Designing a Flexible Supply Chain Network with Autonomous Agents

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Abstract: This paper proposes a supply chain model that enables companies with a software agent to construct a flexible supply chain network automatically, assuming the network is composed of many competitors. Unlike the traditional supply chain model including agents, it is impossible to manage the behavior of all companies directly in the structure of the supply chain network. Each company can handle only its own strategy or planning. We also propose a simple strategy for manufacturing agents focusing on individual profit. Our experimental results demonstrate that our agents can make a supply chain network structure that produces profits in the small-to-medium-scale scenario under some sample models of various scales.

1 INTRODUCTION

Today, companies are required to produce and supply resources at low cost without delivery delays. A supply chain, which is a network between material suppliers, manufacturers, and consumers, produces products and distributes them. Subsequently, supply chain management, which is a method to predict future demand for products and optimizing the production plan, is used to prevent excessive production and the occurrence of excess inventory. It is studied in both academic theory and within the practical use of corporate management.(Lambert and Cooper, 2000)

At a manufacturing echelon for materials in a supply chain, it is uncommon to complete all processes within a single company. Therefore, companies need to procure resources from other companies for production after bargaining for price, deadline, and so forth with them, except cases where all companies in a supply chain network can be controlled like the Toyota production system. When a supply chain network contains many competitors, they may not have information about the competition companies' plans or optimize their behavior.

This paper proposes a supply chain model including agents that dynamically constructs its network according to the behavior of the manufacturers. Companies have information on the bills of materials and templates of manufacturing plants. And they can decide their role (e.g., processing raw materials and assembling parts) in the network by building factory facilities. We also proposed the protocols of communication and negotiation to buy and sell the resources needed to operate factory facilities within the manufacturer's plant from competitors.

By using this model, we can (1) propose a strategy of a company to fully automatize-from the construction of manufacturing factories to the sale of resources, (2) analyze changes in profits of companies within the manufacturing process, and (3) analyze the influence on the network that contains a company with non-rational behavior.

The rest of the paper is organized as follows. In section 2, we describe related work. In section 3, we propose a supply chain model that enables companies to autonomously form a flexible supply chain network, assuming the network will be composed of many competitors. In section 4, we propose a strategy for manufacturing companies. In section 5, we conduct experiments to evaluate the supply chain model with our simulator. Finally, we present conclusions and recommendations for future work.

2 RELATED WORK

Many studies (Chen et al., 1999; Xue et al., 2005) which introduce automated negotiation into supply chain management, do not assume abandonment of contracts after negotiation. If there is a possibility that resources needed by a manufacturer can be obtained from other companies than currently negotiating with an opponent, and for that reason it might be worth negotiating with those companies. Especially, in real-

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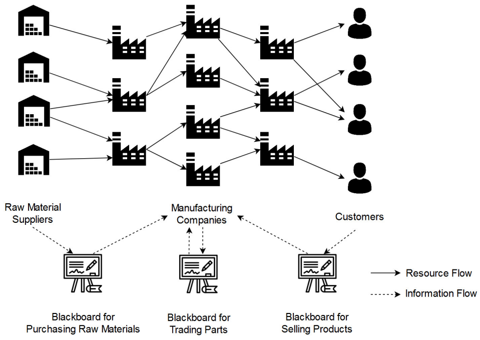

Figure 1: The detail of our proposed supply chain model.

istic inter-company negotiations, after estimating by negotiating with a plurality of companies, it is often the case to contract with the current company (or discarding the pending contract).

Recently, some research (Ivanov et al., 2016; Radziwon et al., 2014) has attempted to make the supply chain network more flexible. Industry 4.0 is a manufacturing digitization project promoted by the German government, and one of its goals is to realize the implementation of a "smart factory." In Smart Factory, by connecting numerous sensors from factories to the network and collecting the operation information, it is possible to detect and automatically repair the malfunction of equipment by using AI technology. In addition, in the conventional supply chain, companies responsible for specific processes of product manufacturing are fixed. In a smart factory, however, the role of the factory can be automatically and flexibly changed, as they are connected not only within a single factory but also on the market with the network. Therefore, such a system is expected to be able to quickly deal with sudden changes of suppliers due to bankruptcy or other reasons and to realize individually customized products rapidly. Compared with Industry 4.0, the focus of our research is similar. However, it differs in that our study tries to automate processes from the construction of the factories to the delivery to consumers via agents.

