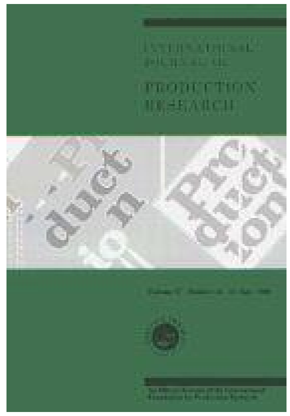
Supply Chain Configuration with Coordinated Product, Process and Logistics Decisions: An Approach based on Petri Nets

Linda Zhang, Xiao You, Jianxin Roger Jiao, Petri Helo



Supply Chain Configuration with Coordinated Product, Process and Logistics Decisions: An Approach based on Petri Nets

Journal:	*International Journal of Production Research*
Manuscript ID:	TPRS-2007-IJPR-0879.R1
Manuscript Type:	Original Manuscript
Date Submitted by the Author:	30-Apr-2008
Complete List of Authors:	Zhang, Linda; University of Groningen, Operations You, Xiao; Nanyang Technological University Jiao, Jianxin; Nanyang Technological University, Div of Systems and Engineering Management Helo, Petri
Keywords:	SUPPLY CHAIN MANAGEMENT, PETRI NETS
Keywords (user):	SUPPLY CHAIN MANAGEMENT, PETRI NETS

Supply Chain Configuration with Coordinated Product, Process and Logistics Decisions: An Approach based on Petri Nets

Lianfeng (Linda) Zhang*[1] and Xiao You[2], Jianxin (Roger) Jiao[2,3], Petri Helo[4]

[1]University of Groningen, Groningen, The Netherlands
[2]Nanyang Technological University, Singapore
[3]Georgia Institute of Technology, Atlanta, Georgia, USA
[4]University of Vaasa, Vaasa, Finland

Abstract: Supply chain configuration lends itself to be an effective means to deal with product differentiation and customization throughout a supply chain network. It essentially entails the instantiation of a generic supply chain network to specific supply chains in accordance with diverse customer requirements. The linchpin of supply chain configuration lies in the coordination of product, process and logistics decisions in relation to a variety of customer orders. This paper aims to provide modeling support to supply chain configuration. The ultimate goal is to assist companies to form appropriate supply chains with the most added value to customer order fulfillment. A formalism based on colored Petri nets is developed for configuring supply chains. System models are built upon the colored Petri nets and used to incorporate product and process concerns into the supply chain configuration process. An industrial case study is reported to illustrate the potential of the colored Petri net modeling formalism and the built system models for supply chain configuration.

Keywords: Supply chain configuration, supply chain network, colored Petri nets.

* Corresponding author. Email: L.Zhang@rug.nl.

1. Introduction

Supply chain management must consider the integration of a business network, encompassing suppliers, manufacturers, distributors and retailers, in order to provide products and services along with the added value to end customers (Yan et al., 2003). Much work has been geared towards the management of the information, financial and physical flows throughout a supply chain network (Huang et al., 2002). Supply chain configuration lends itself to be an effective means of dealing with product differentiation and customization throughout a supply chain network (Yan et al., 2003). It essentially entails the instantiation of a generic supply chain network to specific supply chains in accordance with diverse customer requirements. The linchpin of supply chain configuration lies in the coordination of product, process and logistics decisions in relation to a variety of customer orders. One important area is to design and configure supply chains to reach optimal performance. The major task in supply chain configuration is about supplier selection and resource allocation (Graves and Willems, 2003). However, configuring supply chains from the existing supply chain network involves a number of difficulties, as elaborated below.

(1) Complexity of a supply chain network. A supply chain network is inherently complex due to its multi-level, nested structure. First, multiple levels of suppliers exist in a supply chain network, where suppliers at a lower level provide materials to these at the next higher level and so on throughout the whole network. Piramuthu (2005) states that the total possible configurations from a supply chain network would be the product of the number of levels and the number of combinations of each level. Furthermore, each supplier has its own suppliers and consumers thus constituting a nested supply chain network. The complexity is also compounded by the facts that the companies in a network may also be involved in a number of supply chain networks and assume different roles (Sahin and Robinson, 2002). As a result, it is extremely difficult to match demand and supply so as to select proper suppliers under these

circumstances.

(2) Diversity in customer requirements. The industry today is characterized by the diversity in customer requirements. It is exhibited by a high variety of customized products, reduced batch sizes and shortened delivery times as required by the end customers. Therefore, the variations in customer requirements lead to changes in product specifications and further the suppliers that suppose to provide the constituent materials. As a consequence, to obtain the most added value in terms of the best prices and the fastest services, different supply chains are required to fulfill different customer orders (Piramuthu, 2005). It is not unusual that a company is often in a situation of struggling to select proper suppliers for several customer orders at the same time due to the various requirements.

(3) Coordination of product, process and logistics decisions. The functionalities of a product can be accomplished by different product design, each of which in turn can be achieved by various combinations of different and/or same constituent items. Each combination may necessitate a different set of suppliers. The difference in suppliers in the corresponding supply chains eventually leads to varying overall system performance. Substantial benefits can be expected through proper coordination of supply chain decisions with the design and production of the products to be fulfilled in that supply chain.

Production process design is also influenced by product design. Product design changes may affect decisions regarding how to produce the product and others, e.g., capabilities. Consequently, the choices in product design and item selection add to the complexity in process decision making, such as changes of operations, operations precedence, machines, tools, fixtures. Such changes possess a major influence on the production costs, delivery times and product quality. Thus, considering the process to be adopted to produce the product is of similar importance in configuring supply chains. Blackhurst et al. (2005) recognize that there are considerable benefits in configuring supply chains taking into account both the design of a product and the design of its process.

The dispersed locations of suppliers bring about the complexity in logistics issues such as transport ways, transport tools, costs, and delivery times. The logistics decision making is further complicated by the multiple transport ways and tools of a supplier (to deliver product items to its customers). The different logistics decisions influence the performance of each individual company with respect to costs and delivery times from the lowest level of raw material suppliers to the highest level of final product providers. As a consequence, logistics decision making has a major impact on the overall performance of the entire supply chain to be formed to fulfill a customer order.

Therefore, it raises the importance for a company to select proper suppliers to deliver a customer order taking into account product, process and logistics design. In spite of the many research efforts that have been put in supply chain management, research considering the coordinated supply chain configuration, product and process design is relatively limited (Blackhurst et al., 2005).

Arora and Kumar (2002) point out that it is difficult to understand complex systems and make changes to improve their performance without a comprehensive and precise model of the system. The linchpin of supply chain configuration thus lies in an appropriate modeling tool that can shed light on both the logical process of selecting suppliers and the effects of product, process and logistics design on the selection. Such a modeling tool together with the built system models are expected to assist companies in making right decisions in forming supply chains in response to various customer orders. This paper develops a new formalism based on the technique of colored Petri nets (PNs) and further applies it to model the coordinated process of supply chain partner selection from a large supplier base of a company and product, process and logistics design.

The rest of the paper is structured as follows: The relevant literature regarding supply chain configuration and modeling with PNs is given in Section 2. Section 3 specifies the problem context of supply chain configuration. The new modeling formalism developed based on colored PNs is introduced in Section 4. Section 5 introduces the background of an industrial case company, to which the formalism is applied. The application details of the formalism to supply chain configuration are discussed in Sections 6, 7, and 8. The evaluation of supply chain configuration using PN simulation software is given in Section 9. The discussion of advantages and disadvantages of the developed formalism and the identification of avenues for future research end this paper in Section 10.

2. Related Work

2.1 Supply Chain Configuration

It is well established in literature that a company's supply chain has to be adapted in order to efficiently deliver customized products to the end customers (Pine, 1993; Westbrook and Williamson, 1993). The concept of supply chain configuration has been at the centre of much recent research. The increasing interest in this area has led to the development of various models and tools aiming at supporting the design, configuration and analysis of supply chains. However, insight into how supply chains can be configured through selecting proper suppliers does not appear to be as straightforward. Further, most models and methodologies addressing supply chain configuration focus on product design only.

Yan and Yu (1998) develop an approach based on mathematical programming to optimizing supply chains with focus on the product structure in the form of bill of materials. In their model, how different processes and logistics affect the systems performance of supply chains cannot be captured. Through empirical research, Salvador et al. (2004) discuss how a company's supply chain should be configured in response to different degrees of product customization. Their work focuses on the impact of changes of the modular product architectures on the corresponding supply chains. Dotoli et al. (2003) design a 3-layered decision support system for supply chain configuration. In their system, the fixed product structure, more specifically the bill of materials, is used to evaluate and select supply chain entity candidates without considering the alternative product structures of a same design. Blackhurst et al. (2005) develop a decision support modeling methodology, called PCDM, for supply chain configuration by applying PNs techniques. While PCDM focuses on the impact of sharing information about lead time, inventory and item design on the supply chain performance, it does not address the selection of suppliers among multiple alternatives. Piramuthu (2005) proposes an automated supply chain configurer (ASCC) framework by applying machine learning technique. ASCC is applicable for a company to select its immediate suppliers rather than all suppliers at different levels.

