A Multi-Agent Framework for Modeling Supply Chain Dynamics

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Abstract

Globalization of economy and increase in customer expectations in terms of cost and services have put a premium on effective supply chain re-engineering. As a result, decision support systems that can facilitate these efforts are in great demand. In this paper, we identify essential elements that are required for modeling supply chains and embed them in a multi-agent framework. Our framework uses simulation analysis and provides a platform for rapidly developing customized decision support tools for different supply chain problems with limited additional effort. A subset of concepts from this framework is being utilized by IBM for making supply chain re-engineering decisions.

1 Introduction

A supply chain can be defined as a network of autonomous or semi-autonomous business entities collectively responsible for procurement, manufacturing and distribution activities associated with one or more families of related products (see Figure 1). Different entities in a supply chain operate subject to different sets of constraints and objectives. However, these entities are highly inter-dependent when it comes to improving performance of the supply chain in terms of objectives such as on-time delivery, quality assurance and cost minimization. As a result, performance of any entity in a supply chain depends on the performance of others and, their willingness and ability to coordinate activities within the supply chain. Globalization of economy and increase in customer expectations in terms of cost and service have influenced manufacturers to strive to improve processes within their supply chains, often referred to as supply chain re-engineering. For example, Hewlett Packard's Vancouver division reduced inventory costs by approximately 18 % for HP Deskjet printers through delayed product differentiation (Billington 1994). Similarly, National Semiconductor has managed to reduce delivery time, increase sales and reduce distribution cost through effective supply chain re-engineering (Henkoff 1994).

Supply chain re-engineering efforts have potential to impact the performance of supply chains in a big way. As a result, it has become essential to perform a detailed analysis before adopting a new process in the supply chain. In addition, many times these re-engineering efforts are made under politically and emotionally charged environments. In such situations, decision support tools that can analyze various alternatives can be extremely useful in impartially quantifying gains and helping the organization make the right decision (Feigin et al. 1996). In most organizations, re-engineering decisions are generally based on either qualitative analysis (such as benchmarking) or on customized simulation analysis because complex interactions between different entities and multi-tiered structure of supply chains make it extremely difficult to utilize closed form analytical solutions. Benchmarking solutions provide insights into current trends but are not prescriptive. On the other hand, simulation provides a platform to perform detailed analysis and select among alternative solutions . However, there are two major problems with building customized simulation models: (1) they take a long time to develop and, (2) they are very specific and have limited reuse. Our aim in this paper is to provide a modular and re-usable framework that would enable rapid development of simulation based customized decision support tools for supply chain management.

In order to develop a generic and modular framework it is essential to understand important issues (decision tradeoffs) and common processes in different types of supply chains. Our framework is based on supply chain studies conducted in the following three domains (which differ in the degree of centralized control) - (1) a vertically integrated supply chain of a global computer manufacturer (Swaminathan 1994); (2) a Japanese automotive supply chain which is less tightly coupled (Womack, Jones & Ross 1990); (3) an inter-organizational supply chain in US grocery industry (Swaminathan 1994). We found that there are a number of common processes which are present across these supply chains. We have identified these processes and classified them in a library. The library consists of two main categories- *structural* elements and *control* elements. *Structural* elements (like retailer, distribution center, manufacturer, supplier and transportation vehicles) facilitate modeling production and transportation of products and *control* elements facilitate modeling various control policies (related to information, demand, supply and material flow) that govern product flow within the supply chain. We also classified issues in supply chain management into three broad categories namely *configuration*, *coordination* and *contracts*. *Configuration* deals with issues related to the network structure of a supply chain based on factors such as leadtime, transportation cost and currency fluctuations; *Coordination* deals with routine activities in a supply chain such as materials flow, distribution, inventory con-

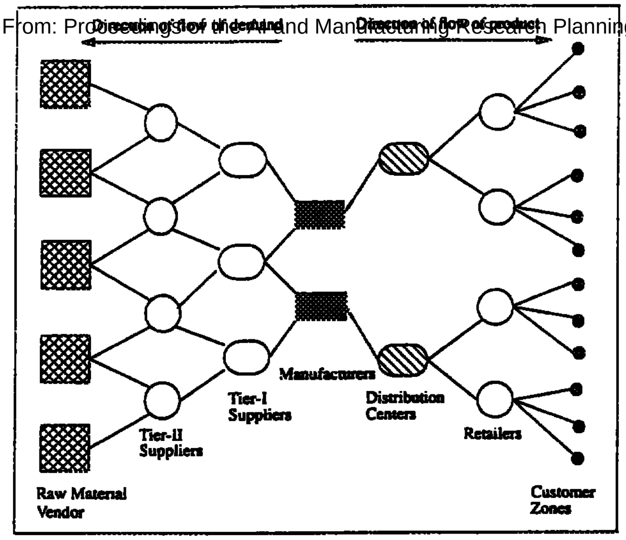

Figure 1: Supply Chain Network

trol and information exchange; *Contracts* control material flow over a longer horizon based on factors such as supplier reliability, number of suppliers, quantity discounts, demand forecast mechanisms and flexibility to change commitments.

