Modeling Supply Chain Configuration Based on Colored Petri Nets

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Abstract—This paper introduces an integrated modeling and analysis formalism based on colored Petri nets (CPNs) for supply chain configuration and evaluation. The structural changes of different configurations are explicitly expressed and formalized as CPNs. The formalism can deal with such issues as generic variety representation, constraint compliance and material flow control. The rationale of modeling supply chain configuration is to capture explicitly important information related to the supply chain network in conjunction with product, process and logistics decision making.

Keywords—supply chain configuration, colored Petri nets

I. INTRODUCTION

Each supply chain represents a configuration of business entities as well as the parts and processes that they provide for generating a final product [1]. Among these supply chain elements (e.g., parts, manufacturing processes, products, logistics, customers), there exist complex and heterogeneous relationships representing dependencies between the elements. A collection of elements and the relationships between them comprises a supply chain configuration.

Supply chain configuration is inherently complex due to the dynamic, decentralized and distributed characteristics of a supply chain network of companies. Each node in such a network often includes several alternative options, which are autonomous organizations with unique resources, capabilities, objectives, and competency. Configuring a supply chain not only requires to decide alternative suppliers, delivery modes and inventory levels, but also to specify manufacturing processes such as operations sequence, lead times, setups, and manufacturing resources [2]. Due to the constant flux of changes in current increasingly competitive global environment, there are many uncertain or random events in the supply chain, e.g., customer demand variations, delivery time alternations, production fluctuations. A number of supply chain configurations that can deliver a customer order can be obtained from a generic supply chain network according to the particular customer requirements and specific operations environments.

In today’s global competition, supply chain configuration is further complicated by the fact that multiple products are often involved in a supply chain. Different products share significant similarity regarding components’ characteristics and the associated manufacturing processes with respect to marketability and functionality [3]. Substantial benefits, including less product development time, lower production cost, high quality, reduced supply chain errors, and smoother product introduction, can be obtained from an integrated consideration of the design of the supply chain and the design of the product [4]. Of similar importance is the consideration of the processes used to manufacture the ordered product. The consideration of process design is directly linked to how the product is designed [5]. Therefore, product, process and supply chain configuration decisions should be coordinately considered and closely integrated. The change of end product structures would have impacts on the final supply chain structures. Similarly, the availability of alternative manufacturing processes and supply resources could affect the design decisions regarding product families.

The linchpin of integrated supply chain, product and process design is the modeling of key elements and their relationships within different domains. Petri nets have been recognized as a significant tool for graphical representation and mathematical analysis. It can capture the precedence relations and structural interactions of stochastic, concurrent and asynchronous event in a supply chain. The application of such a modeling technique can shed light on understanding the behavior of a supply chain and the implications of product and process design changes.

II. CPNS MODELING FORMALISM

A CPNs 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 are products, assemblies, components, or raw materials. Therefore, in a CPNs 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 includes 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 CPNs formalism all changes in product, process and logistics are taken into account. Consequently, modeling configuring supply chains using CPNs 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 those 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 1 shows examples of CPNs models of configuring supply chains for different customer orders. The model in Figure 1(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 \( P_8 \), 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 (\( L \)).

Figure 1. Principles of CPNs model of supply chain configuration

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 1(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 assemblies, \( \{ A_1^{FP_1}, CA_1^{FP_1}, QA_1^{FP_1}, LA_1^{FP_1} \} \) with color \( b \) and \( \{ A_2^{FP_1}, CA_2^{FP_1}, QA_2^{FP_1}, LA_2^{FP_1} \} \) 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 \( P_3 \), 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 \( P_3 \)), one has color \( b \) (or \( c \)). Therefore, at this configuration, \( P_2 \) and \( P_3 \) are represented by token \( b \) and token \( c \), respectively. Other upstream component and raw material suppliers are specified in the same manner. Figure 1(c) shows a supply chain for another customer order \( O_2 = \{ FP_2, C_2, Q_2, L_2 \} \) with color \( A \). For illustrative simplicity, only the colors of the tokens are shown in the figure. The detail information of tokens and their colors are given in Table 1.