2.2 Coordinated Product, Process and Logistics Decisions

The preferences of end customers have been recognized as the basis for configuring supply chains (Lee and Sasser, 1995). In recent years, more and more researchers argue that it is more important for companies to consider the coordinated product, process and logistics decisions during supply chain configuration. Salvador et al. (2002) present one of the most comprehensive studies dealing with the mutual interactions among product families, production processes and supply sources. The industry case studies show general guidance for the decision-making processes. Gupta and Krishnan (1999) investigate the reduction in the complexity of a product family through product design by leveraging common characteristics among products within the family. Based on the concept of ontology-oriented constraint networks, Novak and Eppinger (2001) find statically significant relations between supply chain structures and product architectures for luxury and high performance vehicles.

A set of modeling approaches have been proposed to solve the joint supply chain decision-making problems. Park et al. (2000) present 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) analyze 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) propose a mathematical model and a solution algorithm to assist the manufacturer in configuring its supply chains for a mix of multiple products that share some common raw materials and/or component parts. In summary, the above work provides certain managerial guidelines at a higher level for supply chain management, and the details at an operational level remains untouched. This study intends to assist companies to make decisions in configuring supply chains from a generic supply chain network at a more detailed level.

2.3 PNs for Systems Modeling

As a graphical and mathematical modeling technique, PNs have recently emerged as a promising approach for modeling, simulating and analyzing various systems. However, a PN-based model is highly system dependent and lacks properties such as modularity, reusability and a high degree of maintainability that are commonly required in complex systems to be modeled. Attempting to meet various requirements of systems to be described, many PN variations such as object-oriented PNs (OPNs), colored PNs (CPNs), PNs with changeable structure (PNs-CS) have been developed (Trostmann et al., 1993; Moore and Gupta, 1996; Jiang et al., 1999b).

As a combination of object-oriented (OO) approach and PN techniques, the OPNs excel in modeling such systems that are rather large and complex. This is because models of OPNs are characterized by the encapsulation of physical objects in systems and the 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 OPNs 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 PNs, a CPN (Jensen, 1992) adds colors to tokens, which are black in low-level or ordinary PNs. These colors are used to encode different data types and values that are attached to tokens. The presence of colors makes CPNs the ideal tools to describe systems that contain many similar (but not identical) interacting components (Jensen, 1992). To accommodate the changes of a system to be modeled, PNs-CS are developed to provide such mechanisms that allow changes to be made to the structures of PN models when the system being described changes. In this way, the changes in the actual system are reflected by the structural changes of the built PN models.

The PNs are employed to describe various systems. The OPNs-CS combining OPNs and PNs-CS are adopted to model one-of-a-kind production systems in (Jiang et al., 1999b). In their work, they clearly define the objects and message passing relations among interacting objects in the built model. Furthermore, the authors formulate two different kinds of changes to the OPNs-CS models so as to accommodate the changes in production systems. The two changes include the modification of message passing relations and the adding or removing objects to or from the built models. In a similar work, Jiang et al. (2001) apply CPNs-CS to model one-of-a-kind production systems with focus on the changes and uncertainties of such systems. Aiming at modeling the reliability of production resources, such as machines, robots and buffers, the stochastic OPNs (SOPNs) are proposed in (Jiang et al., 1999a). The difference between SOPNs and OPNs in their work is the addition of stochastic transitions and stochastic places to the OPNs. With understanding of the materials flows, the time constraints, the dynamic behaviors of facilities, and the interaction among facilities in an automated manufacturing system (AMS), Wang and Wu (1998) introduce CTOPN (colored timed object-oriented Petri nets) to model an AMS. The use of colored tokens clearly addresses part routings and the adopted facilities.

3. Problem Description

For a given end customer order, several supply chains can be configured from the existing supply chain network of the company that will deliver the ordered product. Among these feasible supply chains, the optimal one will be selected and implemented as the final solution. All partners in the selected supply chain work towards the common goal of fulfilling the customer order, such that their own interests can be achieved at the same time. To shed light on the elements and their interacting relationships in such a supply chain, some definitions are given below.

Definition 1: A customer order set $O = \{O_i^*\}_n$ is a set of orders launched by end customers. Each O_i^* is defined as a 4-tuple: $O_i^* = \langle P_i^*, C_i^*, Q_i^*, L_i^* \rangle$, 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 2: A supply chain aims to fulfill order O and is defined as a tuple: $S = \langle \Gamma, \Psi \rangle$, where $\Gamma = \{E_e^*\}_E$ is the entity set involved in S, and Ψ is the flow set. $\Psi = F^I \cup F^M$, $F^I \cap F^M = \Phi$, where F^I and F^M are the information flow and material flow across S, respectively.

Definition 3: Each $F_f^*, \forall f = 1, \cdots, F$ in Ψ defines a precedence relationship between entities in Γ, such that $F_f^* = (E_a^*, E_b^*) \in \Gamma \times \Gamma$. If $F_f^* = (E_a^*, E_b^*) \in F^M$, then E_a^* is an upstream entity and provides material items to E_b^*; If $F_f^* = (E_a^*, E_b^*) \in F^I$, then E_a^* is a downstream entity and gives the order information to E_b^*.

Definition 4: In a supply chain S, 4 types of entities are observed, i.e., $\Gamma = E^M \cup E^A \cup E^C \cup E^R$, where E^M, E^A, E^C, and E^R are four disjoint sets of final manufacturers, assembly suppliers, component suppliers, and raw material suppliers, respectively. Note, by following the common practice in the literature, in this study, one upstream entity provides material items to one downstream entity in the same supply chain.

Definition 5: Corresponding to the required item A, each E_e^* is described by a set of attributes, i.e., $E_e^* = \{A_{ea}^*\}_{E \times A}$. An $A_{ea}^*, \forall a = \{1, \ldots, A\}$ is defined as a 4-tuple: $A_{ea}^* = \langle I_{ea}^*, C_{ea}^*, Q_{ea}^*, L_{ea}^* \rangle$, where I_{ea}^*, L_{ea}^*, C_{ea}^*, and Q_{ea}^* represents an item that E_e^* can offer, be it a finished product, an assembly, a component, or a raw material, the lead time and total cost of delivering I_{ea}^*, and the required quantity of I_{ea}^*.

The total cost C_{ea}^* is an aggregation of three types of costs, including the transportation cost (i.e., a cost incurred in transporting I_{ea}^* to the order placer), production cost and inventory cost of I_{ea}^*. Further, both the inventory and production costs rely upon the adopted process and the design of the item I_{ea}^*. According to the product structure of P_i^* of O_i^*, a set of internal orders $O_i^{S*} = O_i^{A*} \cup O_i^{C*} \cup O_i^{R*}$ is placed by entities in S to their upstream entities. O_i^{A*}, O_i^{C*} and O_i^{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. Figure 1 shows the constituent elements and the relationships inherent in a supply chain network.

<<<<<<<<<<<<<<<<<<<<<<<<Insert Figure 1 Here>>>>>>>>>>>>>>>>>>>>

4. 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 lead to difference in supply chains. Such differences may correspond to the structural changes of bill of materials of ordered products or the changes of product items. 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 (Ps) and gates (gs). Each gate connects with two places. A place is an object and denotes a supply chain entity. Thus, a place may represent a final manufacturer that delivers products to customers, 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 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 of the item, the total cost and lead time. The cost data include a transportation cost, inventory cost and production cost. As both the inventory and production costs are determined by the design and process of the item, in the proposed CPN formalism all changes in product, process and logistics are 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 2 shows examples of CPN models of configuring supply chains for different customer orders. The model in Figure 2(a) reflects the supply chain network of a final manufacturer represented by 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 will be selected to form a supply chain in response to a particular customer order. Each end customer order is described by the ordered product (FP), the ordered quantity (Q), the total cost (C), and the allowed delivery time (L).