Multi-agent computational environments are extremely useful in studying classes of coordination issues involving multiple autonomous or semi-autonomous optimizing agents where knowledge is distributed and agents communicate through messages (Bond & Gasser 1988). Since supply chain management is fundamentally concerned with coherence among multiple decision makers, a multi-agent modeling framework based on explicit communication between constituent agents (such as manufacturers, suppliers, distributors) is a natural choice. We model *structural* elements as heterogeneous agents which utilize *control* elements in order to communicate and control flow of products within the supply chain. Our approach emphasizes models that capture the locality that typically exists with respect to the purview, operating constraints and objectives of individual supply chain entities and, simultaneously promotes analysis of supply chain performance from a variety of organizational perspectives. In addition, modular architecture of our framework enables one to develop models for different situations with limited additional effort. In fact, to utilize this framework for modeling any new situation covered by the primitives of the library, one just needs to instantiate different agents and define connections and interactions between them. Simulations using alternative connections and different control policies would provide a detailed analysis of tradeoffs across various alternatives. In this paper, we describe our framework in its current state and provide an example to demonstrate how an issue relevant to supply chain management can be analyzed using the framework. A large number of issues in this domain can be analyzed with our framework and in fact, a subset of concepts from this framework is being used by IBM for supply chain re-engineering efforts.

The rest of this paper is organized as follows. Section 2 reviews existing research and approaches. In Section 3, we describe our multi-agent framework in greater detail. In Section 4, we identify the key elements required to model supply chain dynamics. We conclude and discuss future extensions of this work in Section 5.

2 Literature Overview

Supply chain management has been the subject of considerable research over the years. One can distinguish between three broad approaches: (1) Benchmarking efforts aimed at analysis of current practice in various sectors of industry; (2) Development of static analytical models; (3) Combination of analytical and simulation models to understand dynamics in a supply chain.

Benchmarking efforts at identifying new trends and philosophies in supply chain management based on comparative analysis of current practice in different countries and different sectors of industry include those reported in (Hall 1983), (Lyons, Krachenberg & Henke 1990) and (Womack, Jones & Roos 1990). (Lee & Billington 1992) provides an insightful survey of common pitfalls in current supply chain management practices. Some studies indicate that buyer-supplier relationships are becoming more dependent on factors like quality, delivery performance, flexibility in contract and commitment to work together, as opposed to traditional relationships based on cost (Helper 1991). Electronic Data Interchange (EDI) and Distributed Databases have been identified as important technological advancements that may benefit supply chain performance in a significant manner (Srinivasan, Kekre & Mukhopadhyay 1994). While providing general guidelines and identifying elements of best practice, benchmarking approach has been of limited help to managers who are looking for specific quantitative solutions to every day problems.

On the analytical front, research on multiechelon inventory problems has a long history ((Clark 1972),(Svoronos & Zipkin 1991)). A multiechelon system is one in which there are multiple tiers in the supply chain. This line of work assumes centralized control of the supply network, thus overlooking the possibility of decentralized decision making. More recent supply chain models in this area also include (Cohen & Lee 1988) and (Cohen & Moon 1990) where deterministic scenarios are considered and a global optimization problem is formulated using mixed integer programs. (Lee & Billington 1993) and (Pyke & Cohen 1994) consider stochastic environments and provide approximations to optimal inventory levels, reorder intervals and service levels. (Arntzen et al. 1995) develop an elaborate model for global supply chain management for Digital Equipment Corporation. Most of the above work has contributed in a significant manner to managerial decision making. However, these models are limited in handling issues related to dynamics of supply chains as well as study of decentralized supply chains.