Table 1: Tokens and colors in Figure 1

<table>
<thead>
<tr>
<th>Tokens</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>( FP_1, C_1, Q_1, L_1 )</td>
<td>( a )</td>
</tr>
<tr>
<td>( A_1^{FP_1}, CA_1^{FP_1}, QA_1^{FP_1}, LA_1^{FP_1} )</td>
<td>( b )</td>
</tr>
<tr>
<td>( A_2^{FP_1}, CA_2^{FP_1}, QA_2^{FP_1}, LA_2^{FP_1} )</td>
<td>( c )</td>
</tr>
<tr>
<td>( FP_2, C_2, Q_2, L_2 )</td>
<td>( A )</td>
</tr>
</tbody>
</table>

III. INDUSTRY EXAMPLE

Headquartered in Finland, XYZ (disguised name) is a multinational company. It provides a high variety of motors with a wide output power ranging from 0.25KW to 205KW. 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. Figure 2 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 an Sh form a Case Assembly (CA); a Rt and an St form a Drive Assembly (DA), as shown in Figure 2(c).

Figure 2. Motor variants, main parts and product structure

Figure 3 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.

IV. APPLICATION TO SUPPLY CHAIN CONFIGURATION

Application of CPNs modeling formalism to supply chain configuration involves the construction of three types of systems models, including (1) a static CPNs model of a manufacturer’s supply chain network; (2) a dynamic CPNs model of a supply chain (for a customer order) before change; and (3) a dynamic CPNs model of a supply chain (for another customer order) after change. For keeping records, k is introduced to indicate the number of times that the system has been changed. Since the change of customer orders causes the change of the system models. Thus, it also reflects the number of customer orders. If k=0, it implies the initial state of the system, i.e., system before change. In this research, we use k=0 to represent the initial system state of a particular supply chain (for a customer order) before change and k=1 to model the system of another supply chain (for a new customer order) after change. In other words, when k=0 the dynamic system model of a supply chain before change is established, and the dynamic model of the second supply chain after change is established when k=1.

4.1 Static CPNs model of the supply chain network of VMP

Attempting to encompass all above aspects that have an impact on the selection of upstream supply chain entities, we use several sets of 4-attribute value pairs, \( A_1V_1 \times A_2V_2 \times A_3V_3 \times A_4V_4 \), to describe each entity. The four attributes are item \( A_1 \), quantity \( A_2 \), cost \( A_3 \), and delivery lead time \( A_4 \). The values of \( A_1 \), \( A_2 \), \( A_3 \) and \( A_4 \) correspond to the items, the respective quantities and lead times that an entity can offer, whilst the values of \( A_1 \) include the transportation, production and inventory costs in relation to the values of \( A_1 \) and \( A_2 \).

Figure 4 shows the static CPNs model of the supply chain network of XYZ’s motor plant in Vaasa (VMP). A dummy place \( P_{14} \) and a dummy gate \( g_6 \) are added into the configuration model to ensure computer execution. Table 2 lists all the supply chain objects represented by places in Figure 4. 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

![Figure 3. Supply chain network of XYZ](image)

![Figure 4. The static CPNs model of the SCN of Vaasa motor plant](image)

set of gates, including \( g_1 \), \( g_2 \), \( g_3 \), \( g_4 \), \( g_5 \), and \( g_6 \), indicate the occurrence of certain events, e.g., order decomposition, and control the information flows \( g_6 \) and \( P_{14} \) do not hold any practical meaning. However, they are necessary to guarantee the running of models in computers.

<table>
<thead>
<tr>
<th>Place</th>
<th>Supply Chain Entities</th>
<th>Place</th>
<th>Supply Chain Entities</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_1 )</td>
<td>Vaasa motor plant (VMP)</td>
<td>( P_1 )</td>
<td>New Delhi stator supplier (NSS)</td>
</tr>
<tr>
<td>( P_2 )</td>
<td>Vaasa DA supplier (VDS)</td>
<td>( P_2 )</td>
<td>Warsaw stator supplier (WSS)</td>
</tr>
<tr>
<td>( P_3 )</td>
<td>Oulu DA supplier (ODS)</td>
<td>( P_3 )</td>
<td>Vaasa shield supplier (VSS)</td>
</tr>
<tr>
<td>( P_4 )</td>
<td>Vaasa CA supplier (VCS)</td>
<td>( P_4 )</td>
<td>Helsinki shield supplier (HSS)</td>
</tr>
<tr>
<td>( P_5 )</td>
<td>Temple CA supplier (TCS)</td>
<td>( P_5 )</td>
<td>Oulu base supplier (OBS)</td>
</tr>
<tr>
<td>( P_6 )</td>
<td>Vaasa rotor supplier (VRS)</td>
<td>( P_6 )</td>
<td>Helsinki base supplier (HBS)</td>
</tr>
<tr>
<td>( P_7 )</td>
<td>Munich rotor supplier (MRS)</td>
<td>( P_7 )</td>
<td>Dummy place (DP)</td>
</tr>
</tbody>
</table>

While the static model in Figure 4 conveys all the suppliers’ information, their relationships and all possible information flows in the supply chain network of VMP, it is the dynamic CPNs models that entail the selection of suppliers and the configuration of a supply chain in response to a customer order, as shown in Figure 5 and Figure 6.

