The modeling formalism is expected to assist companies in forming optimal supply chains in response to fast customer demand changes.

CHAPTER 6 MULTI AGENT BASED INFORMATION PLATFORM FOR VIRTUAL SUPPLY CHAIN CONFIGURATION

In this chapter, a multi-agent based information platform for virtual supply chain configuration is proposed. It provides an integrated and homogeneous decision making environment for VSC configuration analysis, operation, coordination, and evaluation. When an order comes from the end customer, a virtual supply chain (VSC) is dynamically created by combining a group of capable agents through task decomposition and allocation. The multi agent platform facilitates the entire lifecycle of a VSC, encompassing initiation, formation, operation, cooperation and decommission. A VSC is coordinated by a particular designed mediator agent, which facilitates information and knowledge sharing, synchronizes the decisions of individual agents and optimizes the overall added-value of the VSC. The message communication and decision synchronization among VSC members are controlled by a series of encapsulated conversation protocols, which are represented as Petri-net based behavioral models.

6.1 Multi Agent Systems

The rapidly expanding Internet provides a promising networking medium, while the agent technology lends itself to the management of global supply chain networks within a distributed environment. An agent is a computer system situated in a certain kind of environment, and is capable of flexible autonomous action in order to meet its designed objectives (Brenner *et al.*, 1998). An agent has characteristics such as autonomous, social, reactive and pro-active (Jennings and Wooldridge, 1998). The agent-based technology has emerged as a new paradigm for conceptualizing, designing, and implementing information systems (Maturana *et al*., 1999).

A multi agent system (MAS) is regarded as a loosely coupled network of problem solvers, that interact to solve problems that are beyond the individual capabilities or knowledge of each problem solving (Shin and Jung, 2004). MASs enhance overall system performance, in particular along such dimensions as computational efficiency, reliability, extensibility, responsiveness, maintainability, and flexibility (Shen and Norrie, 1999). They are also capable of solving the problem of matching supply to demand, allocating resources dynamically in real time, by recognizing opportunities, trends and potentials, as well as carrying out negotiations and coordination (Maturana *et al*., 1999). The studies on MAS-based supply chain management can be classified into three categories. The first category focuses on dynamic classification and formation of an efficient supply chain network to improve its adaptability and efficiency. Fox *et al*. (1993) proposed to organize the supply chain as a network of cooperating, intelligent agents, where each agent performs one or more supply chain functions and coordinates its actions with other agents. While applying a multi-agent framework to model supply chain dynamics, Swaminathan *et al*. (1996) have investigated structural and control elements. Maturana *et al*. (1999) developed a hybrid agent-based mediator-centric architecture, called MetaMorph, to integrate partners, suppliers and customers dynamically with the main enterprise through their respective mediators within a supply chain network via the Internet and Intranets.

The second category shows how a multi agent system can improve the operational efficiency of supply chains by reducing costs and improving performance. Ho *et al*. (2000) implemented several methods to automate the construction of agent-based supply chains by translating UML diagrams and business object documents into state machines. Shen and Norrie (1999) detailed a general, domain independent, collaborative agent system architecture, which incorporates standard agents' services such as ontology, yellow pages, and centralized local coordination managers as well as the notion of a dynamic cooperating domain abstraction for groups of cooperating agents. Ghiassi and Spera (2003) described a multi-agent negotiation test bed (MAGNET), which implements collaboration via an auction model.

The studies in the third category focus on the suggestion of effective agent-based architectures for supply chain management. Swaminathan *et al*. (1998) proposed a supply chain library of software components, such as retailers, manufacturers, inventory policy, etc. Sadeh *et al*. (2001) developed an agent-based architecture for a dynamic supply chain called MASCOT. The MASCOT is a reconfigurable, multi-level, agent-based architecture for a coordinated supply chain. Agents in MASCOT serve as wrappers for planning and scheduling modules. Petersen *et al*. (2001) proposed a multi-agent architecture, called AGORA, for modeling and supporting cooperative work among distributed entities in virtual enterprises.

Most existing MAS approaches for supply chain coordination imply a closed environment consisting of a fixed number of entities that share a common target (Sadeh *et al*., 2001). Such a scenario, however, does not conform to the complex operations of a real-case global manufacturing supply chain (Chen *et al*., 1999). Besides different interests among supply chain entities, there is no obligation for any company to remain within a supply chain for a certain period. Companies may join or leave the chain anytime for their own reasons. This means that functional agents must explicitly deal with the negotiation, along with the collaboration, among different supply chain entities in a dynamic environment. It is imperative to introduce a high-level control mechanism to agent-based supply chain coordination systems.

6.2 VSC Lifecycle

Today's social and economic environment is characterized by complex factors like market globalization, short product life cycle, high variability of customer demand, higher flexibility and reactivity (Zaidat, 2005). Markets are becoming too large and complex for one entity to manage in a competitively dominant way. Rapid and virtual partnering has emerged as a key issue for new supply chain management strategies, with best integrators working together to maximize the overall system value (Anderson and Delattre, 2002). With the development of advanced technologies, a great number of software and hardware tools are showing up and facilitating collaboration through the entire electronic supply chain connection, which leads to the emergence of the virtual supply chain (VSC). A VSC is defined as a temporary, cooperative network that is formed by independent, autonomous companies to exploit a particular market opportunity, under the support of information and communication technologies (Petersen *et al.*, 2001). The involved enterprises are connected to be a large and interactive supply chain network system, in which exist four flows, i.e. flow of goods, flow of information, flow of financing and flow of trading.

Since most VSCs are temporary alliances for particular tasks, VSCs would exist for certain time periods and be dissolved quickly after end customer requirements are fulfilled. Hence, it is important to investigate the entire lifecycle of a VSC, from its conceptual initiation to decommission.

By using the Generic Enterprise Reference Architecture and Methodology (Petersen *et al.*, 2001), the lifecycle of a VSC is divided into six distinct phases as following:

Initiation Phase: The concepts underlying a VSC are defined, which include objectives, strategies, work flow, constraints and durations. It provides inputs to the requirements of the VSC.

Requirement Phase: This phase decomposes the end customer requirements, expressed by orders or quotas, into a series of requirements, including functional specifications, product structures, quality and quantity needs, delivery times and locations, etc.

Design Phase: Identification of necessary information and resources for the requirements. At the end of this phase, functional, behavioral, and resource views of a VSC are specified.

Formation Phase: According to technology, resource and capability requirements, VSC members are evaluated and selected through auction and negotiation. Each member receives its task from downstream consumers and negotiates with its upstream suppliers to further expand the supply chain. This phase performs such activities as allocation of resources and development of production plans or delivery plans.

Operation Phase: It is also the implementation phase of a VSC, while members perform their allocated work and provide material to downstream consumers in the VSC. They cooperate and coordinate with each other to rapidly produce new products to the market, reduce overall system cost and improve customer service.

Decommission Phase: This phase specifies activities required to reform a VSC at the end of its lifecycle. It includes disassembly of the VSC, capturing and reuse of its knowledge for next cooperation.

The VSC lifecycle concept is different from VSC domain defined in Chapter 3. Lifecycle describes the major stages and functionalities in a VSC, while domain represents the major elements and processes in a VSC. The scenarios at each phase can be modeled by identifying the roles performed by members and cooperative work among members. Related responsibility and resource are specified to define a work context. An IDEF0 model of VSC lifecycle is shown in Fig. 6.1, where each box represents a VSC life phase and its related activities. Arrows entering the left side of a box are inputs of activities; arrows entering the top of a box are the controls/constraints of the activity; and arrows leaving the right side of a box are the outputs of the activity.

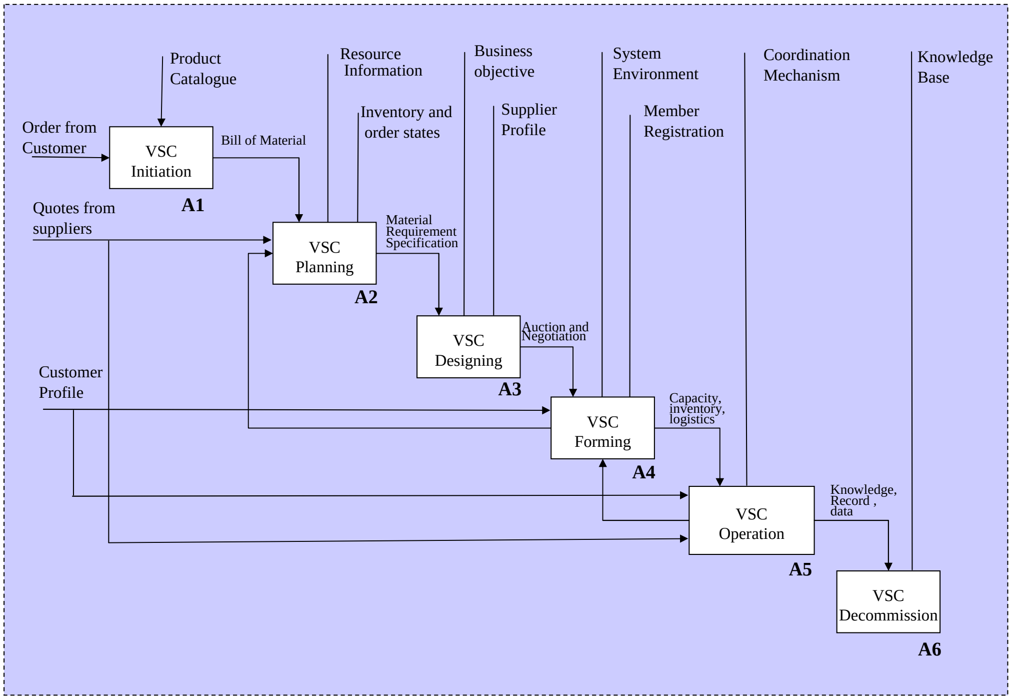


Figure 6.1 VSC lifecycle IDEF0 model

6.3 VSC Behavioral Modeling

In order to manage and control the VSC lifecycle, this study proposes a multi-agent based information platform for VSC configuration. It consists of heterogeneous types of autonomous, intelligent and cooperative agents, which represent various enterprises such as suppliers, manufacturers, retailers, etc. Functions within an enterprise such as scheduling, purchasing, negotiation are encapsulated into agents in the platform. As shown in Fig. 6.2, a VSC is composed of entity agents and functional agents. A mediator agent assumes the coordinator role among VSC members.

Different lifecycle phases of a VSC perform different actions to achieve phase objectives. The interaction and coordination behaviors of member agents follow different patterns. For example, in the formation phase of a VSC, the focus is on order decomposition and allocation. While in the operation phase, decision synchronization and optimization among VSC members are more important. Hence, as shown in Fig. 6.2, a series of agent behavioral models are proposed to guide agent interaction and coordination in various VSC life phases.

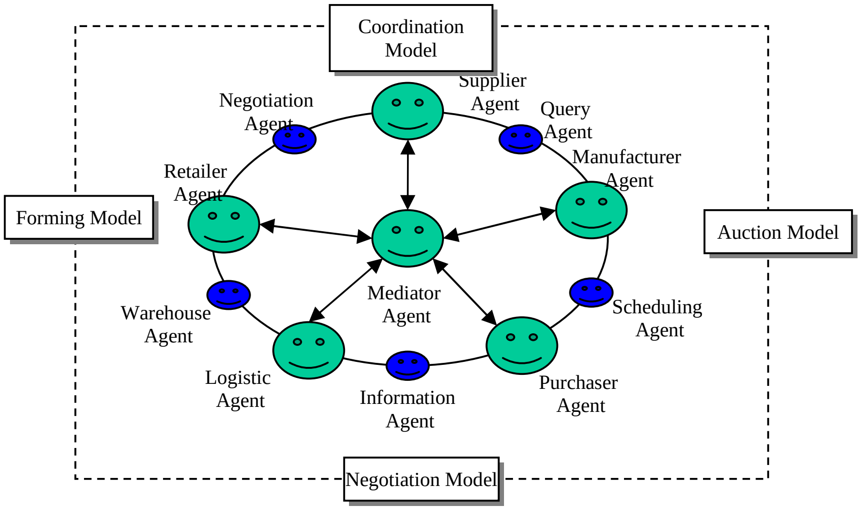


Figure 6.2 VSC behavioral models

The behavioral models of agents are built and visualized using Petri-nets, a tool that has been widely applied in concurrent engineering system modeling and production control. A Petri-net is defined as a directed graph consisting of places, transitions, and arcs, where a circle represents a place, a bar represents a transition, and an arc connects a place with a transition. A marking indicates the distribution of a number of tokens in one place. Movements of tokens from place to place represent the dynamic aspects of processes. A transition is enabled if the input place towards the transition contains at least one token. After a transition is fired, the input place is removed a token while the output place is added a token. When alternative firing transitions exist, a firing rule is applied to choose which of them is to be fired first.