3 FLEXIBLE SUPPLY CHAIN MODEL

In this section, we propose a supply chain model that enables manufacturing companies to form a flexible supply chain network. This model makes it easier for manufacturers to build factories, find opponents and negotiate with them to secure resources, and to close deals with suppliers or consumers.

An overview of the model is shown in Figure 1, and Figure 2 depicts the flow of the day in the model.

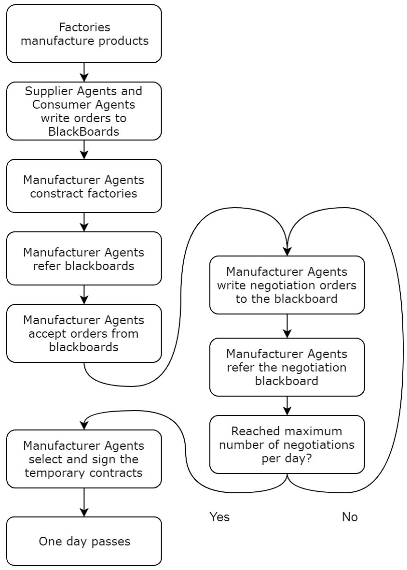

Figure 2: One day flow in our model.

There are three blackboards for transacting resources between companies in addition to three types of companies. These blackboards make it easier to negotiate resources between suppliers and a manufacturer or manufacturers, or a manufacturer and consumers. In order to prevent the problem from becoming too complicated due to the wide range of actions the manufacturers can take, the functions of manufacturing, distribution, wholesale and retail sales are consolidated in the manufacturer, while a typical supply chain model has several kinds of echelons. Furthermore, to make it easier to describe the model, we roughly divided the components of the supply chain into three kinds of agents and seven models.

3.1 Supplier Agent

Supplier Agents produce and selling raw materials to manufacturing agents. They can take three actions: securing raw materials, writing on a blackboard for selling, and selling raw materials to manufacturing agents. Each supplier agent has a single supply model.

Securing Raw Materials. Each agent procures raw materials each *Interval* of days, which is defined in a supply model.

Writing on a Blackboard. After procuring raw materials, the agent writes an order on the blackboard immediately to indicate sales information to manufacturing agents. If any manufacturing agent does not receive the order within a certain number of days, the order will be withdrawn automatically.

Table 1: Example part of a recipe.

Unique name	Deliverable	Quantity to be produced	Items to be processed	Quantity required
Assemble1	Product1	1	Part2	4
Assemble1	Product1	1	Part3	8

Selling Raw Materials to Manufacturing Agents. When a manufacturing agent receives a supply order, the supply agent initiates it to prepare for shipment immediately. As soon as it is ready for shipment, it sells the raw materials to the manufacturing agent. Since it is assumed that any accidents will not occur, supplier agents are assumed to be able to deliver materials on time.

3.2 Manufacturing Agent

Manufacturing Agent processes raw materials and parts. They can take these actions: building factories, writing on or referring to blackboards, negotiating with other companies, and so on. Details of these actions are explained below.

Building Factories. Manufacturing agents can build factories by selecting from predefined factory models. In addition, when building factories, agents can utilize their strategy by referring to BOM models and blackboards.

Referring or Writing on Blackboards. Agents can refer blackboards to improve production plan, purchase raw materials or parts, negotiate with other manufacturing agents for trading every day. Besides, agents can write buy (or sell) orders on blackboards if necessary.

Negotiating and Selecting Temporary Agreements. When agents initiate negotiation, they follow the negotiation protocol defined in Section 3.10. After the negotiation is successful, the negotiation result can be put on hold temporarily, and as long as during the day, a temporary contract can be accumulated by negotiating with other agents. After that, the agent on the side who started the negotiation can sign the contract by selecting one of the negotiation results accumulated at the end of its turn.

3.3 Consumer Agent

Consumer Agents purchase products from manufacturing agents. They can take two actions: write on a blackboard to deal with purchasing products, and buy products from manufacturing agents. Each consumer agent has a single demand model.

Writing on a Blackboard for Purchasing Products. Each consumer agent writes an order on the blackboard every *Interval* day, which is defined in a demand model, to indicate purchase information for manufacturing agents. If no manufacturing agents receive the order within a certain number of days, the consumer agent's order is withdrawn automatically.

Buying Products from Manufacturing Agents. When a manufacturing agent receives an order, it waits until the deadline for products to be delivered from the manufacturer. This agent pays a commission to the manufacturing agent if the products are delivered on time; otherwise it is penalized.

