FRAMEWORK FOR A SYNCHRONIZED SUPPLY CHAIN

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Abstract

This research presents a framework for a multi-echelon, multi-stage synchronized supply chain (SSC), reactive to supplier changes with the objective of maintaining due date. Modeling of the SC environment is accomplished using a hierarchical and modular Generalized Stochastic Petri net (GSPN). The hierarchy includes a Supply Chain Manager (SCM) controlling the supplier selection activities of the lower SC members. This enforcement is achieved by the SCM through the use of supervisory control nets. However, since the supplier subset changes, traditional supervisory methodology for Petri nets was extended to a dynamic situation. This new dynamic control net technique was further decentralized by a new technique utilizing Petri net transition guards imposing a hierarchical set of supplier constraints on each SC member. The SSC was tested and resulted in a dynamically controlled, reactive system can result in lower overall costs, improved on-time shipment performance and lower total inventory than an uncontrolled SC.

Keywords: supply chain, supervisory control, Petri nets

1. Introduction

In its simplest representation, a supply chain is composed of a forward flow of material and a backward flow of information [18]. A disruption in one of the links of a SC can have a devastating impact on the others [2]. Companies must be able to quickly react to disturbances from outside sources. Supply chain modelling has become necessary as companies face more complex and global interactions.

Many models have been handled in the literature involving supply chain risk; however, these models involve various levels of prior investment. A reactive supply chain, however, has the potential to avoid these upfront costs and recover from these errors, thus creating a flexible supply chain. In order to accomplish this, traditional flexibility concepts need to be elevated from an intra-firm focus to a combination of strategic and operational internal focus with external, inter-firm integration [14]. This research develops a methodology for a flexible SC which avoids the costs associated with robust planning under uncertainty and allows firms to react swiftly and effectively. However, this does not come without any form of reactive control, thus creating a hierarchical supply chain model.

2. Backgrounds

Theoretical models exist to enable firms to plan for unforeseen errors [10] [5] [21] [22]. Gaonkar and Viswanadham [10] developed two models which determine optimal partnering selection; the first minimizes operational cost and its variability and the second minimizes risk of backorders in the event of a supply disruption. Sheffi [21] lists three areas which companies should focus on to maintain some insurance against shortfall: supplier relationships, inventory management and knowledge and process backup. The author discussed some internal policies which may be implemented to reduce the impact such as risk pooling and better product visibility. Simchi-Levi et. al. [22], provide four approaches from a strategic level to enhance the reliability of the SC in the face of uncertainty: hedging policies, flexibility, collaboration/outsourcing and a base of what-if scenarios to maintain a plan of action for a range of demand scenarios. The primary issue in this research is to provide a control scheme to handle SC disruptions in a multi-echelon, multi-stage SC.

Maintaining the order due date is the criterion by which control is maintained and due to unreliability in leadtimes, the decision-making becomes stochastic. Furthermore, there are multiple criteria which go into the stochastic decision- making process of a recovery scheme; parameters such as leadtime, raw material and finished goods inventory, profit and customer relationships create a multitude of recovery options. When combining the real-time system with the manufacturing management and supply chain coordination, a method of error-recovery is needed to be able to make the system robust to errors imposed upon it [16]. Once the recovery plan is found, it is up to the individual areas to implement the control, however, the decentralization of supervisory control has virtually gone untouched [11].

The focus of this research is to create a synchronized supply chain (SSC) utilizing collaboration in a multi-stage, multi-echelon supply chain. This is accomplished using a combination of modelling methods, optimization and supervisory control techniques at the enterprise level, and further decentralizing it dynamically to the SC members. This type of reactive control leads to a SC which can exhibit lower overall costs, improved on-time shipment performance and lower total inventory than an uncontrolled SC.

Techniques previously developed for a hierarchical paradigm pertaining to flexible manufacturing systems (FMS) [15] [17] [13] are not necessarily applicable here. First, since each SC member has a competing interest in obtaining the overall goals of the SC, global management is necessary [9], creating the supply chain manager (SCM) or enterprise level. Additionally, differences arise in areas such as the processes and performance measures [1] and, in addition, the cost impact is also seen on a much larger scale at the enterprise level [9]. In order to be most effective, cooperation is required between different areas of the organization [3].

3. Supply Chain Modelling

The supply chain model can be seen in Figure 1. In this environment are two distinct hierarchical levels: Supply Chain Manager (enterprise) level and SC Member (facility) level. There are also N echelons, with each echelon containing $k(i)$, $(i=1,...,N)$ SC members. Each of the SC members is modelled by a modular Generalized Stochastic Petri Net (GSPN). In order to control the actions of the SC members so that they act in the interest of the SC, they must be controlled both locally (at the facility level) and globally (at the upper SCM level). In this research, the SCM exerts control regarding supplier selection (enterprise level control). This supplier selection is up to each SC member to enforce at the local level (facility level control) and illustrated in Figure 1 with dashed arrows.