6.3.1 VSC Formation Model

A Petri-net model for specifying the process of building a virtual supply chain through a multi-agent platform is illustrated in Fig. 6.3. Detailed descriptions of the actions in the places and events in the transitions are given in Table 6.1. Several supply chain entity agents, e.g. supplier agents, customer agents, manufacturing agents and a mediator agent, are involved in the formation process. Initially, one token is deposited in place m_1, which represents the waiting state upon receiving an order from customer or retailer agents. Following with the launch of a customer order, a mediator agent is initiated to build a virtual supply chain to fulfill the order.

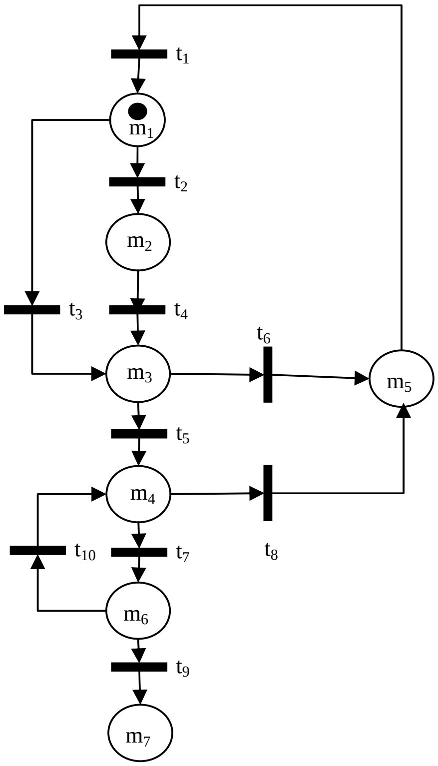


Figure 6.3 VSC formation process model

Table 6.1 Legends in the VSC formation model

Action	Description of an action in the place	Event	Description of an event in the transition
m_1	Receiving order from customers	t_1	Order arrival
m_2	Configuring product	t_2	Product needs customization
m_3	Launching RFQ to suppliers	t_3	Product catalogue
m_4	Making material planning and production scheduling	t_4	Bill of material
m_5	Discussing requirements with the customer	t_5	Supplier available
m_6	Negotiating with suppliers	t_6	Supplier unavailable
m_7	Building VSC coordination relationship	t_7	Material requirement specification
		t_8	Infeasible planning and scheduling
		t_9	Reaching agreement
		t_{10}	Reaching no agreement

Suppose the customer order comes with a new type of product structure that needs customization, the token is transferred to the *place* m_2 for product configuration. This work is done by the configuration agent. The result is a bill of material and transferred to the *place* m_3 for the next step. If the customer order could be satisfied from the current product catalogue, the token is directly transferred to the *place* m_3 to search capable suppliers providing raw material. The firing condition of the *transition* t_6 is there are no available suppliers in the market for certain material. The token is then deposited to the *place* m_6, where the manufacturing agent discusses with customers to change their requirements and issue a new order. If suppliers are available, the token is moved to the *place* m_4 that functional agents begin to make material planning, production scheduling and capacity planning. According to the concrete running situation of the supply chain, planning result might be successful or failed. Failed plan would drive the token to the *place* $m_{5,}$ where the retailer agent need discuss with customers to obtain a new order.

Successful plan would be exploded to material requirement specifications, which are allocated to supplier agents in the VSC. This process is iterated until all the material requirements are contracted to capable suppliers. Finally, the virtual supply chain is composed by all the contracted agents, which represent independent supplier entities.

6.3.2 VSC Coordination Model

After the VSC is established through agent auctions and negotiations, manufacturing agents and supplier agents need constantly interact and cooperate with each other to accomplish their orders. A three-level adaptive coordination mechanism is developed for the VSC operation, as illustrated in Fig. 6.4. It demonstrates how the mediator agent (MA) solves a task requiring coordination of several VSC members. The description of actions and events of the model are listed in Table 6.2.

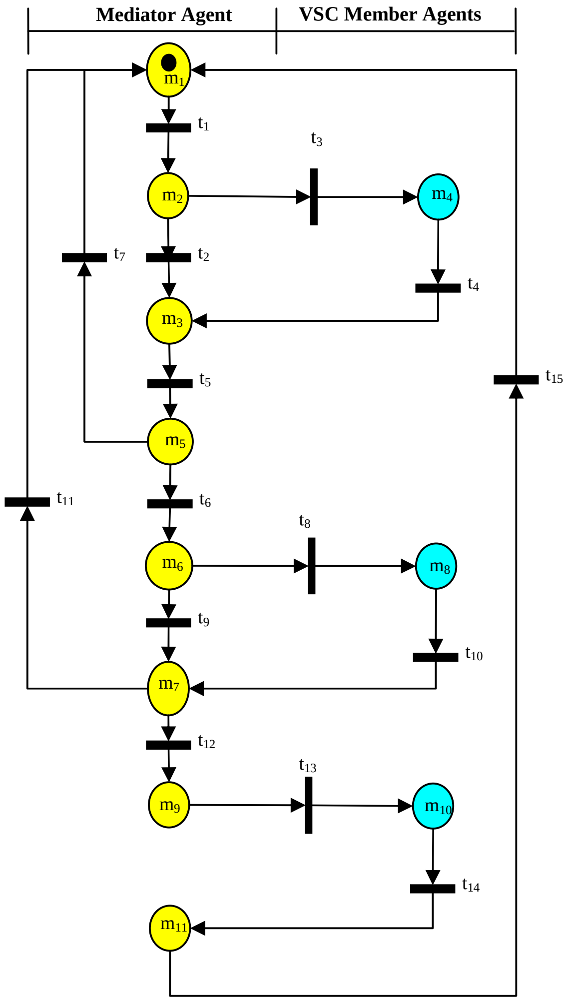


Figure 6.4 VSC coordination model

A token is initially located at the *place* m_1, which represents the waiting state of the VSC. The coordination process starts from the MA receiving a task through the firing of the *transition* t_1, which is launched by a VSC member agent. At the *place* m_2, the MA retrieves its knowledge base to search required information for solving the task. If related information is found, the *transition* t_2 is fired. Information is published to the blackboard of the MA to notify corresponding members. Otherwise, the *transition* t_3 sends a query to supplier agents to obtain task related information. At the *place* m_4, a supplier agent receives the request from the MA. It will check its database and fire the *transition* t_4 to transfer particular message to the MA. Since different types of VSCs perform different coordination actions, the supply chain coordination index (CI) is introduced to divide VSC coordination abilities into three levels: high, medium and low. At the *place* m_5, the MA checks the CI of the VSC. If the CI is low, the token is returned back to the *place* m_1. Otherwise, the MA will make the conflict checking for the VSC. If conflicts exist within members' plans or decisions, the *transition* t_8 is fired to notify affected supplier agents. Upon receiving of conflict notification, supplier agents obtain the token at the *place* m_8. Then, supplier agents need modify their plans and send new plans to the MA through the *transition* t_{10}. At the *place* m_7, the MA rechecks the CI of the VSC. If the CI is medium, the token is returned back to the *place* m_1 through the *transition* t_{11}. If the CI is high, the MA makes systematic-wide centralized planning and scheduling for the entire supply chain. The synchronized plans and schedules are sent to all VSC members through the *transition* t_{13}. At the *place* m_{10}, supplier agents receive their tasks and allocate resource and capacity. The executing states of individual tasks in the supplier agents are sent to the MA through the *transition* t_{14}. At the *place* m_{11}, the MA updates supply chain running states, database, blackboard, etc. The token is returned back to the *place* m_1 and waits for the next task of the VSC.

Table 6.2 Legends in the VSC coordination model

Action	Description of an action in the place	Event	Description of an event in the transition
m_1	The initial waiting state of the VSC	t_1	Supply Chain operation starting
m_2	Retrieving related information	t_2	Information storing in the database
m_3	Publishing information in the blackboard	t_3	No required information
m_4	Querying information	t_4	Sending message to mediator agent
m_5	Checking the CI of the VSC	t_5	Requiring further cooperation
m_6	Conflict checking	t_6	CI is “low”
m_7	Checking the CI of the VSC	t_7	CI is not “low”
m_8	Notifying conflicted agents	t_8	Conflict existing
m_9	Integrated decision making	t_9	No conflict found
m_{10}	Allocating task and resource	t_{10}	Sending new plan
m_{11}	Updating task executing state	t_{11}	CI is “medium”
		t_{12}	CI is “high”
		t_{13}	Sending task to individual agents
		t_{14}	Executing task
		t_{15}	Returning back to waiting state

6.3.3 VSC Negotiation Model

Upon the receipt of tasks allocated by the mediator agent, the manufacturer needs to use a purchasing agent to find suitable suppliers providing certain materials. As purchasing agents and supplier agents belong to autonomous business organizations, they had to negotiate to reach a bilateral beneficial agreement. A negotiation model built by Petri-nets is adopted to guide the behaviors of two agents and assist them to achieve an optimized agreement. The negotiation model between a supplier and a purchaser is illustrated in Fig. 6.5. The involved entity agents include a supplier, a purchaser and a mediator. The actions and events in this model are listed in Table 6.3.

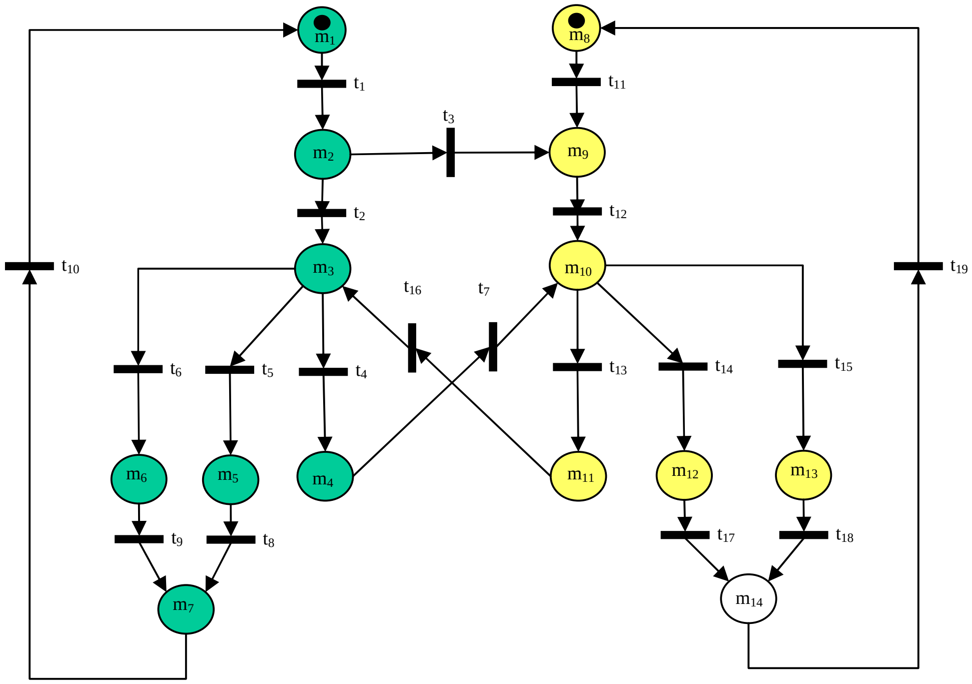


Figure 6.5 VSC negotiation model

Tokens are initially located at the *place* m_1, which represents the waiting state of the purchasing agent before the negotiation process commences. Upon the receipt of a material requirement specification from a mediator agent, a token is moved from the *place* m_1 to the *place* m_2. The *place* m_2 enables two *transitions* t_2 and t_3. The *transition* t_2 initializes the negotiation agent with some bargaining rules. The *transition* t_3 sends a RFQ to the supplier. Since the purchasing agent and the supplier agent follow unified negotiation protocol in the VSC, the author only discusses the actions and transactions of the purchasing agent. After the *place* m_3 receives an offer from the supplier agent, three types of events might happen, corresponding to the *transition* t_4, t_5, and t_6, respectively. The *transition* t_6 means the offer is satisfied to the purchaser. Then the offer is accepted at the *place* m_6. The *transition* t_5 means the offer is unsatisfied to the purchaser. Then the offer is rejected at the *place* m_5. If the offer is partially satisfied in the *transition* t_4, purchasing agent at the *place* m_4 would generate a counter-offer and send it to the supplier agent through the *transition* t_9. This offer exchanging process between the purchaser and supplier would be iterated for several rounds through the transaction t_7 and t_{16}, until one agent reaches the conclusion, either accepts it or rejects it. The *transition* t_8 transfers a negotiation failure message to the place m_7, while the *transition* t_9 transfers a negotiation successful message to the place m_7. The *place* m_7 terminates the negotiation process and sends back the token to the *place* m_1, with a message that negotiation is completed.

