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

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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.

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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

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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

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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

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

2. Related Work

2.1 Supply Chain Configuration

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

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46 Yan and Yu (1998) develop an approach based on mathematical programming to
47 optimizing supply chains with focus on the product structure in the form of bill of materials. In
48 their model, how different processes and logistics affect the systems performance of supply
49 chains cannot be captured. Through empirical research, Salvador et al. (2004) discuss how a
50 company's supply chain should be configured in response to different degrees of product
51 customization. Their work focuses on the impact of changes of the modular product
52 architectures on the corresponding supply chains. Dotoli et al. (2003) design a 3-layered
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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

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3 simulations to evaluate the result. Huang et al. (2005) analyze the impact of platform products,
4 with and without commonality, on decisions pertaining to supply chain configuration and the
5 consequent performance of the configured supply chain. Kim et al. (2002) propose a
6 mathematical model and a solution algorithm to assist the manufacturer in configuring its
7 supply chains for a mix of multiple products that share some common raw materials and/or
8 component parts. In summary, the above work provides certain managerial guidelines at a
9 higher level for supply chain management, and the details at an operational level remains
10 untouched. This study intends to assist companies to make decisions in configuring supply
11 chains from a generic supply chain network at a more detailed level.
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24 **2.3 PNs for Systems Modeling**

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27 As a graphical and mathematical modeling technique, PNs have recently emerged as a
28 promising approach for modeling, simulating and analyzing various systems. However, a
29 PN-based model is highly system dependent and lacks properties such as modularity,
30 reusability and a high degree of maintainability that are commonly required in complex
31 systems to be modeled. Attempting to meet various requirements of systems to be described,
32 many PN variations such as object-oriented PNs (OPNs), colored PNs (CPNs), PNs with
33 changeable structure (PNs-CS) have been developed (Troostmann et al., 1993; Moore and
34 Gupta, 1996; Jiang et al., 1999b).
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46 As a combination of object-oriented (OO) approach and PN techniques, the OPNs excel in
47 modeling such systems that are rather large and complex. This is because models of OPNs are
48 characterized by the encapsulation of physical objects in systems and the increased reusability
49 and maintainability of objects in built models (Wang 1996a; 1996b). Two major elements of
50 an OPN model of a system are objects and message passing relations among interacting
51 objects. The activities and states of an object are also encapsulated in its OPN, thus such OPNs
52 are reusable. As a result, the built model of the entire system is more compact, less complex
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3 and consequently more manageable.
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5 Differing itself from other PNs, a CPN (Jensen, 1992) adds colors to tokens, which are
6 black in low-level or ordinary PNs. These colors are used to encode different data types and
7 values that are attached to tokens. The presence of colors makes CPNs the ideal tools to
8 describe systems that contain many similar (but not identical) interacting components (Jensen,
9 1992). To accommodate the changes of a system to be modeled, PNs-CS are developed to
10 provide such mechanisms that allow changes to be made to the structures of PN models when
11 the system being described changes. In this way, the changes in the actual system are reflected
12 by the structural changes of the built PN models.
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15 The PNs are employed to describe various systems. The OPNs-CS combining OPNs and
16 PNs-CS are adopted to model one-of-a-kind production systems in (Jiang et al., 1999b). In
17 their work, they clearly define the objects and message passing relations among interacting
18 objects in the built model. Furthermore, the authors formulate two different kinds of changes
19 to the OPNs-CS models so as to accommodate the changes in production systems. The two
20 changes include the modification of message passing relations and the adding or removing
21 objects to or from the built models. In a similar work, Jiang et al. (2001) apply CPNs-CS to
22 model one-of-a-kind production systems with focus on the changes and uncertainties of such
23 systems. Aiming at modeling the reliability of production resources, such as machines, robots
24 and buffers, the stochastic OPNs (SOPNs) are proposed in (Jiang et al., 1999a). The difference
25 between SOPNs and OPNs in their work is the addition of stochastic transitions and stochastic
26 places to the OPNs. With understanding of the materials flows, the time constraints, the
27 dynamic behaviors of facilities, and the interaction among facilities in an automated
28 manufacturing system (AMS), Wang and Wu (1998) introduce CTOPN (colored timed
29 object-oriented Petri nets) to model an AMS. The use of colored tokens clearly addresses part
30 routings and the adopted facilities.
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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^* , $\forall f = 1, \dots, F$ 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,

