Information Sharing in the Hardwood Supply Chain

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ABSTRACT

The Hardwood Industry in United States has been challenged by low-cost competition from overseas. Although cost reduction strategies have had minimal success, the proximity of industry to the domestic market has large implications on a more customer-focused strategy. The problem arises that individual companies and supply chains evolved based on the principles of economies of size and not on the flexibility to adapt to customer needs and changing resource constraints. An increased rate at which material and information flows through the hardwood supply chains is the key to the industries' ability to be customer-focused. Information systems may offer benefits for the industry, but changes in material flow of a company or supply chain cannot necessarily be predicted when implementing information systems.

It was hypothesized that by understanding the dynamics between information flow and material flow throughout the supply chain, performance improvement would be possible through more effective release and use of information. A case study analysis of a hardwood supply chain was utilized to identify the effect of increased information flow on the material flow of the supply chain. Value Stream Mapping was utilized to benchmark the current state of lead times of information flow and material flow. System Dynamics was utilized to understand the relationships between the information flow and the material flow. Finally, simulations were performed to identify the specific effects on material flow as increased information flow is released through different information strategies.

The study showed that increased information flow between supply chain members increased material flow through the supply chain. For a case study supply chain, an increase in information flow, through advanced knowledge of customer demand by a supplier, was found to reduce the inventory buffers throughout the supply chain by up to 38 percent and increase the total material flow through the supply chain by 10 percent. In addition to the increased information flow caused by the advanced knowledge of demand (18 percent), information flow

would increase (by an additional 7 percent) based on the reductions in buffer inventory within each company of the supply chain.

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Chapter 1 Introduction

1.1 Background

The Hardwood Industry is a division of the Forest Products Industry. The companies within the Hardwood Industry are differentiated from other forest products companies based on the raw material resources and the primary markets by which they serve. The primary products of the hardwood industry leverage the strength and beauty of the wood found in hardwood trees which typically garner a premium in products such as furniture, flooring, and cabinetry (Luppold et al. 2004).

The Hardwood Industry is more than the companies that manufacture the products that final customers utilize in their daily life. The Hardwood Industry is made up of a chain of suppliers, or a supply chain of companies that transform the raw material, the hardwood trees, into the final product (Kaplinsky et al. 2001). These companies include logging companies, sawmills, component plants, transportation companies, wholesalers, retailers, etc.

As a whole, the United States Forest Products Industry manufactures approximately 187 billion dollars of products each year which represents four (4) percent of the total manufacturing in the United States (United States Census Bureau 2009). Even with an increasing domestic demand, the Hardwood Industry within the United States has been shown to be currently undergoing a decline in production levels marked by closures of manufacturing facilities (U.S. Census Bureau 2006). The primary reason for this decline is an increased flow into the United States from other countries of similar products to that manufactured by companies in the United States (U. S. Department of Commerce 2007). Many of these non-domestically manufactured products are produced in countries such as China, with lower production costs than in the United States (Cao et al. 2004). These lower production costs are low enough to more than compensate for the additional costs of container shipping the products to the United States and still offering the product at a lower price than domestically manufactured products (Houston 2003).

Faced with the international competition, some companies within the Hardwood Industry have made attempts to reduce costs with the hopes that they will be able to match or be lower than the prices offered by the foreign competition. Introduction and implementation of continuous improvement strategies such as Lean Manufacturing and Six Sigma have continued in the Hardwood Industry spurned by the expectations of reduced costs (Sabri et al. 2004;

Motsenbocker et al. 2005). However, companies are finding that outsourcing, or replacing their production with the lower cost imports is a much faster and easier way to cut costs (Bryson et al. 2003). The later approach, outsourcing, can assist in maintaining jobs in the Hardwood supply chain but only from the company doing the importation to the final customer. The traditional suppliers of these outsourcing companies (domestic logging companies, sawmills, etc) then have a reduction in demand from their traditional customers and must find new customers or close their businesses. Overall, Hardwood Industry members have shown a negative outlook for domestic manufacturing (Grushecky et al. 2006).

The traditional management and marketing techniques in the hardwood industry, which have been slow to become more end-customer focused, require a shift in the methods by which these companies have been operating up to this point. Potential shifts include new business, sales, and manufacturing strategies; reinvention of the final product; and innovation (Schuler et al. 2003). Cost can be an important part of competing for a particular market, but it is only one part of the value associated with a product. A study identified four factors that determine the performance strength of a furniture company - 1) Delivery, 2) Value, 3) Flexibility, and 4) Innovation (Vickery et al. 1997). Price was identified as only one of three sub-factors within the factor "value;" the others being reliability and quality. As a whole, the four factors describe a customer-focused company with price (cost) only being one portion of the attributes for which a final customer would associate with a product. One of the advantages the United States furniture industry (and the Hardwood Industry as well) has over overseas competition is its proximity to its intended final market.

For the Hardwood Industry to overcome the current challenges, an alternative solution to competing based on cost is to become more customer-focused, as cost is only one portion of what customers look for in products (Schuler et al. 2003). However, some companies are utilizing larger finished goods inventory to be able to deliver faster (Buehlmann et al. 2007). This practice of larger inventories may assist in getting a product to a customer faster, but it hinders the company from altering the products to better conform to the final customers' needs. In addition, one of the characteristics of imported goods is large inventories at the retailer or wholesaler due to large shipments from overseas, which would be similar to that of the inventories being created by domestic manufacturers. Instead, domestic manufacturers could be looking at a customer-focus that requires companies to be responsive to the changing needs of their final customers and integral coordination among all of those involved in meeting the needs of the final customer (Gulati et al. 2005).

One of the primary issues in the Hardwood Industry's ability to be customer-focused is in the limited methods by which individual companies communicate and collaborate with their supply chain partners (suppliers and customers). A study of the US Hardwood Industry found that the industry still relies on minimal communication between supplier and customer along the supply chain with the primary conveyances being one-on-one meetings or plant visits and less on business-to-business information integration and leveraging the internet (Bowe et al. 2001). Without proper communication, the flow of the specific needs of the final customers are delayed or barred from being passed from customer to supplier throughout the supply chain.

With the absence of effective "real-time" information a company must rely more on forecasting, that is estimating (or perhaps even guessing) what the true demand for their products will be. This reliance on forecasting leads to inventory stockpiling to reduce stock-outs and an artificially induced increase in demand variation along the supply chain leading to deviations and distortions in demand rates from the actual final customer demand (Forrester 1961). In the Hardwood Industry, as well as other industries, forecasting causes individual companies to amass large inventories of finished goods at one end of the production line and large inventories of raw materials at the other end of the production line to account for differences between the forecasted demand and the actual demand. In addition, instead of producing to demand, these companies are producing to fill inventory quotas. If each company along a supply chain forecasts demand and stockpiles inventory at both ends of the facility, the result is a long lead time for material to flow from the source of the raw material to the final customer of the supply chain. Such long lead times make it difficult for the supply chains to adapt to changes in the market and make it impossible for the supply chain to be agile enough to change quickly to immediate changes in the final customers' needs (Lee 2004).

Although an efficiently organized supply chain has many benefits for the individual members of the supply chain such as reduced lead times and reduced costs due to decreased inventory levels (Carlsson et al. 2005), there are many barriers that prevent companies from cooperating as an organized supply chain, the greatest of which is the resistance to change both internally and externally (Krause et al. 1998). A supply chain that is not well organized also faces competition from among its members for control of the supply chain (Cox et al. 2001).

Finally, supply chain members that are closest to the final customer can show resistance to information sharing with those supply chain members further upstream from the customer (Cachon et al. 1997).

For the United States Hardwood Industry, the increased competition from abroad for domestic sales has created a situation in which the barriers to supply chain organization must be overcome. The benefits of an organized supply chain, reduced inventory and decreased delivery times (Cachon et al. 2000), not only assist in making the members of the supply chain more reactive to the needs of their immediate customers but also the final customer. In addition, the reduction in inventories and reduction in duplicated processes between supply chain members can lead to reduced overall costs (Cachon et al. 1999), which can assist the Hardwood Industry with the international competition.

There is an opportunity within the Hardwood Industry to utilize supply chain management methods to become more competitive with foreign companies within the domestic market. However, the lack of information flow within the Hardwood Industry creates a barrier to cooperation for the Hardwood supply chain partnerships. Increasing the flow of critical information between supply chain members may potentially increase material flow, reduce inventory needs and thus make the supply chain more customer-focused.

1.2 Problem Statement

The Hardwood Industry is currently attempting to compete with foreign companies on the prices of their respective products, and by doing so they are trying to reduce costs to be able to offer their products at reduced costs to the final customer. Literature shows that cost (or value) of a finished product is only one factor that drives a consumer to purchase a product (Vickery et al. 1997). Because of proximity to the market, domestic hardwood manufacturers should have an advantage over foreign competition by being more attentive to the needs of the customer. However minimal information is shared between members of the supply chains that make up the Hardwood Industry which greatly affects all of the members' abilities to be more focused on the final customer.

1.3 Hypothesis

The hypothesis of this research is that increased sharing of the right information between individual companies within the hardwood supply chain without changes to production or inventory policies can address the lack of customer-focus of the Hardwood supply chain. By viewing the entire Hardwood supply chain as an individual organization, a systems perspective is needed to incorporate both internal and external information to reduce order delays, production lead-times and inventories, all of which are necessary to create a customer-focused supply chain.

1.4 Objectives

The research quantifiably determines the impact of several methods of information systems implemented in a Hardwood supply chain. In addition, the research compares the effect of implementing an information system to only one company within a supply chain to the implementation of a standard information system to the entire supply chain. To meet this purpose, the objectives of the research included:

1) Determine the pathways of information and production flow through the Hardwood supply chain and benchmark current lead times for both.
2) Identify the inter-relationship between supply chain information and the managerial decision-making process for production within the supply chain.
3) Investigate the impact of increased information sharing on the Hardwood supply chain.