<<<<<<<<<<<<<<<<<<<<<<<<Insert Figure 2 Here>>>>>>>>>>>>>>>>>>>

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 Figure 2(b). The product FP_1 is formed by two assemblies, $A_1^{fp_1}$ and $A_2^{fp_1}$. Accordingly, 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 of the colored tokens that are 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 manner. Figure 2(c) shows a supply chain for another customer order $O_2 = \left(FP_2, C_2, Q_2, L_2\right)$ with color *A*. For illustrative simplicity, only the colors of the tokens are shown in the figure. The detailed information of tokens and their colors are given in Table 1.

<<<<<<<<<<<<<<<<<<<<<<<<Insert Table 1 Here>>>>>>>>>>>>>>>>>>>

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 $\left(A_1^{fp_2}, CA_1^{fp_2}, QA_1^{fp_2}, LA_1^{fp_2}\right)$. Further upstream component and raw material suppliers are also changed, as shown in the figure. The adoption of the change handling mechanism accommodates such configuration variations in the built system models.

5. Industry Example

Headquartered in Finland, XYZ Ltd. is a multinational company. It provides a high variety of electrical motors with a wide output power ranging from 1 KW to 3000 KW. Each year XYZ fulfills around 12000 orders. The total number of motor types in these orders is over 800. These various types of motors require a large number of material items (including raw materials, components and assemblies). In order to obtain the required material items at the right time, XYZ maintains a large supplier base of all potential suppliers, which forms a complex supply chain network. Consequently, the diverse motors, the various required raw materials, components and assemblies, the dispersed location of suppliers, and the different capabilities of suppliers complicate supplier selection and material procurement.

Figure 3 shows some motors that XYZ has offered and the main parts of a motor. For illustrative simplicity, we generalize the components of a motor into four manufactured parts, including Base (Bs), Rotor (Rt), Stator (St), and Shield (Sh). Further, a Bs and a Sh form a Case Assembly (CA); a Rt and a St form a Drive Assembly (DA), as shown in Figure 3(c).

<<<<<<<<<<<<<<<<<<<<<<<<<Insert Figure 3 Here>>>>>>>>>>>>>>>>>>>>>>

Figure 4 shows XYZ's supply chain network. Each node corresponds to a supplier that can provide certain material item. For instance, DAs can be provided either by the supplier at Vaasa, Finland or the one at Oulu, Finland; the final motors are assembled at Vaasa, Finland, Munich, Germany and Helsinki, Finland. Each supplier has its own capacity to produce the required material items at the ordered volumes and costs. 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.

<<<<<<<<<<<<<<<<<<<<<<<<<Insert Figure 4 Here>>>>>>>>>>>>>>>>>>>>>>

6. CPN Representation of a Supply Chain Network

Application of CPN modeling formalism to supply chain configuration involves the construction of a series of systems models, including (1) a CPN representation model of a manufacturer's generic supply chain network; (2) a CPN configuration model of a specific supply chain (for a customer order); and (3) a CPN changing configuration model of a specific supply chain (for different customer orders).

A supply chain network of a manufacturer contains all of 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 depends on the matching of their design and processes of the items that are ordered by their downstream partners, their manufacturing capabilities of producing the items, their financial performance, as well as their delivery times with the items' order requirements. Their financial performance relates to the costs of transporting the ordered items at the right quantities to the right destinations, the costs of producing the items and the inventory costs incurred during production.

Attempting to encompass all above aspects that have an impact on the selection of upstream supply chain entities, we attach a 4-attribute set, $\{A_i V_{ij}^*\}_{4\times n}$, to each 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 items, the respective quantities and lead times that an entity can offer, whilst the values of A_3 include the transportation, production and inventory costs in relation to the values of A_1 and A_2.

Figure 5 shows the CPN representation model of the generic supply chain network of XYZ's motor plant in Vaasa (VMP). Table 2 lists all of the supply chain objects represented by places in Figure 5. These objects are generic in the sense that each of them can offer 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, indicate the occurrence of certain events, i.e., order decomposition, and control the information flows. For example, g_1 not only controls the split of the motor order, the information of which is carried by the token in P_1, into two tokens that record the order information of DA and CA, but also passes them to the proper places (either P_2 or P_3, P_4 or P_5). Gates g_2, g_3, g_4, and g_5 have the similar role as that of g_1. The difference is that they are in charge of converting the assembly order information into the information about orders of the four parts. A dummy place (P_{14}) and a dummy gate (g_6) are added into the configuration model to ensure computer execution. While g_6 and P_{14} do not hold any practical meaning, they are necessary to ensure the models to run in computers.

<<<<<<<<<<<<<<<<<<<<<<<<Insert Figure 5 Here>>>>>>>>>>>>>>>>>>>

<<<<<<<<<<<<<<<<<<<<<<<<Insert Table 2 Here>>>>>>>>>>>>>>>>>>>

While the representation model in Figure 5 conveys all the suppliers' information, their relationships and all possible information flows in the supply chain network of VMP, it is the configuring CPN models that entail the selection of suppliers and the specific supply chain in response to a customer order, as shown in Figures 6 and 7.

7. CPN Model for Supply Chain Configuration

To fulfill a customer order, $O_1 = \left(A_1V_{11}^*, A_2V_{21}^*, A_3V_{31}^*, A_4V_{41}^*\right) = \left(M_3^*, Q_3^*, C_3^*, L_3^*\right)$, where M_3^* indicates the third motor design in VMP, VMP first decomposes the order into two assembly orders for DA and CA. Order decomposition is conducted in a way that 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 of DA and CA are selected. Subsequently, four orders for parts Bs, Rt, St, and Sh are generated according to the requirements of the two assembly orders. Further, four qualified suppliers are determined to deliver the four orders for parts. Figure 6 shows the CPN model of the supply chain configured for fulfilling O_1.

<<<<<<<<<<<<<<<<<<<<<<<<Insert Figure 6 Here>>>>>>>>>>>>>>>>>>>

The model is formally described as follows: (See Appendix for nomenclature.)

$$S_1 = \left(O_1, C_1, R_1, M_{1,1}, L_1\right)$$

(1) The object set:

$$O_1 = \{VMP, ODS, TCS, MRS, NSS, HSS, HBS, DP\}$$

(2) The massage passing relation set:

$$R_1 = \left\{ \begin{array}{l} R_{1VMP-ODS}, R_{1VMP-TCS}, R_{1ODS-MRS}, R_{1ODS-NSS}, R_{1TCS-HSS}, R_{1TCS-HBS}, R_{1MRS-DP}, R_{1NSS-DP}, \\ R_{1HS-SDP}, R_{1HBS-DP} \end{array} \right\}$$

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

$$G_{1VMP-ODS} = (g_1)$$

$$OA_{1VMP-ODS} = (om^{VMP} - g_1)$$

$$IA_{1VMP-ODS} = (g_1 - im^{ODS})$$

$$\begin{aligned} E_{1VMP-ODS} &= (E_{1VMP-ODS}(OA_{1VMP-ODS}), E_{1VMP-ODS}(IA_{1VMP-ODS})) \\ &= \left(\begin{array}{l} (1'(M_3^*, Q_3^*, C_3^*, L_3^*)), \\ (1'(DA_2^*, QDA_2^*, CDA_2^*, LDA_2^*) \rightarrow 1'(DA_2^*, QDA_2^*, CDA_2^*, LDA_2^*)) \end{array} \right) \end{aligned}$$

Thus,

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

(3) The color set: $C_1 = \{PS_1, RS\}$ where

$$PS_1 = \left\{ \begin{array}{l} (M_3^*, Q_3^*, C_3^*, L_3^*), (DA_2^*, QDA_2^*, CDA_2^*, LDA_2^*), (CA_1^*, QCA_1^*, CCA_1^*, LCA_1^*), \\ (R_5^*, QR_5^*, CR_5^*, LR_5^*), (St_2^*, QSt_2^*, CSt_2^*, LSt_2^*), (Sh_3^*, QSh_3^*, CSh_3^*, LSh_3^*), \\ (B_1^*, QB_1^*, CB_1^*, LB_1^*), \left(\begin{array}{l} (R_5^*, QR_5^*, CR_5^*, LR_5^*) \wedge (St_2^*, QSt_2^*, CSt_2^*, LSt_2^*) \wedge \\ (Sh_3^*, QSh_3^*, CSh_3^*, LSh_3^*) \wedge (B_1^*, QB_1^*, CB_1^*, LB_1^*) \end{array} \right) \end{array} \right\}$$

and $RS = e$, where e denotes the availability of manufacturing resources.