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3 complexity of the built system model by reusing model components, i.e., generic objects, OO
4 concepts are incorporated into the proposed CPN modeling formalism. Different customer
5 orders may require different supply chain entities, which in turn lead to difference in supply
6 chains. Such differences may correspond to the structural changes of bill of materials of
7 ordered products or the changes of product items. To accommodate the configuration changes
8 caused by adding or removing entities in the system model, the change handling mechanism in
9 (Jiang et al., 1999b) is also adopted in the CPN modeling formalism.

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

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32 A CPN model of a supply chain consists of a set of places (P_s) and gates (g_s). Each gate
33 connects with two places. A place is an object and denotes a supply chain entity. Thus, a place
34 may represent a final manufacturer that delivers products to customers, an assembly supplier, a
35 component supplier or a raw material supplier. In manufacturing practice, it is common that an
36 entity produces a variety of items, be they products, assemblies, components, or raw materials.
37 Therefore, in a CPN model a number of colored tokens are assigned to each place. Each token
38 represents a particular item that can be produced by the place, and thus relates to an order
39 placed by a downstream entity. Further, a token records information pertaining to the item
40 such as the quantity of the item, the total cost and lead time. The cost data include a
41 transportation cost, inventory cost and production cost. As both the inventory and production
42 costs are determined by the design and process of the item, in the proposed CPN formalism all
43 changes in product, process and logistics are taken into account. Consequently, modeling
44 configuring supply chains using CPN formalism can assist supply chain entities in making
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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

$$R_I = \left\{ \begin{array}{l} R_{IVMP-ODS}, R_{IVMP-TCS}, R_{IODS-MRS}, R_{IODS-NSS}, R_{ITCS-HSS}, R_{ITCS-HBS}, R_{IMRS-DP}, R_{INSS-DP}, \\ R_{IHS-SDP}, R_{IHBS-DP} \end{array} \right\}$$

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.

$$G_{IVMP-ODS} = (g_1)$$

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

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

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

Thus,

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

(3) The color set: $C_I = \{PS_I, RS\}$ where

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

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

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

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

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

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

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

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

Thus,

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

(5) The initial marking set:

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

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

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

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

$$F_1 = \left((VMP, ODS), (VMP, TCS), (ODS, MRS), (ODS, NSS), (TCS, HSS), (TCS, HBS), \right. \\ \left. (MRS, DP), (NSS, DP), (HSS, DP), (HBS, DP) \right)$$

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 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

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

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

message passing relations are generated.

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

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

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

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

Then,

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

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

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

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.

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

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

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

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

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

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

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

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

$$g_1^{\bullet l} = g_1^{\bullet 0} - g_1^{\bullet 0r} + g_1^{\bullet 0a} = (im^{ODS} \wedge im^{TCS}) - (im^{ODS} \wedge im^{TCS}) + (im^{VDS} \wedge im^{VCS}) \\ = (im^{VDS} \wedge im^{VCS})$$

$$L_1(g_1^{\bullet l}) = (im^{VDS} \wedge im^{VCS})$$

$$\text{Thus, } L_2(g_1) = (L_2(\bullet g_1^l), L_2(g_1^{\bullet l})) = ((om^{VMP}), (im^{VDS} \wedge im^{VCS}))$$

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

$$SM_{0,s} = I'(P_1^{VMP}, e) + I'(P_1^{ODS}, e) + I'(P_1^{TCS}, e) + I'(P_1^{MRS}, e) + I'(P_1^{NSS}, e) + I'(P_1^{HSS}, e) \\ + I'(P_1^{HBS}, e) + I'(P_1^{DP}, e)$$