1.5 Approach

At the core of the research, a systems approach was utilized to unravel the intricacies of the relationships within the supply chain with respect to information flow between supply chain partners. Systems Dynamics, an analytical approach for the understanding of complex and interactive systems such as supply chains, was combined with supply chain evaluation tools of Lean Production as well as discrete-event simulation to describe, define, and analyze the Hardwood supply chain.

Lean Production tools, developed for observation and evaluation of supply chains, were utilized to describe the paths by which information and materials flow through the supply chain.

Lean Production is a continuous improvement strategy for manufacturers and service companies that includes a set of tools for implementation.

Systems Dynamics was utilized to define the means by which information flows through the supply chain and controls the rate at which material flows. With this approach, quantifiable factors, such as inventory levels, production rates, and other manufacturing measurements can be tied directly to non-quantifiable factors such as policies, perceptions, and attitudes.

Discrete-event simulation was utilized to analyze the effects of altering the information flow through the supply chain. Since altering an entire supply chain to see the effects of different scenarios is not feasible, simulation allows the analysis of substantial changes to a system with no affect to the original system. The simulation package, Arena by Rockwell Industries was utilized for this research.

1.6 Significance of the Study

The results of this research have contributed to both the areas of Supply Chain Management and Wood Science and Forest Products.

1.6.1 Supply Chain Management

This research enhances the knowledge of Supply Chain Management by:

- Expanding the evaluation and benchmarking of supply chains for the extended forest to consumer value stream. The resultant research of the supply chain utilized in this research, that of one within the Hardwood industry, can be utilized for comparison to other supply chains researched in the future or against general supply chain research.
- Identifying potential barriers to an integrated supply chain. The case study research allowed for a detailed analysis of linkages between management decision-making within companies and the flow of information between companies.

1.6.2 Wood Science and Forest Products Industry

This research enhances the knowledge of the Wood Science and Forest Products field, specifically in the area of industrial management and engineering, by increasing the understanding of the inter-relationship between companies that make up the Hardwood supply chain. Some of the specific areas of interest include:

- Benchmarking of a Hardwood supply chain. The lead time for a supply chain in the Hardwood Industry was analyzed to determine the length of time that it takes material to flow from the forest to the final customer through all of the companies that touch the material. Through this research, the Wood Science and Forest Products Industry has:
  1. An initial benchmark for the Hardwood supply chain, as this information has not been published previously.
  2. A procedure for performing supply chain analysis of lead times for other companies/supply chains in the Hardwood Industry.
- Potential performance measurements and metrics for the Hardwood Industry. Supply Chain Management performance measurements identified in literature were applied to the analysis of the case study supply chain within the research. Metrics for these performance measurements were determined based on criteria required by the research. These performance measurements and metrics can be utilized and/or adapted for future research in the Hardwood Industry supply chains or within the industry for self-evaluation.
- Best practices for management of Hardwood Industry supply chain with regards to minimization of lead times which could lead to improved customer-focused strategies. Through the examination of alternative information strategies within a hardwood supply chain, other companies within the Hardwood Industry have an external reference point by which internal analysis may be built.
- A method/tool to analyze the usa of information technology in the Hardwood Industry. The applications of mapping information flow through a hardwood supply chain utilizing Lean Manufacturing tools and System Dynamics to understand how that information flow is inter-related to management procedures/protocols can give management within the Hardwood Industry the tools required to improve information flow within their own organizations. This analysis method includes the ability to evaluate the benefits of investments in technologies such as automation, information systems, and Radio Frequency tracking tools.

1.7 Literature Review

1.7.1 Supply Chain

For many products, the process of getting from raw material to final customer involves going through a number of different companies. Each company takes the products of its suppliers and makes the product more desirable for its customers through additional production or services. The complete path of companies through which material flows from raw material to final customer, is called a *supply chain*.

The term *supply chain* is defined a number of ways. One definition is “an integrated process wherein a number of various business entities (i.e., suppliers, manufacturers, distributors, and retailers) work together in an effort to: (1) acquire raw materials, (2) convert these raw materials into specified final products, and (3) deliver these final products to retailers”(Beamon 1998). Another definition is “all the activities involved in delivering a product from raw material through to the customer including sourcing raw materials and parts, manufacturing and assembly, warehousing and inventory tracing, order entry and order management, distribution across all channels, delivery to the customer, and the information systems necessary to monitor all of these activities” (Lummus et al. 1999).

From both definitions, a supply chain can be viewed as a community of business entities that transform raw materials to a product (or service) for a final customer. How well the organization performs is determined by how well the individual companies perform to meet the needs of the final customer in terms of product design, delivery, quality and cost.

A supply chain can be represented as a serial formation of events and/or processes that creates a final product from raw materials. A simplistic model of a supply chain is shown in Figure 1-1. Each link of the chain is a step represented by a process, a company, or other definable subdivision of the entire system that plays an integral part in bringing a product or products to the final customer. The top arrow shows the direction of the flow of the product through the supply chain while the bottom arrow shows the generally accepted flow of information (product requirements, customer specifications, demand quantities) which begins at the final customer.

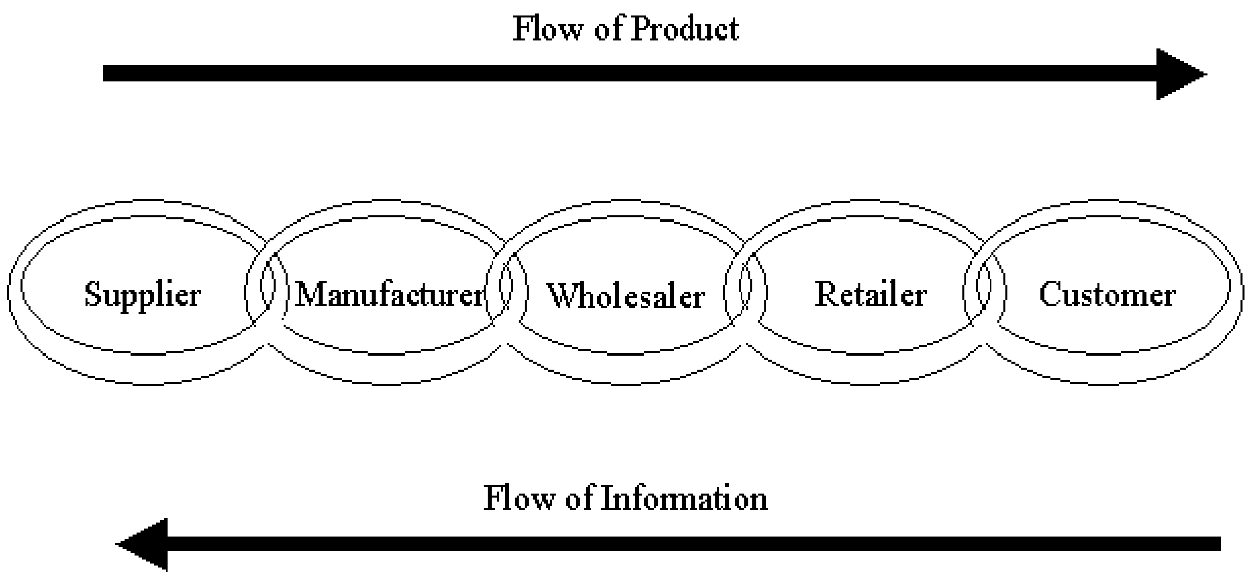

Figure 1-1 Simplified Representation of a Supply Chain

In reality, the supply chain is a much more complex system in which each company may be a part of any number of supply chains all with their own end customers each requiring information flow patterns. Due, in part, to this growing complexity of the supply chain systems, a relatively new field of business has evolved called Supply Chain Management (SCM), which can be defined as “the integration of business processes from end user through original suppliers that provides products, services and information that add value for customers” (The International Center for Competitive Excellence 1994). Though the terms SCM and Logistics are sometimes interchanged, logistics is generally associated with management by single organizations along the supply chain and more product-oriented than process-oriented. A more formal definition of logistics is “the function responsible for moving materials through their supply chains” (Waters 2007), whereas Supply Chain Management is the inter-organizational management of the supply chain with more of a customer focus (Cooper et al. 1997). As an example of the difference, trucking companies serve as logistical contractors for companies that do not have their own fleet of trucks, whereas a company that works with the various members of a supply chain to determine the rate of production of each facility, the where and how much inventory should be held, and marketing to final customer would be supply chain management.

1.7.2 **Hardwood Supply Chain**

The usage of the hardwood resource can be divided into three broad categories or markets: industrial, fiber/composites, and appearance/aesthetic (Luppold et al. 2004). Industrial markets value only the large-scale strength of the raw material, with example markets of pallets, containers, and railroad ties. The fiber/composites markets value the strength of the material on a micro scale with an example product of panel boards. Finally, the appearance/aesthetic markets value not only the strength of the raw material but also the beauty with example products such as flooring, furniture, cabinets, and millwork. This final market pays more per unit of the raw material than the other markets, and demands higher quality material with visual aesthetics for which consumers are looking to differentiate their final products. The appearance/aesthetic market is the focus of this research.

The Hardwood Supply Chain is so named because of the dominance of the raw material, the wood from hardwood trees, through the entire supply chain. The typical final consumer products created from this supply chain are furniture, flooring, and cabinetry, most of which have the raw material of hardwood as the primary constituent of the finished product by volume. Other products/raw materials such as metal fasteners, finishes, etc., are minimal compared to the hardwood resource. Thus, the Hardwood Supply Chain can be shown (Figure 1-2) to be controlled predominantly by the hardwood raw material (Kaplinsky et al. 2001).