The use of simulation as a vehicle for understanding issues of organizational decision-making has gained considerable attention and momentum in recent years ((Feigin et al. 1996), (Kumar, Ow & Prietula 1993), (Malone 1987)). (Towill, Naim & Wikner 1992) use simulation techniques to evaluate effects of various supply chain strategies on demand amplification. (Tzafestas & Kapsiotis 1994) utilize a combined analytical/simulation model to analyze supply chains. (Swaminathan, Sadeh & Smith 1995) utilize simulation to study the effect of sharing supplier available-to-promise information. However, one of the major concerns in utilizing simulation models as decision support tools is that they have limited reuse. Our aim in this paper is to provide a modular and re-usable framework that would enable rapid development of simulation based customized decision support tools for supply chain management.

3 Multi-Agent Framework

The approach in this work has been to utilize a multi-agent paradigm for modeling and analysis of supply chains. Multi-agent computational environments are extremely useful in studying a broad class of coordination issues involving multiple autonomous or semi-autonomous problem solving agents. Knowledge-based multi-agent systems have been found useful in many applications related to manufacturing including scheduling, vehicle routing and enterprise modeling ((Kwok & Norrie 1993), (Pan, Tanenbaum & Glicksman 1989), (Robaum, Sycara & Fox 1991), (Sadeh 1994), (Smith 1989)). In this work we have extended the use of multi-agent paradigms to the domain of supply chain management. Our approach has been to identify generic processes in this domain and classify them in a library. We embed the library elements in a multi-agent framework. These elements allow incorporation of various policies (derived from analytical models such as inventory policies, just-in-time release, routing algorithms) for demand, supply, information and materials control within the supply chain. Our analysis is based on discrete event simulation of the various alternatives and control policies. Combination of analytical and simulation models makes our framework extremely attractive to study both the static and dynamic aspects of problems.

Our framework consists of heterogeneous agents which communicate with each other through messages (communication protocols). We have defined a generic agent which is then specialized to perform different activities within a supply chain. For example, a manufacturing agent is different from a distribution agent or a transportation agent. Specialized agents correspond to *structural* elements identified in the supply chain library that are involved with production and transportation of products within the supply chain. Incoming messages are selected by each agent based on an event selection mechanism such as first come first served (FCFS). Response to each type of message is defined by its *message handler* routine which in turn uses *control* elements identified in the supply chain library. For example, when a *request for goods* message is processed at the retailer the following sequence of events occur. First, it is checked if the product is available in stock. If that is the case then the demand is satisfied and inventory on-hand is updated. Then the inventory control policy (say a base stock policy) is invoked. The control policy may generate a *request for goods* message for the supplier of the product based on inventory on-hand. If the product is not available in the first place, then the demand is lost or backlogged based on the policy at the retailer. In essence, agents (*structural* elements) utilize *control* elements and *messages* for communication purposes.

In the next subsection we introduce the generic agent architecture. Subsequently, we define various messages in our framework. Finally, we provide a simple example related to supply chain re-engineering and show in detail how we can model and analyze that problem.

3.1 Agents

Agent descriptions provide an ability to specify both static and dynamic characteristics of various supply chain entities. Each agent is specialized according to its intended role in the supply chain (for example manufacturer agents, transportation agents, supplier agents, distribution center agents, retailer agents, end-customer agents). An agent is defined by the following set of characteristics. Note that an interaction is same as a message.

- S_i - Set of attributes that characterize its (simulated) state at a given instant of time. State attributes include base information about an agent's processing state (for example, current product inventories, different costs associated with production, financial position). Associated with each aspect of local state are methods for accessing and (in the case of dynamic parameters) updating current values. Dynamic parameters change over time either as the result of internally triggered events (for example, when material gets transferred from work-in-process inventory into finished-goods inventory) or as a result of interactions with other agents (for example, receipt of an order from a customer, shipment of an order to a customer, payment for an order delivered to a customer).
- D_i - Knowledge at agent i about other agents. This includes information about the past performance of the different agents. These values may also be updated dynamically during simulation. For example, when it is known that a reliable supplier defaults often in terms of due date then that agent's reliability factor is updated accordingly.
- IC_i - Set of interaction constraints that define the agent's relationship with other agents in the supply chain. Each agent description designates the set of agents with which it can interact, and for each, indicates (1) its relationship to this agent (customer, supplier), (2) the nature of agreement that governs the interaction (production guarantees, agreement length) and inter-agent information access rights (which aspects of that agent's local state are accessible for consultation during local decision-making). All the information about other agents that is available without message transfers is controlled by the real-time information control policy (described in section 4.2.5).
- Q_i - Priorities of agent i. These help in sequencing incoming interactions for processing.
- PM_i - Vector of performance measures of agent i.
- I_i - Set of incoming interactions at agent i.
- O_i - Set of outgoing interactions at agent i.

