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SUPPLY CHAIN SIMULATION MODELING USING THE SUPPLY CHAIN OPERATIONS REFERENCE MODEL

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ABSTRACT

Simulation is a very useful tool for predicting supply chain performance. Because there are no standard simulation elements that represent accurately the activities in a supply chain, there exist a variety of approaches for developing supply chain simulation models. To improve this situation, this paper describes a novel supply chain simulation framework that follows the Supply Chain Operations Reference (SCOR) model. This framework has been used for building powerful simulation models that integrate discrete event simulation and spreadsheets. The simulation models are hierarchical and use submodels that capture activities specific to supply chains. The SCOR framework provides a basis for defining the level of detail in a way as to include as many features as possible, while not making them industry specific. This approach enables the reuse of submodels, which reduces development time. The paper describes the implementation of the simulation models and how the submodels interact during execution.

Keywords: supply chains, simulation models

1. INTRODUCTION

A supply chain is a network of suppliers, manufacturers, distributors, and retailers who are collectively concerned with the conversion of raw materials into goods that can be delivered to the customer. Three kinds of flow are to be considered in any supply chain: material flow, information flow, and cash flow. Material flows from suppliers and manufacturers to warehouses and retailers and, finally, customers. This flow includes both transporting products from one participant to another and moving raw material and parts on the shop floor. The information flow includes the data that are generated every time a change in the system status occurs. For example, every customer order generates information that is used to fulfill the order. The cash flow is the flow of money in the supply chain from customers to retailers and back to suppliers.

A supply chain is a dynamic, stochastic, and complex system. The performance of any particular participant in a supply chain depends to a large extent on the behavior of other participants. Optimizing the performance of each participant is important, but for improving the overall performance of a supply chain, it is necessary to view the system as a whole. This makes the problem very complicated.

Supply chain simulation models can be used to improve supply chain decision-making. The relevant decisions can be classified into three categories [1]: strategic, operating, and control. Strategic decisions such as selecting the location of a facility have long-term significance. Operating decisions refer to decisions about production to meet demand. These decisions are made on a weekly or monthly time frame. Control decisions are concerned with problems in execution. This can be classified as disruption management. Examples include the decisions to be taken when a certain machine in the shop floor fails. Simulation models can be used to evaluate policies (such as inventory management policies) or to predict the outcome of a specific alternative.

Each participant of the supply chain performs a distinct set of activities. Despite differences between these sets, a number of processes are common to the participants of the supply chain. Components that represent these common process elements can be used to construct a model of the entire supply chain. Independent components with well-defined interfaces will promote reusability.

A number of researchers have described studies that used simulation models to evaluate supply chains. Swaminathan *et al.* [2] studied the influence of sharing supplier capacity information on the performance of a supply chain. They use simulation for comparing different information sharing scenarios after deriving the optimal inventory policy for the manufacturer under stochastic demand. Towill *et al.* [3] conducted a simulation study to analyze the effect of system redesign strategies on the performance of a supply chain. Bhaskaran [4] performed an analysis of supply chain instability for an automobile industry using simulation.

In addition to these reports, a variety of approaches for building supply chain simulation models have been described. Some of these approaches used general-purpose discrete event simulation, others developed specialized software, and others used distributed simulation.

Jain *et al.* [5] observe that the level of detail included in the development of a simulation model should be appropriate to the objective of the study. The paper describes a high level supply chain simulation model that includes order fulfillment, procurement, forecasting, and replenishment. Their approach uses general-purpose simulation software because it lets the user select the desired level of abstraction.

Bhaskaran [4] used an automobile supply chain simulation software originally developed to GM's specifications. Chatfield *et al.* [6] describe an approach that automatically generates supply chain simulation models. The analyst must first describe the supply chain structure using a special modeling language. A model generation routine creates a simulation model using a library of Java classes.

Eliter *et al.* [7] worked on the concept of Agent Programs. An agent consists of a body of software code that supports a well-defined application programmer interface and a semantic wrapper that contains a wealth of information. As part of the work, the team developed agents for various functions of supply chain management systems. A simulation model of a supply chain application based on agents was built using commercial softwares such as Microsoft Access and ESRI's MapObject. Swaminathan *et al.* [8] describe a supply chain modeling framework through software components for representing various types of supply chain agents such as retailers, manufacturers, and transporters.