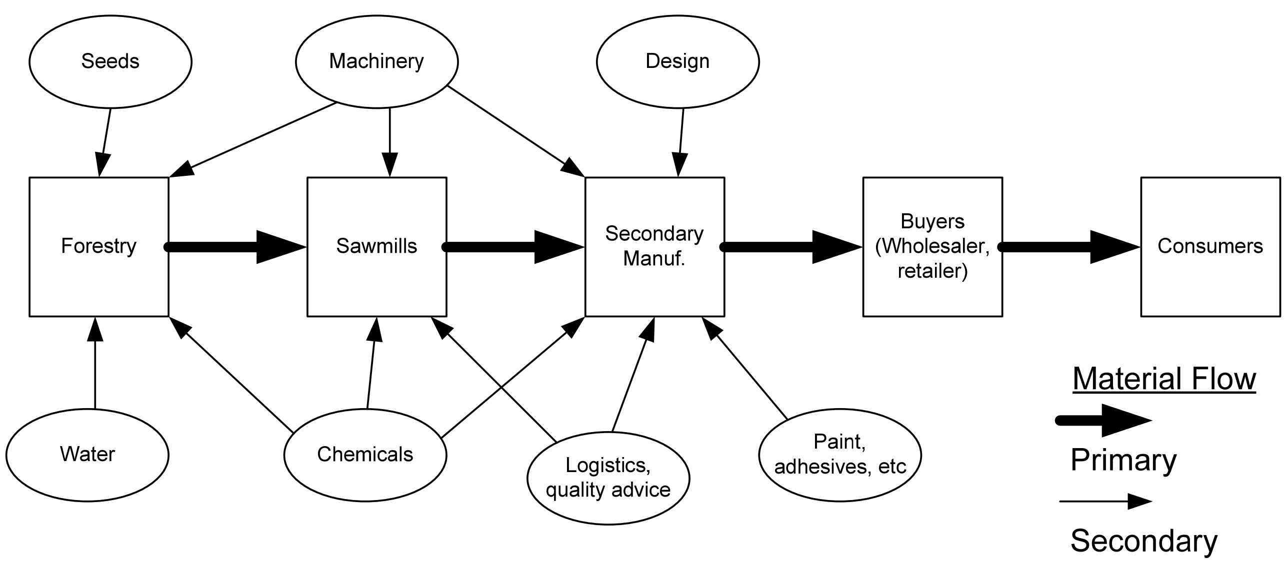

Figure 1-2 A Model of the Flow of Material through the Hardwood Supply Chain

The Hardwood Supply Chain begins with the harvesting of the trees from the forest. The trees are felled, de-limbed, and cut to specific lengths. The logs are then merchandised to maximize their return or profit. Potential clients for harvesters include veneer mills, sawmills, and fiber/chip mills. Each client segment has requirements of size and grade and in turn pays a price for the logs accordingly. Approximately 3% of raw materials harvested is deemed high enough grade for the veneer mills, 43% meet the grade requirements of sawmills, and the remaining is the low value / low cost material utilized for fiber/chip mills (Luppold et al. 2004).

The logs that are sent to the sawmills, and not chipmills, are processed into lumber with the goals of maximizing the value of each log. High log value at the sawmill is typically obtained by maximizing the lumber yields of the higher quality material from the log which is valued by the aesthetic/appearance markets. The lumber that does not meet the higher grades is sold to the industrial markets that value the lumber's material strength properties. Lumber is typically sold by the sawmill as kiln dried (natural occurring water mostly removed) or green (with the water still remaining). If it is sold as green, the drying process will be done by the immediate customer, as is required for finished applications.

Most of the lumber that is of aesthetic/appearance grade goes to companies specializing in furniture, cabinetry, flooring, or millwork. These companies process the lumber into finished products that will end up with the end consumer. For the initial conversion of lumber to parts, the cost of the lumber can represent approximately 50 percent of the total costs (Mitchell et al. 2005), thus care is taken to maximize efficiencies while meeting the needs of the end customer.

The remaining portion of the supply chain is bridging the gap between manufacturer and end customer. This segment can include some combination of wholesalers, distributors and retailers. Though the segment aids in linking the consumer product manufacturer with the end customer, it can create a significant gap in time and understanding between the two groups.

In addition to wholesalers and distributors at the end of the supply chain, there are also opportunities for intermediate distributors at other stages in the supply chain. For example, lumber distributors can be utilized between the sawmill and the consumer product manufacturers. These distributors can have both positive and negative affects over direct dealings between the manufacturers. On the positive side, they can add a valuable service by consolidating products from many sources and then sorting and distributing according to market needs. On the negative side, they can make the flow of materials and information more complex, add delays and add costs to the supply chain.

Finally, there can be another intermediate step between the sawmills and the consumer product manufacturer. This can be either a dimension mill or other subcontractors. The dimension/component mill is a manufacturer that specializes in the conversion of lumber to intermediate parts or blanks. Other subcontractors can include any manufacturer that produces parts for the consumer product manufacturer. These parts may be subcontracted due to equipment limitation, capacity limitation, or cost limitation.

Supply Chain research for the wood industry has been primarily focused on the supply of logs to sawmills and pulp mills. The issues in this portion of the wood supply chain fall into two major categories: 1) minimization of inventory at the mills due to variable logging schedules caused by inclement weather and 2) logging crews not being able to work effectively based on the short production scheduling horizons at the mills.

Research at a large pulp producer with five mills was conducted due to changes in demand affecting the logging and delivery schedules (Bredstrom et al. 2004). The mills had issues in the changing product mix affecting the log supply. To minimize flow and storage cost, simulations were conducted to compare the current "manual planning" system with several modeled systems to assist in the decision-making process with regards to supplying the mill with logs. It was determined that the optimized decision models could help to minimize inventories and costs of the log yard by supporting those in charge of planning.

Another research study in pulp mill operations looked at the affect of the varying weather conditions on inventory levels of the log yard at the mill (Luc et al. 1997). In this case, the problem being investigated was the variability in inventory at the mill due to inclement weather impeding harvesting. Using simulation modeling, it was determined that a buffer inventory of two days at the log deck in the forest greatly assisted in controlling variability at the mill. Additionally, the buffer inventory creates a higher efficiency of the loggers during fair weather days. Though not specifically discussed, the buffer stock in the forest appeared to serve as a form of communication from the mill to indicate the production rate required of the loggers.

1.7.3 **The Extended Value Stream**

The term "extended value stream" is sometimes used interchangeably with the term "supply chain." First, the term "value stream" by itself is associated with production within a facility and is defined as "all the actions, both value added (product's final value to customer is increased) and non-value added (processes such as transportation and inventory) currently required to bring a product through the main flows essential to every product: (1) the production of flow from raw material into the arms of the customer, and (2) the design flow from concept to launch" (Rother et al. 1998). It is also defined as "the set of all the specific actions required to bring a specific product (whether a good, a service, or, increasingly, a combination of the two) through the three critical management tasks of any business: the problem-solving task running from concept through detailed design and engineering to production launch, the information management task running from order-taking through detailed scheduling to delivery, and the physical transformation task proceeding from raw materials to a finished product in the hands of the customer" (Womack et al. 2003).

The Extended Value Stream is the supply chain viewed as a single organization in which all of the processes, regardless of company affiliation, are within one value stream. The Extended Value Stream then becomes "all the actions – both value-creating and wasteful – required to bring a product from raw materials into the arms of the customer. The relevant actions consist of two flows: (a) orders traveling upstream from the customer (or from the sales department when forecasts substitute for confirmed orders) and (b) products coming down the value stream from raw materials to customer. Together these constitute a closed circuit of demand and response (Jones et al. 2003). The Extended Value Stream can be utilized to assist in describing the decision-making processes in the supply chain by defining the information utilized at specific points within the supply chain and the methods by which the information flows throughout the supply chain.

1.7.4 **"Virtually" Integrated Supply Chains**

A company that controls an entire supply chain from raw material to retail is said to be vertically integrated. Henry Ford believed that by controlling all of the manufacturing, transportation, warehousing, and resource of a particular product, a company would reduce waste in the system and increase profit, by not sharing profits with other companies. However, the large capital investments, and complex organizational structure can make Henry Ford's vertical integration almost infeasible (Bowersox et al. 2000).

With increases in competition, companies are partnering up with suppliers and customers along the supply chain in an effort to reduce costs and increase efficiencies. These partnerships are imitating the concepts of the vertically integrated supply chain but without a centralized management. These new organizations are identified as "Virtually" integrated supply chains (Bowersox et al. 2000).

Increased cooperative management, or "virtual" integration, by members of a supply chain has a number of benefits. Forecasting that is shared between members of a supply chain has been shown to be more beneficial than forecasting developed at each tier of the supply chain, resulting in reduced inventories, less shortages, and overall cost (Aviv 2001). Inventory levels can be reduced through collaborative stocking and information sharing, such as with vendor managed inventories in grocery stores (Cachon et al. 1997).

1.7.5 **Measuring Performance in a Supply Chain**

In recent years, there have been increased problems associated with information overload in businesses due to advances in communication and information technologies (Edmunds et al. 2000). Identifying data within the large depositories of information that is linked to the objectives of the company and is useful to the decision-makers of the company is the basis for identifying critical performance measures and performance measurement systems (Hammer 2002). For the long term success of a company, the performance measurements must depict not only a financial perspective of a company, but also the customer, internal efficiency and effectiveness, and learning/growth perspectives to create a balanced view of success across the entire organization (Kaplan et al. 2000).