Table 6.3 Legends in the VSC negotiation model

Action	**Description of an action in the place**	**Event**	**Description of an event in the transition**
m_1	Waiting for task	t_1	Material Requirement Specification
m_2	Initialization of negotiation	t_2	Evaluation criteria
m_3	Receiving offer	t_3	RFQ
m_4	Generating counter-offer	t_4	Unsatisfied offer
m_5	Rejecting the offer	t_5	Partially satisfied offer
m_6	Reaching agreement	t_6	Satisfied offer
m_7	Terminating negotiation	t_7	Counter offer
m_8	Waiting for task	t_8	Negotiation failure
m_9	Initialization of negotiation	t_9	Negotiation successful
m_{10}	Receiving offer	t_{10}	Negotiation finished
m_{11}	Generating counter-offer	t_{11}	Current material states
m_{12}	Rejecting the offer	t_{12}	Evaluation criteria
m_{13}	Reaching agreement	t_{13}	Unsatisfied offer
m_{14}	Terminating negotiation	t_{14}	Partially satisfied offer
		t_{15}	Satisfied offer
		t_{16}	Counter offer
		t_{17}	Negotiation successful
		t_{18}	Negotiation failure
		t_{19}	Negotiation finished

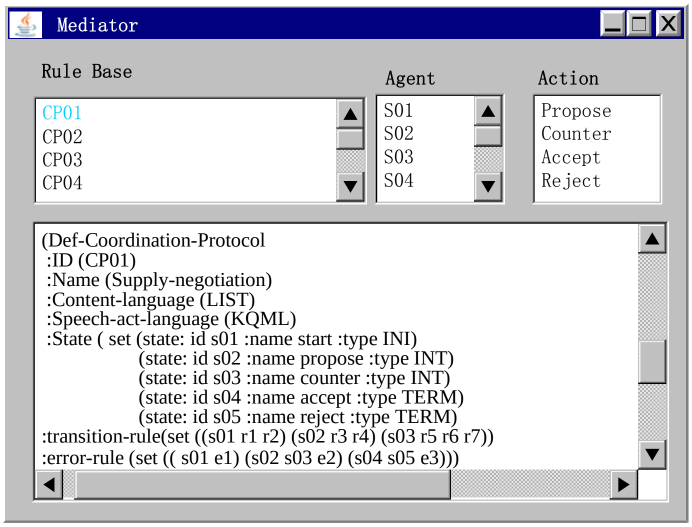
6.3.4 Agent Conversation Protocol

In order to mange and control the VSC interaction and coordination, aforementioned behavior models are encapsulated into conversation protocols. A conversation is a sequence of messages involving two or more agents, intended to achieve a particular purpose. Conversation protocols are rule-based instructions of how an agent acts and reacts with other agents and environment. The functions of conversation protocols are: firstly, they define causal-relation sequences of messages; then they restrict how agents react to these messages during communications. Without using them, individual agents in each conversation step may face difficulties in determining the message type, sequence and responding actions. Since a VSC is an open community that new members and service are continuously added and the situations are fast changing, it is difficult for agents making quick response to those changes without unified conversation protocols.

The multi-agent platform adopts conversation protocols to manage and control different kinds of VSCs. Each VSC applies suitable conversation protocols in different lifecycle phases to supervise the interaction and coordination among members. The following is the syntax for transforming and parsing conversation protocols.

```
<conversation-protocol>
                        = id <string> : name <string> :description <string> <state-
                          description> <transition-description>
                          <parameter-description> <state-description>
                        = state '('set ('('state: id<string>: type INI | INT | TERM')'
                          <transition-description>
                        = transition '('set('('transition :id<string>: from <string>: to
                          <string>:  performer INI | COUNTER | <string> :MA
                          <communication-act> :parameter <string>  ')'
                          <parameter-description>
                        = parameter '('set ('('parameter: id<string>:
                          content<string>: ontology <string>: type ACT | REF
                          |PROP ')')') <communicative-act>
                        = request | inform | informIF | queryRef | refuse | failure|
```

Fig. 6.6 shows an example of a series of conversation protocols embedded in the mediator agent. In the rule base of the agent, there are four conversation protocols programmed in pre-mentioned syntax. Rule CP01 refers to the negotiation protocol, which specifies four types of actions during a negotiation, namely *propose*, *counter offer*, *accept*, *reject*. Transition rules and error rules are regulated responding to different negotiation steps.



```
(Def-Coordination-Protocol
 :ID (CP01)
 :Name (Supply-negotiation)
 :Content-language (LIST)
 :Speech-act-language (KQML)
 :State ( set (state: id s01 :name start :type INI)
              (state: id s02 :name propose :type INT)
              (state: id s03 :name counter :type INT)
              (state: id s04 :name accept :type TERM)
              (state: id s05 :name reject :type TERM)
:transition-rule(set ((s01 r1 r2) (s02 r3 r4) (s03 r5 r6 r7))
:error-rule (set (( s01 e1) (s02 s03 e2) (s04 s05 e3)))
```

Figure 6.6 Supply negotiation conversation protocol

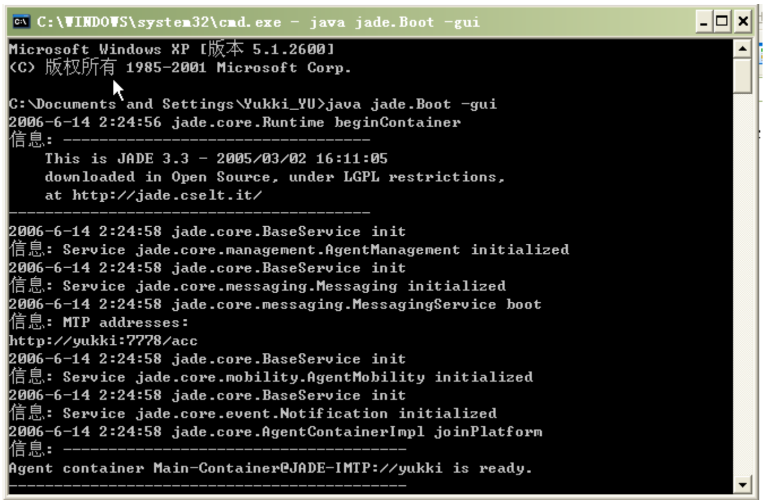
6.4 Platform Development and Validation

The multi-agent based platform provides an environment for independent enterprises making a temporary alliance to exploit market opportunities. Hundreds agents register their services to the platform on behalf of the owner's benefit. A virtual supply chain is dynamically created once an end customer order is received. According to the requirements of customers, different types of entity agents, e.g. retailers, manufacturers, distributors and suppliers, cluster together to build a temporary and dynamic VSC. It involves multi-lateral negotiation and task distribution. A mediator agent is created as an information hub and decision center for the VSC. It identifies critical information from incoming resource, monitors information content and triggers actions.

6.4.1 System Set-up

Before the initiation of the multi-agent platform, all the involved computers must be installed with Java SDK 1.4.1 and JADE version 2.5. The procedures to set-up the system are as following:

(1) Under the DOS environment, the system users key in a command to launch the GUI of the main container: ***Prompt> java jade.Boot –gui***



```
Microsoft Windows XP [版本 5.1.2600]
(C) 版权所有 1985-2001 Microsoft Corp.

C:\Documents and Settings\Yukki_YU>java jade.Boot -gui
2006-6-14 2:24:56 jade.core.Runtime beginContainer
信息: ----------------------------------
    This is JADE 3.3 - 2005/03/02 16:11:05
    downloaded in Open Source, under LGPL restrictions,
    at http://jade.cselt.it/
----------------------------------------
2006-6-14 2:24:58 jade.core.BaseService init
信息: Service jade.core.management.AgentManagement initialized
2006-6-14 2:24:58 jade.core.BaseService init
信息: Service jade.core.messaging.Messaging initialized
2006-6-14 2:24:58 jade.core.messaging.MessagingService boot
信息: MTP addresses:
http://yukki:7778/acc
2006-6-14 2:24:58 jade.core.BaseService init
信息: Service jade.core.mobility.AgentMobility initialized
2006-6-14 2:24:58 jade.core.BaseService init
信息: Service jade.core.event.Notification initialized
2006-6-14 2:24:58 jade.core.AgentContainerImpl joinPlatform
信息: --------------------------------------
Agent container Main-Container@JADE-IMTP://yukki is ready.
--------------------------------------------
```

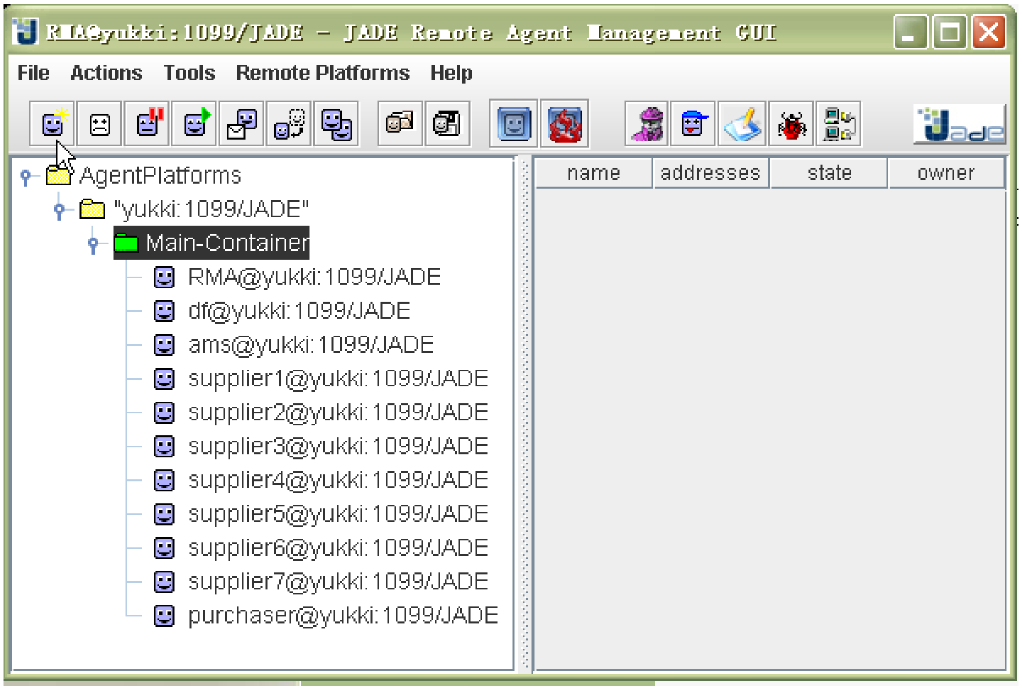
Figure 6.7 Startup of the multi-agent platform

(2) Loading agents into the multi-agent platform. The system user could add different type of agents into the platform through the instantiation of predefined agent classes. Agents belonging to the same classes have same structures, yet are equipped with different performance parameters on behalf of their owners.

Firstly, the user creates some supplier agents through instantiation of the class SUPPLIERAGENT. They were loaded in the platform, which is shown in Fig. 6.8. Each supplier agent is capable to provide a type of material under certain conditions.

Secondly, several purchaser agents were loaded in the platform through instantiation of the class BUYERAGENT. The purchaser agents are equipped with detailed requirements.

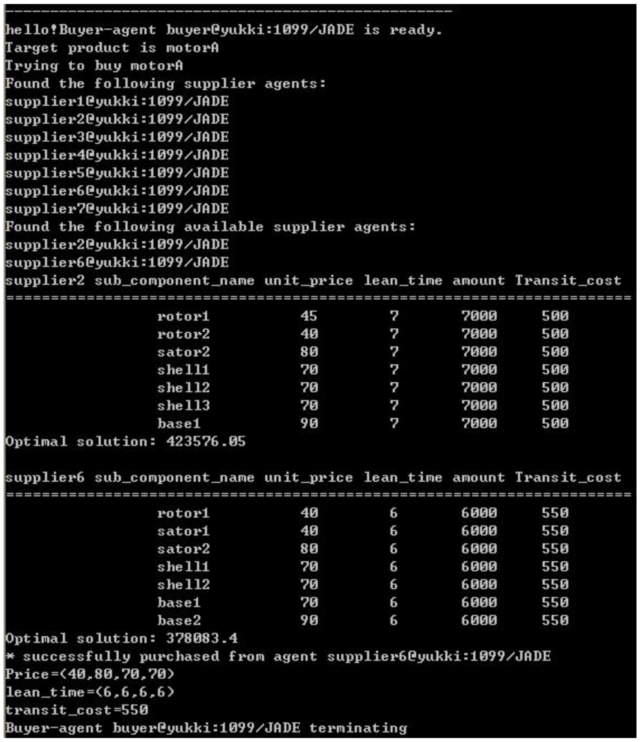
Thirdly, other functional agents such as logistics and warehouse are generated and loaded into the platform through instantiation of corresponding classes.