Commercial vendors also offer supply chain simulators such as IBM Supply Chain Simulator [9], Supply Chain Builder [10], and e-SCOR [11].

Although these supply chain simulation models are discrete-event simulation models, some supply chain variables such as inventory levels can be viewed as continuous variables. See, for example, Lee *et al.* [12]. Our approach includes planning activities that manage these variables using Excel VBA (see Section 3.1).

The proliferation of supply chain simulation models has yielded competing approaches. To attack this problem, this research adopted the Supply Chain Operations Reference (SCOR) model [13,14], which has been proposed as a standard for describing supply chain management processes, their relationships, and best practices. Barnett and Miller [15] describe specialized supply chain simulation software that implements SCOR. Our goal was to implement supply chain simulation models using the SCOR model with reusable components from general-purpose discrete-event simulation software to facilitate model construction. This will enable firms that are using the SCOR model to more easily create simulation models of their supply chains. We have constructed a variety of simulation models using this framework; these are described in more detail in Pundoor [16]. In addition, a more detailed description of the model and links to examples are available online at the following URL:

http://www.isr.umd.edu/Labs/CIM/SC_Simulation/

The remainder of the paper is organized as follows. Section 2 presents our new framework for building supply chain simulation models. Section 3 describes the implementation using Arena and Microsoft Excel, discusses how the submodels interact, and describes cash flow and performance measures. Section 4 concludes the paper.

2. SUPPLY CHAIN SIMULATION FRAMEWORK

The hierarchical simulation modeling approach presented here is based on the Supply Chain Operations Reference model, Version 4.0, proposed by the Supply Chain Council [13]. The SCOR model was developed to describe the business activities associated with all phases of satisfying a customer's demand. SCOR is founded on four distinct supply chain management processes: Plan, Source, Make, and Deliver. Supply chains can be described using these process building blocks, which are known as Process Categories. Each of the Process Categories consists of Process Elements.

SCOR model also distinguishes between Planning, Execution, and Enable level process categories. Planning processes balance aggregate demand across a consistent planning horizon. Planning processes generally occur at regular intervals. Execution processes are triggered by planned or actual demand that changes the state of products. These include scheduling and sequencing, transforming materials and services, and moving product. Enable processes prepare, maintain and manage information or relationships upon which planning and execution processes rely.

For explaining our approach, it is convenient to identify three kinds of participants: consumers, producers, and traders. Consumers are those participants who place orders for finished products, but do not supply any products to any other participants. They are the most downstream participants in the model of the supply chain. Producers are the most upstream participants in the model of the supply chain. Producers supply parts to other participants, but do not receive any. Traders are the intermediate participants in the supply chain. Traders both place orders with some participants and deliver orders to other participants. Traders include manufacturers, warehouses, and retailers.

In this framework, a simulation model of a supply chain has three levels. The first level is the simulation model. The second level has submodels that correspond to the supply chain participants (consumers, producers, and traders). The third level has submodels that correspond to the process elements (across all process categories) that each participant performs. Figure 1 displays the corresponding hierarchy of submodels. Each participant submodel includes a subset of the process element submodels shown in Fig. 1.

Each process element is implemented as a separate submodel that represents a specific activity in the supply chain. Each process element submodel has clearly defined interfaces, which are used to integrate the submodels. The process element submodels contain Arena blocks. The participant submodels contain process element submodels and other submodels needed to initialize the simulation model.

There are small differences in the submodels for consumers, traders, and producers. In the case of the producers, raw material sourcing is not performed. A fixed amount of raw materials is assumed to be available all the time. The consumer acts as a place for receiving the products corresponding to the orders that he places. So the consumer does not perform production and delivery activities. Because participants such as distributors or retailers do not have any manufacturing processes, the corresponding participant submodels do not have produce and test submodels.

3. IMPLEMENTATION

This section describes the implementation of the framework using Arena and Microsoft Excel, the initialization of a supply chain simulation model, the interactions of the process element submodels, and the cash flow and performance measures.