3.4 Bill of Materials Model

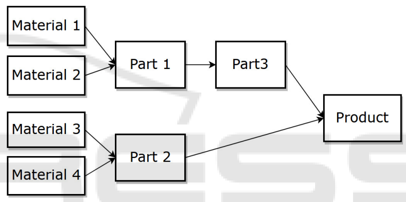

Figure 3: An example of bills of materials (BOM).

The bill of materials (BOM) model defines items (i.e., raw materials, parts, products) and recipes for manufacturing a product. The details of this process are as follows:

Item: *Item name*, *Item type* (material, part, product)

Recipe: *Recipe name*, *Deliverables*, *Quantity to produce*, *Items to be processed*, *Quantity required*

Table 1 shows an example part of recipe, and Figure 3 indicates the set of recipes.

3.5 Factory Model

Factory model defines a factory that manufacturing agents can build. The detail of attributes are as follows: *ItemRecipe* indicates a recipe to be processed by the factory. *FactoryName* is a unique name of this model. *ConstractionTime* is days needed to build a factory. *ConstractionCost* indicates an initial cost to build a factory. *CostPerUnit* stands for the cost to manufacture an item. *ProductionRate* is a quantity that this factory can manufacture per day, which follows a Gaussian distribution with a standard deviation of *stddevProductionRate*. *MaintenanceCost* is the cost per day.

3.6 Decision-making Model

Decision-making model describes manufacturing and negotiating strategies of manufacturing agents, which precepts of the environment, judgments regarding behavior, and instructs regarding actions required of the agent. We propose a detailed strategy for agents in Section 4.

3.7 Demand Model

Demand Model defines the demand for products, and it is used by the consumer's agent. The detail of these attributes is as follows: *ModelName* is a unique name of the demand model. *Item* with *Amount* and *Price* are items that are required by the consumer's agents. *Deadline* is the number of days until hitting the deadline received from manufacturing agents that has an accepted order to fulfill delivery. *Deadline* follows a Gaussian distribution with a standard deviation of *stddevDeadline*. *Interval* is an average interval of days between the time the item is delivered and the time the next demand for an item occurs that follows a exponential distribution. *Penalty* is the penalty price when manufacturing agent does not deliver the products by the deadline.

3.8 Supply Model

A supply model describes the supply of raw materials provided by supply agents. The detail of these attributes is as follows: *ModelName* is a unique name of this model. *Item* with *Amount* and *Price* is an item that will be supplied by consumer agents. *DeliveryDate* is a day needed to deliver raw materials, and this value follows a Gaussian distribution with a standard deviation of *stddevDeliveryDate*. *Interval* is an average interval of days between the time the materials are delivered, and the time that the next supply need occurs, and this follows an exponential distribution. There is no penalty included because the supply model assumes that delivery delays will not occur.

3.9 Blackboard Model

Blackboard Model defines communication protocols that enable agents to trade resources or initiate negotiations. To make it easier for agents to find negotiating opponents, this paper uses a Blackboard system (Sadeh et al., 2001), which is widely used in the multi-agent research field. Bulletin board trading (Kikuchi, 2006) is an example in which a model similar to the Blackboard system is used, and it is used by

Table 2: An example order for negotiation.

Attribute	Example value
From	ManufacturerAgent1
Type	BUY
Item	Part1
Since	20

Japan Electric Power Exchange (JEPE), which provides power trading in Japan.

As shown in Figure 1, There are three kinds of blackboards in the supply chain model, and each one has a different function.

Blackboard for Purchasing Raw Materials. This blackboard is used to trade raw materials between a supplier's agent and a manufacturer's. The details of an order written by supply agents are as follows: *Supplier* is the name of the person who wrote the order, and *SupplyModelName* is the name of the model described in Supply Model. The attribute *Since* is the day when the order was placed.

Blackboard for Trading Parts. This blackboard is used to trade items between manufacturing agents. When a manufacturing agent needs to secure parts from other companies or wants to sell parts to others, it writes an order as described in Table 2. The attribute *From* is the name of the agent who wrote the order. *Type* indicates whether the agent wants to buy or sell. *Item* is the item the agent wants to trade. The attribute *Since* is the day when the order was written. Other agents can refer the blackboard every day, and they can initiate negotiations with the agent who posted the entry. Once the negotiation is started, the entry is deleted so other agents cannot reference it.

Blackboard for Selling Products. This blackboard is used to place an order for products by consumer agents. When product demand occurs, they write orders on the blackboard to purchase products from manufacturing agents. The order contains three attributes: *Consumer* is the name of the person who placed the order, *DemandModelName* is the name of Demand Model, and *Since* is the day when the order was placed.