- c_i - Incoming interaction that is chosen for processing by agent i
- Φ_i- Set of control elements available at agent i. A control element is invoked when there is a decision to be made which processing a message. For example, in order to determine the next destination on a transportation vehicle a route control element will be invoked.
- $M_i(c_i)$ - This defines the message processing semantics for message type c_i at agent i. Message handling routines may use one or more control elements which processing a message. For example, when a *request for goods* message is processed it invokes a inventory control policy. In some cases, more than one control element may be used. For example, real-time information control element may be invoked to obtain capacity information from the supplier agent before invoking the inventory control policy.
- $P(D_i, S_i, I_i, Q_i)$ - A selector function that chooses and sequences a set of incoming interactions based on domain knowledge, current state and the priorities of agent i. For example, when a manufacturer has orders from two customer agents then this function would determine the sequencing rule based on the priority given to each customer agent. Sequencing becomes important when the manufacturer does not have enough inventory to satisfy all the orders.

The sequence of events that occur at each agent that processes incoming messages is as follows (refer Figure 2). Each type of agent is defined with respect to a specific set of goals which determine commitments and control elements that it uses while interacting with other agents. For example, goal at the retailer is to reduce the turn-around time that the customer experiences. Performance measures of the agent as well as above commitments influence priorities Q_i of the agent. These priorities determine the sequence in which incoming interactions I_i are processed. The first interaction in the sequence c_i is analyzed for the type. It could be a material, information or financial message (as described in section 3.2). Each interaction or message type has a message handler $M_i(c_i)$ that performs a sequence of operations which may involve usage of one or more control policies as described in the example at the beginning of this section.

The message handling routines for the same message type may be different in different agents. For example, when a *goods delivered* message is encountered in a standard distribution center, the way materials are handled and stored is different from a cross-dock operation. Control elements that are triggered by the message handler help in making a decision for the agent. For example, a reordering decision or a routing decision. Message handling routines may also update the internal state and the domain knowledge, and, generate one or more outgoing interactions. Once the message processing operations have been completed, performance measures of the agent PM_i and the global performance measure GPM are updated. Outgoing interactions have the address of the destination as well as the time that they will be activated at that agent.

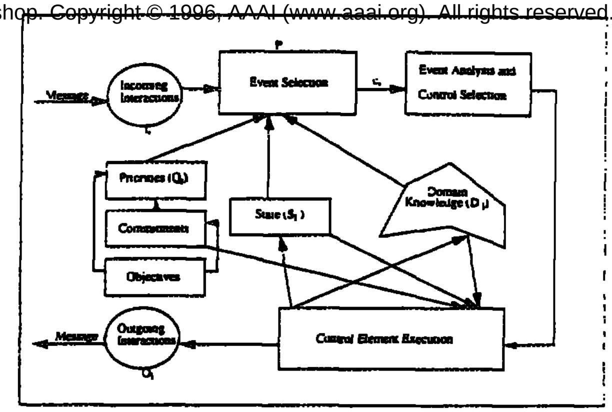

Figure 2: Agent Architecture

This process continues at an agent till there is no active incoming message at the given instant of time.

Since our framework is based on a discrete event simulator, agents are activated based on the time of activation of incoming messages. There is a global sorted (in terms of time of activation) list of incoming messages across all agents and the agent which has the first message is processed next. The simulation clock is advanced to the activation time. If this time is different from the current time of simulation then all the agents are updated in terms of their state and knowledge about other agents. Processing at each agent follows the above sequence and outgoing interactions are dynamically inserted into the global sorted list. Agents that did not process an interaction at a given time instant retain their state and knowledge about other agents in the next time instant. Simulation continues for the total simulation time specified by the user at the beginning of the simulation.

3.2 Interaction Protocols

Incoming and outgoing interactions are facilitated by control elements and are simulated via exchange of messages between agents. A basic set of *message classes* define types of interactions that can take place within the network. All message classes share specific common attributes, including the (simulated) time at which they are posted, the time they get activated, the posting agent and the recipient agent. Associated with each message class, in addition to any content specific parameters, are message handlers that define message processing semantics. As indicated earlier, this semantics may depend on the type of agent where the message is processed.