(4) The gate set: $G_1 = \{g_1, g_3, g_5, g_6\}$

$$\begin{aligned} L_1(g_1) &= (L_1({}^\bullet g_1), L_1(g_1^\bullet)) = ((om^{VMP}), (\wedge / \vee (im^{ODS}, im^{TCS}))) \\ &= ((om^{VMP}), (im^{ODS} \wedge im^{TCS})) \end{aligned}$$

Similarly, we can get $L_1(g_3)$, $L_1(g_5)$ and $L_1(g_6)$ as follows.

$$L_1(g_3) = \left(L_1({}^\bullet g_3), L_1(g_3^\bullet)\right) = \left(\left(om^{ODS}\right), \left(im^{MRS} \wedge im^{NSS}\right)\right)$$

$$L_1(g_5) = \left(L_1({}^\bullet g_5), L_1(g_5^\bullet)\right) = \left(\left(om^{TCS}\right), \left(im^{HSS} \wedge im^{HBS}\right)\right)$$

$$L_1(g_6) = \left(L_1({}^\bullet g_6), L_1(g_6^\bullet)\right) = \left(\left(om^{MRS} \wedge om^{NSS} \wedge om^{HSS} \wedge om^{HBS}\right), \left(im^{DP}\right)\right)$$

Thus,

$$\begin{aligned} L_1(G_1) &= \{L_1(g_1), L_1(g_3), L_1(g_5), L_1(g_6)\} \\ &= \left\{ \begin{aligned} &\left(\left(om^{VMP}\right), \left(im^{ODS} \wedge im^{TCS}\right)\right), \left(\left(om^{ODS}\right), \left(im^{MRS} \wedge im^{NSS}\right)\right), \\ &\left(\left(om^{TCS}\right), \left(im^{HSS} \wedge im^{HBS}\right)\right), \left(\left(om^{MRS} \wedge om^{NSS} \wedge om^{HSS} \wedge om^{HBS}\right), \left(im^{DP}\right)\right) \end{aligned} \right\} \end{aligned}$$

(5) The initial marking set:

$$M_{1,0} = \{MM_{1,0}, SM_{1,0}\}$$

Where $MM_{1,0} = \phi$ and

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

The information flow in the net model in Figure 6 is described as follows.

$$F_1 = \begin{pmatrix} (VMP, ODS), (VMP, TCS), (ODS, MRS), (ODS, NSS), (TCS, HSS), (TCS, HBS), \\ (MRS, DP), (NSS, DP), (HSS, DP), (HBS, DP) \end{pmatrix}$$

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 the two assembly orders flow to P_3 and P_5 (representing ODS and TCS) since they can satisfy the delivery requirements. The data attached to each token are a particular set of four-attribute value pairs pertaining to an ordered item. The logic relationship function of g_1 specifies the token flow, which goes to the qualified suppliers. Similarly, the other three gates (g_3, g_5 and g_6) are fired and the qualified suppliers are selected

8. Dealing with Diverse Customer Requirements

In a mass customization environment, customer orders often contain different requirements that lead to specific configurations of supply chain elements. Suppose that a different customer order $O_2 = (A_1V_{12}^*, A_2V_{22}^*, A_3V_{32}^*, A_4V_{42}^*) = (M_5^*, Q_5^*, C_5^*, L_5^*)$ is placed for motor M_5. The specific supply chain for O_1 cannot fulfill O_2 due to changes in quantity, cost and delivery date, and different product specifications of two motors as well. Therefore, the supply chain needs to be reconfigured, as shown in Figure 7. To fulfill O_2, assembly suppliers represented by P_2 and P_4 rather than P_3 and P_5 are selected. Likewise, part 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 new suppliers and the removal of existing ones, other model elements, e.g., message passing relations and logic relationship functions of gates, are also changed. The following formulations detail how these changes are handled.

<<<<<<<<<<<<<<<<<<<<<<<Insert Figure 7 Here>>>>>>>>>>>>>>>>>>>>>

Let S_2 denote the CPN model of the system for O_2, then

$$S_2 = (O_2, R_2, L_2, C_2, M_{2,1})$$

(1) The new object set:

$$O_2 = O_1 - O_1^r \cup O_1^a$$

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

(2) The new massage passing relation set:

$$R_2 = R_1 - R_1^r \cup R_1^a$$

$$
\begin{aligned}
&= R_1 - \\
&\{R_{1VMP-ODS}, R_{1VMP-TCS}, R_{1ODS-MRS}, R_{1ODS-NSS}, R_{1TCS-HSS}, R_{1TCS-HBS}, R_{1MRS-DP}, R_{1NSS-DP}, R_{1HSSDP}, R_{1HBS-DP}\} \\
&\cup \{R_{2VMP-VDS}, R_{2VMP-VCS}, R_{2VDS-VRS}, R_{2VDS-WSS}, R_{2VCS-VSS}, R_{2VCS-OBS}, R_{2VRS-DP}, R_{2WSS-DP}, R_{2VSS-DP}, R_{2OBS-DP}\} \\
&= \{R_{2VMP-VDS}, R_{2VMP-VCS}, R_{2VDS-VRS}, R_{2VDS-WSS}, R_{2VCS-VSS}, R_{2VCS-OBS}, R_{2VRS-DP}, R_{2WSS-DP}, R_{2VSS-DP}, R_{2OBS-DP}\}
\end{aligned}
$$

For the added message passing relations, $R_{2VMPVDS}$ is used to explain how the new message passing relations are generated.

$$OA_{2VMP-VDS} = \left(om^{VMP} - g_1\right)$$

$$G_{2VMP-VDS} = \left(g_1\right)$$

$$IA_{2VMP-VDS} = \left(g_1 - im^{VDS}\right)$$

$$
\begin{aligned}
E_{2VMP-VDS} &= \left(E_{2VMP-VDS}\left(OA_{2VMP-VDS}\right), E_{2VMP-VDS}\left(IA_{2VMP-VDS}\right)\right) \\
&= \begin{pmatrix} \left(1'\left(M_5^*, Q_5^*, C_5^*, L_5^*\right)\right), \\ \left(1'\left(DA_3^*, QDA_3^*, CDA_3^*, LDA_3^*\right) \rightarrow 1'\left(DA_3^*, QDA_3^*, CDA_3^*, LDA_3^*\right)\right) \end{pmatrix}
\end{aligned}
$$

Then,

$$
\begin{aligned}
R_{2VMP-VDS} &= \left(OA_{2VMP-VDS}, G_{2VMP-VDS}, IA_{2VMP-VDS}, E_{2VMP-VDS}\right) \\
&= \begin{pmatrix} \left(om^{VMP} - g_1\right), \left(g_1\right), \left(g_1 - im^{VDS}\right), \\ \begin{pmatrix} \left(1'\left(M_5^*, Q_5^*, C_5^*, L_5^*\right)\right), \\ \left(1'\left(DA_3^*, QDA_3^*, CDA_3^*, LDA_3^*\right) \rightarrow 1'\left(DA_3^*, QDA_3^*, CDA_3^*, LDA_3^*\right)\right) \end{pmatrix} \end{pmatrix}
\end{aligned}
$$

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

(3) The new color set:

$$C_2 = C_1 - C_1^{\,r} \cup C_1^{\,a} = \{PS_2, RS\}$$

where

$$
PS_2 = \left\{ \begin{array}{l}
\left(M_5^*, Q_5^*, C_5^*, L_5^*\right), \left(DA_3^*, QDA_3^*, CDA_3^*, LDA_3^*\right), \left(CA_2^*, QCA_2^*, CCA_2^*, LCA_2^*\right), \\
\left(R_2^*, QR_2^*, CR_2^*, LR_2^*\right), \left(St_1^*, QSt_1^*, CSt_1^*, LSt_1^*\right), \left(Sh_1^*, QSh_1^*, CSh_1^*, LSh_1^*\right), \\
\left(B_4^*, QB_4^*, CB_4^*, LB_4^*\right), \begin{pmatrix} \left(R_2^*, QR_2^*, CR_2^*, LR_2^*\right) \wedge \left(St_1^*, QSt_1^*, CSt_1^*, LSt_1^*\right) \wedge \\ \left(Sh_1^*, QSh_1^*, CSh_1^*, LSh_1^*\right) \wedge \left(B_4^*, QB_4^*, CB_4^*, LB_4^*\right) \end{pmatrix}
\end{array} \right\}
$$

and $RS = e$.

(4) The new gate set: $G_2 = \{g_1, g_2, g_4, g_6\}$

$$L_2(G_2) = \{(L_2({}^\bullet g_1), L_2(g_1^\bullet)), (L_2({}^\bullet g_2), L_2(g_2^\bullet)), (L_2({}^\bullet g_4), L_2(g_4^\bullet)), (L_2({}^\bullet g_6), L_2(g_6^\bullet))\}$$

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 1) the changes to the input message places connecting to g_1; and 2) the changes in output message places connecting to g_6. For illustrative simplicity, g_1 is used to show how to modify the gate logic relationship functions.