AgentPlatforms
"yukki:1099/JADE"
Main-Container
RMA@yukki:1099/JADE
df@yukki:1099/JADE
ams@yukki:1099/JADE
supplier1@yukki:1099/JADE
supplier2@yukki:1099/JADE
supplier3@yukki:1099/JADE
supplier4@yukki:1099/JADE
supplier5@yukki:1099/JADE
supplier6@yukki:1099/JADE
supplier7@yukki:1099/JADE
purchaser@yukki:1099/JADE

Figure 6.8 Loading member agents

(3) Information interaction among agents. A buyer agent representing the purchaser sends an ACL message to all the suppliers represented by supplier agents. The communication act of the message should be query-ref in order to be accepted by the supplier agents. Based on this message, the VSC forming process is started, including negotiation, selection, and optimization, as shown in Fig. 6.9.



```
--------------------------------------------------
hello!Buyer-agent buyer@yukki:1099/JADE is ready.
Target product is motorA
Trying to buy motorA
Found the following supplier agents:
supplier1@yukki:1099/JADE
supplier2@yukki:1099/JADE
supplier3@yukki:1099/JADE
supplier4@yukki:1099/JADE
supplier5@yukki:1099/JADE
supplier6@yukki:1099/JADE
supplier7@yukki:1099/JADE
Found the following available supplier agents:
supplier2@yukki:1099/JADE
supplier6@yukki:1099/JADE
supplier2 sub_component_name unit_price lean_time amount Transit_cost
=====================================================================
                 rotor1         45        7       7000     500
                 rotor2         40        7       7000     500
                 sator2         80        7       7000     500
                 shell1         70        7       7000     500
                 shell2         70        7       7000     500
                 shell3         70        7       7000     500
                 base1          90        7       7000     500
Optimal solution: 423576.05

supplier6 sub_component_name unit_price lean_time amount Transit_cost
=====================================================================
                 rotor1         40        6       6000     550
                 sator1         40        6       6000     550
                 sator2         80        6       6000     550
                 shell1         70        6       6000     550
                 shell2         70        6       6000     550
                 base1          70        6       6000     550
                 base2          90        6       6000     550
Optimal solution: 378083.4
* successfully purchased from agent supplier6@yukki:1099/JADE
Price=(40,80,70,70)
lean_time=(6,6,6,6)
transit_cost=550
Buyer-agent buyer@yukki:1099/JADE terminating
```

Figure 6.9 Information interactions among agents

To facilitate multi-agent collaboration, it is vital that agents exchange task-related information via effectively communication. As agents are usually heterogeneous and running in an open and distributed environment, the main requirement is to ensure system reliability and flexibility, so that: (1) There are no possible inconsistencies, deadlocks, and livelocks; (2) Conversation end with the expected acts and the expected beliefs in the memory of each agent; and (3) The inference burden for selection of communicative act is reduced. Table 6.4 lists the specific messages, which are used to transfer information among agents in the platform.

Table 6.4 VSC message type and description

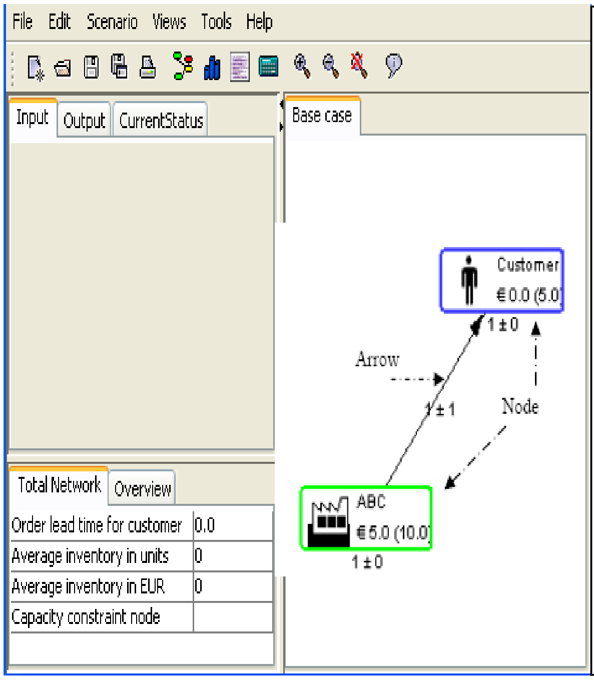
Message Type	Description
Order-Issue	A retailer agent sends a message with "order-Issue" header. It includes such information as product specification, order quantity, due date, etc. When the MA receives a message with this header, it changes the header to "product-configuration" and forwards to the design agent.
Product-Configuration	When a design agent receives a message with a header of "product-configuration", it configures product structure according to the order requirements. Next, appending a header of "product-structure", the design agent will return the result as a message to the MA.
BOM-Decompose	When the MA receives a message with a header of "product structure", it will change the header of the message to "BOM-Decompose", and forward the message to purchasing agent, which decomposes the product into separated parts, components and raw material according to product structure.
Make-Schedule	Upon receiving this message, the functional agent performs production scheduling according to order requirement, production capacity and inventory. It sends the result back to the MA.
MRS	When the MA receives this kind of message, it will check the content of material requirements and forward the message to the purchasing agent.
Quote-MRS	The MA sends messages with this kind of header to SAs. It aims to get the quota for certain material required by the manufacturer.
Conflict-Check	When the MA receives this type of message, it checks material plans or production schedules, which come from other EAs. If there are conflicts among VSC members' plans, the MA sends a message with header "local-conflict" or "system conflict" to notify corresponding EAs or FAs.
Local-Conflict	When functional agents received this message from the MA, it revises its plans according to the violated constraints noticed by the message.
System-Conflict	When EAs receives this message from the MA, it either revises its plan or rejects it.

6.4.2 Supply Chain Design

In order to validate the multi-agent platform, a case study of a practical supply chain has been done. The investigated supply chain in the ABC Ltd. produces and delivers electrical motors globally. ABC Ltd. is a multi-national company that produces electrical product in six countries: Finland, Sweden, Spain, Italy, India and China. In the year 2003, the revenue of ABC Ltd. was €132m. The number of employees was 625 and 37870 types of products were manufactured. The market of ABC Ltd. is highly customized, that most of the customer orders are less than ten units, with special product specifications that need engineering-to-order. The ABC electrical company wants to redesign its global supply chain network to become a fast and reliable service provider. For reasons of confidentiality, the data and figures used in the thesis have been modified.

6.4.2.1 System Window

In order to build the supply chain network, we first initiate software package from a Web Server (http://sourceforge.net/projects/asdn), which is supported by Java Virtual Machine. The default configuration of the basic screen contains the title–bar, located at the very top of the screen; the menu–bar, generally found directly below the title bar; the tool–bar that provides shortcuts to menu commands, generally located just below the menu bar; the main window (construction window) –base Window by default and its left side–Input/Output forms and forms of total network data. With default, the user can start in the “Base Case” window to create logistics networks ready for use. User can also add, open or remove a new scenario from the scenario window.



Order lead time for customer	0.0
Average inventory in units	0
Average inventory in EUR	0
Capacity constraint node	

Defition:

Node: a basic unit of a network; represents a company.

Arrow: an element of a network; represents supplier customer relationships (transfer of goods from a supplier to a customer) between two companies.

Attribute: the data and information used to describe and differentiate individual node and arrow.

Network: a combination of nodes and arrows that represents a certain layout of supplier-customer relationships between companies.

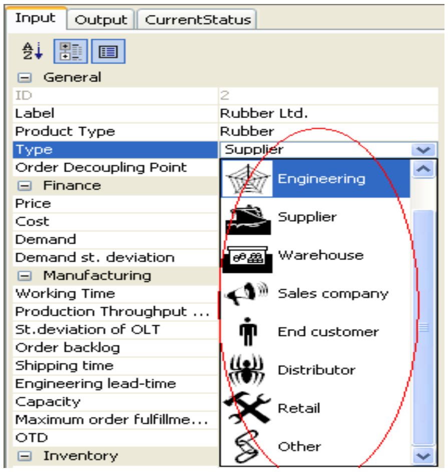
Scenario: a certain layout of supplier-customer relationships between companies and/or values of companies' attributes.

Figure 6.10 System main window

6.4.2.2 Basic Supply Chain Elements

From definitions, there are two major classes of elements in the system for building supply chain network: nodes and arrows. Nodes are used to generate, modify, combine, and display participants in the network. Arrows are used to combine and transfer goods from one node to another. The type of nodes in a drop–down menu from the "Type" indicates the general classes of nodes available to use:

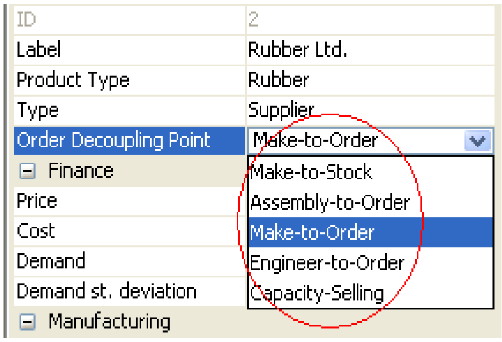
1. Engineering
2. Supplier
3. Warehouse
4. Sales company
5. End user
6. Distributor
7. Retailer



ID	2
Label	Rubber Ltd.
Product Type	Rubber
Type	Supplier

The order de-coupling point of nodes in the drop down menu indicates different production modes:

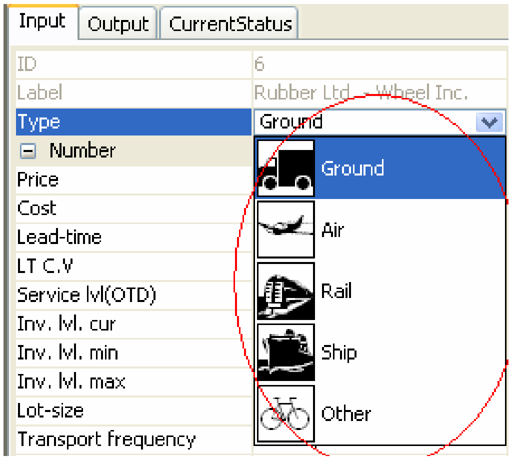
1. Make to Stock
2. Assemble to Order
3. Make to Order
4. Engineering to Order
5. Capacity Selling



ID	2
Label	Rubber Ltd.
Product Type	Rubber
Type	Supplier
Order Decoupling Point	Make-to-Order
⊟ Finance	
Price	
Cost	
Demand	
Demand st. deviation	
⊟ Manufacturing	

The type of arrows indicates different transportation modes with various cost and TAT time. The available types are defined as follows:

1. Ground
2. Air
3. Ship
4. Rail
5. Other

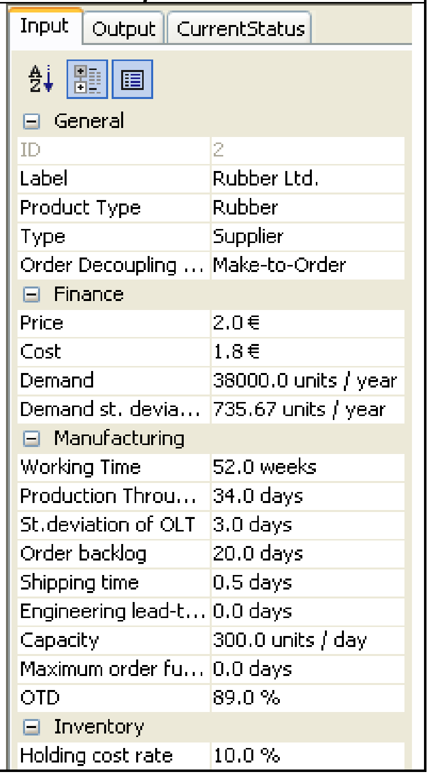


ID	6
Label	Rubber Ltd. - Wheel Inc.
Type	Ground
⊟ Number	
Price	
Cost	
Lead-time	
LT C.V	
Service lvl(OTD)	
Inv. lvl. cur	
Inv. lvl. min	
Inv. lvl. max	
Lot-size	
Transport frequency	

6.4.2.3 Supply Chain Element Attribute

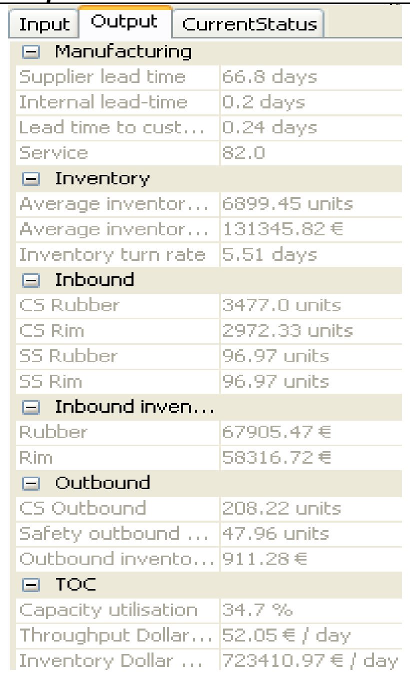
For each supply chain element, there are relevant attributes describing its behavior. The attributes are differentiated as input and output. The user can key in the data into input section of nodes or arrows. The output section of nodes or arrow can automatically be calculated based on the input parameters. Table 6.5 and Table 6.6 list the input and output attributes of nodes.