4.2 Dynamic CPNs model of a supply chain before change

To fulfill a customer order, \( O_1 = \{ \alpha_1V_1^1, \alpha_2V_2^1, \alpha_3V_3^1, \alpha_4V_4^1 \} \) = \( \{ M_3^1, Q_5^1, C_3^1, L_3^1 \} \) (\( M_3^1 \) 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 the way that the receiving of the decomposed orders contributes to the timely delivery of the motor order \( O_1 \). Based on the delivery requirements in the decomposed orders, the qualified suppliers 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

![Figure 5. The dynamic CPNs model of the supply chain for \( O_1 \)](image)
qualified suppliers are determined to deliver the four orders for parts. Figure 5 shows the CPNs model of the supply chain configured for fulfilling $O_1$.

The model is formally described as follows.

$$S_0 = (O_1, C_0, R_0, M_{0.0}, L_0)$$

(1) The object set:

$$O_0 = (VMP, ODS, TCS, MRS, NSS, HSS, HBS, DP)$$

(2) The message passing relation set:

$$R_0 = \left\{ R_{VMP, ODS}^*, R_{VMP, TCS}^*, R_{MRS, ODS}^*, R_{MRS, TCS}^*, R_{TCS, HSS}^* \right\}$$

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

$$G_{VMP, ODS} = (g_1) \quad OA_{VMP, ODS} = (\text{im}^{\text{VMP}} - g_1)$$

$$IA_{VMP, ODS} = (g_1 - \text{im}^{\text{ODS}})$$

$$E_{VMP, ODS} = \left\{ E_{VMP, ODS}^* (OA_{VMP, ODS}) \right\} \left\{ E_{VMP, ODS} (IA_{VMP, ODS}) \right\}$$

Thus,

$$R_{s,m}^* = \left\{ OA_{VMP, ODS}, G_{VMP, ODS}, IA_{VMP, ODS}, E_{VMP, ODS}^* \right\}$$

$$= \left\{ \text{im}^{\text{VMP}} - g_1, (g_1, \text{im}^{\text{ODS}}), (g_1 - \text{im}^{\text{ODS}}) \right\}$$

$$= \left\{ \text{im}^{\text{VMP}} - g_1, (g_1, \text{im}^{\text{ODS}}), (g_1 - \text{im}^{\text{ODS}}) \right\}$$

(3) The color set: $C_0 = (PS_0, RS)$

$$PS_0 = \left\{ M_1, Q_1, C_1, L_1 \right\} \left\{ D_1, Q_1, C_1, L_1 \right\}$$

$$= \left\{ M_1, Q_1, C_1, L_1 \right\} \left\{ D_1, Q_1, C_1, L_1 \right\}$$

$$RS = e \cdot e$$

denotes manufacturing resources available.

(4) The gate set: $G_{0} = (g_1, g_1, g_1, g_1)$

$$L_0(g_1) = \left\{ \left\{ L_{g_1}^*(g_1), L_{g_1}^*(g_1) \right\} = \left\{ \text{im}^{\text{MRS}} \land \text{im}^{\text{TCS}} \right\} \right\}$$

Similarly, we can get $L_0(g_2), L_0(g_3)$ and $L_0(g_4)$ as follows.

$$L_0(g_2) = \left\{ \left\{ L_{g_2}^*(g_2), L_{g_2}^*(g_2) \right\} = \left\{ \text{im}^{\text{MRS}} \land \text{im}^{\text{TCS}} \right\} \right\}$$

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

$$F_0 = \left\{ (VMP, ODS), (VMP, TCS), (ODS, MRS), \right\}$$

As shown in the figure, the involved objects include VMP ($P_1$), ODS ($P_1$), TCS ($P_1$), MRS ($P_1$), NSS ($P_1$), HSS ($P_1$), HBS ($P_1$), and DP ($P_1$). 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 $P_2$ and $P_3$ (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 relation function of $g_1$ specifies the token flow, which goes to the qualified suppliers. Similarly, the other three gates ($g_2, g_3$, and $g_4$) are fired and the qualified suppliers are selected.