Thus,

$$MM_{2,0} = MM_{0,s} - MM_{0,s}^r + MM_{0,s}^a \\ = \Phi - \Phi + I'im^{VDS}(DA_3^*, QDA_3^*, CDA_3^*, LDA_3^*) + I'im^{VCS}(CA_2^*, QCA_2^*, CCA_2^*, LCA_2^*) \\ = I'im^{VDS}(DA_3^*, QDA_3^*, CDA_3^*, LDA_3^*) + I'im^{VCS}(CA_2^*, QCA_2^*, CCA_2^*, LCA_2^*)$$

$$SM_{2,0} = SM_{0,s} - SM_{0,s}^r + SM_{0,s}^a \\ = SM_{0,s} - (I'(P_1^{ODS}, e) + I'(P_1^{TCS}, e) + I'(P_1^{MRS}, e) + I'(P_1^{NSS}, e) + I'(P_1^{HSS}, e) + I'(P_1^{HBS}, e)) \\ + (I'(P_1^{VDS}, e) + I'(P_1^{VCS}, e) + I'(P_1^{VRS}, e) + I'(P_1^{WSS}, e) + I'(P_1^{VSS}, e) + I'(P_1^{OBS}, e)) \\ = I'(P_1^{VMP}, e) + I'(P_1^{VDS}, e) + I'(P_1^{VCS}, e) + I'(P_1^{VRS}, e) + I'(P_1^{WSS}, e) + I'(P_1^{VSS}, e) \\ + I'(P_1^{OBS}, e) + I'(P_1^{DP}, e)$$

Thus,

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

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

$$F_2 = \left((VMP, VDS), (VMP, VCS), (VDS, VRS), (VDS, WSS), (VCS, VSS), (VCS, OBS), \right) \\ \left((VRS, DP), (WSS, DP), (VSS, DP), (OBS, DP) \right)$$

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 $(DA_3^*, QDA_3^*, CDA_3^*, LDA_3^*)$ for DA and $(CA_2^*, QCA_2^*, CCA_2^*, LCA_2^*)$ 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

1
2
3 basic idea of supply chain configuration evaluation and adopt a PN simulator to illustrate the
4
5 evaluation process. Due to limited functionality of the PN simulator, we have to evaluate
6
7 supply chains only based on delivery time performance indicated by the number of generated
8
9 tokens
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11
12 The developed PN formalism is advantages with respect to graphical representation, which
13
14 provides companies with a visualization of the impact of different product, process and
15
16 logistics decisions on the overall performance of configured supply chains. Based on this
17
18 intuition and the resulting easy understanding, companies can, thus, make timely decision
19
20 about suppliers to be used by considering product, process and logistics design. Second, the
21
22 existing several PN design/construction tools pave a way towards quick development of
23
24 computational implementation of supply chain configuration based on the proposed model.
25
26 This eventually enables supply chain configuration automation. In spite of the significance of
27
28 the proposed model in this study, there are some disadvantages inherent in the formalism. First,
29
30 the formalism was developed to address supply chain configuration without paying too much
31
32 attention to supply chain evaluation. As a result, it does not lend itself to evaluate the
33
34 configured supply chains. Second, the well-recognized limitation of PN techniques is that PN
35
36 models grow fast in accordance with the increase of system elements to be modeled. In this
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38 regard, if a large number of suppliers are involved, the supply chain configuration model to be
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40 constructed based on the proposed formalism may become too large for companies to
41
42 understand.
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50
51 In view of the limitations described above, the current work can be extended to cope with
52
53 them. To address both supply chain configuration and supply chain evaluation, research efforts
54
55 should be made to develop a comprehensive formalism by integrating the basic principles of
56
57 well-defined PN extensions. Moreover, the formalism should be developed to reduce
58
59 complexities when building system models in spite of the fact that many suppliers at different
60

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., $O_k = \{o_{ki} | \forall i = 1, \dots, I_k\}$ (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., $R_k = \{R_{kij} | i, j = 1, \dots, I_k, i \neq j\}$ (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)

1
2
3
4 E_{kij}^a The set of added expression functions after the k -th change (19)
5
6