Table 6.5 Network node input attributes

General attribute	***Explanation***	***Graph Illustration***
ID	Ordinal number of the node	
Label	Name of the node	
Product Type	Type of the node	
Order decoupling point	Production mode	
Financial		
Price	Price per unit	
Cost	Cost per unit	
Demand	Demand per day	
Demand standard deviation	Demand variance	
Manufacturing		
Manufacturing stage time	Time from production to shipment	
Capacity	Production capacity per day	
Maximum order fulfill.time	Maximum order fulfillment time to the customer	
Service level (OTD)	Percent of order delivered on time	
Order backlog	Time to replenish old order	
Inventory		
Holding cost rate	Percent of cost of keeping a unit in inventory for a period	

General	
ID	2
Label	Rubber Ltd.
Product Type	Rubber
Type	Supplier
Order Decoupling ...	Make-to-Order
Finance	
Price	2.0 €
Cost	1.8 €
Demand	38000.0 units / year
Demand st. devia...	735.67 units / year
Manufacturing	
Working Time	52.0 weeks
Production Throu...	34.0 days
St.deviation of OLT	3.0 days
Order backlog	20.0 days
Shipping time	0.5 days
Engineering lead-t...	0.0 days
Capacity	300.0 units / day
Maximum order fu...	0.0 days
OTD	89.0 %
Inventory	
Holding cost rate	10.0 %

Table 6.6 Network node output attributes

Manufacturing	***Explanation***	***Graph Illustration***
Order lead time for manufacturing unit	Time from the order comes to its shipment	
Inventory		
Average inventory in units	*Cycle stock +Safety Outbound Stock + Safety Inbound Stock*	
Average inventory in value	*Inbound inventory value+ Outbound inventory value +Cycle stock*price*	
Inventory turn rate	*Demand *365/ Inventory in units*	
Stock		
Cycle stock	*Manufacturing time*Demand/2*	
Safety inbound stock	*Demand *(100-supplier service level)*	
Safety outbound stock	*Demand *Demand standard deviation*service level*	
Inbound inventory value	*Price*Average inventory in units*	
Outbound inventory value	*Price* Safety outbound stock*	
TOC (Theory of Constraint)		
Capacity utilization	Demand/capacity	
Throughput Dollar Days	(Price-Cost)/Manufacturing time	
Inventory Dollar Days	Average inventory time	

Manufacturing	
Supplier lead time	66.8 days
Internal lead-time	0.2 days
Lead time to cust...	0.24 days
Service	82.0
Inventory	
Average inventor...	6899.45 units
Average inventor...	131345.82 €
Inventory turn rate	5.51 days
Inbound	
CS Rubber	3477.0 units
CS Rim	2972.33 units
SS Rubber	96.97 units
SS Rim	96.97 units
Inbound inven...	
Rubber	67905.47 €
Rim	58316.72 €
Outbound	
CS Outbound	208.22 units
Safety outbound ...	47.96 units
Outbound invento...	911.28 €
TOC	
Capacity utilisation	34.7 %
Throughput Dollar...	52.05 € / day
Inventory Dollar ...	723410.97 € / day

6.4.2.4 Supply Chain Network Example

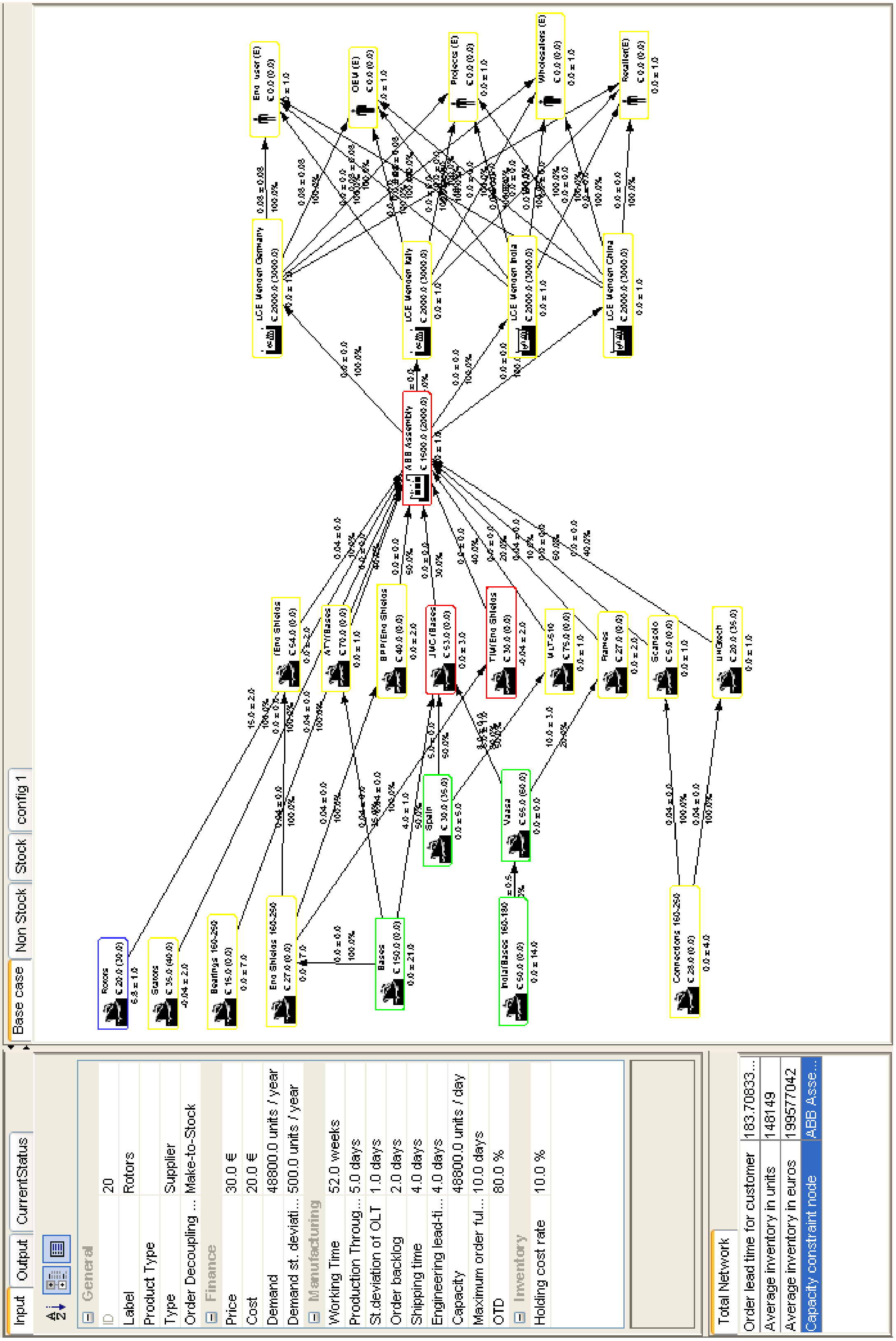
The system provides an icon–driven interface (main window) for the construction of a diagram representation of an industrial logistics network. Building the network construction is then accomplished through three steps:

1. The necessary nodes including supplier, manufacturer, DC and retailer are added into the main window.

2. The data of the nodes are then modified to correspond with the requirement we are building.

3. Finally, the nodes are connected with arrows to complete the construction and the type of arrows is then modified to correspond with the requirement of delivery.

Fig. 6.11 illustrates a typical agent-based virtual supply chain network. It is shown in a graphical interface, which contains several supplier agents, manufacture agents, assembly agents, distribution agents, and customer agents. The right window shows the structure of the supply chain network, including nodes and arrows. The left window illustrates relevant attributes of agent nodes, including production cost, manufacturing time, production capacity, etc. Arrows among agents represent transportation channels. Each arrow contains information like route, cost, delivery time and frequency, etc.



General	
ID	20
Label	Rotors
Product Type	
Type	Supplier
Order Decoupling ...	Make-to-Stock
Finance	
Price	30.0 €
Cost	20.0 €
Demand	48800.0 units / year
Demand st. deviati...	500.0 units / year
Manufacturing	
Working Time	52.0 weeks
Production Throug...	5.0 days
St.deviation of OLT	1.0 days
Order backlog	2.0 days
Shipping time	4.0 days
Engineering lead-ti...	4.0 days
Capacity	48800.0 units / day
Maximum order ful...	10.0 days
OTD	80.0 %
Inventory	
Holding cost rate	10.0 %

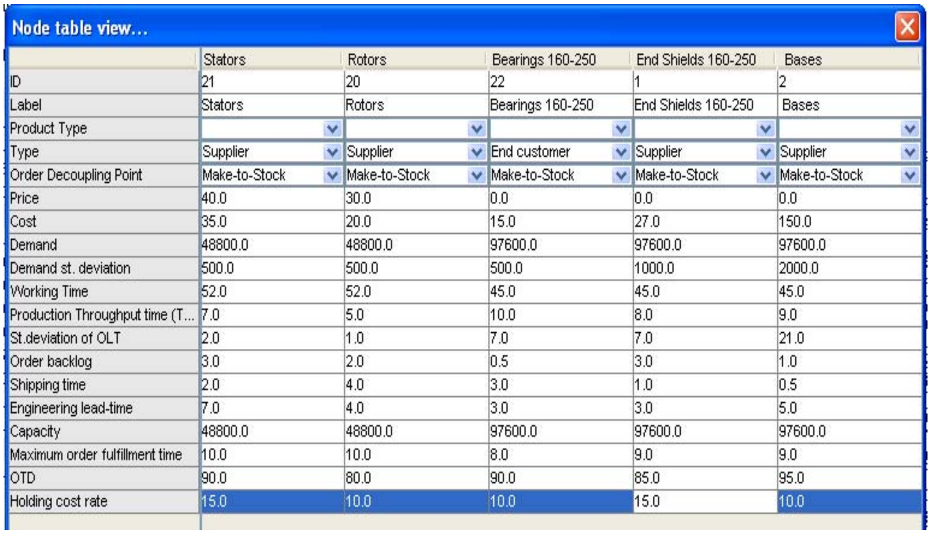
Total Network	
Order lead time for customer	183.70833...
Average inventory in units	148149
Average inventory in euros	199577042
Capacity constraint node	ABB Asse...

Figure 6.11 The ABC Ltd. supply chain network

6.4.3 Supply Chain Analysis

After the supply chain is constructed, the next step is to analyze and optimize it. The multi-agent platform provides a variety of analysis tools that visualize the VSC from multiple dimensions.

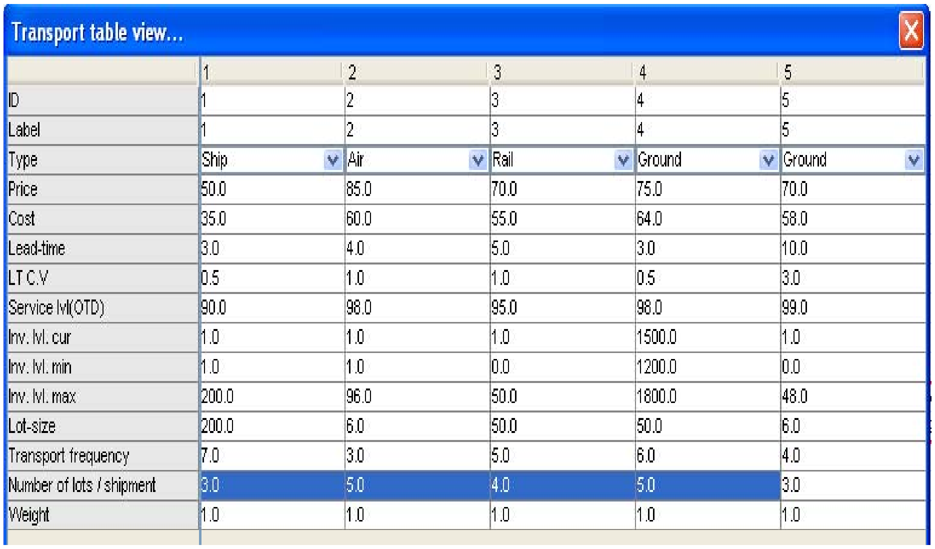
Two tabular reports in the platform record detailed structure information of supply chain network nodes and arrows. The following supply chain network analysis and optimization are based on the structure information shown in Fig. 6.12 and Fig. 6.13.