In an effort to minimize wastes and increase efficiencies to better serve the final customer, many businesses have begun viewing themselves not as a stand alone company but as part of a "virtual" organization that involves the chain of companies from raw material to final customer (Bowersox et al. 2000). Thus, a system of performance measurements must be developed not only for the individual business but for the new "virtual" organization in such a manner that the two measurement systems work together.

There are two distinct ways in which performance measurements can be applied to supply chains. First, performance measurements can be applied such that the entire supply chain is treated as a single corporate organization ("virtual" integration – viewed as one entity, though made up of individual profit centers) (Bowersox et al. 2000). In this way, the same measures that are typically used by individual companies are utilized by the supply chain. The second way is to consider the supply chain as a unique organizational structure that requires an expanded performance measurement system with metrics that are not typically found within the performance measurement systems of companies.

When applying performance measurements to a supply chain as if it were a single corporate organization, those measures that would be chosen are based on standard measures for an individual profit center and would consist of sales, profit, on-time delivery, backorders, response time, lead time, shipping errors and customer complaints (Beamon 1999). These performance measures do not, however, deal with the fact that the "virtual" integration of the supply chain does not have a centralized management, but is instead a series of individual profit centers.

However, when viewing a supply chain as a group of individual companies it becomes necessary to create an expanded performance measurement system that includes measures that are not typically found in a single corporate organization. These performance measures are needed to identify how well the individual companies interact with each other. These can be classified into five categories based on the literature (Beamon 1999; Chan et al. 2003): *Information Integration*, *Visibility and Trust*, *Flexibility*, *Functional Duplication*, and a redefined *Final Customer Satisfaction.*

Information Integration (Beamon 1999)- Information is a fundamental component of practically every activity of any company. The quality of a decision can be a reflection of the quality of the information available. Within individual companies, information systems are utilized to put the necessary information in the hands of managers and supervisors making the decisions. However, in the creation of virtually integrated supply chain organizations, information does not necessarily flow freely among the participating companies. This lack of information sharing may be due to technological issues such as incompatibility of computer hardware and software, misalignment of interests within the supply chain, lack of motivation to do so, and trust. Metrics that can be utilized for information integrity can include: computer integration as a percent of total integration, timeliness or availability of partnership data, or refusal of information by partners.

Visibility and Trust (Chan 2003)- A supply chain whether a “virtually” integrated organization oriented to the needs of a final customer or simply a series of inter-business relationships, has a certain level of visibility and trust among its members. Companies that have more trust in their partners will make their policies, decisions, and information more available or visible to their partners. The shift to a more collaborative relationship does have a number of issues that are difficult to overcome such as the self-serving nature of business and the sensitivity to potential negative implications in decisions to supply chain partners. One of the ways to deal with these issues is to encourage the inter-organizational relationships through the development of frameworks and performance measurements (Bowersox et al. 2000). Metrics can include: partner representation in meetings, hours of management sharing, or availability of documentation.

Flexibility (Beamon 1999; Chan 2003) - A supply chain that is flexible is one that can quickly and easily respond to changes in demand while maintaining the clear channels of flow of product and information. However, for individual companies within the supply chain, it is not just a measure of how fast and effective reactions can occur within their own company, but also how these changes affect the entire supply chain. Since a supply chain is the sum of all planning and processing in all companies along the chain, the responsiveness to changes in demand can be extremely slow due to long lead times in manufacturing and in decision-making, especially for long and extended value streams (or supply chains). Metrics that can be utilized for flexibility can include: supply chain lead time, new product development cycle-time, or hours of partners involved in new product development.

Function duplication (Beamon 1999): Within a supply chain in which all the members of the chain are to some degree communicating and cooperating, it is advantageous to identify those processes that may be duplicated from one company to the next. Duplication represents additional lead time and costs that reduce the overall efficiency and effectiveness of the supply chain. Thus, it is necessary to monitor the processes of companies along the supply chain to minimize the duplication that can occur. Metrics that may be utilized are: number of documents required in transaction, number of times products are evaluated for quality issues, or number of times items are packaged/unpackaged.

Final Customer Satisfaction (Beamon 1999) - Although measurements for customer satisfaction can be found for supply chains as well as individual companies, it is important to note that there is a difference between the final customer satisfaction for a supply chain and what is typically assumed to be customer satisfaction for individual companies. From a non-supply chain organizational viewpoint, a company will view its customer as the next company downstream along the particular supply chain – the customer that purchases products or services directly from the company. Thus, the customer satisfaction that is measured would be that of the immediate customer company. When viewing a supply chain as an organization, it is understood that companies along a supply chain are considered business partners with the ultimate goal of serving the final customer.

These supply chain performance measurements can be utilized by companies throughout the supply chain to evaluate their performance towards an integrated supply chain. These performance measurements can also be utilized by individual managers to assist in making decisions that increase the success of their company through success of the supply chain(s) that the company belongs.

1.7.6 **Information Flow in a Supply Chain**

Information sharing between companies has been identified as one of the keys to successful supply chain logistics. (Lee et al. 1997b; Spekman et al. 1998; Bowersox et al. 2000b) The lack of information flow or limited information flow can lead to what is called “demand amplification” (Forrester 1961) or the “Bullwhip Effect” (Lee et al. 1997) within supply chains.

The Bullwhip Effect is an increase in the variance of demand through the supply chain causing demand to appear chaotic farther upstream in the supply chain from the actual demand of the final customer. Typically, this can result in large inventories or unexpected stock-outs. Management games such as the Beer Distribution Game (Sterman 1989) and the Forest Supply Game (Moyaux et al. 2003) illustrate the natural tendency of management’s decision-making for the creation of this phenomenon.

An example of the Bullwhip Effect is shown in Figure 1-3 which was adapted from Forrester (1961), in which the demand for products at the different stages of a supply chain are shown. In this figure, one cycle of ordering is shown through all of the members of the supply chain: retailer, distributor, and manufacturer. For this example, the retail sales are shown to be constant. However, due to ordering practices, such as inventory protocol or cyclic order practices, the retailer's orders to the distributors were higher than the actual demand. The distributor probably saw an increase or peak in demand due to the retailers increased order and ordered more to account for their ordering delay and expected increase in sales. The manufacturer in turn increases the order size again and has a much larger delay, probably due to lead time for production. Thus, delays and forecasting can result in fluctuations in ordering which will lead to fluctuations in inventory levels even if retail sales are constant.

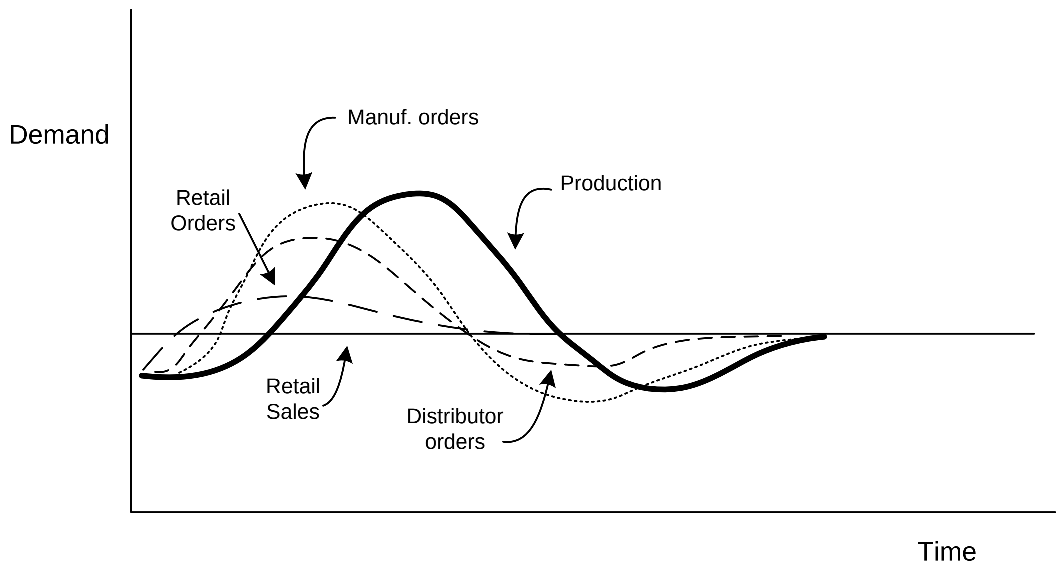

Figure 1-3 Example of Bullwhip effect created by a change in retail sales

There are a number of reasons for the Bullwhip Effect in a supply chain. The four major causes are 1) demand forecast updating, 2) order batching, 3) price fluctuations, and 4) rationing and shortage gaming (Lee et al. 1997). Most of these causes are based on the fact that accurate real-time information is not being transferred among supply chain members.

Much research has been done in the role of appropriate information in this demand amplification or Bullwhip Effect and it has been found that as information availability increases demand amplification will decrease (Lee et al. 2004; Steckel et al. 2004; Croson et al. 2005). Research has shown as more reliable and trustworthy information becomes available and if it is portrayed effectively, the more appropriate the decision-making can be to the situation.

Information Technologies in Supply Chains

Supply chain management relies on accurate and timely information from different facilities that can be next door or half-way around the world. Information can be passed between companies through many channels from low-tech methods of faxes or quarterly reports to complex computer systems involving Electronic Data Interchange (EDI). Moreover, technology is being used not only to store and convert information, but also to collect information through Universal Product Codes (UPC) and Radio Frequency Identification (RFID).

The application of Information Technology (IT) in general businesses has been shown to be beneficial to companies regardless of application. Comparisons of organizational performance versus IT capabilities were studied and it was determined that "IT leaders have significantly higher income ratios" (Bharadwaj 2000).