We recognize three broad categories of message classes, each associated with the simulation of a specific type of flow through the supply chain:

- *Material flows*: Messages in this category relate to delivery of goods by one agent to another. The processing semantics associated with material delivery messages minimally dictate adjustment to inventories of the posting and recipient agents by the quantity specified in the message. However, it can also trigger messages relevant to other supply chain flows (cash transactions) as well as local processing activities (determination of whether all the components required to initiate the assembly of a product are now available). Material delivery messages can be either sent directly by a supplier agent to a consumer agent (in cases where simulation of transportation delays and costs are not relevant) or may involve an intermediate transportation agent.

- *Information flows:* This category of messages model exchange of information between supply chain agents. It includes *request for goods* messages (flow of demand), *capacity information* (communication of expected available capacity), *demand-forecast information* (communication of demand forecasts) and *supply-related information* (expected delivery dates). Other messages that fall in this category include *order cancellation* messages and *order modification* messages (modified quantity or due date). The processing semantics associated with these messages will often be more complex than for other categories of messages. For instance, upon receipt of a *request for goods* message, an agent might perform a series of MRP-like computations and determine whether it needs to order additional raw materials or components from its own suppliers and might in turn issue *request for goods* messages to one or more of its suppliers.
- *Cash flows:* The final category of message classes concern the movement of capital through the supply chain. This category includes a *payment* message sent by customer agents to their supplier upon delivery of goods.

3.3 Performance Measures

One of the objectives of developing an integrated framework is to provide an ability to simultaneously observe global and local performance of the supply chain. Empirical studies have shown that sometimes taking a global perspective may be harmful to some of the entities in the supply chain ((Cash & Konsynski 1985), (Swaminathan, Sadeh & Smith 1995)). In our framework we separate local performance (PM_i) from the global performance measures (GPM). A global performance measure may be an appropriate yardstick for an intra-organizational supply chain (most of the entities belong to the same organization) however, local performance becomes an important measure for inter-organizational supply chains.

Supply chain performance measures can be classified into two broad categories. *Qualitative* performance measures such as customer satisfaction, integration of information and material flow and, effective risk management. *Quantitative* performance measures relate to cost minimization, profit maximization, fill-rate maximization, customer response time minimization, supplier reliability and lead time minimization. In our framework, we consider only quantitative performance measures. We provide the capability for analysts to monitor appropriate performance measures (either local or global or both) depending on the situation. It should be noted that there is a very strong link between goals of the agent in terms of the performance measures PM_i and priorities Q_i of an agent. These priorities determine the sequence in which incoming interactions are selected and in some sense drive the simulation.

3.4 An Example

In this subsection, we present a simple model to illustrate how our framework could be utilized for analyzing problems in the domain of supply chain management. One of the major concerns in the grocery chain industry is to try to reduce inventory within the supply chain. In order to achieve high level of service while keeping less inventory, they are considering a cross-docking mechanism at distribution centers. A cross-docking center differs from a standard distribution center in that inventory is never stored there. Inventory comes on one truck and leaves on another based on its destination. A cross-docking center only helps in sorting and shipping inventory to the correct destination. As a result, in a cross-docking environment, it may take more time to replenish orders at the retailer because inventory is not stored at the distribution center. A cross-docking environment is also information intensive because all that information is used in effectively sorting and shipping products. The question of interest here is to understand the tradeoff between inventory and service in the alternative arrangements. Since a grocery chain typically consists of different organizations, it is all the more important to understand effect of any change in the supply chain on the different entities. As a result, tracking individual performance is as important as tracking the global performance measure. We track the inventory and as well as customer service measure locally as well as globally. We now develop a simple model and illustrate how it fits in our framework.

We consider three retailer agents, one distribution agent, three manufacturing agents and one customer agent. Each of the three manufacturing agents produce one unique product. State of these agents is defined by finished goods inventory and outstanding orders. The customer agent generates demand for the three retailer agents for a mix of these three products. State of the customer agent consists of only orders that have not been delivered as yet. Each retailer agent stocks inventory of all three products and operates under an inventory control policy such as base-stock for each product. State of the retailer agents is determined by the inventories associated with each of the three products and the outstanding orders from the customer. We assume that these products can be made by the manufacturers without purchase of any components and as a result, the supply chain ends there. In a model with a standard distribution center, orders (messages) from retailer agents would come to it whereas in a cross-docking environment we assume that the orders go directly to the manufacturer. We also assume that products are transferred in truck loads and the release policy at the manufacturing agents is a batch policy. State of the standard distribution center is characterized by similar attributes as a retailer agent however, a cross dock is characterized by inventory of incoming and outgoing products. We have neglected transportation issues related to coordination of trucks by assuming that trucks are available in plenty. A more detailed model could be developed using a transportation agent.