7 $E_{kij}(OA_{kij})$ The set of expression functions of OA_{kij} (20)
8
9

10 The set of expression functions of IA_{kij} , together with $E_{kij}(OA_{kij})$, they
11 $E_{kij}(IA_{kij})$ determine the number and the color of tokens flowing through OA_{kij} and IA_{kij} (21)
12 for each firing of G_{kij}
13
14

15 The set of initial markings of system CPN model after the k -th change and
16 $M_{k,0}$ defined as a tuple: $M_{k,0} = (MM_{k,0}, SM_{k,0})$ (22)
17
18

19 $MM_{k,0}$ Initial markings of input/output message places of objects after the k -th change (23)
20
21

22 $MM_{k,0}^r$ Markings of input/output message places of removed objects after the k -th
23 change (24)
24
25

26 $MM_{k,0}^a$ Markings of input/output message places of added objects after the k -th change (25)
27
28

29 $SM_{k,0}$ Initial markings of state places of objects after the k -th change (26)
30
31

32 $SM_{k,0}^r$ Markings of state places of removed objects after the k -th change (27)
33
34

35 $SM_{k,0}^a$ Markings of state places of added objects after the k -th change (28)
36
37

38 C_k The color set of the system CPN model after the k -th change and defined as a
39 tuple: $C_k = (PS_k, RS)$ (29)
40
41

42 PS_k The set of product states after the k -th change (30)
43
44

45 RS Resource state with e representing resource available (31)
46
47

48 g A gate after the k -th change (32)
49
50

51 $\bullet g^k$ The set of output message places connected to g after the k -th change (33)
52
53

54 $g^{\bullet k}$ The set of input message places connected to g after the k -th change (34)
55
56

57 l_i The number of output message places connected to g (35)
58
59

60 l_o The number of input message places connected to g (36)
61
62

63 \vee Relationship operator *OR* (37)
64
65

66 \wedge Relationship operator *AND* (38)
67
68

69 $\wedge / \vee (x_i, x_j)$ Logic operation by operators \vee and \wedge over message places x_1, x_2, \dots, x_n , e.g., (39)
70

$x_1 \vee x_2$ 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

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

$$L_k(g) = \left[\begin{array}{l} \{ \bullet g^k = (om_1, om_2, \dots, om_{l_i}), L_k(\bullet g^k) = \wedge / \vee (om_1, om_2, \dots, om_{l_i}) \}, \\ \{ g^{\bullet k} = (im_1, im_2, \dots, im_{l_o}), L_k(g^{\bullet k}) = \wedge / \vee (im_1, im_2, \dots, im_{l_o}) \} \end{array} \right] \quad (40)$$

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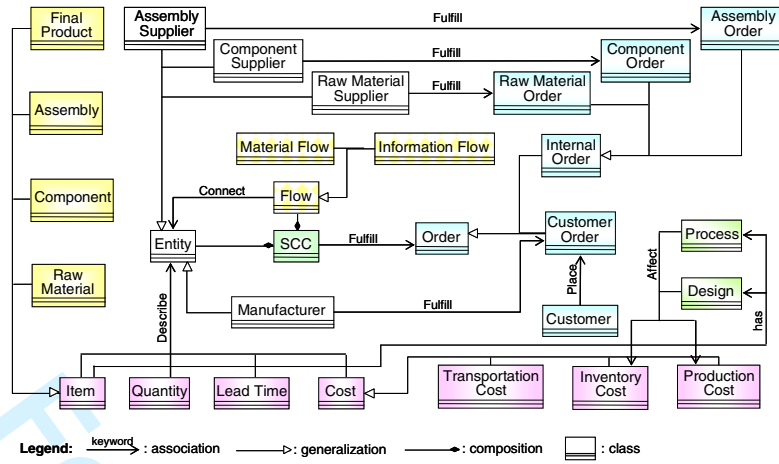