EDI is an early implementation of IT in the supply chain. It is defined simply as "the electronic transmission of data between a firm and its suppliers" (Bowersox et al. 2002). A more complex definition is "the movement of business data electronically between or within firms (including their agents or intermediaries) in a structure, computer-processable data format that permits data to be transferred without re-keying from a computer-supported business application in one location to a computer-supported business application in another location" (Ferguson et al. 1989).

In the early stages of computer utilization within production facilities, it was found that EDI was of critical importance to supply chain management. With EDI, companies can link with suppliers to schedule the flow of parts. One of the early pioneers of this was Chrysler, which implemented an electronic communication system with a few suppliers in 1969. A study done of this facility in the mid 90s found that utilizing EDI "significantly reduced operating costs associated with carrying inventories, obsolescence, and transportation" with an estimated savings per car of $100 (Mukhopadhyay et al. 1995).

As supply chain management has grown, EDI has become an essential part of advanced supply chain programs such as Collaborative Planning, Forecasting and Replenishment (CPFR) which was developed by the Voluntary Inter-industry Commerce Standards Association (Seifert 2003). CPFR utilizes IT to expand the interrelationship between supply chain members beyond the basics of EDI and into cooperative planning and forecasting efforts that strengthen the supply chain as a whole. A case study of West Marine found that with implementation of CPFR in-stock rates, forecast accuracy and on-time shipment increased "significantly" (no specific information given) (Denend et al. 2005).

With the information transference becoming faster and more critical between companies utilizing the EDI systems and systems such as CPFR, the ability to collect information has also seen the need for improved speed and accuracy.   Input of information into computer systems has grown quite dramatically in the previous decades. Where once manual inputting had to be done through punch cards and keyboards, UPC scanners "read" labels with lasers for faster input into computers and more accurate inputs while Radio Frequency Identification (RFID) tags allow computers to identify objects within a detectable radius with no need of line-of-sight.

UPC codes or bar codes have been around since the early 1980s. A series of lines of varying thicknesses and distances apart are translated into alpha-numeric codes which can be used to identify products through a standardized coding system. From the standpoint of decision-makers, managers have been found to have a "higher level of comfort" with the analysis of data obtained from the UPC technologies and much of the issues associated with implementation of data obtained with UPC is based on the incompatibility between this method and the older methods (Bucklin et al. 1999).

Radio Frequency Identification (RFID) utilizes radio waves to transmit codes stored on microchips from a tag to a reader which is attached to a computer. This process of reading tags does not require human involvement (e.g. scanning UPC codes or keyboards). The only requirement of RFID is that the tag passes within the proper range of the reader. With RFID technology, it becomes possible to collect more information, automatically, with minimal human error, in real time.

The companies that make up the United States Hardwood Industry are looking for opportunities to increase their market strength in the face of increased competition. The benefits of the implementation of new technologies, such as RFID, to inventory and production systems within companies can be difficult. In many cases, companies only have a rudimentary understanding of the costs associated with operations. In addition, the expected outcome of implementation of information systems can be difficult to discern, especially as it relates to a company's ability to be more customer-focused. Increased knowledge within a company is assumed to increase the effectiveness and efficiency of inventory and production systems, however determining quantifiable results in the planning stage can be difficult. This research utilized methods by which the resulting affects to inventory and production of increased knowledge in a supply chain can be determined.

Chapter 2 Research Methodology and Methods

2.1 Introduction

The objectives of the research required an in-depth analysis of a hardwood supply chain with the purpose of determining how information from supply chain partners affects the decision-making process for the individual members of the hardwood supply chain. To obtain the necessary level of detail on the flow of information and the usage of information, a case study approach was taken. A representative supply chain within the hardwood industry was identified and a comprehensive analysis of material/information flow including the details on supply chain information utilization was performed.

The case study supply chain was first analyzed to identify the pathways of information and production flow through the supply chain segments and to benchmark the lead times for both (Research Objective 1). The information and material flows were utilized to identify the inter-relationship between supply chain information and the managerial decision-making process for production of the supply chain (Research Objective 2). Finally, an investigation was conducted into the impact of increased information sharing on the supply chain (Research Objective 3).

To complete the first research objective (to determine the pathways of material and information flow through the case study supply chain) information and material was followed through the case study supply chain and each process and waiting period was identified and recorded. To accomplish this, the procedures outlined in the books *Seeing the Whole* (Jones et al. 2003) and *Learning to See* (Rother et al. 1998) were followed. Once the data was collected, the data was analyzed, in part, utilizing Value Stream Mapping (see section 2.2.2 for a detailed description). The results of completing the first objective assisted in completing the second objective.

The second research objective (to determine the inter-relationship between supply chain information and decision-making in the members of the case study supply chain) required an analysis of the ways that information from supply chain partners was utilized by the management within each company in the case study supply chain. The pathways of information flow identified in the completion of Objective #1 were used to identify who utilized the information within each company. Through data mining, observation, and interviews, the specific information utilized by each manager in procurement, shipping and production was identified.

The data was analyzed utilizing System Dynamics tools (see section 2.2.4 for a detailed description) to identify what role supply chain information had in the decision-making process at a managerial level and how that information was passed to subsequent managers.

For the completion of the final objective, (to identify potential improvements in the hardwood supply chain as a whole) the performance of the case study supply chain as a supply chain was evaluated, potential improvements identified, and System Dynamics simulations were run to evaluate the potential improvements. The case study supply chain was evaluated utilizing the supply chain performance measures identified in the literature (Section 1.7.5). The potential improvements were based on expected improvements in the case study supply chain through increased information sharing and utilizing the supply chain performance measures.

2.2 Research Methodology

The research methodology required that the three objectives be completed sequentially as each objective required the analysis and completion of the previous objective. Figure 2-1 outlines the specific methodology followed in the completion of the objectives. The research methodology was separated into four phases which included the initial analysis of literature and the hardwood industry to develop the research protocol for the completion of the objectives. Each of the remaining phases of the research (2-4) corresponds to each of the objectives determined for the research. This section contains the methodology utilized for the completion of the research as presented in Figure 2-1.

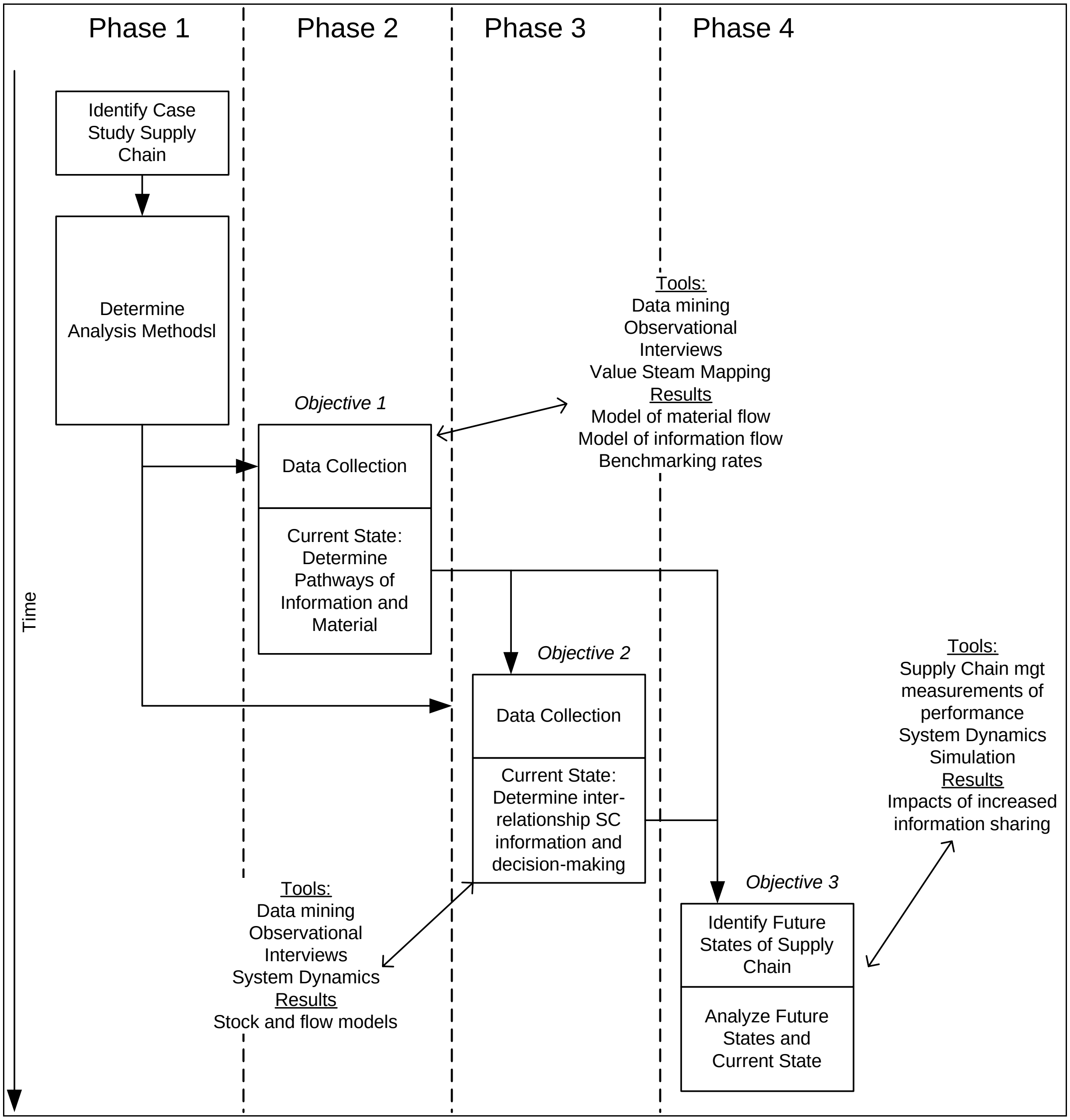

Figure 2-1 Phases in the Research Methodology

2.2.1 **Identify Case Study Supply Chain**

After the development of the purpose and objectives of the research, the first step in the research methodology was to identify the supply chain to be utilized for the case study. Since this is a study of the Hardwood Supply Chain, the supply chain to be utilized as the case study must meet the definition of a Hardwood supply chain as defined in the literature (Section 1.7.2). Specifically, the supply chain must include the processes of forestry, sawmill, secondary manufacturing, and distribution.