3.1 SIMULATION AND SPREADSHEET INTEGRATION

The simulation models were built using Arena 4.0 and Microsoft Excel 2000. The Arena software interacts with Microsoft Excel using Arena VBA (as shown in Fig. 2). Each participant of the supply chain has an Excel workbook associated with it. The submodels associated with a participant include VBA blocks that communicate with tables in the corresponding Excel workbook (to get or save data) using Excel VBA. The Excel VBA routines include functions and procedures to take care of planning activities such as allocating raw materials for orders.

Planning activities are carried out using Excel VBA. Execution is carried out in Arena. Enable processes are modeled as input to the simulation either in the form of Excel data or parameters in the Arena model. Every time a planning activity is carried out, the system status is checked and actions are taken depending on the status. The Excel workbooks are used to record the status of the system and to calculate the performance measures. In order to prevent the Excel files from becoming too large in the course of a simulation run, clean up actions are triggered at periodic intervals. The customer orders and purchasing orders that have been fulfilled are archived once the performance measures relating to those orders are taken. The archived customer orders are put in a text file and this can be viewed at the end of the simulation run if desired.

3.2 MODEL INITIALIZATION

Constructing the supply chain simulation model requires constructing the Arena submodels and the Excel workbooks for each participant, since both the Arena submodels and the Excel workbooks include data needed to specify the complete model. The Excel workbooks are also used to process and store information during the execution of the model.

3.3 MODEL EXECUTION

This section describes how the submodels work together to execute the key activities that occur in supply chain operations:

1. A trader checks the inventory and places orders for raw materials with other traders or producers if necessary.
2. A trader or producer checks the existing open orders for production and obtains the production plan based on material availability.
3. A trader or producer checks the open orders for delivery to construct a delivery plan.

Note that orders placed by consumers are a special case of the first activity listed above.

3.3.1 SOURCING

Traders perform sourcing at periodic intervals. The trader orders raw materials from his supplier based on an inventory control policy, which, in the models that we have created, is a periodic (R, s, S) policy. R is the interval at which inventory is checked, s is the reorder level, and S is the order up to quantity. These values are defined for each type of product and are specified in the Inventory Management table in the corresponding Excel workbook. The net inventory position is calculated using the on-hand inventory, the on-order inventory, the allocated inventory, and the backorders.

For each trader, the Schedule Product Deliveries submodel in Arena, which corresponds to module S2.1 in SCOR, triggers an event periodically that invokes the Excel procedure for checking the inventory levels (Fig. 3). The values for on hand inventory, inventory on order, allocated inventory, and backorders for each component can be obtained from the Item Master table. Excel VBA calculates the sourcing quantity based on these values. The trader's (or producer's) name for each component is obtained from the Item Master table.

Figure 4 shows the process elements and worksheets involved in the receipt of sourced products. Sourced products are received in three stages: Receive Product, Verify Product, and Transfer Product. In the Receive Product stage, the sourced products seize a resource at the receive module. The processing time distribution depends upon the product type. After receiving, the product goes through the Verify Product stage, which delays the movement of the sourced product. The Transfer Product stage seizes a resource that moves the verified products into the raw material inventory. Each of these processes has an associated cost and this cost is added to the sourced product depending on the amount of time the product spends at each resource.

Once the sourced products reach the raw material inventory (after the Transfer Product stage), the Arena VBA block calls the Excel VBA procedure for updating the inventory status in the Item Master table. It also updates the Purchase Action Report and the Material Release table, which tracks the values of the raw material available in the inventory.

3.3.2 CHECKING OPEN ORDERS FOR PRODUCTION

All unfinished customer orders have their status indicated by a tag in the Customer Order table. The status of an existing order is either Received, In process, FGI, In transit, or Delivered. The Customer Order Tracking table lists the orders that are open for production (their status is Received). That is, these orders have been received, but not yet scheduled for production. Periodically, these orders are checked for production release. The interval between each such check depends on the production rescheduling period. If material for processing the whole order is available, then it is released for production. All of the open orders for which material is available are released at the same time for production. If the available material is insufficient, the order remains open and is checked again during the next production order release cycle.

Figure 5 shows the process elements and Microsoft Excel worksheets that are used for simulating the production activity. During each production order release cycle (the Schedule Production stage), Excel VBA checks the inventory status in Item Master worksheet to identify orders that can be released for production. For checking the material availability, both the order size and the bill of materials for the corresponding product have to be considered. This is carried out in Excel VBA. During each planning cycle, open orders are listed for processing based on a heuristic. Raw material requirements are calculated using the bill of materials. Whenever an order is released for production, the necessary raw material is removed from inventory. When an order is released for production, its status changes from Received to In process.