The interaction constraints at each agent are limited to specifying the buyer-supplier relationships. We restrict our attention to only inventory control policies. The customer agent generates product demands based on the demand control policy employed which basically determines the type of demand (periodic or continuous) as well the nature (deterministic or stochastic). The *request for goods* message generated has the address of the retailer as well as the due date by which it is required. Incoming messages from the retailers have the due date as well as the current time. Statistics are maintained on the late orders as a performance measure. Each retailer agent processes an incoming message based on its type. It is either *request for goods* or *goods delivered*. If it is *goods delivered*, then the inventory level is adjusted accordingly, outstanding orders are taken care of and messages are sent to the customer agent. If it is *request for goods*, then the inventory position is checked. If inventory is available the order is fulfilled and future orders placed based on the inventory control policy. If inventory is not available then the order is made outstanding or lost based on whether demand is backlogged or not. Inventory position is tracked at each instant of time at each agent and is maintained as a performance measure. The distributor agent (in the standard mode) has very similar structure to a retailer agent. It stores inventory and replenishes them from the manufacturers. The prime difference being that products are shipped to retailers in truck loads. So, a number of *goods delivered* messages are collected together before being sent to the retailer. In a cross-docking mode, no inventory is stored. Each of the manufacturing agents maintain finished goods inventory and produce in batches. Shipments to distributor agent are made in truck loads.

With the above simple model it is possible to analyze some of the trade-offs in the alternative arrangements for distribution. Moreover, the results bring out benefits for different entities in alternative arrangements and provide a basis for negotiating cost and benefit sharing in the supply chain. Other variations of this supply chain can be easily analyzed as well. Suppose, if we wanted to analyze the effect of changing the inventory control policy at the retailer agent, we just need to specify a different control policy (from the set of existing control policies in our supply chain library) at the agent and simulate again. Similarly, we can study the effect of introducing one more retailer or one more manufacturer by introducing an agent of that type, defining its relationship to other agents and simulating the new supply chain. Our aim in this example was just to illustrate the ability of model such problems and develop a decision support tool using our framework with limited efforts. As a result we have not presented some of the other issues related to information and transportation which also play an important role in this problem. However, our framework has the capability to handle the above issues. The ability to combine simulation and analytical results as well develop models rapidly, has made this framework extremely popular with researchers in the industry. Concepts from our framework have been used to study various problems including inventory-servicability tradeoffs in a multi-tiered supply chain producing a large number of products, validating postponement strategies while facing short lead times (Swaminathan 1994), and, effect of supplier information (Swaminathan, Sadeh & Smith 1995) In the next section, we explain our supply chain library in greater details.

4 Supply Chain Library

Supply chain dynamics can become complicated to model due to presence of heterogeneous entities, multiple performance measures and complex interaction effects. Variety of supply chains poses a limitation on reusability of processes across them. For example, a supply chain could be highly centralized and have most of the entities belonging to the same organization (like IBM integrated supply chain) or could be highly decentralized with all the entities being separate organizations (like grocery supply chain). As a result, it is a difficult task to develop a set of generic processes that capture the dynamics of supply chains across a wide spectrum. In this section, we present a classification which enables modeling and analysis of a large variety of problems though it is not exhaustive by any means.

We classify different elements in the supply chain library into two broad categories- Structural elements and Control elements. Structural elements (modeled as agents) are involved in actual production and transportation of products and Control elements help in coordinating flow of products in an efficient manner with the use of messages. Structural elements are further classified into two basic sets of elements namely, Production and Transportation elements. Control elements are classified into Inventory Control, Demand Control, Supply Control, Flow Control and Information Control elements.

4.1 Structural Elements

As indicated earlier, structural elements are involved in production and transportation of products. Strategic placement of these elements constitutes major issues relating to supply chain configuration. In the following subsections we briefly describe each of the structural elements.

4.1.1 Production Elements

Production elements use inventory control elements for managing their inventory, contracts with the downstream entity for supply control, flow control elements for loading and unloading products, forecast elements for propagating forecasted demand to the downstream entity and may use either periodic or real time information control with other entities in the supply chain.

- Retailer: A retailer is where customers buy products. Main focus here is on reducing the cycle time for the delivery of a customer order and minimizing stockouts. The above goals define the objectives and priorities of this agent which are used while sequencing incoming interactions. When customer order for a product is received, it is determined which is the product that is being ordered. The product is packed and shipped to the customer if it is available as finished good inventory else the order is added to a queue (for the particular product) according to its priority (if the priority of all the orders are same then it is

FIFO (first-in-first-out)). When the product is delivered from the distribution center or the manufacturing (it is possible that some products may come from the manufacturing plant while others could come from the distribution center) plant, order is removed from the queue and product is packed and shipped to the customer. Many times, orders may be for multiple products in which case the processing becomes more complicated. Marketing elements (described in section 4.2.2) are used for controlling demand generated by customers.