The selection of a supply chain was simplified by first selecting a focal company. The focal company was a company that defined the supply chain. The criteria for selecting a focal company was based on a number of factors: 1) the company must be representative of a company in the Hardwood Industry, 2) the company must maintain a proportion of the market share within the particular industry segment which lends itself to be compared to a large cross-section of other companies within the industry segment, 3) the company must have suppliers and customers (supply chain partners) that are representative of the Hardwood Industry and maintain relationships with these suppliers and customers in a manner representative of the Hardwood Industry.

The next step was to identify the remaining members of the case study supply chain. This was done by selecting a specific product and/or component of interest at the focal company. Once the product of interest was selected, the case study supplier(s) to the focal company could be identified as an average or predominant supplier of the raw material that went into that product. Likewise, the case study customer(s) to the focal company can be identified as an average or predominant customer for the product. If necessary, the supplier to the supplier and the customer to the customer were identified in the same manner, until the entire case study supply chain was identified (the determination of case study supply chain is further described in Appendix A).

2.2.2 **Research Analysis Methods**

The Case Study

The case study methodology/approach to systems analysis was critical in the completion of the objectives of the research. The ability to analyze the complexity at which information flows between companies in a supply chain and how the individual companies internally utilize the information is complex. In addition, minimal supply chain analysis of this type has been conducted for the hardwood industry, which makes case study analysis critical in building the foundation for future research in this field.

The case study is a research methodology that “focuses on understanding the dynamics present within a single system” and includes the combination of several methods of data collection, interviews, history, and direct observations – both qualitative and quantitative- to describe a system, test a theory or create theory (Eisenhardt 1989). Case studies provide insights into systems that may not be revealed in broad-scope research. By focusing the research on one particular system, case studies can draw out more detailed analysis on how or why a system reacts or operates.

The case study approach has very specific applications within research. Table 2-1 shows a comparison of various research methods typically utilized in research and their associated applications (Yin 2003). The research associated with this study is of current or contemporary issues in the Hardwood supply chain. However, the size of the system makes changing the studied system difficult if not impossible – this lends the research to a survey, an archival or a case study. Because the nature of the research requires an in-depth analysis of the relationships between information and the decision-making process, a survey across a number of different supply chains would not give the level of detail necessary. Thus a case study with an archival analysis was appropriate for the research.

Table 2-1 Comparison of Various Research Methods

	Questions Answered	Requires changing studied system	Contemporary issues studied
Experiment	How? Why?	Yes	Yes
Survey	Who? What? Where? How many? How much?	No	Yes
Archival analysis	Who? What? Where? How many? How much?	No	Yes/No
History	How? Why?	No	No
Case Study	How? Why?	No	Yes

As a research methodology, the case study approach typically utilizes small sample sizes including a single system case study. The benefit is that a more thorough examination of a system can be performed; however, the inferences made on the parent population based on the sample become more complex.   Most experimental methodologies base sample size on statistical motivations relating variation and population; inferences are then made based on statistical significance. The case study relies on causal inference to “relate theoretically relevant characteristics reflected in the case to one another in a logically coherent way” (Mitchell 1983).

In supply chain research, many studies rely on the analysis of a particular supply chain (a case study). The study of supply chains requires that there be a deep understanding and knowledge of the way that the individual companies within the supply chain interact with each other (Lambert et al. 1998). With regards to supply chain research, the case study has been found to 1) explore and build theory, 2) test theory, and 3) extend theory (Seuring 2005).

The use of a case study analysis is an integral part of this research and must be utilized to obtain the required level of detail pertaining to the flow of information and the decision-making processes of managers within the companies that make up the supply chain. It has been utilized in past research in this way to develop and test similar models for supply chain analysis (Arbulu et al. 2002; Michelsen et al. 2005; Angerhofer et al. 2006). The case study approach involved interviews with key personnel within each company and performance analysis of the systems that make up the flow of product/production and the systems that make up the information channels.

Value Stream Mapping

Before an analysis of the inter-relationship between supply chain information and the decision-making process can occur (Objective 2), it must be determined how information flows through a supply chain and what specific information is passed from supply chain partner to supply chain partner (Objective 1). As supply chain information is tied to the flow of material through the supply chain, to determine the flow of information through the supply chain, it is necessary to relate information flow to the flow of material. A good tool for modeling the relationships between flows of material and information through a supply chain is Value Stream Mapping.

Value Stream Mapping (VSM) is a tool developed in 1995 for the purpose of analyzing processes such as supply chains. VSM is defined as “the simple process of directly observing the flows of information and materials as they now occur, summarizing them visually, and then envisioning a future state with much better performance” (Jones et al. 2003). Originally, VSM was developed as a tool for Lean production to identify opportunities for improvement in manufacturing production lines (Rother et al. 1998) but has been expanded to include supply chains (Jones et al. 2003).

The concept of a Value Stream Map is to “create a simple way for managers to see the flow of value” (Womack 2006). A standardized iconic system is utilized to represent the flow of material and information through a process, whether production or service. VSM utilizes standard symbol representations of inventory, processing, transportation, and information flow. VSM gives researchers or practitioners a tool “to identify waste in individual value streams and, hence, find an appropriate route to removal, or at least reduction”(Hines et al. 1997).

An example of VSM is shown in Figure 2-2. The production is a job-shop moulding (flooring, door trim, etc) operation in which moulding orders come from contractors and are processed from lumber purchased from a sawmill. The production manager takes the daily orders from the contractors and schedules production in the facility. The three processes in the factory (plane, rip, and mould) are separated from each other with a certain amount of work-in-progress inventory (all inventories are denoted by triangles) between them. The arrows show the direction of information and process flow. Following the processing arrows, lumber is taken from the lumber inventory which is approximately 25,000 board feet[1], planed, ripped, moulded, and shipped off to the customer on a weekly schedule. To maintain the lumber inventory, the Production Manager orders lumber once a month from the sawmill and it is delivered bi-monthly.

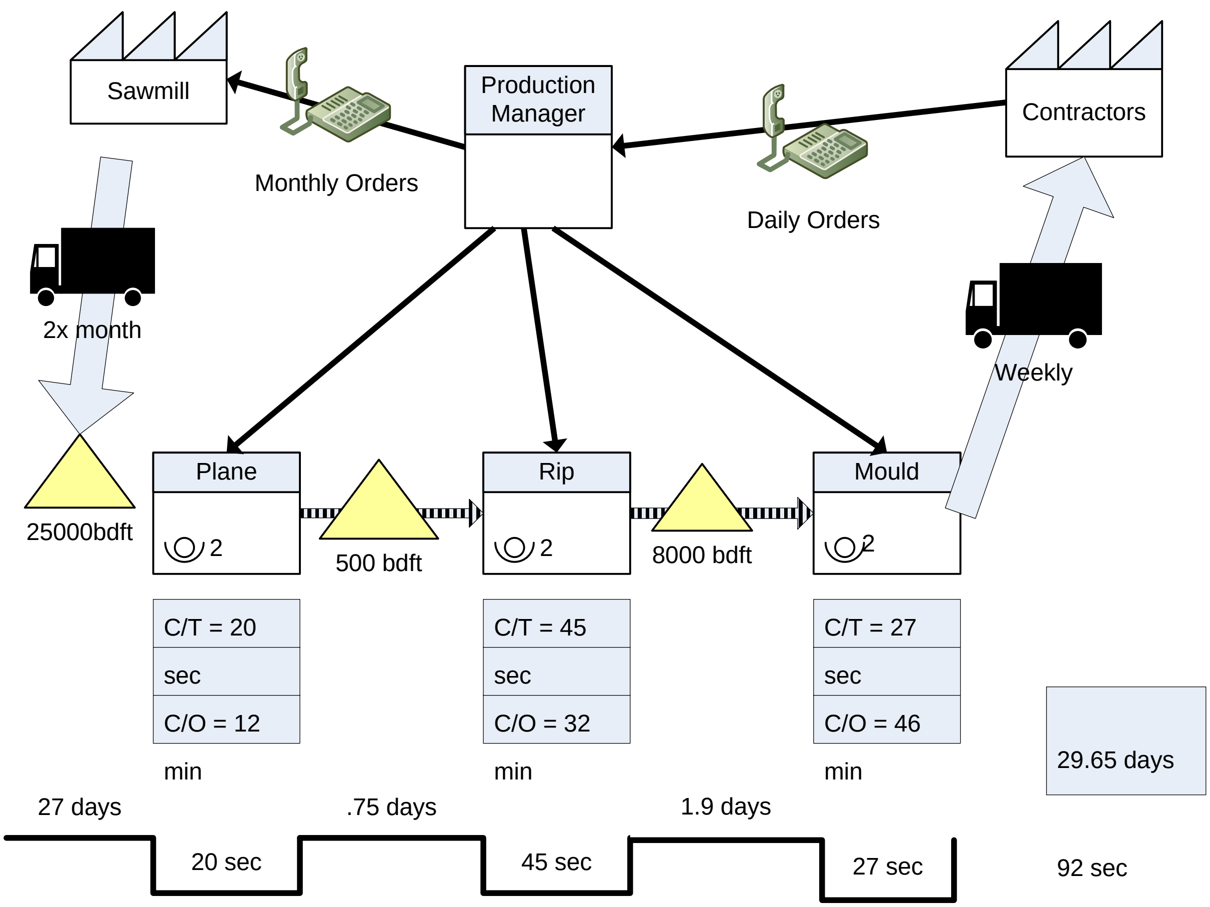

Figure 2-2 Example of Value Stream Map for a Job-Shop Moulding Operation

[1] [1] *Board Feet* is a measure of lumber volume. One *Board Foot* is equivalent to 144 cubic inches. 1000 bdft = 2.36 cubic meters