The released orders seize the Issue Product resource, which transports the raw materials from the raw material inventory to the shop floor. The processing time distribution for this stage depends upon the product and the order quantity.

After the raw material has been issued to the shop floor, the order goes through the Produce and Test stage. (This stage is absent in participants such as warehouse and retailers that do not perform any production activities.) The test stage includes a rework loop that sends a portion of the orders to rework.

The order then enters the Package stage. After packaging, the order moves to the Stage Product stage, and then the order is ready for delivery and moves to the finished goods inventory. (Note that this stage uses, in a different manner, the same Customer Order table that the Schedule Production stage uses.) At this time, the status of the order changes from In process to FGI. The order waits in the finished goods inventory until a delivery plan releases it for delivery. Each of the processes mentioned above has costs associated with it and the costs are added to the order using job order costing method.

3.3.2 CHECKING OPEN ORDERS FOR DELIVERY

The finished goods inventory status is checked periodically. The Customer Order Tracking table keeps track of the orders that are available for delivery in the finished goods inventory. As shown in Fig. 6, these orders are sent for delivery during the Schedule Delivery process. The delivery process requires seizing a transporter resource. The processing time here corresponds to the transportation time from the producer (or trader) to the customer. Each order is delivered separately. The cost for transportation gets added to the cost of the order. Once the order is delivered, its status is changed to Delivered. The price for the order is obtained from the Item Master table. This value, along with the accumulated cost, is used for calculating the profit. After the performance measures corresponding to the order have been taken, it is removed from the Excel file and archived in a text file.

3.4 CASH FLOW

In addition to time based performance measures (discussed in the next section), the simulation model also records financial performance measures. Cash flow is obtained by associating costs to each order. Cost accumulation methods (the manner in which costs are collected and identified with specific customers, jobs, batches, orders, departments and processes) vary from firm to firm. In the models developed, job order costing method is followed. In job order costing, costs are accumulated by jobs, orders, contracts or lots. In the simulation model, each order is considered as a job and costs are assigned to it. Direct material, direct labor, and overhead rates are considered for assigning costs to each order. All the process costs, including manufacturing costs, are applied to orders using predetermined rates along with an overhead rate associated with each activity. Direct material cost is obtained at the point of order release using first-in-first-out policy for the raw material inventory. The cost assigned to an order at a particular resource depends on the amount of time the resource was utilized by the order. Costs at various stages are added to arrive at the final cost for the order.

3.5 PERFORMANCE MEASURES

Periodically, Arena VBA triggers Excel procedures that calculate the performance measures based on the entries in the corresponding Excel sheets. At the end of each replication, these performance measures are put together and the overall performance measures for the entire replication are calculated. The performance measures include cycle time, percent tardiness, inventory, cost performance, and resource utilization. Order based performance measures are calculated based on the orders that have been delivered during any given period. For purposes of cycle time calculations, the whole process from placing of an order to the delivery of the finished product at the customer site is divided into four stages. The cycle time refers to the average time at each of the stages, the average being taken over the customer orders. The overall cycle time is calculated as the average time between the placing of an order by the customer and the delivery of that order by the producer (or trader) at the customer site. Each product has an associated lead time. Whenever an order is placed, its estimated delivery date is given based on the lead time for that product. If the order is delayed beyond its estimated delivery date, then the order is considered tardy. Percentage of orders that were delivered after the due date is calculated as the percentage tardy performance measure. For calculating the resource utilization, variables are used to keep track of the amount of time the resource was busy in any given period. Cost performance measures are calculated based on job order costing. Costs are associated with each order and these values are used to obtain performance measures such as cost of goods sold.

Delivery Performance: Delivery performance includes the average cycle time at each stage, the overall cycle time, and the percentage of orders that were tardy. For calculating the cycle times, four stages are considered: order receipt to start build, start build to finished goods inventory, finished goods inventory to release for delivery, and release for delivery to delivery at customer site. The sum of the average cycle times at these four stages gives the overall cycle time.