- Distribution Center: A distribution center is involved in receiving products from the manufacturing plant and either storing them or sending them right away (cross-dock) to the retailer. Main focus here is to reduce the inventory carried and maximize throughput. In a standard distribution center products come in from the manufacturing or supplier plants. They are unloaded and stored in the storage area. When orders come from the retailer, relevant products are removed from the storage area (if the buffer has them or they wait till the products arrive into the buffer) and are sent to the appropriate loading dock where they are loaded and sent to the destination. As opposed to a standard distribution center, in a cross-dock there is no inventory storage. Products are unloaded from one transportation vehicle and are directly loaded onto outgoing vehicles to different retailers.
- Manufacturing Plant: A manufacturing plant is an element where components are assembled and a product is manufactured. In general, orders come from the distribution center but they could also come from the retailer (when there is a cross-dock or the supply chain does not have a distribution center). Main focus here are on optimal procurement of components (particularly common components) so that they are available when required and, efficient management of inventory and manufacturing process. Each product has an associated bill of materials (BOM). Manufacturing can be based on either a "Pull" or "Push" mechanism. In a Pull system, product is made only when an order is received for it, however, in a Push system, products are built based on demand forecast.
- Suppliers: A supplier element models external suppliers. These suppliers could be a manufacturing plant or assembly plant or could have their own supply chain for production. However, we model all these situations through a single element because the parent organization has no direct control on their internal operations. Supplier elements supply parts to the manufacturing plant. They focus on low turn-around time and inventory. Their operation is characterized by the supplier contracts which determines the leadtime, flexibility arrangements, cost-sharing and information-sharing with customers.

4.1.2 Transportation Elements

- Transportation Vehicles: Transportation vehicles move product from one production element to another. Each vehicle has associated characteristics in terms of capacity and relative speed. Vehicles use flow control elements in order to load and unload the products as well as to determine the route. The route taken by the vehicle depends on the state of the vehicle (which contains information on destination of products that have been loaded). Using distance of the next destination from the current destination, time needed to reach the next destination is obtained. At that time, products (destined for that production element) are unloaded and other products may get loaded.

4.2 Control Elements

Control elements facilitate production and transportation of products within the supply chain. Choice of appropriate control elements is the objective of problems related to supply chain contracts and supply chain coordination. We briefly describe the control elements that we have identified in our study.

4.2.1 Inventory Control

Inventory control elements are an integral part of any supply chain. They control flow of materials within the supply chain. They are mainly of two types - Centralized and Decentralized control.

- Centralized Control: These elements control the inventory at a particular production element while taking into account the inventory levels in the supply chain as a whole. A typical example is the inventory control based on *echelon* inventory. According to this policy, inventory control is done while considering the total inventory upstream also called *echelon* inventory. Thus, the order-upto levels are set according to *echelon* inventory levels. Another example is the integrated MRP(materials requirement planning) environment. An important requirement for implementing a centralized inventory policy is the ability to access information on inventory levels at other entities in the supply chain.
- Decentralized Control: These elements control inventory at a particular production element by considering inventory levels at that entity in the supply chain. Typical examples of these kinds of policies are- order-upto or base stock policy, MRP based ordering (with no information about inventory status at other agents) and (Q,R) or (s,S) policy. These policies are also used in centralized control though inventory levels in that case are calculated based on *echelon* stock. In a base-stock policy, orders are placed as soon as the inventory level reaches below the base-stock level in order to bring it back to that level. In MRP based ordering, the requirements are based on the MRP explosion (considering the forecasts as exact) and in (s,S) [(Q,R)] policy, ordering is done when the inventory levels goes below s [is equal to R] and orders are placed so that inventory is brought upto S [Q+R].

4.2.2 Demand Control

The demand process within a supply chain is sustained through actual and forecasted orders (these are modeled as messages in our framework). Orders contain information on - types of products which are being ordered, the number of products that are required, the destination where the product has to be shipped, and the due date of the order.