4.3 Dynamic CPNs model of another supply chain after change

Another customer order $O_2 = \left\{ A_1V_1^*, A_2V_2^*, A_3V_3^*, A_4V_4^* \right\}$ is placed for motor $M_5$. Current supply chain for $O_1$ cannot fulfill $O_2$ due to the different quantity, cost and delivery date, as well as the difference in design specifications of two motors. Another supply chain is configured, as shown in Figure 6. To fulfill $O_2$, assembly suppliers represented by $P_2$ and $P_4$ rather than $P_3$ and $P_5$ are selected; 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 details how these changes are handled by describing the system model after change.
Let $S_1$ denote the CPNs model of the system after change, then $S_1 = (O_1, R_1, L_1, C_1, M_{1,0})$

(1) The new object set:
\[
O_1 = O_0 - O_0' \cup O_0''
\]
\[
= (VMP, ODS, TCS, MRS, NSS, HSS, HBS, DP) \cup (ODS, TCS, MRS, NSS, HSS, HBS)
\]
\[
= (VMP, VDS, VCS, VRS, WSS, VSS, OBS, DP)
\]

(2) The new message passing relation set:
\[
R_1 = R_0 - R_0' \cup R_0''
\]
\[
= \left( R_{VMP}^{VMP} \cup R_{VMP}^{VCS}, R_{ODS}^{MRS} \cup R_{ODS}^{NSS}, R_{TCS}^{HSS} \cup R_{TCS}^{HBS} \cup R_{HBS}^{DP} \right)
\]
\[
\cup \left( R_{VMP}^{VDS} \cup R_{VMP}^{VCS}, R_{ODS}^{MRS} \cup R_{ODS}^{NSS}, R_{TCS}^{HSS} \cup R_{TCS}^{HBS} \cup R_{HBS}^{DP} \right)
\]
\[
= \left( R_{VMP}^{VMP} \cup R_{VMP}^{VCS}, R_{VDS}^{VCS}, R_{VCS}^{VCS}, R_{VCS}^{VCS}, R_{VCS}^{VCS}, R_{VCS}^{VCS}, R_{VCS}^{VCS} \right)
\]

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

\[
O_{VMP} = (\text{om}^{VMP} \cup g_1) \text{ VMP} = (g_1) \text{ IA}_{VMP} = [g_1 - \text{im}^{VDS}]
\]
\[
E_{VMP} = [E_{VMP}^{VMP} (O_{VMP}), E_{VMP}^{VMP} (I_{VMP})]
\]
\[
= \left\{ \left[ \left( M', Q', C', L' \right), \text{im}^{VDS} \right] \right\}
\]
\[
= \left\{ \left[ \left( M', Q', C', L' \right), \text{im}^{VDS} \right] \right\}
\]

Then,
\[
R_{VMP} = \left( O_{VMP} \cup g_1 \right) \text{ IA}_{VMP} = [g_1 - \text{im}^{VDS}]
\]
\[
= \left\{ \left[ \left( M', Q', C', L' \right), \text{im}^{VDS} \right] \right\}
\]

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

(3) The new color set: $C_1 = C_0 - C_0' \cup C_0'' = (PS_1, RS)

PS_1 = \left\{ M', Q', C', L' \right\}
\]
\[
= \left\{ M', Q', C', L' \right\}
\]

(4) The new gate set: $G_1 = (g_1, g_2, g_3, g_4, g_5)$

\[
L_1 (g_1) = \left\{ \left[ L_1 \left( g_1 \right), L_2 \left( g_1 \right) \right], \left[ L_1 \left( g_2 \right), L_1 \left( g_2 \right) \right], \left[ L_1 \left( g_4 \right), L_1 \left( g_4 \right) \right], \left[ L_1 \left( g_5 \right), L_1 \left( g_5 \right) \right] \right\}
\]

The changes to objects, i.e., the change from $P_1$, $P_2$, $P_3$, $P_4$, $P_5$, $P_6$, $P_7$, $P_8$, $P_9$, $P_{10}$, and $P_{11}$ to $P_2$, $P_4$, $P_5$, $P_6$, $P_7$, $P_8$, $P_9$, $P_{10}$, and $P_{12}$, result in (1) the changes to the input message places connecting to $g_1$; and (2) the changes to output message places connecting to $g_5$.