Inventory Performance: Inventory is measured in dollars. Each inventory performance measure is the average of the inventory at the beginning of the period and the inventory at the end of the period. The inventory performance measures include raw material, work in process, and finished goods inventory.

Inventory Holding Expenses: Each product has an inventory holding cost associated with it. Inventory holding expenses are calculated based on the average inventory level.

Inventory Days of Supply: This is calculated based on the cost of goods manufactured and the average inventory level. This ratio measures the number of days it takes to sell the entire stock of inventory.

Cost of Goods Sold: The cost of goods sold is calculated based on the production costs, purchases, work in process, and finished goods inventory. For a manufacturing firm, cost of goods sold is the manufacturing expenses, along with other expenses for goods sold during the period, including raw material, direct labor, and overhead. For a retail firm, the manufacturing process is not present. Cost of goods sold can be used to find the gross profit during the period. The gross profit is defined as the difference between the sales and the cost of goods sold. The total sales can be obtained from the total price for the orders delivered during the period.

Cost of Goods Manufactured: Cost of goods manufactured is the cost of orders that were put in the finished goods inventory during the period. This includes the cost of orders that were released for production in an earlier period but completed during the current period. This value is dependent on the manufacturing expenses for the period, including the overhead, and the work in process inventory at the beginning and end of the period.

Process Element Utilization: Process element utilization for each of the resources is calculated at the end of the period. This value is dependent on the time for which the corresponding resources were busy during the period.

4. SUMMARY AND CONCLUSIONS

As companies concentrate on improving the performance of the entire supply chain instead of viewing it as a set of independent organizations, coordination among various organizations becomes important. Simulation is a very effective way of evaluating different scenarios in such an environment. With the advent of more powerful computers, it has become easier to simulate complex systems. But the amount of time needed to develop the simulation model can be quite high. Libraries of reusable submodels can be used to build supply chain models with less time and effort, thus increasing the amount of time available for evaluating the system.

Arena, like other simulation software, offers numerous features to simulate discrete event systems. But the modules available in Arena are at a very basic level compared to those used in supply chain simulation models. Developing models hierarchically (using submodels that represent supply chain processes) can overcome this limitation. In addition, by using Arena VBA, the simulation model can communicate with other applications such as Microsoft Excel. By combining the simulation capabilities of Arena and the spreadsheet capabilities of Microsoft Excel, we have constructed a very efficient and flexible library for developing supply chain simulation models. In order to make the submodels more common (and thus more useful), we have followed the Supply Chain Operations Reference model.

Our implementation does not use distributed simulation or parallel simulation techniques like the Simulation Object Model or the Run Time Infrastructure that HLA (High Level Architecture) employs to define data, pass messages, and synchronize time. For an example of using such techniques for supply chain simulation, see Turner *et al*. [17]. However, in our approach, the simulation components, which can be modeled as web service components, may communicate through remote procedure calls in a distributed environment.

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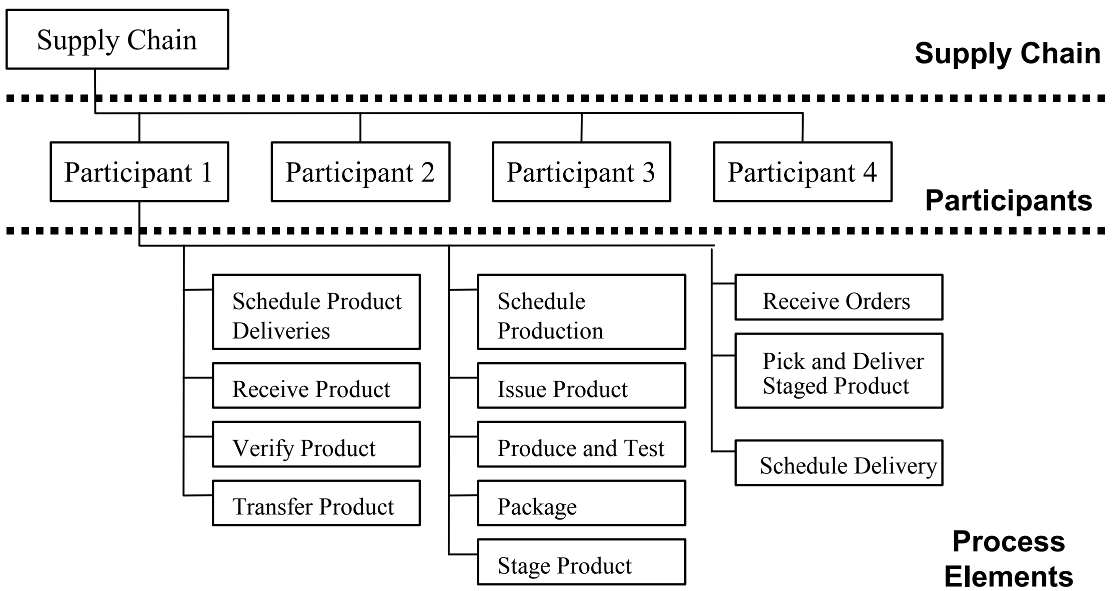