The constraints, both enterprise and facility, are exerted using control nets as supervisors. The supervisory control technique developed by Moody and Antsaklis [20] uses invariant analysis to formulate the control net supervisors and is used to develop the facility level constraints. However, since the supplier subset, exerted by the SCM is dynamic, the constraints must be dynamic as well. Existing techniques require that the control net be manually adjusted each time a constraint is added or modified and are therefore not suitable. In this research dynamic enterprise level constraints are developed by extending the static supervisory control technique of Moody and Antsaklis [20].

3.1 Petri Net Modelling

The advantage of using the PN methodology over a simulation package that handles synchronous events is the following:

All potential supplier subsets for each SC member can be modelled in one PN. The choice of the appropriate subset can then be automated using the dynamic control procedure as described in 4.1. Control of a simulation software package cannot be changed dynamically.

For example, when a SC member changes their upstream supplier subset, a simulation model would need manual adjustment to account for the change. By incorporating dynamic supervisory control, the PN can make the change of supplier subset automatically.

In this research, a generic PN module is developed for each echelon. They are decomposed to a level which yields the places that output the required performance measures, requiring many levels of decomposition. A primary goal of the SSC considered is to minimize lateness to the end customer. At any point in time, then, the timeliness of each SC member is desired. For example, it would be helpful to know how late, if at all, a particular entity is so that its downstream partner which receives the shipment of material can plan accordingly.

Thus, the PN must be timed and since all transitions do not happen immediately, it must be modelled as a Generalized Stochastic Petri Net (GSPN). The details of the PN model can be seen in [6].

3.2 Constraint Generation

The constraints discussed in Section 3 must be imposed on the GSPN model of the SC. These constraints assist in creating a control net which will limit the reachable markings (or states) of the system, μ_s. In this research, the undesirable markings consist of ordering from an upstream supplier which is not optimal. The undesired states are prohibited by a controller which enforces the constraints and drives the system so that those states are not reached. In this research, a chance constrained program (CCP) was utilized to determine state-dependent supplier choices [6]. Each supplier state (light, normal, congested) and lead-time distribution parameters are inputted into the CCP. The objective is to minimize the overall SC cost while meeting customer requirements within a specified customer service level. The output of this program is a plan which details the order quantities for each supplier within the SC. This plan or decision is enforced on the world model via supervisory control from the SCM and is the focus of this research.

4. Supervisory Control

4.1 Control Nets Via Place Invariants

The control net is used to control the actions of the suppliers in the SC, modelled as Petri nets and is based on place invariants. There are two levels of control nets: enterprise and facility, corresponding with Figure 1. The control nets at the enterprise level dictate an overall control strategy for each SC member. Each SC member then must implement this control yielding another set of control nets at the facility level. Both the enterprise and facility level control nets are found using the place invariant technique of Moody and Antsaklis [20].

The major objective of this research is the control of the PN representing the environment. There are two levels of control: enterprise and facility level. The enterprise level (SCM) will dictate an overall policy (supplier set and order quantity), and the facility level will implement the policy. However, since this is a hierarchical system, the upper level SCM constraints must be decentralized to the lower facility level. There are two issues: first is the development of control nets for the enterprise and facility levels. Second is the link between the two levels; in order for the SC member to know what control to impart on its own organization, the control from the SCM must be decentralized to each SC member.

Control nets for Petri nets were developed by Moody and Antsaklis [20]. Decentralization of control, however, has rarely been considered in literature [11]. Although decentralization of control for discrete event systems has been proposed by Lin and Wonham [12] and Chen and Hu [4] for manufacturing applications, the constraints considered in their work were static. The control method is based on the structural invariants of the PN and determines supervisors which prohibit certain states of the system from occurring. Lin and Wonham [12] developed a method of solving this problem using linear integer programming; however, Moody and Antsaklis [20] later introduced a simpler method of solving this problem by performing matrix algebra manipulations [19]. To date, the only known research on decentralization of centralized control has been performed by Iordache and Antsaklis [11]. This was accomplished by a segmentation of the transitions of the PN.

In this research the constraints specifying the supplier set and order quantity are state dependent and therefore dynamic. The research issue discussed here is a means to extend the ideas of decentralized control to a dynamic constraint situation.

4.2 Decentralization of Control in the Enterprise Level

In the GSPN considered in this research a global constraint may need to be enforced through transitions which are not observable or controllable to that constraint. The methods of Iordache and Antsaklis [11] would work if the constraints enforced by the SCM were static. However, the SCM enforces the global constraint of supplier choice (and ordering quantity) on each SC member, which may be dynamic. Using the static method, the constraints would have to be changed for each change in the supplier set, which is undesirable as PN modification at each time period would be cumbersome. Existing methods need modified so that supervisors for all potential supplier sets are in place (but not utilized) at the facility level and only those which are needed at a particular instance are employed. The outputs of the CCP consist of a set of suppliers from which to order and the ordering quantities.