Information is collected for each process to determine the time to process an order, the amount of time that is spent processing the parts, and efficiencies of each machine work center in the processing of the mouldings. Specific information to be collected is based on investigative needs. For the moulding company in the example, information was collected for cycle time (C/T), changeover time (C/O), machine efficiency (uptime), and the time it takes for orders to wait at each machine. The time chart at the bottom of Figure 2-2 shows the total times for getting a product through the processes across the chart tops and the time of the actual value-added manufacturing along the bottom. In the example shown in Figure 2-2, a standard size moulding requires 92 seconds of process (value-added) time but requires a lead time of more than 29 days to move through the system. Management can then evaluate this information for opportunities for improvement within the company to help reduce this lead time for faster customer response time.

Once the benefits of performing VSM on individual companies was determined, this evaluation tool was extended to the supply chain or “extended value stream” in which mapping is done “across plant, divisional, and company boundaries” (Jones et al. 2003). Though some of the icons were changed to represent a “higher vantage point,” the general procedures of mapping remain similar.

VSM has been utilized in a number of supply chains covering a broad spectrum of products. VSM was utilized in a study of a company that supplies pipe supports in power plants and it was determined “that more than 96% of the time in the supply chain of pipe support is non-value-added time, which has a direct impact on lead times” and that the non-value added time is related in part to information flow through the systems (Arbulu et al. 2002). In the United Kingdom, the pork agricultural sector was evaluated using VSM by mapping the supply chain from farm to market identifying “significant opportunity to improve” through integrated value chains (Taylor 2006).

VSM has also been utilized to analyze more than just production or supply chain material flow. This tool has been utilized to analyze leadership and organizational improvements (Emiliani et al. 2004) and can be used in the processes of administration and office processes such as customer service (Keyte et al. 2004; Barber et al. 2008).

System Dynamics

System Dynamics (SD) is a classification of research devoted to solving complex issues. A definition of System Dynamics is a "computer-aided approach for analyzing and solving complex problems with a focus on policy analysis and design" (Angerhofer et al. 2000). This field is attributed to supply chain management research performed by Jay Forrester of the Massachusetts Institute of Technology who wrote *Industrial Dynamics*. Forrester defined the field of Industrial Dynamics as "the study of the information-feedback characteristics of industrial activity to show how organizational structure, amplification (in policies), and time delays (in decisions and actions) interact to influence the success of the enterprise" (Forrester 1961).

Industrial Dynamics has grown beyond Mr. Forester's usage in factories and supply chains in the 1960s into a broad range of topics which include environmental engineering (Ford 1999), business strategy (Lyneis 1999), and software design (Landes et al. 1999). However, with more emphasis being placed on supply chains and distribution channels in the past decade, the System Dynamics that was originally developed for the research and analysis of supply chains has been re-introduced to this field.

There are a number of different tools and techniques used in System Dynamics research. For research and analysis of supply chain management, the System Dynamics tools of Causal Loop Diagramming and Stock and Flow Diagramming are utilized separately and integrated for the purpose of "understanding of a system through theory-building" (Angerhofer et al. 2000).

Stock and Flow Diagrams allow simulation which can be "essential in formulating and testing" theories (Senge et al. 1992). Also called Continuous Simulation, Stock and Flow Diagramming is used to model systems in which variables change at specific rates (flows) and inventories (stocks) are increased or decreased due to the flows. The relative rates through the model will then affect the "stock" levels throughout.

Originally designed for industrial analysis, the Stock and Flow Diagram is utilized to analyze systems such as production and material flow within factories and supply chains (Forrester 1961). Figure 2-3 shows a basic Stock and Flow Diagram for a production setting with boxes representing "stocks" and the valves between the boxes representing the "flow." In this case, "stocks" are inventories of goods, such as lumber inventory, and "flows" are production and usage rates which add or subtract from inventories, such as procurement rate and production rate.

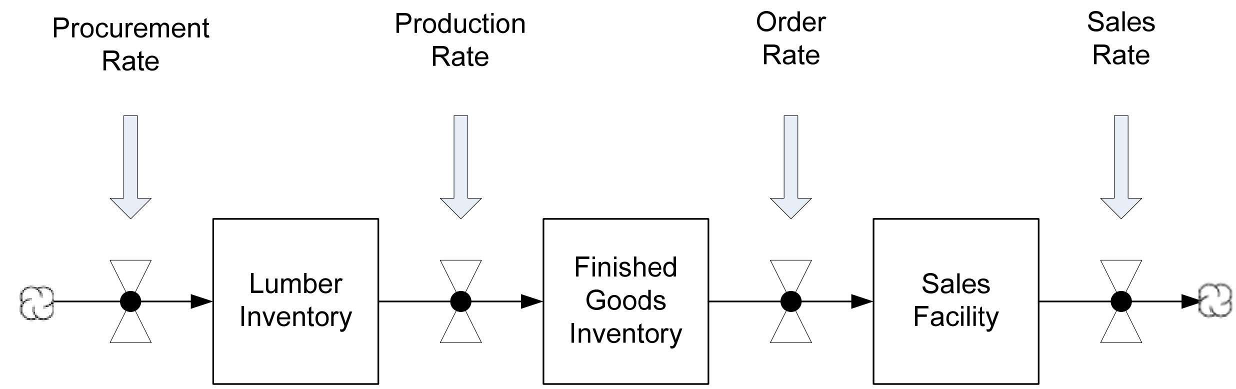

Figure 2-3 Example of Stock and Flow Diagram

This form of analysis is easily utilized for other systems that maintain inventory levels and have varying rates of flow. Examples of these would be human population studies and investment research (Spector et al. 1997). In both cases, physical inventories are affected by the rate of incoming flows and outgoing flows.

Stock and Flow Diagramming is not limited to researching the effects of production rates on physical inventories. When researching waiting times at hospitals, “Stocks” were designated as waiting backlog and perceived waiting times which were affected by changes in referrals, demand, treatment rate and actual waiting times (Smith et al. 2002). Stocks can also represent non-quantifiable inventories, such as policies (Richardson et al. 1995) or information levels.

Alone, Stock and Flow Diagrams are a static analysis of a system. In Figure 2-3, there are no mechanisms by which values change; all rates and inventory levels are constant. Stock and Flow Diagrams are typically combined with Causal Loop Diagrams to identify the controlling mechanisms within the system.

To understand systems or to have a systems perspective, one must understand all of the factors that affect the system and understand the interrelationship between these factors. Causal Loop Diagramming is the System Dynamics tool for analyzing systems in this manner.

Like Stock and Flow Diagramming, Causal Loop Diagramming (CLD) was originally utilized for analyzing production systems and supply chains. Figure 2-4 shows an example of a

Causal Loop Diagram developed for advertising and consumer markets (Forrester 1961) modified to include the effects on production rate. The directions of the arrows indicate the direction of influence of the factors within the diagram. In this example, the Production Planning Information influences the Advertising Decision-Making which in turn influences the Agencies and Media. From this diagram, an understanding of those factors that create the supply and demand can not only be identified, but it shows how they affect each other.

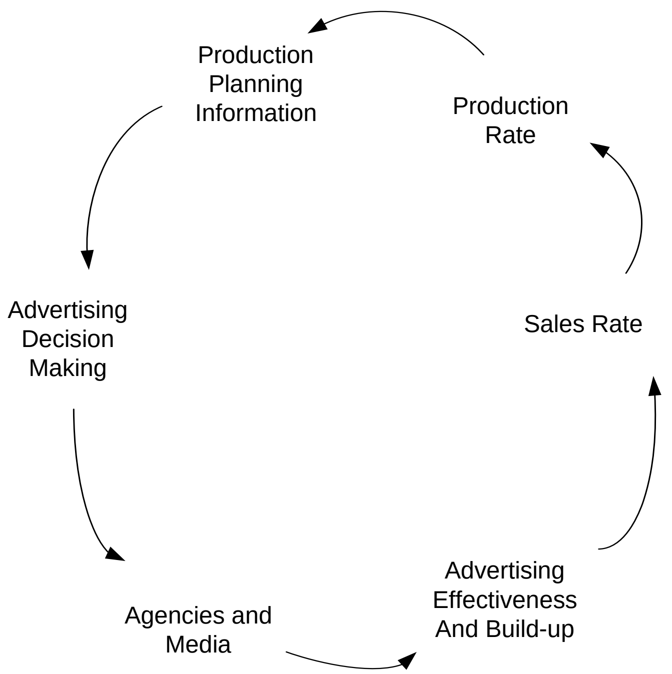

Figure 2-4 Example of Causal Loop Diagram

Because of its ability to connect both quantitative and qualitative variables, such as Production Rates and Advertising Decision-making (Figure 2-4), Causal Loop Diagrams are excellent tools for creating an overall model of factors that can influence a system. However, Causal Loop Diagrams, alone, do not allow for as complete analysis of a system as the combination of Causal Loop Diagrams and Stock and Flow Diagrams (Forrester 1994).