Figure 1. Constituent elements and relationships in a supply chain network

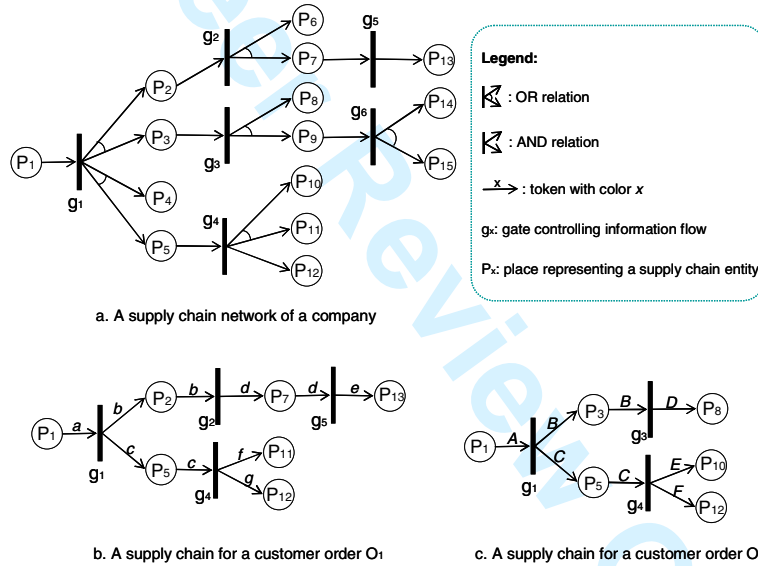
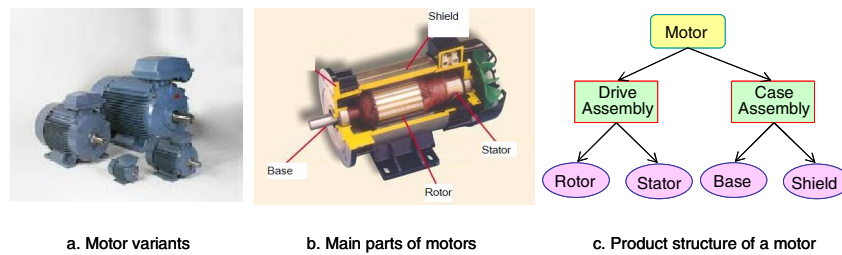