3.10 Negotiation Model

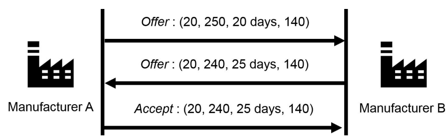

Figure 4: Alternating Offers Protocol.

The negotiation model defines the negotiation protocol that is used by manufacturing agents. Alternating offers (Rubinstein, 1982), a bilateral negotiation protocol, is used for this protocol. The flow of alternating offers is shown in Figure 4. We consider the case in which agents A and B conduct negotiations. In the beginning, agent A makes a proposal to agent B. Next. Agent B takes one of the following actions with respect to agent A:

- Offer: Rejecting the previous proposal and proposing a new one.
- Accept: Accepting the previous proposal.
- EndNegotiation: Ending the negotiation without agreement before the deadline reaches.

Afterwards, agent *A* takes come up with a new action for agent *B*, In alternating offers, negotiations will be continued until the following conditions are satisfied:

- One agent accepts the proposal.
- The negotiation deadline passes before an agreement was reached.
- One agent terminates the negotiation by selecting EndNegotiation.

4 STRATEGIES FOR MANUFACTURING AGENT

In this section, we propose six kinds of strategies for manufacturing agents to focus on individual profit as follows: building factories, receiving demand orders, receiving supply orders, writing orders on a blackboard, selecting negotiation opponents, and negotiation.

Building Factories. While manufacturing agents can freely build factories, construction of unplanned factories can cause losses due to running costs up. This strategy described in Algorithm 1 prevents agents from building the same factory that other companies built. Building factories are continued until the maximum construction quantity is satisfied.

Receiving Demand Orders. This strategy described in Algorithm 2 prevents that agents receive an order for products that their factories cannot produce. In addition, this strategy also prevents excessive orders.

Receiving Supply Orders. Algorithm 3 makes agents to purchase only the resources required by their factories and prevent holding too many resources.

Algorithm 1: Building Factories.

```
Require: maximum number of facilities F_max
p ⇐ a random value in (0,1)
if current number of factories ≧ F_max then
    do nothing
end if
if p < 0.3 then
    do nothing
else if p < 0.6 then
    choose and build a factory randomly from factory templates
else
    refer the blackboards to confirm current demands
    select a factory which satisfies the demand from the templates and
    build it.
end if
```

Algorithm 2: Receiving Demand Orders.

```
Require: current number of factories n, types of items that currently owned
    factory can produce I
if n = 0 or the size of demandboard = 0 then
    do nothing
else
    extract only the demand that needs I and receive one of them.
end if
```

Algorithm 3: Receiving Supply Orders.

```
Require: current number of factories n, types of items that currently owned
    factory requires to manufacture items I
if n = 0 or the size of supplyboard = 0 then
    do nothing
else
    L ⇐ extract only the supply that supplies I
    K ⇐ extract from L what currently owned amount does not exceed
    twice the amount necessary to manufacture.
    receive an order randomly from K
end if
```

Writing Orders on the Blackboard. Algorithm 4 describes the strategy that permits agents to sell the parts manufactured to other manufacturing agents by writing it on the negotiation blackboard.

Selecting Negotiation Opponents. Algorithm 5 allows the agent select an opponent who wants resources that the agent owns. Also, in order to reduce the number of negotiations, we adjusted the probability of negotiation.

Negotiation. In this strategy (Algorithm 6), the agent negotiates with the opponent about the price. First, when the agent is a seller, they propose a price 1 to 2 times the price required for manufacturing parts. After that, it decides whether to accept or reject it based on the proposed price.

Algorithm 4: Writing Orders on the Blackboard.

Require: current number of factories n, types of items that currently owned factory requires to manufacture items $I = \{i_1, i_2, ..., i_k\}$

if $n = 0$ **then**
  do nothing
end if
for $j = 0$ to k **do**
  if the currency amount of $i_j > 2*$ the amount i_j owned factory requires **then**
    add i_j to list L
  end if
  select one from L randomly and write a request on the blackboard
  $i \leftarrow i + 1$
end for

Algorithm 5: Selecting Negotiation Opponents.

Require: current number of factories n, types of items that currently owned factory can produce I

if $n = 0$ or the size of negotiation blackboard $= 0$ **then**
  do nothing
else
  $L \Leftarrow$ refer to the negotiation blackboard and extract the entry that including I.
  select one of L and initiate negotiation with 10% chance
end if

Algorithm 6: Negotiation Strategy.