Figure 1. Submodel Hierarchy

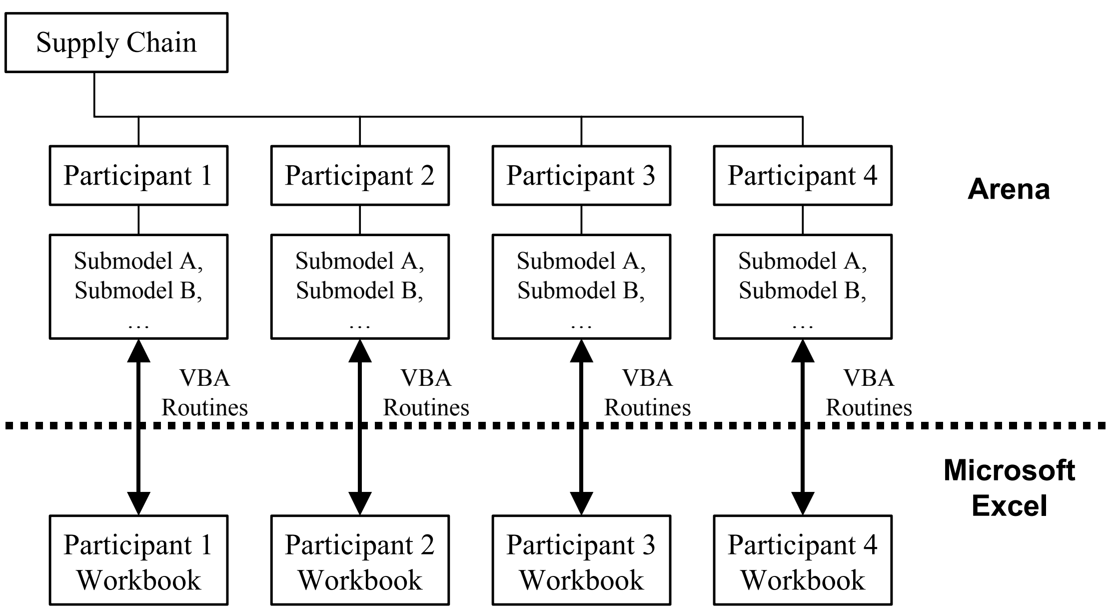

Figure 2. Arena and Excel Integration

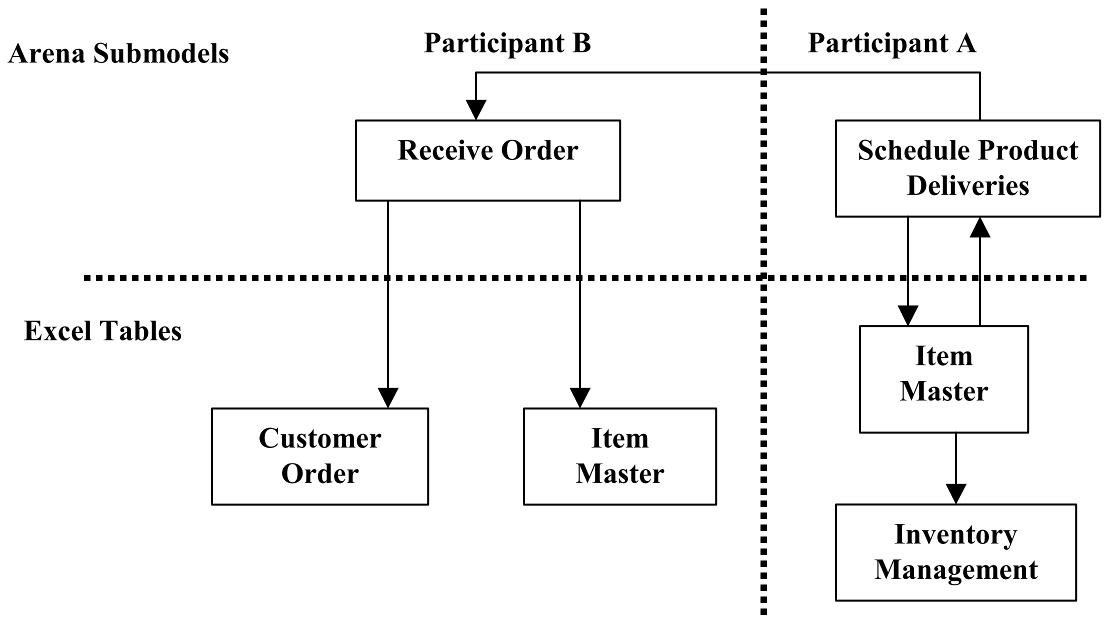