Figure 2. Principles of CPN model of supply chain configuration



a. Motor variants b. Main parts of motors c. Product structure of a motor

Figure 3. Motor variants, main parts and product structure

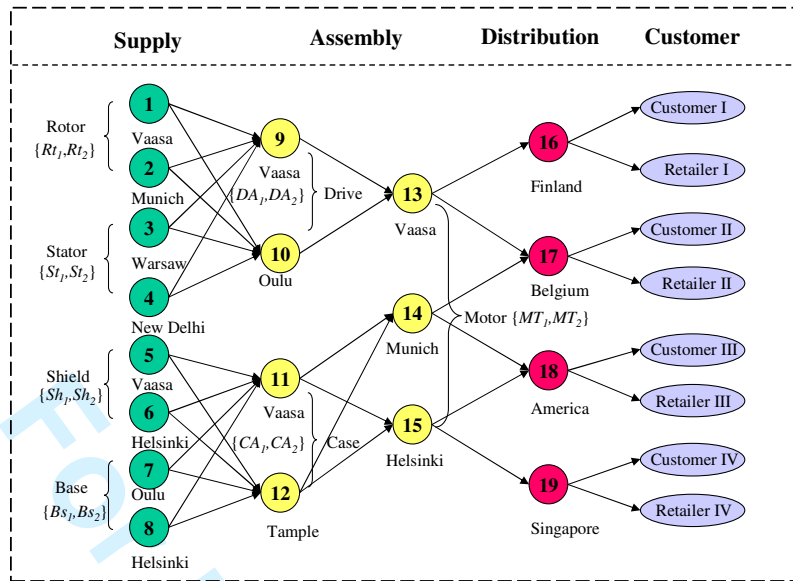


Figure 4. Supply chain network of XYZ

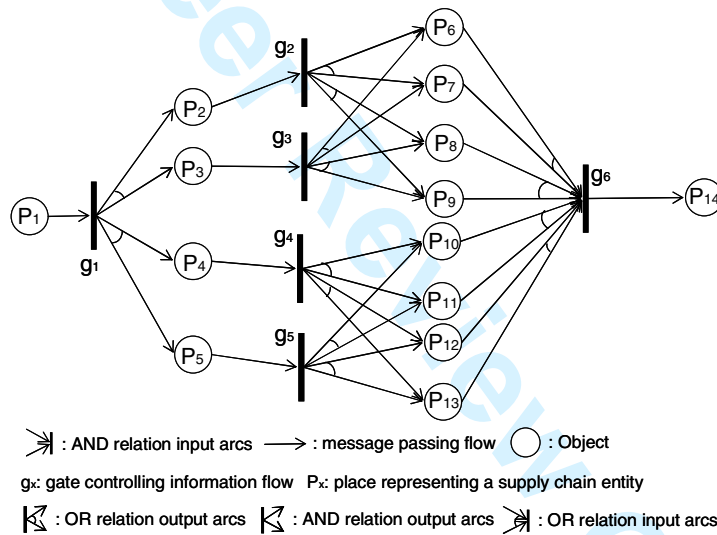


Figure 5. The static CPN model of the supply chain network of Vaasa motor plant

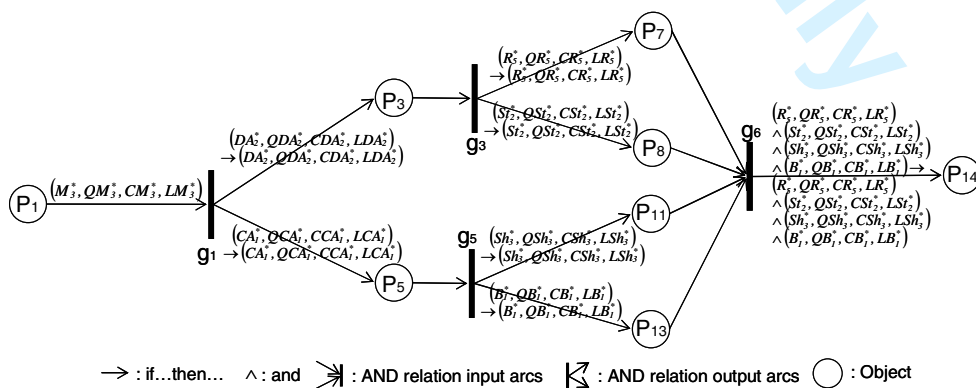


Figure 6. The CPN model of the supply chain configured for O_1

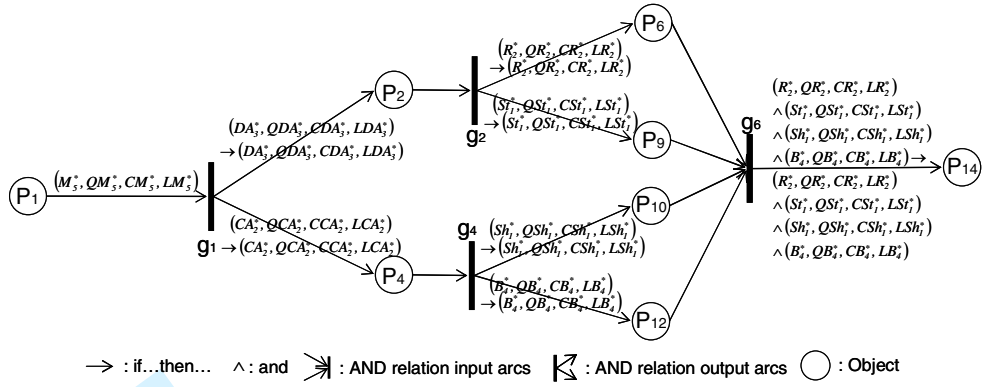


Figure 7. The dynamic CPN model of the supply chain for O_2

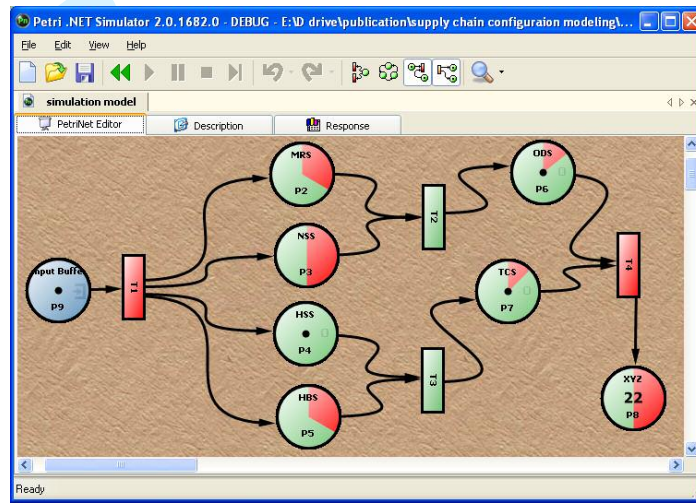


Figure 8. PN simulation model of $S_1^{O_1}$

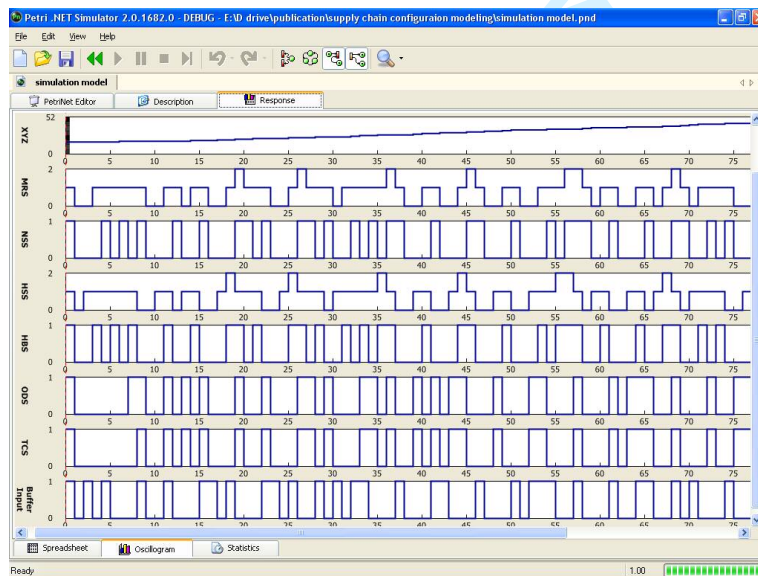


Figure 9. Simulation result of $S_1^{O_1}$

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