These two pieces of information are denoted the ordering policy and is dictated by the SCM. Once a SC member knows the ordering policy, it must be implemented by that SC member at the facility level. Shown in Figure 2, the following sets are defined:

R=set of constraints dictated by the SCM to the SC members
Q=set of constraints, relative to set ***R***, which are internal to each SC member, that serve to enforce set ***R*** constraints

Note that the SCM cannot enforce directly, set ***Q*** because the transitions within each SC member are not observable to the SCM. Therefore, they must be enforced locally like the method shown in Section 4.1. Those transitions at the facility level are uncontrollable to the SCM, yet controllable locally at the facility level.

Essentially, the SCM can dictate **what** the members must do but not **how** they should do it.

The enforcement of each potential supplier set comes from the enterprise level SCM. Supervisors are in place at the facility level and then employed through a higher enterprise level order, creating a hierarchical level of control. In order to accomplish this, the following are defined:

T_i: a set of controllable transitions which control policy i
Sf_i: a facility level supervisor that controls the set of facility level transitions T_i
Se_i: an enterprise level supervisor that controls facility level supervisor, Sf_i
The method of determining the supervisors is as follows:

Dynamic Supervisor Procedure for Enterprise Control of a Synchronized Supply Chain

1. Determine the incidence matrix of each facility level supervisor, SF_i
2. Create supervisor SE_i and connect it to SF_i using place fusion techniques
3. Employ supervisor SF_i by firing its initial marking from its respective enterprise level supervisor.

This new procedure enables the facility level control nets to remain in place and not change. The appropriate facility level control net is engaged through the use of the enterprise level supervisor thus decentralizing the control.

4.3 Facility Level Control Policy Development

The SC used in this research is seen in Figure 3. Each SC member has a choice of three supplier sets. In general, for supplier $(i - 1)$, the supplier sets are $\{i_1, i_2\}$, $\{i_1\}$ and $\{i_2\}$.

The current value of raw material inventory is known, as well as the reorder point for each supplier. A new demand triggers the PN, and, assuming no disruptions have occurred, the order quantity will simply be the demand. However, the SCM can also designate a different order quantity. Thus, for each SC member, there are 4 potential policies:

Policy 1-standard policy: use only supplier i_2 with order quantity determined by supplier i_2
Policy 2: use only supplier i_1, with order quantity OQ_{i1}
Policy 3: use only supplier i_2, with order quantity OQ_{i2}
Policy 4: use both suppliers, with order quantities OQ_{i1} and OQ_{i2}

In this research, it is assumed that supplier $(i - 1)$ uses a policy of ordering 100% of its raw material from the least expensive supplier i_2. This will be called the standard policy. The remaining three policies have order quantities which are the result of the CCP optimization and dictated by the SCM. Due to the modularity of the GSPN model, the facility level supervisors Sf_i, will be identical for each SC member. Define the following:

SF_1: facility level supervisor enforcing policy 1
SF_2: facility level supervisor enforcing policy 2
SF_3: facility level supervisor enforcing policy 3
SF_4: facility level supervisor enforcing policy 4

Control policy 1 was rendered the standard policy and is typically employed by each SC member. However, this research utilizes an architecture which includes a SCM that may dictate a different policy other than the one chosen by the SC member. This is done for 2 reasons:

1. a different policy may be in the better interest of the SC as a whole
2. a disruption may have occurred which either reduces the capacity or eliminates a SC member from the supplier set

When either of these occurs, the SCM makes a decision as to what ordering policy to use based on the results of the CCP optimization and exerts this control from the enterprise level as a global constraint which is then to be enforced at the facility level. The SCM must decentralize the control policy to each appropriate facility level supervisor from the enterprise level.

5. Testing

In this section, the complete synchronized supply chain (SSC) model is built and tested. This SSC utilizes the techniques developed in Section 3 and 4, combining the Petri net environment with the supervisory control and subsequent decentralized control net technique. This supervisory control procedure is governed by the outputs of the chance constraint programming [6]. The SC used for testing consists of 3 echelons with 2 suppliers in echelon 3 and echelon 2 and one end retailer as seen in Figure 3. The reason for a 3 echelon SC is the following. If a 2-echelon SC were used, there would be only one ordering decision to make (the quantity to order from suppliers in echelon 2) and it would be based only on the states of the suppliers in that echelon. However, a 3-echelon SC has 2 ordering decisions based upon the states of 4 suppliers (2 in echelon 2 and 2 in echelon 3). Therefore a dependency issue is introduced here: the ordering decisions at echelon 2 are based also on the states of the suppliers in echelon 3. It should be noted that while more echelons would increase the size of the problem and change the results, a 3-echelon chain is considered sufficient since it demonstrates dependency between suppliers. Furthermore, 2 stages were considered in the 2 supply echelons (echelons 2 and 3) for the purposes of comparing a more reliable to a less reliable supplier.