Node table view...

	Stators	Rotors	Bearings 160-250	End Shields 160-250	Bases
ID	21	20	22	1	2
Label	Stators	Rotors	Bearings 160-250	End Shields 160-250	Bases
Product Type					
Type	Supplier	Supplier	End customer	Supplier	Supplier
Order Decoupling Point	Make-to-Stock	Make-to-Stock	Make-to-Stock	Make-to-Stock	Make-to-Stock
Price	40.0	30.0	0.0	0.0	0.0
Cost	35.0	20.0	15.0	27.0	150.0
Demand	48800.0	48800.0	97600.0	97600.0	97600.0
Demand st. deviation	500.0	500.0	500.0	1000.0	2000.0
Working Time	52.0	52.0	45.0	45.0	45.0
Production Throughput time (T...	7.0	5.0	10.0	8.0	9.0
St.deviation of OLT	2.0	1.0	7.0	7.0	21.0
Order backlog	3.0	2.0	0.5	3.0	1.0
Shipping time	2.0	4.0	3.0	1.0	0.5
Engineering lead-time	7.0	4.0	3.0	3.0	5.0
Capacity	48800.0	48800.0	97600.0	97600.0	97600.0
Maximum order fulfillment time	10.0	10.0	8.0	9.0	9.0
OTD	90.0	80.0	90.0	85.0	95.0
Holding cost rate	15.0	10.0	10.0	15.0	10.0

Figure 6.12 The supply chain node table



Transport table view...

	1	2	3	4	5
ID	1	2	3	4	5
Label	1	2	3	4	5
Type	Ship	Air	Rail	Ground	Ground
Price	50.0	85.0	70.0	75.0	70.0
Cost	35.0	60.0	55.0	64.0	58.0
Lead-time	3.0	4.0	5.0	3.0	10.0
LT C.V	0.5	1.0	1.0	0.5	3.0
Service lvl(OTD)	90.0	98.0	95.0	98.0	99.0
Inv. lvl. cur	1.0	1.0	1.0	1500.0	1.0
Inv. lvl. min	1.0	1.0	0.0	1200.0	0.0
Inv. lvl. max	200.0	96.0	50.0	1800.0	48.0
Lot-size	200.0	6.0	50.0	50.0	6.0
Transport frequency	7.0	3.0	5.0	6.0	4.0
Number of lots / shipment	3.0	5.0	4.0	5.0	3.0
Weight	1.0	1.0	1.0	1.0	1.0

Figure 6.13 The supply chain arrow table

As a multi-national company, the ABC Ltd. develops a very complex supply chain, which involves a number of tiers and many participants. Due to the highly customization of customer demands, most orders are fulfilled by a specifically configured supply chain. Before the information platform is implemented, it is hard to get a clear overall view of the supply chain, because it is too large and keeps changing. Now, based on the analysis tools provided by the platform, supply managers could easily take a snap-shot of the VSC from different viewpoint.

(1) *Gantt chart of lead time*.

Fig. 6.14 illustrates the lead time view of the VSC by using Gantt charts. It draws a clear picture about how the supply chain allocates participants' time schedules; which company is the capacity bottleneck; what is the available-to-promise for the next customer order, etc. The visibility across the entire supply chain provided by Gantt charts can reduce lead-time variability through more effective time management and more efficient cross-docking operations.

From Fig. 6.14, the supply chain manager found the Rubber supplier has the longest lead time of 16 days. This company is located in India, thus the transport time is quite long and on-time delivery level is rather low. Although compared with other suppliers, purchasing cost from this company is 20% cheaper. Its long lead time and low delivery level make trouble to downstream processes. Now the ABC considers changing the supplier to improve the delivery efficiency.

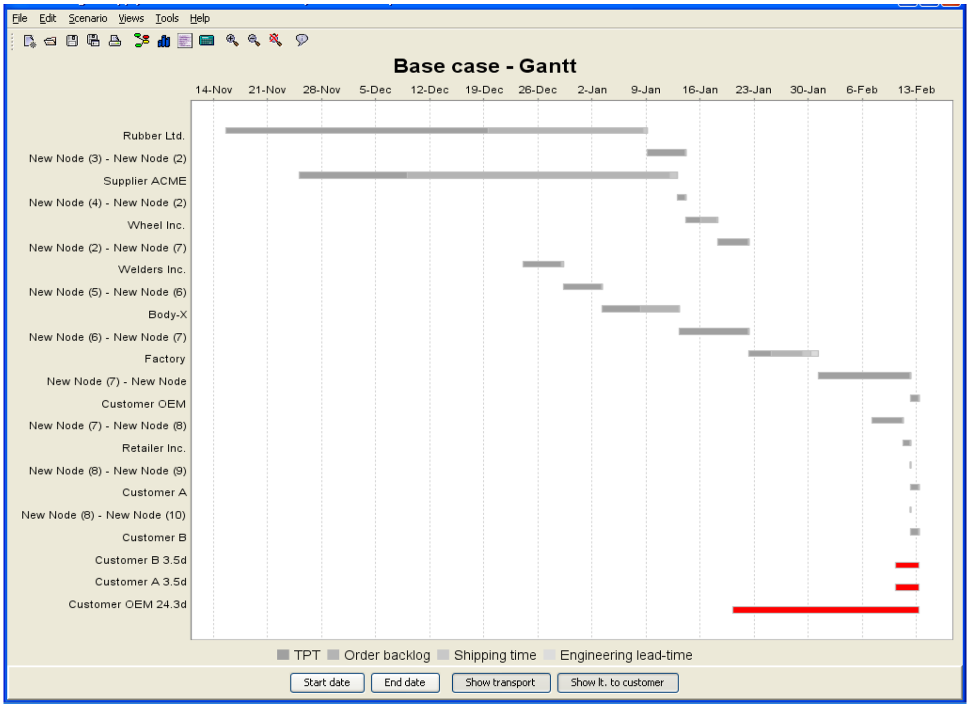


Figure 6.14 Supply chain network lead time Gantt chart

(2) *Service chart.*

As an important performance measure of customer satisfaction, the on-time delivery (OTD) level has attracted great attention in companies. However, most companies only have the vision of organization OTD, yet ignore the network OTD. They fail to align the supplier OTDs with manufacturer OTDs. Fig. 6.15 and Fig. 6.16 demonstrate the system service chart of the VSC in different scenarios. Fig. 6.15 shows that low supplier OTDs deteriorate the production of assembly plant, whose OTD only achieved 20%. In order to improve the OTD of the assembly plant, the platform adjusted the OTDs of two suppliers. The OTD of the Lisalmi Ltd. is improved from 50% to 80%, and the OTD of Chende Ltd. is improved from 55% to 85%. Fig. 6.16 shows that the OTD of the assembly plant has been improved to 85%. Based on this visualization tool, the supply chain manager can easily identify the problem and find optimal OTDs for companies.

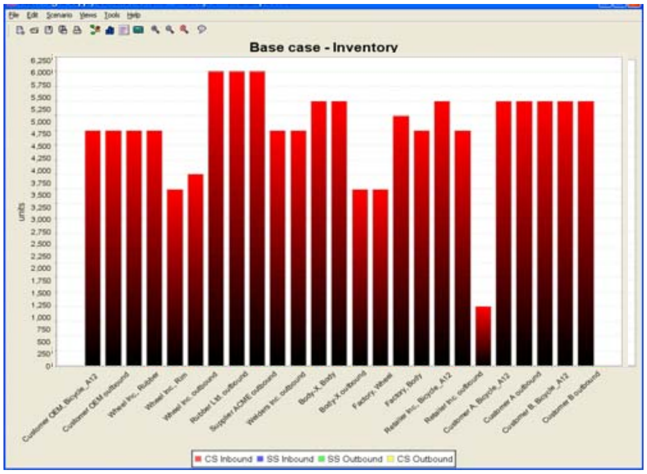


Figure 6.15 Supply chain network service chart

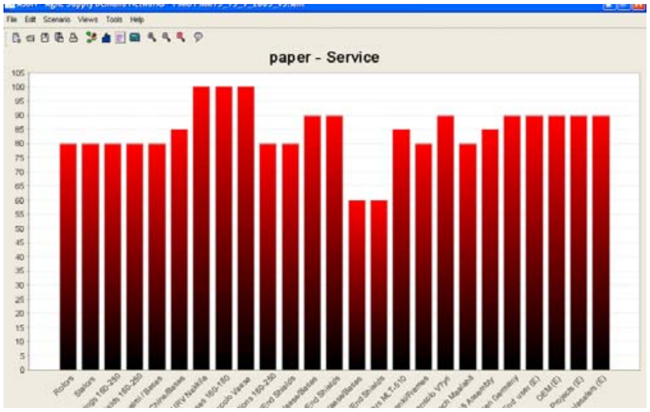


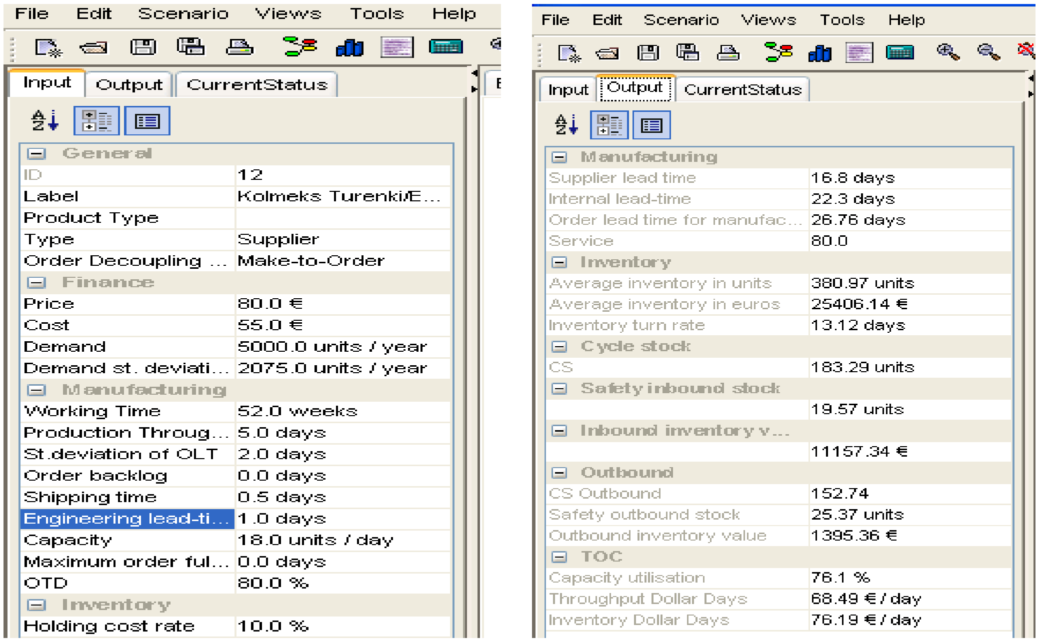
Figure 6.16 Improved supply chain network service chart

3) *Inventory amount and inventory value*

Maintaining right level of inventory at the right place and right time helps cost reduction, customer responsiveness, and supply chain efficiency. Excess inventory incurs extra holding costs, storage space, depreciation, price-take-down, and salvage cost. On the other hand, inventory shortage causes poor customer serviceability or business loss to competitors. Inventory level is a key decision associated with supply chain performance.

Since the ABC supply chain is serving customized markets, high demand uncertainty causes huge inventories in different stock-points. The system allows tracking three types of inventory: Safety Stock Inbound, Safety Stock Outbound and Cycle Stock.

Users click node and check the output attribute to get the inventory status. Figure 6.17 gives an example of the inventory state of a supplier. The left column exhibits the basic property of a supplier, like production type, lead time, demand deviation, shipping time, capacity, etc. The right column is the output of the node, which includes the information of average inventory in units, inventory turn rates, cycle stock, inbound stock, outbound stock and capacity utilization etc.



General	
ID	12
Label	Kolmeks Turenki/E...
Product Type	
Type	Supplier
Order Decoupling ...	Make-to-Order
Finance	
Price	80.0 €
Cost	55.0 €
Demand	5000.0 units / year
Demand st. deviati...	2075.0 units / year
Manufacturing	
Working Time	52.0 weeks
Production Throug...	5.0 days
St.deviation of OLT	2.0 days
Order backlog	0.0 days
Shipping time	0.5 days
Engineering lead-ti...	1.0 days
Capacity	18.0 units / day
Maximum order ful...	0.0 days
OTD	80.0 %
Inventory	
Holding cost rate	10.0 %

Manufacturing	
Supplier lead time	16.8 days
Internal lead-time	22.3 days
Order lead time for manufac...	26.76 days
Service	80.0
Inventory	
Average inventory in units	380.97 units
Average inventory in euros	25406.14 €
Inventory turn rate	13.12 days
Cycle stock	
CS	183.29 units
Safety inbound stock	
	19.57 units
Inbound inventory v...	
	11157.34 €
Outbound	
CS Outbound	152.74
Safety outbound stock	25.37 units
Outbound inventory value	1395.36 €
TOC	
Capacity utilisation	76.1 %
Throughput Dollar Days	68.49 € / day
Inventory Dollar Days	76.19 € / day

Figure 6.17 Inventory value of a supplier node

Fig. 6.18 A and B give the supply manager an overall view of the inventory amounts and how the value is spread along the supply chain. Various colors represent different types of inventory. For example, the red color refers to the safety stock; the green color points to the cycle stock. It is obvious that the inventory in the final assembly plant and distribution center are quite high in either amount or value. The manager should shift the inventory from downstream plants to the upstream supplier to balance the network.