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

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

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

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

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

$$g^\bullet{}_1^0 = (im^{ODS} \wedge im^{TCS})$$

$$g^\bullet{}_1^{0r} = (im^{ODS} \wedge im^{TCS})$$

$$g^\bullet{}_1^{0a} = (im^{VDS} \wedge im^{VCS})$$

$$g^\bullet{}_1^1 = g^\bullet{}_1^0 - g^\bullet{}_1^{0r} + g^\bullet{}_1^{0a} = (im^{ODS} \wedge im^{TCS}) - (im^{ODS} \wedge im^{TCS}) + (im^{VDS} \wedge im^{VCS}) = (im^{VDS} \wedge im^{VCS})$$

$$L_1(g^\bullet{}_1^1) = (im^{VDS} \wedge im^{VCS})$$

Thus, $L_2(g_1) = (L_2({}^\bullet g_1^1), L_2(g^\bullet{}_1^1)) = ((om^{VMP}), (im^{VDS} \wedge im^{VCS}))$

Similarly, $L_2(g_2)$, $L_2(g_4)$ and $L_2(g_6)$ can be generated.

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

$$M_{o,s} = \{MM_{o,s}, SM_{o,s}\}$$

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

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

Thus,

$$
\begin{aligned}
MM_{2,0} &= MM_{0,s} - MM_{0,s}^{r} + MM_{0,s}^{a} \\
&= \Phi - \Phi + 1' im^{VDS}\left(DA_3^*, QDA_3^*, CDA_3^*, LDA_3^*\right) + 1' im^{VCS}\left(CA_2^*, QCA_2^*, CCA_2^*, LCA_2^*\right) \\
&= 1' im^{VDS}\left(DA_3^*, QDA_3^*, CDA_3^*, LDA_3^*\right) + 1' im^{VCS}\left(CA_2^*, QCA_2^*, CCA_2^*, LCA_2^*\right)
\end{aligned}
$$

$$
\begin{aligned}
SM_{2,0} &= SM_{0,s} - SM_{0,s}^{r} + SM_{0,s}^{a} \\
&= SM_{0,s} - \left(1'\left(P_1^{ODS}, e\right) + 1'\left(P_1^{TCS}, e\right) + 1'\left(P_1^{MRS}, e\right) + 1'\left(P_1^{NSS}, e\right) + 1'\left(P_1^{HSS}, e\right) + 1'\left(P_1^{HBS}, e\right)\right) \\
&\quad + \left(1'\left(P_1^{VDS}, e\right) + 1'\left(P_1^{VCS}, e\right) + 1'\left(P_1^{VRS}, e\right) + 1'\left(P_1^{WSS}, e\right) + 1'\left(P_1^{VSS}, e\right) + 1'\left(P_1^{OBS}, e\right)\right) \\
&= 1'\left(P_1^{VMP}, e\right) + 1'\left(P_1^{VDS}, e\right) + 1'\left(P_1^{VCS}, e\right) + 1'\left(P_1^{VRS}, e\right) + 1'\left(P_1^{WSS}, e\right) + 1'\left(P_1^{VSS}, e\right) \\
&\quad + 1'\left(P_1^{OBS}, e\right) + 1'\left(P_1^{DP}, e\right)
\end{aligned}
$$

Thus,

$$
\begin{aligned}
M_{2,0} &= \left\{MM_{2,0}, SM_{2,0}\right\} \\
&= \left\{
\begin{aligned}
&\left(1' im^{VDS}\left(DA_3^*, QDA_3^*, CDA_3^*, LDA_3^*\right) + 1' im^{VCS}\left(CA_2^*, QCA_2^*, CCA_2^*, LCA_2^*\right)\right), \\
&\left(
\begin{aligned}
&1'\left(P_1^{VMP}, e\right) + 1'\left(P_1^{VDS}, e\right) + 1'\left(P_1^{VCS}, e\right) + 1'\left(P_1^{VRS}, e\right) + 1'\left(P_1^{WSS}, e\right) + 1'\left(P_1^{VSS}, e\right) \\
&+ 1'\left(P_1^{OBS}, e\right) + 1'\left(P_1^{DP}, e\right)
\end{aligned}
\right)
\end{aligned}
\right\}
\end{aligned}
$$

As shown in Figure 7, due to the selection of different suppliers, the information flow is changed as follows:

$$
F_2 = \begin{pmatrix}
(VMP, VDS), (VMP, VCS), (VDS, VRS), (VDS, WSS), (VCS, VSS), (VCS, OBS), \\
(VRS, DP), (WSS, DP), (VSS, DP), (OBS, DP)
\end{pmatrix}
$$

In Figure 7, a new colored token is created to represent O_2 in P_1. Based on the logic relationship function of g_1, two new tokens corresponding to the two decomposed assembly orders in relation to O_2 are generated. They record such information 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. The two tokens are directed 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. According to the requirements of two assembly orders, four orders for parts, in turn, are generated, including

$(R_2^*, QR_2^*, CR_2^*, LR_2^*)$ for Rt, $(St_1^*, QSt_1^*, CSt_1^*, LSt_1^*)$ for St, $(Sh_1^*, QSh_1^*, CSh_1^*, LSh_1^*)$ for Sh, and $(B_4^*, QB_4^*, CB_4^*, LB_4^*)$ for Bs. Subsequently, four suppliers represented by P_6, P_9, P_{10}, and P_{12} are selected. With the presence of four orders, g_6 is fired. A new token, $\begin{pmatrix}(R_2^*, QR_2^*, CR_2^*, LR_2^*) \wedge (St_1^*, QSt_1^*, CSt_1^*, LSt_1^*) \wedge \\ (Sh_1^*, QSh_1^*, CSh_1^*, LSh_1^*) \wedge (B_4^*, QB_4^*, CB_4^*, LB_4^*)\end{pmatrix}$, is generated and flows to P_{14}.

Table 3 gives the items, orders, assigned colors to tokens that represent orders, and the suppliers that can match with the colors in two models in Figures 6 and 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 to 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 gate g_6, one token with a certain color is generated at the presence of four tokens residing in the four input 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}).

<<<<<<<<<<<<<<<<<<<<<<<<Insert Table 3 Here>>>>>>>>>>>>>>>>>>>>

9. Evaluation of Supply Chain Configuration

Since more than one supply chain for an end customer order can be configured from the existing supply chain network of a company, it is necessary for the company to identify the optimal one so as to achieve the best added value. As it involves multiple decision variables and multiple performance criteria, it is difficult for a human being to directly compare all solutions. Simulation has been proven as a promising analysis tool to assist decision makers. In this research, we adopt the Petri.NET Simulator 2.0 (http://petrinet.bigeneric.com) to support supply chain configuration evaluation.

Evaluation of supply chain configuration is not as straightforward as simply selecting one from a number of alternatives. Due to the complexity of supply chain network and the fast customer demand changes, two aspects are involved in supply chain configuration evaluation. First, among all of the supply chains for fulfilling a customer order, an optimal one can be determined. However, when multiple orders are to be fulfilled at the same time, a company must configure a number of supply chains for the corresponding orders from its supply chain network. Due to the interrelations among suppliers, the optimal supply chain for each individual customer order may not be the optimal one considering the cohort of all of the customer orders. Thus, the second aspect addresses the evaluation of all possible supply chains with consideration of the supply chains for all the customer orders as a whole. The configured supply chains for these customer orders may or may not be identical.

We use the two orders, O_1 and O_2, to carry out supply chain configuration evaluation using PN simulator 2.0. Two supply chains are considered for each order, respectively. Table 4 shows the product items, orders, and suppliers in the four supply chains.

<<<<<<<<<<<<<<<<<<<<<<<<Insert Table 4 Here>>>>>>>>>>>>>>>>>>>>

Figure 8 shows the PN simulation model of $S_1^{O_1}$. Unlike the information flow in Figure 6, the flow in this simulation model reflects the material flow from parts to the final products. To meet the system requirements of PN simulator 2.0, place P_9 is added as a buffer and holds the aggregation of the four parts of the four suppliers, including MRS (P_2), NSS (P_3), HSS (P_4), and HBS (P_5). Two assemblies, DA_3^* and CA_2^*, are formed at place P_6 representing ODS and place P_8 representing TCS, respectively. The final product M_3^* will be generated in place P_8 representing company XYZ. The number 22 in P_8 indicates the number of M_3^* that have been generated at the time of simulation.