5.1 Enterprise Level Supervisory Control Net

Here, the actual Petri net and control net are modeled. The SCM PN is shown in Figure 4 and a listing of the places and transitions is given in Tables 1 and 2. The SCM of Figure 4 is a colored PN (CPN) and represents the control for supplier $_{11}$. Supplier$_{11}$, from Figure 3 contains two upstream suppliers 21 and 22. In this colored PN, a new color, N, is defined which contains four elements: one, two, three and four. These four elements represent the control policies 1, 2, 3 and 4. When the output of the chance constrained program is received, the SCM knows the control policy for supplier 11 and a token with the correct corresponding name (one, two, three or four) is placed in place P1 and is assigned to variable x. The order quantities for each of the two upstream suppliers, also obtained from the CCP, are placed in place 10. The values are carried by the 2 variables in the arcs (oq21, oq22).

5.1.1 Control Procedure

When a token resides in place SCM of Figure 4, typically transitions T1, T2, T3 and T4 would all be enabled, creating conflict in the colored PN. In order to determine the correct firing (i.e., the correct control policy is implemented), transition guards (restrictions on the input of the transition) are employed. In this case a restriction on the element from color N is used. Thus, for example, if the token value is not two, control policy two will not fire. The procedure is summarized formally for the enterprise level SCM CPN as follows:

Generic SCM Control Policy Firing Procedure

Step 1: Assign the initial marking of place P1 as policy i from the policy output of the CCP and assign that value to variable x. For Figure 4, $i \in 1,2,3,4$
Step 2: Place a guard on transition Tj stipulating the variable $x = i \forall j \in i$
Step 3: Place constraint on output arc of Tj ensuring that if variable x = i then a token is placed in output place p(i+1), otherwise control policy i is not used.

This procedure ensures that only one of transitions T5, T6, T7 and T8 are enabled at a time and the correct ordering policy is employed by the SCM. These transitions receive the control policy and also the ordering quantities from place P10. The appropriate transition fires and places the ordering quantities in the proper control place P6, P7, P8 or P9. For Figure 4, these places are then the enterprise level supervisors such that: Se1 = P6; Se2 =P7; Se3 = P8; Se4 = P9. The enterprise level must communicate the correct control policy to the facility level. This is accomplished with place fusion. The enterprise level constraints are fused to the lower level control places which are the supervisors SF1, SF2, SF3 and SF4, so that the appropriate control policy is employed.

6 A Synchronized Supply Chain: Testing and Results

6.1 Controlled Model: The SSC

6.1.1 An Algorithm for the SSC

Figure 4 shows an overview of the SSC, or controlled system model. The SSC, using the PN environment, CCP outputs, and dynamic control nets was simulated to determine effectiveness. In particular, the procedure to simulate the SSC and test its effectiveness is as follows:

SSC Simulation Procedure

For an N-echelon SSC with k(n) stages in echelon $n \in N$:

1. Accept customer demand into each supplier ij, $i \in N, j \in k(i)$.:
2. Determine offline the states, m and leadtime distributions, of all upstream suppliers
3. Set customer service level, α.
4. Offline, optimize order quantities for each supplier ij from upstream suppliers using the CCP.
5. Determine which policy $p \in 1, \dots 4$ and subsequent facility level supervisor SF_{pij} needs enforced for SC member ij.
6. Enforce policy p for SC member ij with enterprise level supervisor SE_{pij} .
7. Place order(s) from stage ij with their upstream supplier(s).
8. If i = N - 1 end, else i = i + 1 and go to step 1.

6.1.2 Scenario Generation

The actual SC used for testing is a 3-echelon SC with 2 suppliers in echelons 2 and 3 and one supplier in echelon 1 as seen in Figure 3. The following assumptions are also made:

A1: The supply leadtimes of upstream suppliers are independent, identically distributed random variables.
A2: The distribution describing the leadtimes will be dependent upon the state of the supplier. Three states are considered: light, normal and congested.
A3: Demand is normally distributed.
A4: For comparison purposes, one supplier will be more reliable than the other. This reliability is given within the parameters of the leadtime distribution. In each echelon, the more reliable supplier charges a higher price for their product. Three ratios of cost are investigated (2:1, 3:1 and 4:1).
A5: When the leadtime is considered to be normally distributed, with a specified mean (μ) and variance (s2), the reliability is given in terms of the standard deviation (i.e. more reliable supplier has a lower standard deviation).
A6: When leadtimes are beta distributed, with a specified alpha (a) and beta (b) value, the reliability is given in terms of the alpha-parameter value.

The 3 echelon SC was simulated and the CCP solved at echelons 1 and 2 to determine the optimal quantities to be ordered from suppliers 21, 22, 31 and 33. The CCP was solved assuming first a normal and then a beta distribution of leadtime.

6.2 Uncontrolled Model Procedure and Assumptions

In order to illustrate the benefit of control, an uncontrolled model (UCM) was used as a baseline. In the UCM, the Petri net model is the same, however, no chance constraint programming was used and no control was added. This model, which is discussed below, makes use of the same 50 incoming demands as the SSC model in order to make the UCM results comparable to the SSC results. The UCM differs from the SSC in the following ways:

1. Each supplier only orders from the least expensive upstream supplier.
2. Leadtimes are stochastic but not state-dependent
3. Order quantity is determined using the modified base-stock policy for stochastic lead-times, without any CCP optimization.