$(C_1^{fp_1 a_1}, CC_1^{fp_1 a_1}, QC_1^{fp_1 a_1}, LC_1^{fp_1 a_1})$	d	$(C_1^{fp_2 a_1}, CC_1^{fp_2 a_1}, QC_1^{fp_2 a_1}, LC_1^{fp_2 a_1})$	D
$(R_1^{fp_1 a_1 c_1}, CR_1^{fp_1 a_1 c_1}, QR_1^{fp_1 a_1 c_1}, LR_1^{fp_1 a_1 c_1})$	e	$(C_1^{fp_2 a_2}, CC_1^{fp_2 a_2}, QC_1^{fp_2 a_2}, LC_1^{fp_2 a_2})$	E
$(C_1^{fp_1 a_2}, CC_1^{fp_1 a_2}, QC_1^{fp_1 a_2}, LC_1^{fp_1 a_2})$	f	$(C_2^{fp_2 a_2}, CC_2^{fp_2 a_2}, QC_2^{fp_2 a_2}, LC_2^{fp_2 a_2})$	F
$(C_2^{fp_1 a_2}, CC_2^{fp_1 a_2}, QC_2^{fp_1 a_2}, LC_2^{fp_1 a_2})$	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^*	$(B_1^*, QB_1^*, CB_1^*, LB_1^*)$
O_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^*	$(B_4^*, QB_4^*, CB_4^*, LB_4^*)$
O_2	$S_2^{O_2}$	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*}	$(B_4^{1*}, QB_4^{1*}, CB_4^{1*}, LB_4^{1*})$