<<<<<<<<<<<<<<<<<<<<<<<<<<*Insert Figure 8 Here*>>>>>>>>>>>>>>>>>>>>

Figure 9 shows the simulation result in terms of time performance for $S_1^{O_1}$. The similar results are generated for the other three supply chains. The number of tokens in each place is presented as a function of time, as shown in the figure. At the top of the figure, the line headed by "XYZ" represents the number of tokens generated in P_8 at different time units in simulation. The last line headed by "Buffer Input" (i.e., P_9) at the bottom of the figure shows the stochastic arrival of tokens, which reflects the random arrival of customer orders. In turn, this stochastic arrival of tokens in P_9 affects the generation of tokens in P_8 in a linear trend, as shown by the resulting linear line at the top. To compare the simulation result, the simulation time is set at 1000,000 time units for the first run. In total, 100 simulation runs are conducted for the four supply chains. The final result in terms of the number of tokens generated in P_8 shows the optimal process for O_1 and O_2 are $S_1^{O_1}$ and $S_2^{O_2}$, respectively.

<<<<<<<<<<<<<<<<<<<<<<<<<<*Insert Figure 9 Here*>>>>>>>>>>>>>>>>>>>>

10. Conclusions

This paper introduces a new formalism based on colored PNs to model supply chain configuration with coordinated product, process and logistics design decision making. By shedding light on the implications of product, process and logistics decisions, the formalism is able to assist companies to form optimal supply chains in response to fast customer demand changes. This is accomplished by incorporating OO technique and a mechanism to handle structural changes into 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. Two steps have been identified in supply chain configuration, including configuring all possible supply chains and evaluating the configured supply chains. While both steps deserve more research efforts, we focus on configuring supply chains in the first step. We explain the basic idea of supply chain configuration evaluation and adopt a PN simulator to illustrate the evaluation process. Due to limited functionality of the PN simulator, we have to evaluate supply chains only based on delivery time performance indicated by the number of generated tokens

The developed PN formalism is advantages with respect to graphical representation, which provides companies with a visualization of the impact of different product, process and logistics decisions on the overall performance of configured supply chains. Based on this intuition and the resulting easy understanding, companies can, thus, make timely decision about suppliers to be used by considering product, process and logistics design. Second, the existing several PN design/construction tools pave a way towards quick development of computational implementation of supply chain configuration based on the proposed model. This eventually enables supply chain configuration automation. In spite of the significance of the proposed model in this study, there are some disadvantages inherent in the formalism. First, the formalism was developed to address supply chain configuration without paying too much attention to supply chain evaluation. As a result, it does not lend itself to evaluate the configured supply chains. Second, the well-recognized limitation of PN techniques is that PN models grow fast in accordance with the increase of system elements to be modeled. In this regard, if a large number of suppliers are involved, the supply chain configuration model to be constructed based on the proposed formalism may become too large for companies to understand.

In view of the limitations described above, the current work can be extended to cope with them. To address both supply chain configuration and supply chain evaluation, research efforts should be made to develop a comprehensive formalism by integrating the basic principles of well-defined PN extensions. Moreover, the formalism should be developed to reduce complexities when building system models in spite of the fact that many suppliers at different levels may be involved. Another avenue for future research may be directed to develop a computational system based on the enhanced formalism to automatically configure supply chains.

Appendix: Nomenclature

S_k	The system CPN model after the *k*-th change	(1)
I_k	The total number of objects after the *k*-th change	(2)
O_k	The set of physical objects after the *k*-th change, i.e., $O_k = \{o_{ki} \| \forall i = 1, \cdots I_k\}$	(3)
O_k^r	The set of removed objects after the *k*-th change	(4)
O_k^a	The set of added objects after the *k*-th change	(5)
R_k	The set of message passing relations among objects after the *k*-th change, i.e., $R_k = \{R_{kij} \| i, j = 1, \ldots, I_k, i \neq j\}$	(6)
R_k^r	The set of removed message passing relations after the *k*-th change	(7)
R_k^a	The set of added message passing relations after the *k*-th change	(8)
O_{ki}	Message sending object after the *k*-th change	(9)
O_{kj}	Message receiving object after the *k*-th change	(10)
R_{kij}	Message passing relations between O_{ki} and O_{kj} after the *k*-th change and defined as a four tuple: $R_{kij} = (OA_{kij}, G_{kij}, IA_{kij}, E_{kij})$	(11)
OM_{ki}	Output message places of O_{ki}	(12)
IM_{kj}	Input message places of O_{kj}	(13)
G_{kij}	The set of gates between OM_{ki} of O_{ki} and IM_{kj} of O_{kj} after the *k*-th change	(14)
OA_{kij}	The set of output connection arcs from OM_{ki} of O_{ki} to G_{kij}	(15)
IA_{kij}	The set of input connection arcs from G_{kij} to IM_{kj} of O_{kj}	(16)
E_{kij}	The set of expression functions of connection arcs between OM_{ki} and IM_{kj}, defined as $E_{kij} = [E_{kij}(OA_{kij}), E_{kij}(IA_{kij})]$	(17)
E_{kij}^r	The set of removed expression functions after the *k*-th change	(18)

E_{kij}^{a}	The set of added expression functions after the *k*-th change	(19)
$E_{kij}(OA_{kij})$	The set of expression functions of OA_{kij}	(20)
$E_{kij}(IA_{kij})$	The set of expression functions of IA_{kij}, together with $E_{kij}(OA_{kij})$, they determine the number and the color of tokens flowing through OA_{kij} and IA_{kij} for each firing of G_{kij}	(21)
$M_{k,0}$	The set of initial markings of system CPN model after the *k*-th change and defined as a tuple: $M_{k,0} = (MM_{k,0}, SM_{k,0})$	(22)
$MM_{k,0}$	Initial markings of input/output message places of objects after the *k*-th change	(23)
$MM_{k,0}^{r}$	Markings of input/output message places of removed objects after the *k*-th change	(24)
$MM_{k,0}^{a}$	Markings of input/output message places of added objects after the *k*-th change	(25)
$SM_{k,0}$	Initial markings of state places of objects after the *k*-th change	(26)
$SM_{k,0}^{r}$	Markings of state places of removed objects after the *k*-th change	(27)
$SM_{k,0}^{a}$	Markings of state places of added objects after the *k*-th change	(28)
C_k	The color set of the system CPN model after the *k*-th change and defined as a tuple: $C_k = (PS_k, RS)$	(29)
PS_k	The set of product states after the *k*-th change	(30)
RS	Resource state with e representing resource available	(31)
g	A gate after the *k*-th change	(32)
$^{\bullet}g^{k}$	The set of output message places connected to *g* after the *k*-th change	(33)
$g^{\bullet k}$	The set of input message places connected to *g* after the *k*-th change	(34)
l_i	The number of output message places connected to *g*	(35)
l_o	The number of input message places connected to *g*	(36)
$\vee$	Relationship operator *OR*	(37)
$\wedge$	Relationship operator *AND*	(38)
$\wedge/\vee(x_1, x_2$	Logic operation by operators $\vee$ and $\wedge$ over message places $x_1, x_2, ..., x_n$, e.g.,	(39)

$x_1 \vee x_2$ 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

$$L_k(g) = \begin{bmatrix} \{ {}^{\bullet}g^k = (om_1, om_2, \cdots, om_{l_i}), L_k({}^{\bullet}g^k) = \wedge / \vee (om_1, om_2, \cdots, om_{l_i}) \}, \\ \{ g^{\bullet k} = (im_1, im_2, \cdots, im_{l_o}), L_k(g^{\bullet k}) = \wedge / \vee (im_1, im_2, \cdots, im_{l_o}) \} \end{bmatrix} \quad (40)$$

Acknowledgements

The authors would like to thank the anonymous reviewers and the editor for their insightful and constructive comments on the earlier version of this paper.

References

Arora, S. and Kumar, S. (2000), "Reengineering: a focus on enterprise integration", *Interfaces*, Vol. 30(5), pp. 54-71.

Blackhurst, J. Wu, T. and O'Grady, P. (2005), "PCDM: a decision support modelling methodology for supply chain, product and process design decisions", *Journal of Operations Management,* Vol. 23(3-4), pp. 325-343.

Dotoli, M. Fanti, M.P. and Meloni, C. (2003), "A decision support system for the supply chain configuration", *Proceedings of the 2003 IEEE International Conference on Systems, Man and Cybernetics*, Washington, USA, Vol. 3, pp. 2667-2672, 5-8 Oct. 2003.

Graves, S.C. and Willems, S.P. (2003), "Optimizing the supply chain configuration for new products", Working Paper, Leaders for Management Program and A.P., Sloan School of Management, MIT.