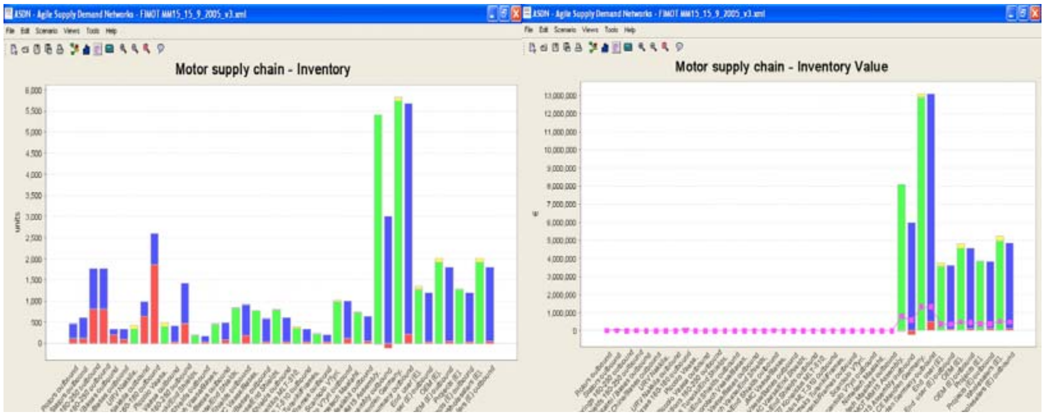


Figure 6.18 A. Inventory amount B. Inventory value

(4) *Inventory vs. Service level.*

Supply chain managers always find themselves in a dilemma to balance inventory and service level. The improvement of service level often costs increase of inventory. It takes a lot of time and efforts to find a balancing point, which maintains a good service level without comprising cost efficiency. The multi-agent platform provides an analytic tool to assist the decision making. As shown in Fig. 6.19, the curve straightforwardly describes the function relationship between inventory value and service level. For example, to the motor frame supplier, 752,000 units inventory obtain 62% service level, while 761,000 units achieve 97% service level. The supply manager could observe the curve of each supplier separately by adjusting the parameters. Therefore, it is easier to find the balancing point of inventory and service level.

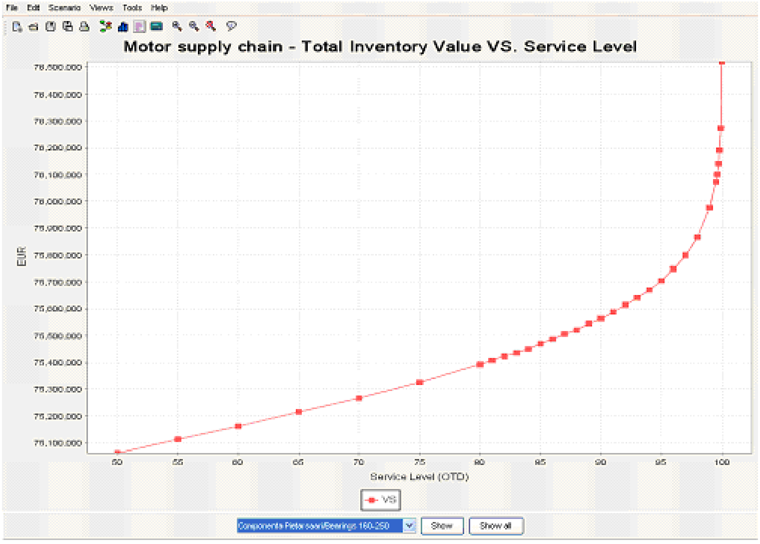
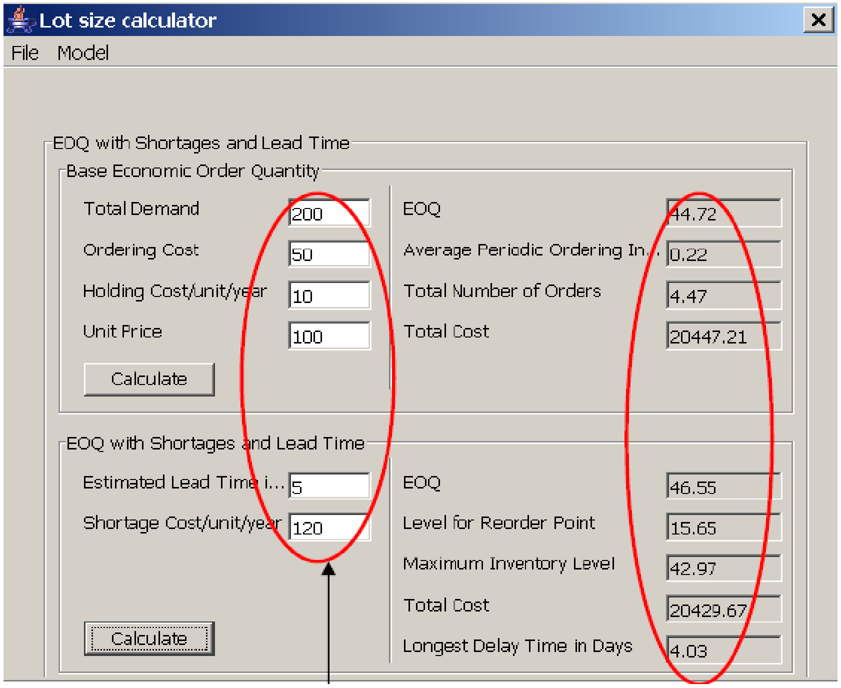


Figure 6.19 Inventory vs. service level charts

6.4.4 Supply Chain Optimization

Now the supply chain network has been built and analyzed, it should be optimized to improve efficiency and reduce operational cost. The multi-agent platform optimizes a supply chain network through a series of built-in mathematical models. Integrated inventory management can be improved by the analytical inventory mediator and optimization methods for every single stock-point.

The platform provides several spreadsheet models for supply chain network optimization. It can be easily extended according to the requirements of specific scenarios. Fig. 6.20 lists a calculator for lot size analysis, which optimizes batch size and cost by using classic EOQ model.



EDQ with Shortages and Lead Time

Base Economic Order Quantity

Total Demand: 200
Ordering Cost: 50
Holding Cost/unit/year: 10
Unit Price: 100

EOQ: 44.72
Average Periodic Ordering In...: 0.22
Total Number of Orders: 4.47
Total Cost: 20447.21

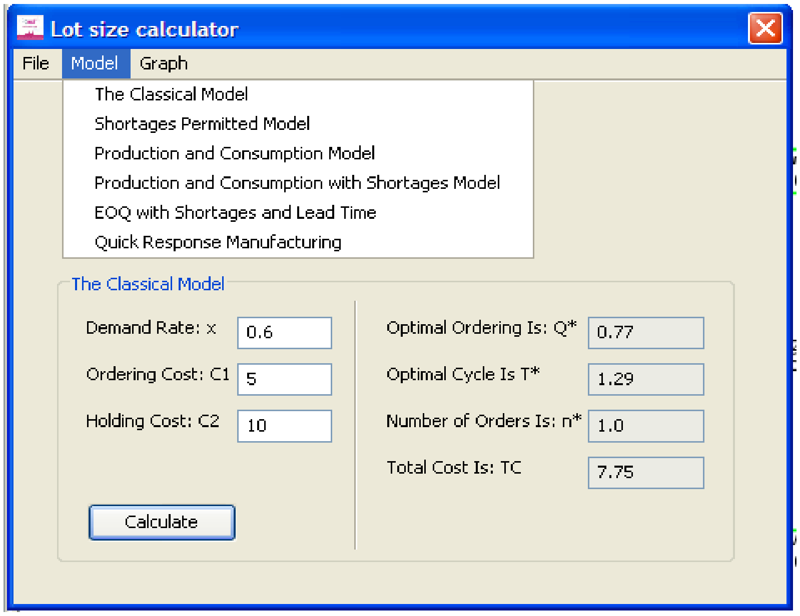
EOQ with Shortages and Lead Time

Estimated Lead Time i...: 5
Shortage Cost/unit/year: 120

EOQ: 46.55
Level for Reorder Point: 15.65
Maximum Inventory Level: 42.97
Total Cost: 20429.67
Longest Delay Time in Days: 4.03

Figure 6.20 A calculator for lot size analysis

The system user can select the optimizing models according to their requirements. It could easily be done by clicking on tools in the pop-up window and selecting the optimizing models, as shown in Fig. 6.21. Fig. 6.22 demonstrates other two models with different parameters and constraints.

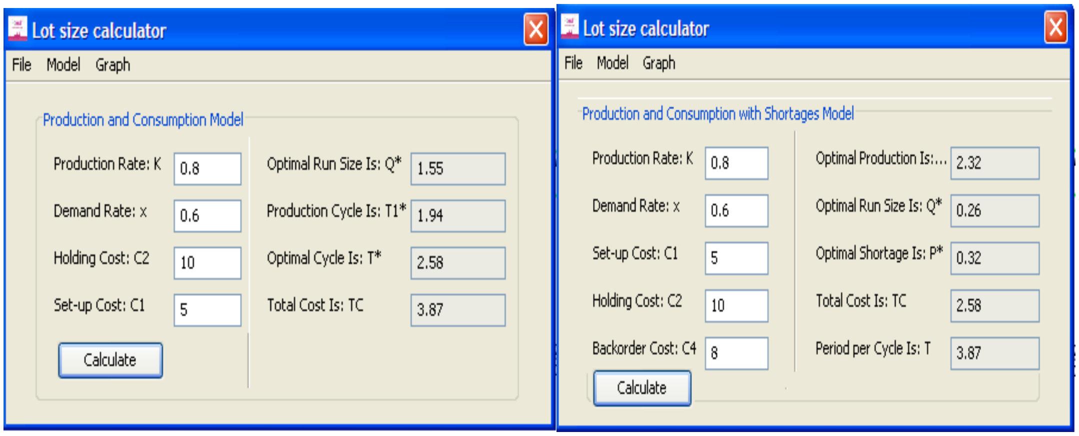


The Classical Model

Demand Rate: x: 0.6
Ordering Cost: C1: 5
Holding Cost: C2: 10

Optimal Ordering Is: Q*: 0.77
Optimal Cycle Is T*: 1.29
Number of Orders Is: n*: 1.0
Total Cost Is: TC: 7.75

Figure 6.21 Multiple-model lot size calculator



Production and Consumption Model

Production Rate: K 0.8
Demand Rate: x 0.6
Holding Cost: C2 10
Set-up Cost: C1 5
Optimal Run Size Is: Q* 1.55
Production Cycle Is: T1* 1.94
Optimal Cycle Is: T* 2.58
Total Cost Is: TC 3.87

Production and Consumption with Shortages Model

Production Rate: K 0.8
Demand Rate: x 0.6
Set-up Cost: C1 5
Holding Cost: C2 10
Backorder Cost: C4 8
Optimal Production Is:... 2.32
Optimal Run Size Is: Q* 0.26
Optimal Shortage Is: P* 0.32
Total Cost Is: TC 2.58
Period per Cycle Is: T 3.87

Figure 6.22 Optimal lot sizing model

6.5 Discussion

Supply chain partners in a virtual network need a complete view of their business, and greater insights into supply chain channels and process to improve decision-making and business operations, as well as to adapt systematically and rapidly to market fluctuations. The agent based e-supply chain tracks collaborative channel events and processes, extracts and presents decision-oriented information. Data analysis processing allows supply chain members to derive information from data warehouse systems by providing tools for querying and analyzing data, leading to multidimensional view of the specific partners. Knowledge management capabilities such as analysis module, data mining module, web-enabled technology can be used to transform the data from the partners' data warehouse into useful partners' knowledge.

This multi-agent platform enables the collaborative management and monitoring of disparate companies members of the supply chain in a virtual environment. It drives all partner and customer related activities, capturing the required data/information. It sets the procedures and accountability, performance measurement criteria, and capabilities to resolve business exceptions. This gives companies both flexibility and control to connect with new business models, and provides a mechanism to analyze and understand the impact of collaborative businesses processes on its own operations. Supply chain partners in a virtual network collaborate in the forecasting, purchasing, production and inventory management processes and synchronize delivery and distribution schedules.