For illustrative simplicity, $g_5$ is used to show how to modify the gate logic relationship functions.

\[
\omega = \left( \text{om}^{VMP} \right) \cdot \omega = \Phi \cdot \omega \]
\[
\omega = \left( \text{om}^{VMP} \right) \cdot \omega = \Phi \cdot \omega \]
\[
\omega = \left( \text{om}^{VMP} \right) \cdot \omega = \Phi \cdot \omega \]
\[
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\[
\omega = \left( \text{om}^{VMP} \right) \cdot \omega = \Phi \cdot \omega \]

Thus,
\[
L_1 (g_5) = \left\{ \left[ L_1 \left( g_1 \right), L_1 \left( g_1 \right) \right], \left[ L_1 \left( g_4 \right), L_1 \left( g_4 \right) \right], \left[ L_1 \left( g_5 \right), L_1 \left( g_5 \right) \right] \right\}
\]

Similarly, $L_1 (g_2)$, $L_1 (g_4)$ and $L_1 (g_6)$ 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 recorded the information of order $O_2$ has been placed in $P_1$. This state is indicated by the following markings.

\[
M_{o,s} = \left( M_{o,s} \cup M_{o,s} \right) \text{ where } M_{o,s} = \Phi
\]

\[
M_{o,s} = \left( M_{o,s} \cup M_{o,s} \right) \text{ where } M_{o,s} = \Phi
\]

Finally,
\[
M_{1,0} = \left( M_{1,0} \cup M_{1,0} \right) \text{ where } M_{1,0} = \Phi
\]

As shown in Figure 6, the information flow is also changed as follows due to the selection of different suppliers.

\[
F_1 = \left[ \left( VMP, VDS \right), \left( VMP, VCS \right), \left( VDS, VRS \right), \left( VDS, WSS \right), \left( VCS, VSS \right) \right]
\]

In Figure 6, a new colored token is assigned to the second order $O_2$ and appears in $P_1$. Based on the logic function of $g_1$, two
new tokens corresponding to the two decomposed assembly orders are generated. They record such information as \( \{D_4, Q_4, C_4, D_4, L_4\} \) for DA and \( \{C_4, Q_4, C_4, D_4, L_4\} \) 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 the two assembly orders, four orders for parts are generated, including \( \{R_2^*, Q_2^*, C_2^*, L_2^*\} \) for Rt, \( \{St_1^*, Qt_1^*, C_1^*, Lt_1^*\} \) 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, \( s_6 \) is fired. A new token, \( \{(R_2^*, Q_2^*, C_2^*, L_2^*) \wedge (St_1^*, Qt_1^*, C_1^*, Lt_1^*) \wedge (Sh_1^*, QSh_1^*, CSh_1^*, LSh_1^*) \wedge (B_4^*, QB_4^*, CB_4^*, LB_4^*)\} \), is generated.

V. EVALUATION OF SUPPLY CHAIN CONFIGURATION

To evaluate the configured supply chains, two configurations for \( O_1 \) and two for \( O_2 \) are adopted. Figure 7 shows the PN simulation model of \( S_1^{O_1} \) (a supply chain for \( O_1 \)). 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 (P2), NSS (P3), HSS (P4), and HBS (P5).

Two assemblies, \( DA_4^* \) and \( CA_4^* \), are formed at place \( P_6 \) representing ODS and place \( P_7 \) representing TCS, respectively. The final product \( M_1^* \) will be generated in place \( P_8 \) representing company XYZ. The number 22 in place XYZ indicates the number of \( M_1^* \) that have been generated at the time of simulation.

Figure 7. PN simulation model of \( S_1^{O_1} \)

Figure 8 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. The stochastic arrival of tokens in \( P_9 \) (reflecting the random arrival of customer order) affects the generation of tokens in \( P_8 \) in a linear trend. The delivery time set for each supplier, as shown in the figure, also influences the generation of tokens in \( P_8 \).

To compare the simulation result, the simulation time is set at 1,000,000 time units for the first run. In total, 100 simulation runs are conducted for the four supply chains under different system parameter settings. The final result shows the optimal supply chains for \( O_1 \) and \( O_2 \) are \( S_1^{O_1} \) and \( S_2^{O_2} \), respectively.

VI. CONCLUSIONS

This paper introduces a formalism based on CPNs to model supply chain configuration with consideration of product, process and logistics design. The formalism is able to shed light on the implications of product, process and logistics decision making, which assists companies in predicting the performance of the configured supply chains. This is accomplished by incorporating OO technique and a mechanism to handle structural changes into CPNs. While the colored tokens and the object PN’s collaboratively address the large number of suppliers and the various product items that they can produce, the change handling mechanism deals with the different structures of the configured supply chains. The proposed PN-based modeling formalism in this paper performs better than the traditional modeling, which is based on mathematical programming technique. The main reason lies in (1) the difficulty in developing such mathematical models to reflect the complex supply chains in the real practice; and (2) the heavy computational burden to solve such complex models.

REFERENCES