Gupta, S. and Krishnan, V. (1999), "Integrated component and supplier selection for a product family", *Production and Operations Management*, Vol.8 (2), pp.163–182.

Huang, S.H., Uppal, M. and Shi, F. (2002), "A product driven approach to manufacturing supply chain selection", *Supply Chain Management: An International Journal,* Vol. 7(4), pp.

189-199.

Huang, G.Q., Zhang, X.Y. and Liang, L. (2005), "Towards integrated optimal configuration of platform products, manufacturing processes, and supply chains", *Journal of Operations Management*, Vol. 23(3-4), pp. 267-290.

Jensen, K. (1992), *Colored Petri Nets: Basic Concepts, Analysis Methods and Practical Use,* Volume 1, Springer-Verlag, New York.

Jiang, Z., Zuo, M.J. and Fung, R.Y.K. (1999a), "Stochastic object-oriented Petri nets (SOPNs) for reliability modeling of manufacturing systems", *Proceedings of the 1999 IEEE Canadian Conference on Electrical and Computer Engineering,* Alberta, Canada.

Jiang, Z., Zuo, M.J., Tu, P.Y. and Fung, R.Y.K. (1999b), "Object-oriented Petri nets with changeable structure (OPNs-CS) for production system modeling", *International Journal of Advanced Manufacturing Technology,* Vol. 15, pp. 445-458.

Jiang, Z., Zuo, M.J., Fung, R.Y.K. and Tu, P.Y. (2001), "Colored Petri nets with changeable structures (CPN-CS) and their applications in modeling one-of-a-kind production (OKP) systems", *Computers and Industrial Engineering,* Vol. 41(3), pp. 279-308.

Kim, b., Leung, J.M.Y., Park, K.t., Zhang, G. and Lee, S. (2002), "Configuring a manufacturing firm's supply network with multiple suppliers", *IIE Transactions*, Vol. 34(8), pp. 663-677.

Moore, K.E. and Gupta, S.M. (1996), "Petri nets models of flexible and automated manufacturing systems: a survey", *International Journal of Production Research,* Vol. 34 (11), pp. 3001-3035.

Novak, S., Eppinger, S.D. (2001), "Sourcing by design: product architecture and the supply chain", *Management Science*, Vol. 47(1), pp. 189-204.

Park, B., Ghosh, S. and Murthy, N.N. (2000), "A framework of integrating product platform development with global supply chain configuration", National DSI conference, Orlando, FL.

Pine, J.B., II. (1993), *Mass Customization – The New Frontier in Business Competition*, Cambridge MA: Harvard Business School Press.

Piramuthu, S. (2005), "Knowledge-based framework for automated dynamic supply chain configuration", *Production, Manufacturing and Logistics,* Vol. 165, pp. 219-230.

Sahin, F. and Robinson, E. (2002), "Flow coordination and information sharing in supply chains: review implications and directions for future research", *Decision Sciences*, Vol. 33(4), pp. 505–536.

Salvador, F., Rungtusanatham, M. and Forza, C. (2004), "Supply-chain configurations for mass customization", *Production Planning & Control* Vol. 15 (4), pp. 381-397.

Salvador, F., Forza, C., Rungtusanatham, M. (2002), "Modularity, product variety, production volume, and component sourcing: theorizing beyond generic prescriptions", *Journal of Operations Management*, Vol. 20, pp.549–575.

Trostmann, E., Conrad, E., Holm, H. and Madsen, O. (1993), "Cybernetic modeling and control in integrated production systems-a project overview", *Proceedings of the 8th IPS Research Seminar,* Fuglso, Denmark.

Wang, L.C. and Wu, S.Y. (1998), "Modeling with colored timed object-oriented Petri nets for automated manufacturing systems", *Computers and Industrial Engineering,* Vol. 34(2), pp. 463-480.

Westbtrook, R. and Williamson, P.J. (1993), "Mass customization: Japan's new frontier", *European Management Journal*, Vol. 11(1), pp. 38–45.

Yan, H. and Yu, Z. (1998), "A strategic model for supply chain design with logical constraints: formulation and solution", Working Paper, No. 04/98-9

Yan, H., Yu, Z.X. and Cheng, T.C.E. (2003), "A strategic model for supply chain design with logical constraints: formulation and solution", *Computers & Operations Research,* Vol. 30(1), pp. 2135-2155.

Wang, L.C. (1996a), "Object-oriented Petri nets for modeling and analysis of automated manufacturing systems", *Computer Integrated Manufacturing Systems,* Vol. 26(2), pp.111-125.

Wang, L.C. (1996b), "An integrated object-oriented Petri net paradigm for manufacturing control systems", *International Journal of Computer Integrated Manufacturing,* Vol. 9(1), pp.73-87.