Each of these is discussed next.

6.2.1 Upstream Suppliers in the UCM

In this UCM, the following assumption is made:

Assumption

Each supplier will only order from the least expensive upstream supplier.

This assumption creates a 3-echelon serial supply chain for this research. In this research the less reliable and less expensive suppliers are 22 and 32.

6.2.2 Leadtimes in the UC

The leadtime distributions of the suppliers in the UCM are also normal- or beta-distributed, however, since there is no CCP optimization, there are no state-dependent distributions and only one distribution of leadtime is used.

Normal Distribution Parameters for the UCM

The normal distribution parameters for the uncontrolled situation were determined by generating 300 normal random variables for each of the 24 variance ratios (VR). The mean and variance of the 300 random numbers was determined and used as the uncontrolled distribution mean and variance. This was done for each VR.

Beta Distribution Parameters for the UCM

Similarly, for the beta distribution, 300 beta random variables were generated for each of the 7 alpha ratios (AR). In order to determine the parameters at each AR, the betafit function in Matlab (Version 7.01) was used with a 99% confidence interval. From this, the revised PERT equations were used to find the mean and variance parameters of the uncontrolled distribution. Since the same 50 demands were used for each scenario and the uncontrolled simulation uses only one leadtime distribution, the 50 instances of leadtime were found once for each of the 31 scenarios (24 normal and 7 beta) and used for all three cost ratios.

Ordering Policy

Since no CCP optimization takes place in the UCM, 100% of the order quantity is placed with the least expensive upstream supplier. These parameters are used to characterize the UCM. The results and comparisons between the uncontrolled and controlled model are discussed next.

7. Numerical Results and Managerial Insights

The total order quantity for each echelon was set to 100. Note that in the results, the order quantities discussed are the quantities to be ordered from that particular supplier (not the quantities that a particular supplier orders).

7.1 Normal Distribution

Two representative graphs are shown in Figures 5 and 6. In general, the amount of material ordered from the reliable supplier in echelon 3, (31), is a constant at approximately 48%, except when the less reliable supplier is congested. However, the behavior of echelon 2 is different; here significantly more material is always ordered from the more reliable supplier, (21), anytime any supplier is in a congested state. This pattern exaggerates as the cost ratio and VR increase. Typically, an increase in congestion yielded an increase in ordering more from the more reliable supplier. The standard deviation of cost is, on average, \$2.33 higher with the higher cost ratio. When the more reliable supplier costs 4 times more than the less reliable, the costs increase by an average of \$6.48, however the standard deviation decreases with the higher cost ratio by an average of \$0.54.

7.2 Beta Distribution

Compared to the normal distribution, the results in the beta distribution are not as intuitive. Two representative graphs are shown in Figures 7 and 8. As the discrepancy between suppliers increases (AR increases), the more reliable supplier (31) had an ordering percentage of about 4% for all points except when the downstream suppliers were congested. However, the more reliable supplier was utilized 96% of the time in echelon 2 (supplier 21) for all points except at an alpha ratio of 1.1. In this instance, the less expensive (less reliable) supplier was used for about 80-90% of the material in the situations when no supplier was congested.

8. Conclusion

This research presents an architecture for a synchronized supply chain capable of reacting quickly and effectively enabling decision making under uncertainty. A 3-echelon SC was used for testing purposes, with 3 discrete congestion levels. Reliability was either normal or beta distributed and the system was tested over the 24 VRs (normal) and 7 ARs (beta) at 3 distinct cost levels. For each trial, the system was re-optimized using chance constrained programming to determine order quantities. In general, the results indicate that, under similar conditions, each echelon does not always order the same percentage from the more reliable supplier. Furthermore, optimal ordering percentages are quite different between the normal and beta distribution. Other related work includes a comparison of this system to an uncontrolled system using leadtime, cost and order quantities as measures of performance, seen in [5].