Require: current number of factories n, types of items that the currently owned factory can produce I, last received proposal from opponent $lbid$, price from $lbid$ lpr, penalty from $lbid$ lpe function to offer a proposal $Offer(amount, price, deadline, penalty)$, function to accept the proposal $Accept(proposal)$, function rand(x, y) returns the uniformly distributed random number on (x,y), $N = 5, D = 15$

while negotiation continues **do**
  if $self$ is a buyer **then**
    if $lbid$ is not exist **then**
      $Offer(N, 0.0, D, 0)$
    else
      $Offer(N, (1 - rand(0,1)/4) * lpr, D, 3/4 * lpe)$
    end if
  else
    $U_p \Leftarrow$ calculate unit costs needed to produce an item currently being negotiating for.
    if $lbid$ is not exist **then**
      $Offer(N, 2 * U_p * N, D, U_p/3)$
    else
      if $lbid > N * U_p * 1.3$ **then**
        $Accept(lbid)$
      else
        $Offer(N, U_p * (1 + rand(0,1)) * N, D, U_p/3)$
      end if
    end if
  end if
end while

5 EXPERIMENTS

For evaluating the proposed supply chain model and agent, we implemented a simulator in Java. Although there are datasets for evaluating a supply chain model(Georgiadis et al., 2011), these datasets cannot be applied to our model due to the fact that they lack some necessary data needed to simulate our model. Therefore, two sample scenarios are generated to evaluate by random parameters. An overview for these scenarios is depicted in Figure 5. (see Appendix for details) To evaluate our proposed strategy, we prepared a "Random Agent," which all behaviors (such as building factories, selecting a negotiations opponent, and so on) are random.

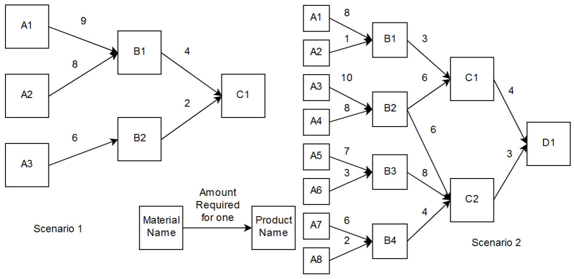

Figure 5: Overview of Scenario 1 and 2.

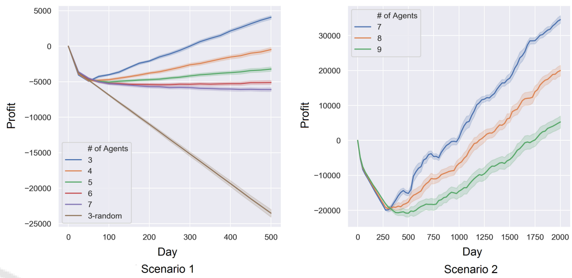

Figure 6: Average profits in Agents (Scenario 1 and 2) with 95% confidence bands.

5.1 Experimental Settings

This experiment was carried out to clarify that manufacturer strategies affect its profit. We have used two kinds of agents (our proposed agent and Random Agent) for the experiment. The following are the details of the experimental settings:

- # of manufacturing agents in the supply chain: 3 to 7 for Scenario 1, 7 to 9 for Scenario 2
- Factories can be built per agent: 1
- Maximum number of negotiations per day: 3
- Maximum contracts can be made per day: 1
- Maximum rounds per negotiation: 1000
- Simulation days: 500 for Scenario 1, 2000 for Scenario 2
- # of simulations: 100

Table 3: Average materials supplied and product offered (Scenario 1).

	# of agents					
	3-random	3	4	5	6	7
Material supplied	38.55	130.11	134.61	137.93	141.22	145.16
Product offered	0	43.08	42.99	42.45	41.90	42.03

Table 4: Average negotiation contracts (Scenario 1).