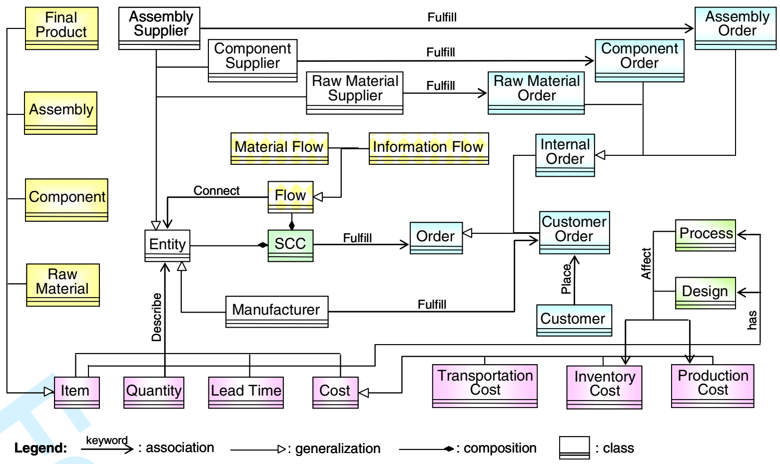


Figure 1. Constituent elements and relationships in a supply chain network

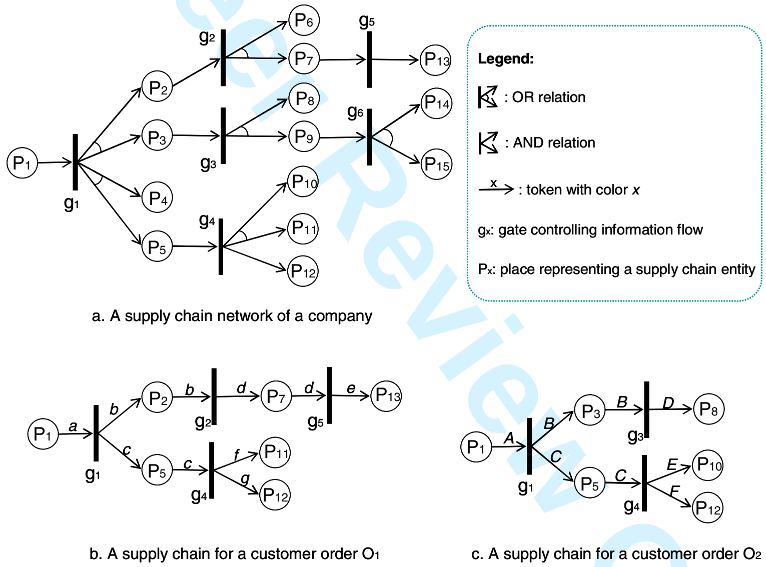


Figure 2. Principles of CPN model of supply chain configuration

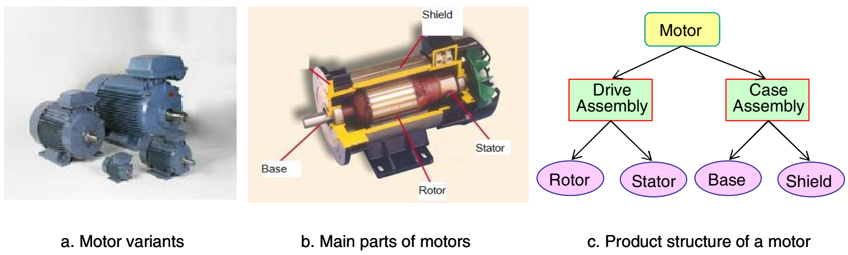


Figure 3. Motor variants, main parts and product structure

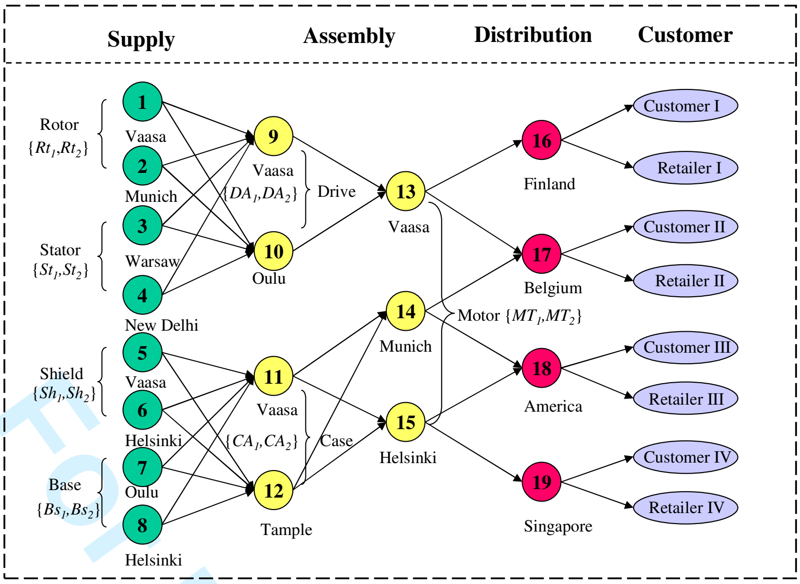


Figure 4. Supply chain network of XYZ

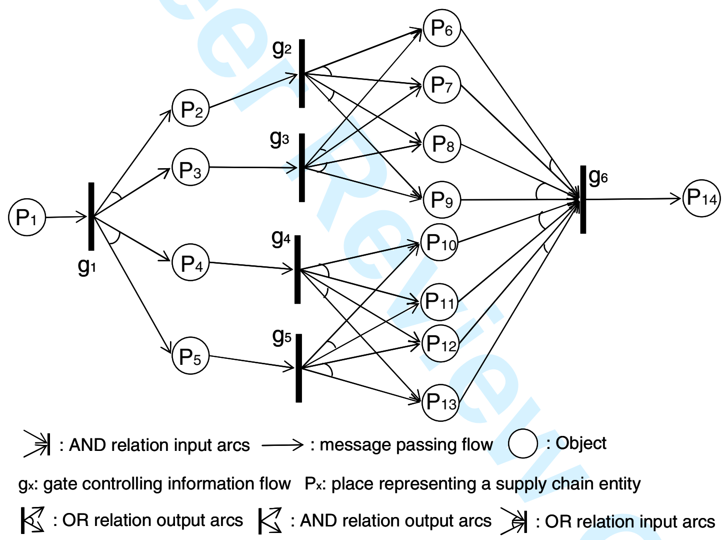


Figure 5. The static CPN model of the supply chain network of Vaasa motor plant

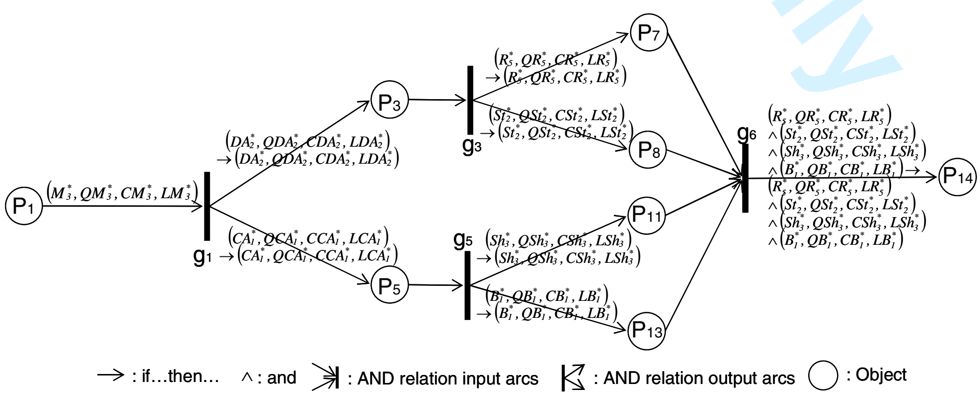


Figure 6. The CPN model of the supply chain configured for O_1

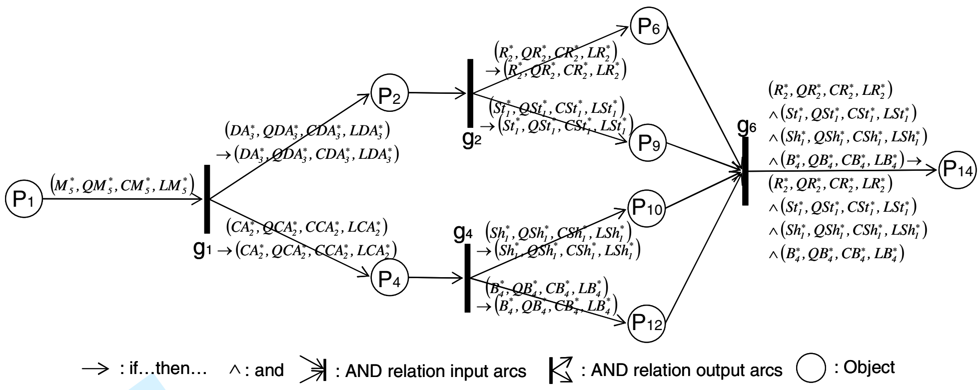


Figure 7. The dynamic CPN model of the supply chain for O_2

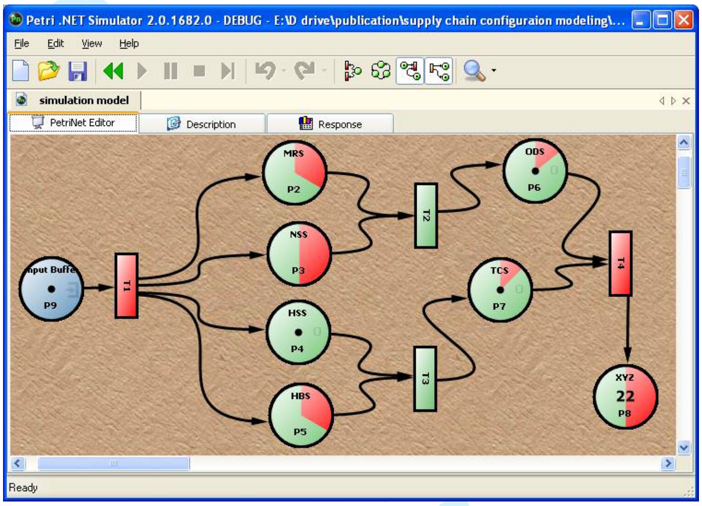


Figure 8. PN simulation model of $S_1^{O_1}$

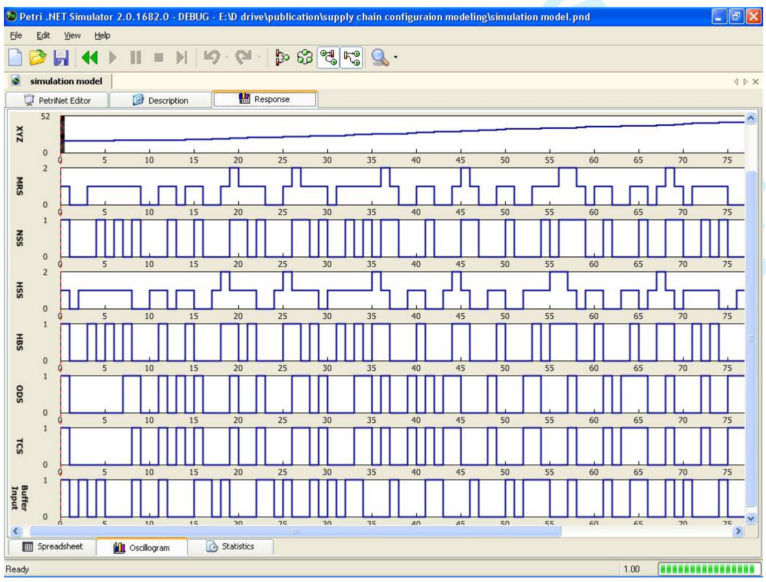


Figure 9. Simulation result of $S_1^{O_1}$

Table 1. Tokens and colors in Figure 2

Tokens and Colors in Figure 2(b)		Tokens and Colors in Figure 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
$(R_1^{fp_1a_1c_1}, CR_1^{fp_1a_1c_1}, QR_1^{fp_1a_1c_1}, LR_1^{fp_1a_1c_1})$	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		

Table 2. Places in relation to supply chain entities in the CPN model in Figure 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	Tample 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)

Table 3. Configuration details in two models in Figures 6 and 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’

Table 4. 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*}	$(B_4^{1*}, QB_4^{1*}, CB_4^{1*}, LB_4^{1*})$