FIGURES

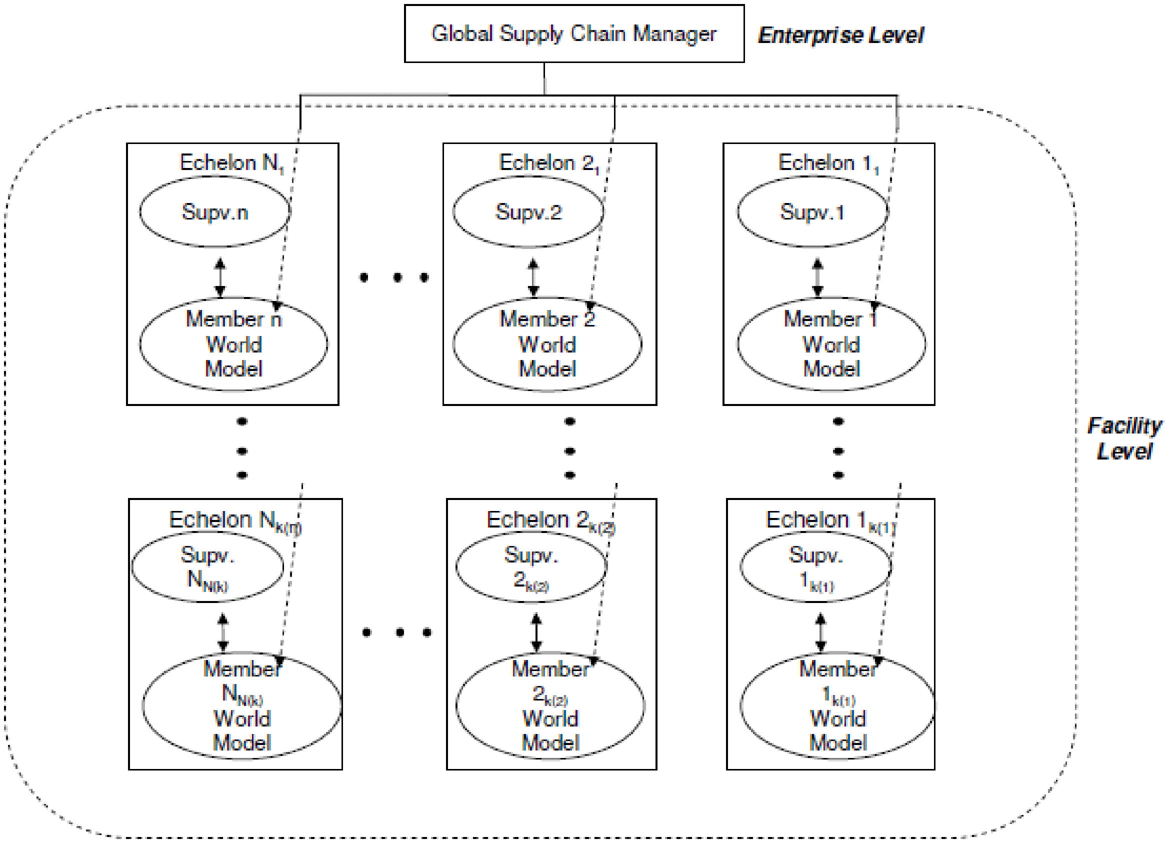

Figure 1. Bi-Level Supply Chain Model

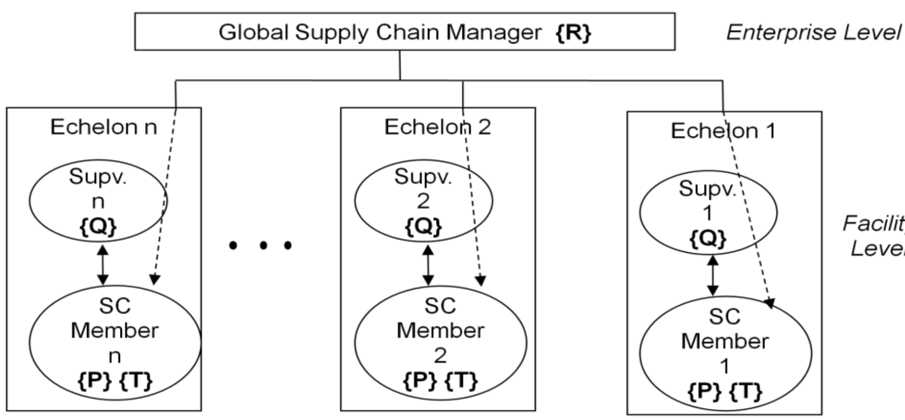

Figure 2: Supply Chain Petri Net Sets

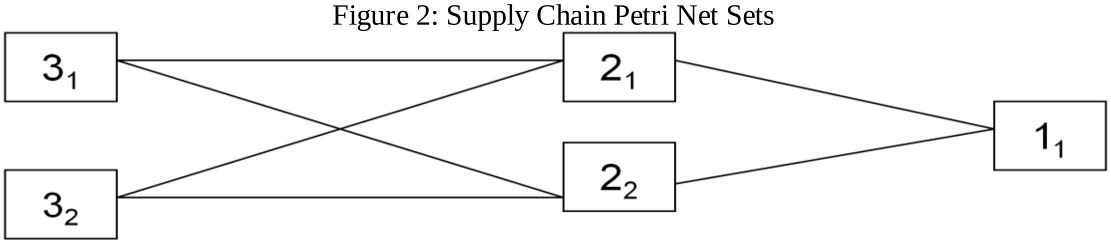

Figure 3: Supply Chain Used for Testing

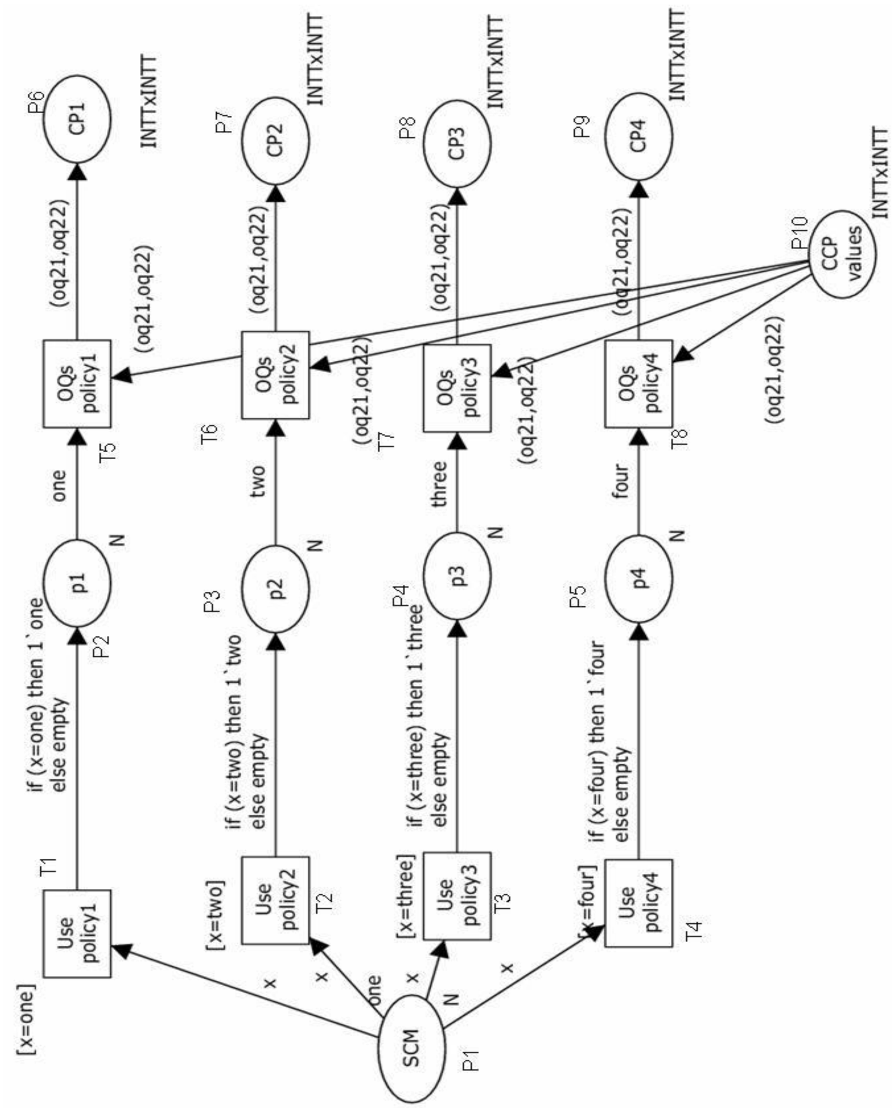

Figure 4: Enterprise Level Petri Net

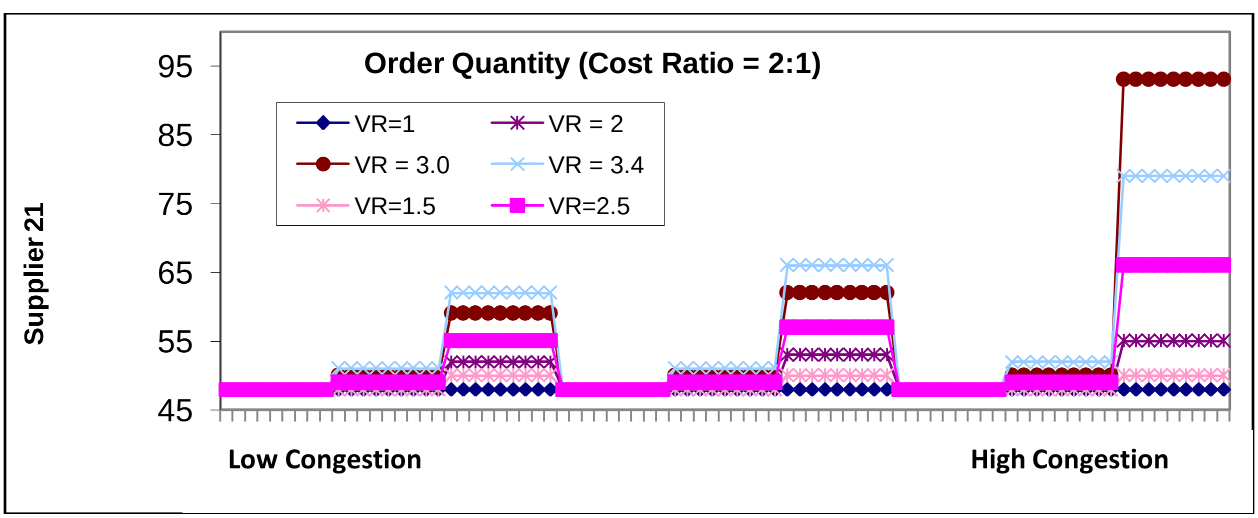

Figure 5: Sample Ordering Quantity from Supplier 21-Normal Distribution

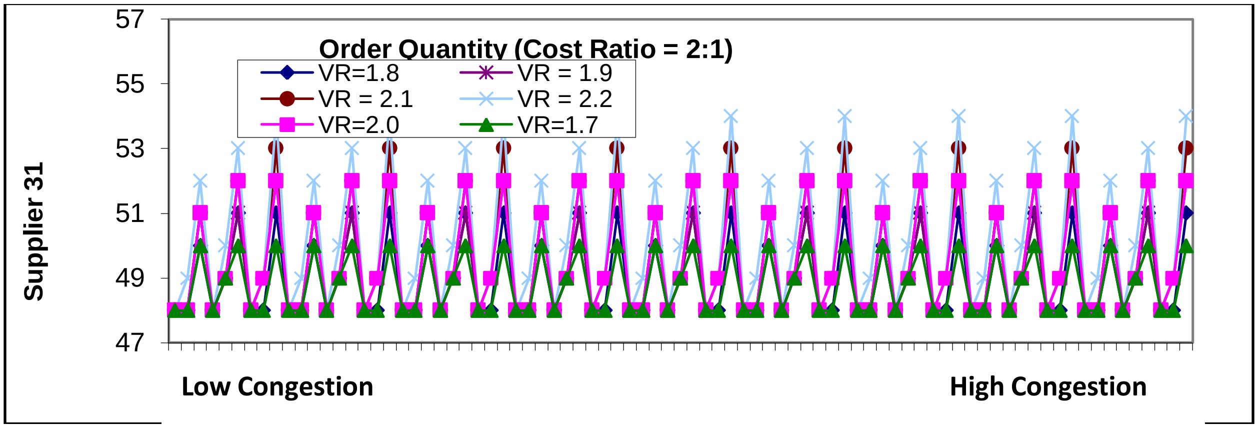