Figure 3. Participant A placing an order with Participant B

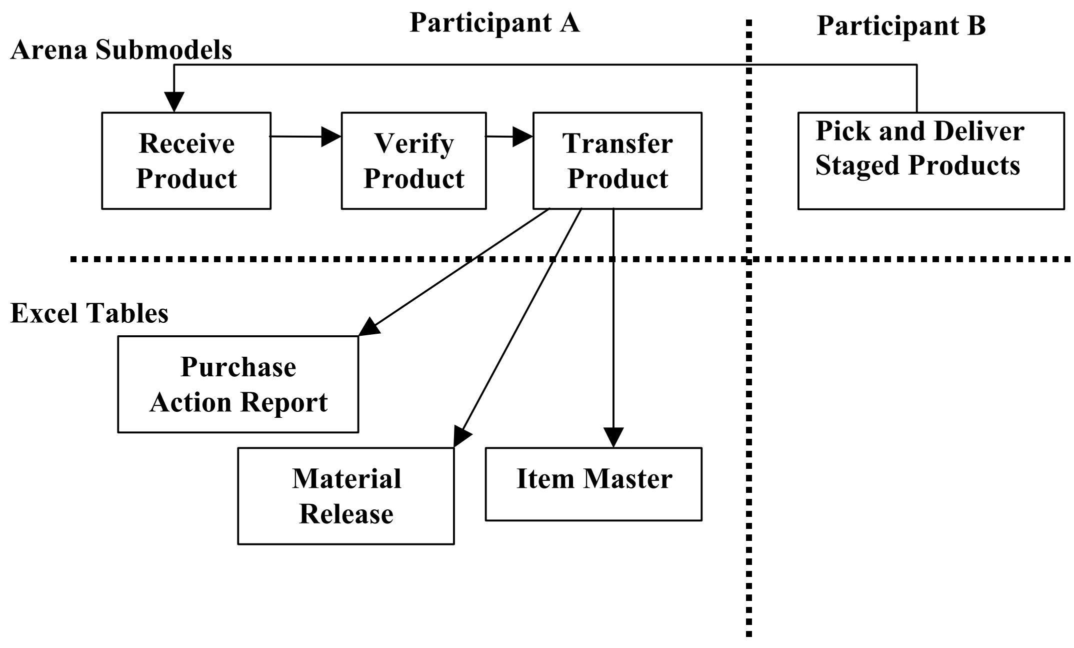

Figure 4. Participant A receiving delivery of orders from Participant B

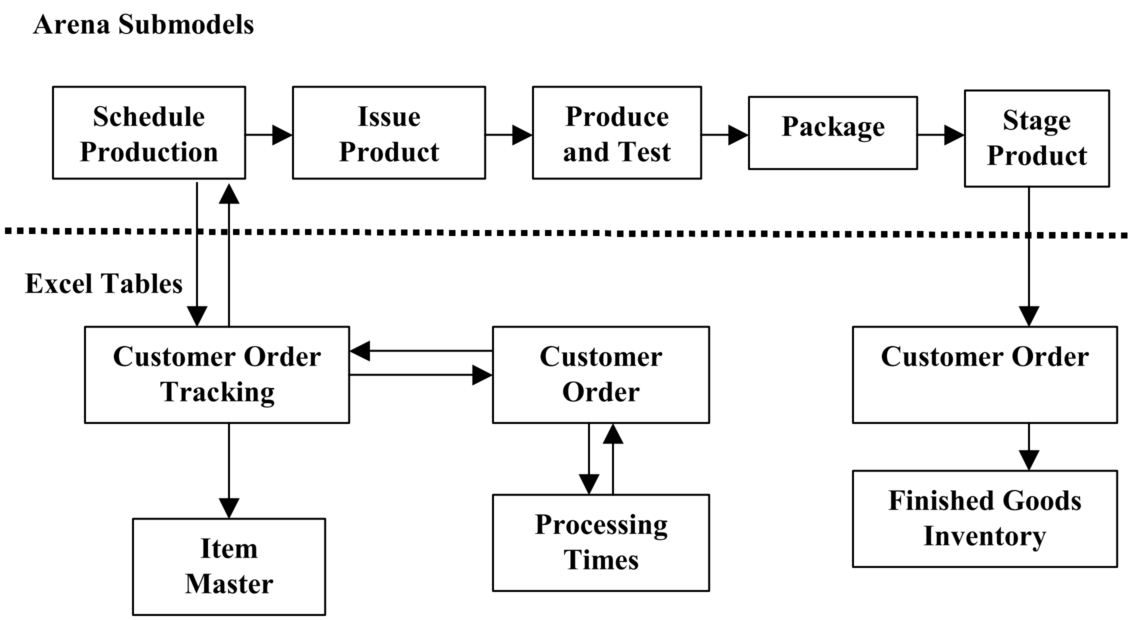