The challenge is to the capture and storage of partners' transactions and supply chain events actions across disparate touch points, and additionally partners data from backend transactional systems and external sources. A centralized partner data warehouse with a reliable, scalable and highly available storage infrastructure gives the solution to the problem of data consolidation and integration of diverse partners' data assets. The output of the intelligence module should be delivered as an extensible tool that uses a set of partners' profile and profitability models and reports. Partners' analysis results should integrate with supply chain management decisions in order to transform partners' information into building better relationships.

6.6 Summary

To shed light on practical validation of the VSC methodology, this chapter has developed an advanced information platform based on the multi-agent system infrastructure. It provides an integrated and homogeneous decision making environment for VSC analysis and evaluation. Different types of agents have been developed to assume various roles in the VSC. The multi-agent platform facilitates handling of the entire lifecycle of a VSC, encompassing initiation, formation, operation, cooperation and decommission. A series of Petri-net based behavior models are adopted to streamline agent interaction in different scenarios. A detailed case study of the ABC Ltd. supply chain network has been investigated to validate the virtual supply chain analysis and optimization.

CHAPTER 7 CONCLUSIONS AND FUTURE WORK

This chapter summaries the research work studied in the dissertation, highlights the important findings and draws conclusions from this research. The major contributions and limitations of this research are also reviewed. The avenues for future research are proposed to shed light on further studies in virtual supply chain management.

7.1 Conclusions

Effective configuration of global supply chains is nowadays recognized as a key determinant of competitiveness and success for most manufacturing organizations. While many quantitative models have been constructed to provide decision support for the management of materials in different supply chain subsystems, the most pressing challenge to the SCM community is to develop efficient modeling and analyzing techniques for supply chain configuration in order to gain a full understanding of its characteristics, performances and tradeoffs involved. Typically, research concentrates on smaller parts of supply chain management, such as supplier selection, production planning and inventory optimization. Without the consideration of integration and coordination, models would lead to non-improving results or just exploit partial benefits. Therefore, it is imperative to employ both analytical approaches and information and communication technologies to develop modeling and decision making methodologies for integrated and coordinated supply chain configuration.

E-Supply chain has become a core competitive strategy. As organizations continuously seek to provide their products with faster, cheaper and better service, they have realized that they must work on a cooperative basis with the best organizations in their supply chains in order to succeed. Technology, quality, cost availability and collaborative business practices are important to each business partner in the supply chain network. Moving from traditional supply chains to virtual chain networks requires that partners focus on communications, relationships, and knowledge. Once partners enter into the e-supply chain relationship, mutual success will depend on trust, information and knowledge sharing, communication, and co-owned product service design and performance measures.

This research has proposed virtual supply chain paradigm to deal with the huge varieties during supply chain configuration. It aims to establish ICT based e-supply chain to facilitate coordination and cooperation among supply chain partners. In current manufacturing environments, supply chain configuration imposes a significant impact on the success of mass customization and global competition. Each product often encompasses hundreds of components provided by thousands of globally-distributed suppliers. Accordingly, this dissertation has put forward virtual supply chain configuration methodologies for companies to generate specific supply chains from a generic supply chain network for new customers or new products. In addition to assisting the theoretically sound supply chain configuration, the VSC also entails well-structured modeling mechanisms for companies to manage product and supply variety from their own perspectives. A practical global motor supply chain network has been modeled as a virtual supply chain and dynamically configured based on the proposed CPN modeling mechanisms and MAS information platform.

To facilitate conceptualization of the VSC paradigm, a domain-based reference framework is introduced to represent the interdependent relationships among customer orders, product structures, process operations, and logistics networks. Key elements and activities of the VSC, e.g. product BOM, process operations, and delivery routes are classified into corresponding domains. Logical models have been established to formulate a VSC in terms of constituent elements, functionalities and interacting relationships. The object-oriented concept and set theory have been adopted to design systematic and rigorous VSC formulation. It was accomplished by establishing models of (i) the generic structure of a virtual supply chain, (ii) data representation solutions, and (iii) the specific solution for supply chain configuration. In addition, the variety coordination mechanism embedded in a VSC is formulated based on variety parameters and their possible value sets. To achieve this, the concepts of objects and their special instances are introduced for variety parameters and value instances, respectively.

In order to rapidly and effectively configure supply chains from a VSC, this study has developed a nested modular modeling approach and a series of formalisms. Major concerns in supply chain configuration, including variety handling, change accommodation, levels of abstraction, and constraints satisfaction, have been analyzed and addressed. The CPN, OPN and changeable Petri net techniques are adopted to model the constituent elements, structure correlation, and variable instantiation of the supply chain network. A series of basic units, such as supply nets, assembly nets and distribution nets, have been developed as modular building blocks to design complex supply chains. Different types of supply chain elements, regarding product items, process elements and manufacturing resources, have been attached with colored tokens in the PN model. In a nested net system, the lower level more elaborated nets are nested in the places of higher level more abstract nets as colored tokens. When the lower level nets are nested in the higher level nets, they denote the particular item variants produced by the defined processes. A structure-change handling mechanism has been developed to analyze dynamic decisions with respect to tradeoffs of various supply chain configurations.

This research has applied the multi-agent technology to build an information platform, supporting VSC integration and coordination. Autonomous, intelligent and distributed agents are on behalf of independent members in the VSC. Each VSC is composed by a series of intelligent agents, responsible for one or more activities in the supply chain and interacting with other agents to fulfill their responsibilities. The platform addresses VSC integration and coordination issues from three fundamental aspects: lifecycle management, distributed system and modular architecture. A particular agent was designed to mediate the VSC. It facilitates information and knowledge sharing, synchronizes the decisions of individual agents, and optimizes the overall VSC. The decision synchronization process among mediator and VSC members is controlled by a series of embedded conversation protocols.

7.2 Research Contributions and Limitations

7.2.1 Contributions

The major contribution of this thesis manifests itself through the development of a coherent framework of virtual supply chain configuration modeling and decision making. The deliverables are elaborated as following:

Formulation of virtual supply chain paradigm**:** The reference framework provides systematic and rigorous understanding of generic supply chain network and variety configuration. Domain-based theory and object-oriented technique have been applied to extend traditional supply chain into a wide spectrum, including customer, product, process and logistics.

Development of a nested modular modeling approach for the virtual supply chain**:** This thesis has addressed the virtual supply chain modeling issue through the development of a series of nested modular formalism of colored object-oriented Petri nets. A supply chain net ($SCNet$) is built to describe the conceptual process of the entire supply chain, including a number of $MNets$, $SNets$, $ANets$, and $DNets$. The concept of net nesting is introduced for coping with granularity issues, such that lower level nets are nested as colored tokens in the higher-level nets.

Development of a CPN modeling formalism for virtual supply chain configuration**:** The formalism represents the configuration and operation of a supply chain as an abstracted network, where the supply entity is modeled as a net node attached with attributes and related parameters. It is able to shed light on the implications of joint product, process and logistics decision making, which assists companies in predicting the performance of the configured supply chains. This is accomplished by incorporating OO technique and a mechanism to handle structural changes in colored PNs.

Development of a multi-agent information platform**:** It provides an integrated and homogeneous decision making environment for VSC analysis and evaluation. Different types of agents have been developed to assume various roles in the VSC. The multi-agent platform facilitates handling of the entire lifecycle of a VSC, encompassing initiation, formation, operation, cooperation and decommission.

A full-scale practical supply chain network case study**:** Based on the working and research experience in a motor company at Finland, the author applies the proposed domain framework, CPN model and multi-agent platform into a practical global motor supply chain. The consistent and comprehensive case studies, including parameter illustration, model validation, and system implementation, have demonstrated the feasibility and potential of the proposed virtual supply chain configuration framework.

7.2.2 Limitations

The concepts of virtual supply chain configuration discussed in this research have been proposed to deal with certain problems from particular considerations. The limitations of presented research originate from its ability of solving large-scale problems, more specifically in terms of the following aspects:

(1) The VSC methodologies proposed in this research handles products with clear BOM structures and routings. Assembly operations and sequences play an important role in such products. Since the production of mechanical products depends heavily on manufacturing operations, the VSC configuration may not guarantee expected competitive edges for companies providing mechanical products. For example, as there is no BOM structure in the steel and pharmacy production, the approach proposed in the thesis cannot be applied into steel and pharmacy industry supply chain.

(2) Configuration attempts to obtain an optimal result from all the possible ones of the same problem. The evaluation should be considered from manifold perspectives. For example, different parameter settings in the same supply chain network may produce different outputs. By the nature of the problem, multiple results can satisfy the exactly same requirements. Two kinds of configuration evaluation should be involved: (i) the evaluation of generic supply chain network, and (ii) the evaluation of configured specific supply chains. Virtual supply chain evaluation should guarantee that the obtained supply chain network is most common to all individual products in a family.

(3) CPN modeling methodology adopted in the thesis still work on a centralized planning environment. It assumes there are complete and up-to-date information consolidated into one decision maker to configure supply chain. However, in the modern supply chain management, partners are independent and distributed; data and information are dispersed over various systems such as PDM, ERP, CRM. It would be inefficient to use CPN modeling methodology to handle the real-time structure change in the highly dynamic business environment. For example, in the aforementioned motor supply chain, if one supplier suddenly reduces its production capacity, or there is a new supplier joining into the supply chain network, this structure change cannot be factored into the virtual supply chain model immediately. Therefore, the configuration solution based on out-of-date information would be not optimal.

7.3 Future Work

Throughout this dissertation, the author has developed a variety of novel concepts, formalisms and methodologies for VSC configuration modeling and decision making. From a holistic view, there is still much to be desired to achieve system-wide solutions. In this regard, the following areas appear to be promising avenues for further research efforts.

Supply chain variety analysis**:** Due to the constant flux of change in current increasingly competitive global environment, there are many uncertainty or varieties in the supply chain, e.g. customer demand variation, delivery time alternations, and production fluctuations. The scenario is further complicated by the fact that multiple products and various manufacturing abilities are often involved in a supply chain. A huge number of varieties in every aspect of the supply chain generate the complexity and difficulty of supply chain modeling and configuration. Therefore, it raises the importance in proper analysis of supply chain varieties so as to evaluate the impact of different types of factors, and reasonably arrange resource to optimize overall performance in a coherent manner.

CPN-based real-time VSC configuration platform**:** A virtual supply chain network should ideally be built on sharing a multi-dimensional core of assets, such as standardized components, manufacturing, supply and distribution processes, customer segmentation and brand positioning. To support the coordination of the demand chain and supply chains with product families, it is necessary to extend the proposed CPN modeling to the entire continuum of product fulfillment, including customer platforms, brand platforms, product platforms, process platforms, and global platforms. Greater complexity must be addressed to real-time configuration platform when considering more decision variables or parameters pertinent to the coordination across the product, manufacturing process and supply chain domains. The configuration platform will allow the possibility of developing simulation, mathematical analysis and real-time control models for managing product, process and network variety while leveraging upon existing product families, process platforms and supply chain network.

Supply chain configuration evaluation**:** In Chapter 4, the preliminary evaluation has been conducted towards the identified configurations. While the evaluation validated the proposed methodology and found the optimal solution, it does not focus on the implementation of configured supply chains. Thus, more powerful approaches need to be developed to perform evaluation on both the supply chain platforms and the configured solutions. Such approaches should possess the ability to judge from a variety of performance metrics with explicitly quantitative comparison.

Mobile-agent supported communication**:** Due to the dispersed nature of the multi-agent system, each agent is located with different host and interacted through

Internet. It causes heavy network load and information delay. A mobile agent is able to transport itself from one host to another. Problems related to communication load, which is a critical deficiency of the classic message passing-based negotiation, can be overcome by using mobile agents. When many messages have to be exchanged, it is more efficient and reliable to send an agent to a target system and perform the job locally than to communicate with the system by message passing.

Integration of VSC lifecycle and domain-based framework**:** The lifecycle and domain-based framework support the VSC paradigm from different perspectives. Lifecycle (initiation, formation, operation, cooperation and decommission) defines the VSC major development stages and functionalities from the vertical level while domain (customer, product, process, logistics) represents the VSC major elements and varieties from the horizontal level. The integration of VSC lifecycle and domain framework would provide a systematic and comprehensive VSC solution based on the support of CPN modeling and agent communication technologies. It will more effectively manage and control the VSC varieties and complexities into different lifecycle stages and domains. The integrated solution will identify the VSC members, define the role and responsibility of each member, specify functionalities in different stages, establish coordination and cooperation mechanisms among members, etc. Therefore, the VSC paradigm is further strengthened from theoretical research to practical application.

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