Figure 6: Sample Ordering Quantity from Supplier 31-Normal Distribution

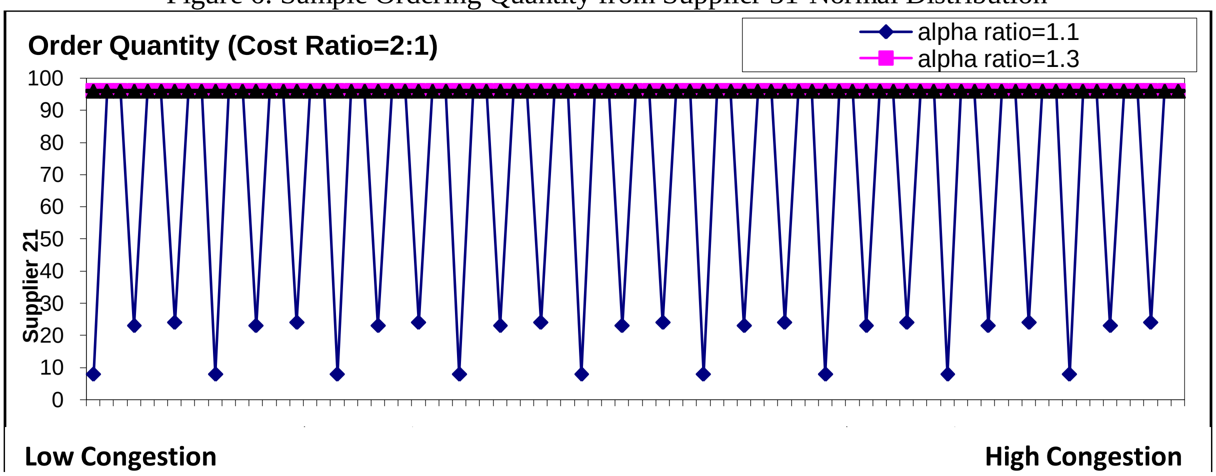

Figure 7: Sample Ordering Quantities from Supplier 21-Beta Distribution

Figure 8: Sample Ordering Quantities from Supplier 31-Beta Distribution

TABLES

Table1: Places of the Enterprise Level Net

Place Name	Description	Place No
SCM	Supply Chain Manager	1
po1	Use policy 1	2
po1	Use policy 2	3
po1	Use policy 3	4
po1	Use policy 4	5
CP1	Control place 1	6
CP2	Control place 2	7
CP3	Control place 3	8
CP4	Control Place 4	9
CCP Values	CCP Output	10

Table2: Transitions of the Enterprise Level Net

Transition Name	Description	Transition No
Use Policy 1	Select policy 1	1
Use Policy 2	Select policy 2	2
Use Policy 3	Select policy 3	3
Use Policy 4	Select policy 4	4
Oqs Policy 1	Order quantities for policy 1	5
Oqs Policy 2	Order quantities for policy 2	6
Oqs Policy 3	Order quantities for policy 3	7
Oqs Policy 4	Order quantities for policy 4	8

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