Figure 5. Checking Open Orders for Production

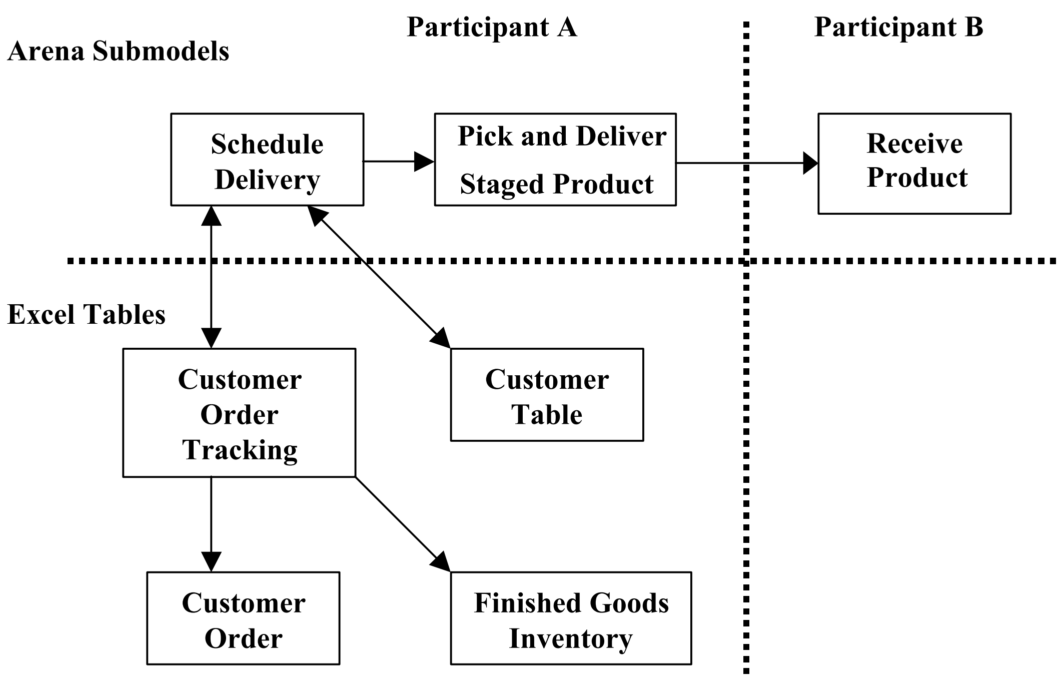

Figure 6. Participant A delivering completed orders to Participant B