Two important demand control elements are:

- Marketing Element: One of the important aspects of product management is how well the product is marketed to consumers. There are numerous ways to increase demand for a particular product. Advertisements, discounts, coupons and seasonal sale are some of them. Marketing element provides a mechanism that can trigger additional demand for products. Increase in demand could be seasonal, random or permanent. This element allows us to capture marketing strategies that might be used in the supply chain. We restrict the usage of these elements only at the retailers because these elements can have a direct impact on demand experienced by the supply chain (in some sense we capture the effect on end-consumers only). Demand can be influenced by other agents as well without utilizing these elements (like supplier agent providing bulk rates to increase the purchases made by the manufacturer).
- Forecast Element: Forecast elements determine how forecasts are generated within the supply chain and how they evolve over time. In a "Push" system, forecast evolution plays a very important role because manufacturing decisions are based on forecasted orders. Greater forecast inaccuracy leads to greater mismatch between products demanded and products produced, and as a result leads to higher inventory costs. In a "Pull" system, forecast accuracy does not play an important role because products are built-to-order.

4.2.3 Supply Control

Supply Control elements dictate terms and condition for delivery of the material once orders have been placed. Contractual agreements are the only form of supply control element that we have identified. Contracts contain information on the price of the material, length of the contract, volume to be purchased over the contract period, penalty for defaulting, leadtime to get the product once final order has been placed, amount of flexibility that the buyer has in terms of updating demand forecasts over time (often referred to as *flexibility* offered by the supplier) and types of information control that could be used. Supply contracts may differ in characteristics and rigidity depending on whether supplier of the product belongs to the same organization or not. Transfer pricing mechanisms are employed while dealing with internal suppliers (this could be thought of as a form of centralized supply control).

4.2.4 Flow Control

Flow control elements coordinate flow of products between production and transportation elements. Two types of flow control elements are:

- Loading Element: Loading Element control the manner in which the transportation elements are loaded and unloaded. This control is different based on the type of the production element where products are loaded or unloaded. For example, the loading and unloading operations require different specifications depending on whether the production element is a standard distribution center or a cross-dock. This control element is located in the corresponding production element.
- Routing Element: Routing element control the sequence in which products are delivered by the transportation element. The route taken by the transportation vehicle depends to a great extent on the destination of products that it is carrying. So, the routing is dynamic in that sense. The route can be decided in a centralized or a decentralized manner depending on how much information is available about destination of other transportation elements.

4.2.5 Information Control

Information control elements are extremely important for coordination within the supply chain. Two types of information flow are:

- Real Time: Real time information transfer refers to the instantaneous propagation of information. For example this could be information on inventory levels, capacity allocations, machine breakdowns etc. at other production elements or the routes to be taken by other transportation elements.
- Periodic: Periodic information updates may be sent by different production and transportation elements to indicate changes in business strategy, price increase, introduction of new services or features in the products, introduction of new production element etc. Periodic information is sent to all the entities in the supply chain in the form of messages, as opposed to real-time information, which is explicitly agreed upon in the supply control element.

The above defined set of elements along with the Customer agent that generates demand for the system constitute our framework.

5 Conclusions

As manufacturers attempt to increase supply chain performance, there is a critical need to gain a deeper understanding of ways various supply chain decisions affect their operations as well as those of their partners. Decision support systems that can facilitate these efforts are in great demand. In this paper, we identify essential elements that are required for modeling supply chains and embed them in a multi-agent framework. Our approach underscores the importance of models in which different partners operate subject to their own local constraints and objectives and have different local views of the world, and the need to understand performance from a variety of organizational perspectives. Our framework uses simulation analysis and provides a platform for developing customized decision support tools for different supply chain problems with limited additional effort. The library of supply chain elements makes our framework modular and easy to re-use. The ability to combine simulation and analytical results as well develop models rapidly, has made this framework extremely popular with researchers in the industry. In fact, a subset of concepts from this framework is being utilized by IBM for supply chain re-engineering efforts.

The current version of our framework is suitable for addressing issues related to (1) inventory/servicability tradeoff (2) manufacturing, distribution and retailer location and (3) inventory control policies. However, we do realize that there are certain dimensions in which our framework can be improved. We plan to work on the following enhancements in future - (1) development of features in messages related to cash flows to enable simulation of global environments including currency exchange rates, (2) development of processes to simulate continuous manufacturing, (3) incorporation of learning in agents and make them adaptive agents, (4) choice in control policies that agents could use at any time, and, (5) improvement in the efficiency of the software in order to enhance the speed of simulation. In conclusion, we feel that our framework is a first step towards enabling easy development of decision support tools in the domain of supply chain management and would be extremely useful to supply chain managers.

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