	# of agents					
	3-random	3	4	5	6	7
Penalties imposed	458.84	1.84	3.15	4.06	4.77	5.14
Successfully transacted	26.51	18.40	14.11	11.40	9.61	8.35
Transaction success rate	0.054	0.90	0.81	0.73	0.66	0.61

5.2 Experimental Results

5.2.1 Scenario 1

Figure 6 shows average profits. Comparing the result of two agents, while the Random Agent continued to earn large losses, our proposed agent made a profit finally, although it experienced a loss in the early stages of the simulation. Thus, the random agent may have caused the funds to flow out to the supplier or to the consumer. In addition, it can be said that as the number of agents decreases, the overall profit increases. Table 3 and Table 4 show the statistics on contract statuses at the end of simulation. Table 3 indicates that our proposed agent ordered more from the supplier than the random agent. In addition, while the random agent does not correspond to consumer demand, our agent has never failed to deliver because it receives only demand orders that are already in inventory. These results imply that the main reason why the random agent loses is by paying the penalty for consumers. Table 4 indicates that the random agent has succeeded in transacting with a probability of 5.4%, on the other hand, our proposed agent has 90% successful rate. Therefore, our agent can avoid unreasonable contracts. However, the result also indicates that as the number of agents increases, the transaction success rate diminishes. This is because our agent signed many contracts without considering other agents, and could not produce products on time.

5.2.2 Scenario 2

We conducted additional experiments to clarify that the shortage of suppliers and the high cost of sales ratio are the cause of losses. The experimental settings of scenario 2 are the same as scenario 1, except that the cost percentage is reduced from 50% to 33.3% and that the number of suppliers per a supply model is doubled. The results are shown in Figure 6, Table 5, and Table 6. Although we cannot show the experimental results when the cost percentage and the number of suppliers per a supply model are same as scenario 1 due to space limitations, we see that the number of suppliers of raw materials and the number of times they provided final products increased. In addition, a profit is made by lowering the cost percentage and increasing the number of times of providing the final products. Therefore, these results showed that securing a large number of raw materials and lowering the cost percentage are necessary for profit in a complex supply chain model.

Table 5: Average materials supplied and product offered (Scenario 2).

	# of agents		
	7	8	9
Material supplied	828.19	830.93	833.56
Product offered	16.87	16.22	15.10

Table 6: Average negotiation contracts (Scenario 2).

	# of agents		
	7	8	9
Penalties imposed	14.91	14.45	14.06
Successfully transacted	57.84	50.43	44.69
Transaction success rate	0.80	0.77	0.76

6 CONCLUSIONS AND FUTURE WORK

This paper focused on a modeling supply chain network which is composed of many competing companies. We proposed a supply chain model that enables companies to autonomously form a supply chain network flexibly. Our model assumes that manufacturing companies can construct factory facilities, secure necessary resources by negotiating, and writing orders on blackboards freely. We also proposed a strategy for manufacturing agents that focuses on individual profit by selling at a higher price than the purchase price. The experimental results demonstrated that our supply chain model shows the best performance when the number of agents is equal to the number of manufacturing processes.

One possible future study would be to improve the current model by employing a more realistic situation. It is difficult to approach realistic situations in this model compared to typical supply chain models, but it can be realized by improving the agent's strategy such as predicting demand.

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APPENDIX

Scenarios used in experiments. For convenience, we assume $rand(x,y)$ is the uniformly distributed random number on (x,y) and $randi(x,y)$ is the uniformly distributed random integer on [x,y].

Common settings. Common model settings in all scenarios are shown in Table 7, Table 8, and Table 9.

Table 7: Factory Model.

Attribute	Parameter
ConstractionTime	$randi(3,20)$
ConstractionCost	$randi(1000,5000)$
CostPerUnit	$randi(5,20)$
ProductionRate	$randi(5,30)$
stddevProductionRate	$rand(0,3)$
MaintenanceCost	$randi(10,30)$

Table 8: Supply Model.

Attribute	Parameter
Amount	$randi(20,50)$
Price	$randi(5,30)$ per item
DeliveryDate	$randi(5,15)$
stddevDeliveryDate	$randi(0,3)$
avgInterval	$randi(5,15)$

Table 9: Demand Model.

Attribute	Parameter
Amount	1
Price	$2.0 * rawmaterialcost$
Deadline	$randi(3,20)$
stddevDeadline	$rand(0,3)$
Interval	$randi(5,20)$
PenaltyPrice	$rawmaterialcost/3.0$

Scenario 1

- BOM Model : 3 raw material, 1 final product with 3 manufacturing processes. (see Figure 5)
- # of Suppliers : 6 (2 for each supply model)
- # of Consumers : 2 (2 for each demand model)

Scenario 2

- BOM Model : 8 raw material, 1 final product with 7 manufacturing processes. (see Figure 5)
- # of Suppliers : 32 (4 for each supply model)
- # of Consumers : 2 (2 for each demand model)
- Price in Demand Model : $3.0 * rawmaterialcost$ (33.3% cost percentage)