Continuous Simulation models incorporate Causal Loop Diagramming with the Stock and Flow Diagramming. This can be viewed as necessary due to the fact that "in most realistic stock management situations the complexity of the feedbacks among the variables precludes the determination of optimal strategy" (Sterman 1989). With the combination of Causal Loop

Diagramming and Stock and Flow Diagramming, Continuous Simulation models can give a much more detailed analysis of a system. Figure 2-5 demonstrates this by linking the Stock and Flow example from Figure 2-3 with the Causal Loop example in Figure 2-4.

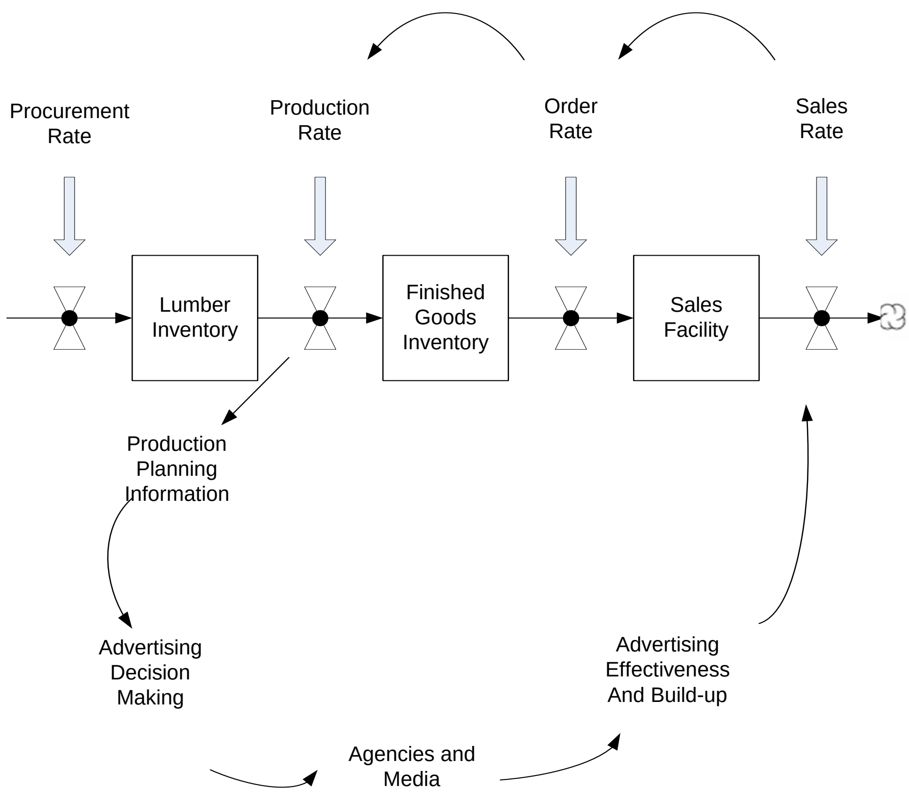

Figure 2-5 Example of Stock and Flow with Causal Loop Diagramming

From Figure 2-5, there is a more in-depth analysis of the system. It can be seen how the roles of the attributes of Production Planning and Advertising affect the sales rate and the supply chain as a whole. As such, the modeled system is no longer static. The Causal Loop can increase or decrease flow rates dynamically over time depending on the nature of organizational relationships and resulting decision-making responses made within the system. Like the other System Dynamics tools, Continuous Simulation, though originally developed for production and supply chain analysis, as shown in this example, can also be utilized for research in other fields.

System Dynamics has been utilized to analyze many aspects of Supply Chain Management because of its ability to create “understanding of a system’s structure” and to deduce the “behavior from it” (Schieritz et al. 2003). This ability of System Dynamics has allowed for research into Supply Chain Management across a broad spectrum of topics, such as inventory management, demand amplification, organizational structures and information sharing.

System Dynamics was utilized to identify proper inventory management techniques for the apparel industry (Barlas et al. 1999). Simulations were performed on the effects of production and ordering polices on the patterns of demand and the inventory levels. It was determined that ordering policies must consider how information and product flows through a supply chain – discretely, continuously, or in some combination of both.

The organizational structure of supply chain management has also been examined utilizing System Dynamics by evaluating the relative cooperativeness of the supply chain members against the cost and fill rate performances (Zhang et al. 2004). Through conceptual models, it was found that a de-centralized organizational structure makes the supply chain more adaptive to dynamic demands. In lieu of the advantages of decentralization, it was determined that models in which cooperative relationship amongst the members of a supply chain showed better results in cost and fill rate performance than a competitive relationship.

Cooperative relationships in supply chains indicate some level of information sharing amongst its members. System Dynamics was utilized to evaluate "non-collaborative" versus conditions of either collaborative forecasting or collaborative planning in which specific information was shared (Ovalle et al. 2003). The models showed that either of the two collaborative models showed desirable results for inventory levels in the supply chain and service levels of final customers (orders filled on time).

From the previous research, System Dynamics tools have been utilized to analyze the effects of different decision-making strategies on the performance of supply chains. The objective of this research was to look at this system from the other direction and to identify how information and measures of supply chains affect the decision-making process.

2.2.3 **Methodology for Completion of Objective 1 (Phase 2)**

The overall methodology for mapping a Value Stream (VSM) or an Extended Value Stream is outlined by Rother and Shook (1998). VSM is a versatile tool that can be utilized for addressing numerous objectives. In general, once the objectives of the value stream research are developed, the research would follow four steps (Figure 2-6).

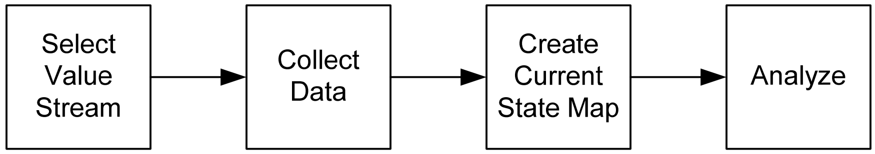

Figure 2-6 Value Stream Mapping Methodology

The first step in mapping a value stream is the identification of the specific product or product family that will be followed through the value stream. In the case study supply chain, the product was chosen based on a number of different factors. First, the product must be representative of the supply chain and not a low production product. Second, the product must flow through all of the members of the case study supply chain. Finally, the flow of the product through the case study supply chain must be driven by the information systems of interest within each supply chain member.

The second step is collecting data for Value Stream Maps. This is performed by following the flow of the product through the supply chain. It is typically infeasible to follow the exact material from the source to the final customer as the entire process may require months due to processing and inventory delays. It is typically recommended that the process be followed backwards, starting with the finished product and working towards the raw material.   Some of the key information that is obtained as part of this process includes inventory levels throughout the system, direction and time of processing goods and services, direction and timing of processing information, the mechanisms of motion through the system, and the inherent value of the process as it relates to the customer. Other information such as defective rates and batch sizing is also required as needed depending on the level of detail required to meet the specified study objectives. Some examples of methods of data collection used in the analysis of material flow are presented in Table 2-2.

Table 2-2 Data Collection for Material Flow

Information Type	Methods for Determination
Processing Times	
Individual Machines	
No batching	Time between consecutive parts
Batching	Time between consecutive batches / # parts in batch
Machine Centers or facilities	Lead time for production from facility records
Inventory	
Total inventory in facility	Obtained from facility records
Average per part followed	Obtained from facility records
Time in inventory	Maximum inventory level / usage rate
Transportation - Trucking	Quantity of material transported at one time Distance traveled for one trip Number of trips (from facility records)
Information Flow	Identify drivers of production, inventory and transportation utilizing facility records, and interviews with personnel to determine what records are utilized to create the drivers

In addition to product flow through the supply chain, the information flow through the supply chain must also be analyzed utilizing Value Stream Mapping. Data collection for information flow is similar to that of data collection for product flow except that orders are followed instead of material. Value Stream Mapping of orders has been done previously within one particular company (Ketkamon et al. 2009). For information flow, the orders and information flow are followed in the same manner as the material flow with data collection presented in Table 2-3. In some cases, the information flow data can be obtained from the material flow analysis, specifically that of the direction of the flow and the steps through the supply chain that the information follows.

Table 2-3 Data Collection for Information Flow

Information Type	Methods for Determination
Process time	Time it takes to process an order or the time between information arriving and departing one step (or through facility records)
Transportation	Time between departing one step and arriving at the next (or through facility records)

Creating the "current state" maps, both material flow and information flow, of the system was the third step in Value Stream Mapping. During this step, the data that has been collected in the second step was utilized in the creation of a model that represents the system's current conditions. The model (or map) that was created from this step looked similar to that in Figure 2-2, but extended further through the supply chain with the forest resources and the final customers being at the extreme ends of the map.

Step four was the analysis of the current state utilizing the Value Stream Map created in step three. The objective of the analysis was to determine opportunities for improvements of the current state. These opportunities may be identified solely from the map that was created or in combination with goals that were determined at the onset of the Value Stream Mapping Process.

2.2.4 **Methodology for Completion of Objective 2 and Objective 3**

The final two objectives of the research were 1) to identify the inter-relationship between supply chain information and the managerial decision-making process for production within the supply chain and 2) to investigate the impact of increased information sharing on the hardwood supply chain. To accomplish these objectives, System Dynamics modeling was utilized. The Causal Loop Diagramming / Stocks and Flows Diagramming were utilized together to develop an understanding of the inter-relationship between the steps in the flow of information and material through the supply chain. From these models, potential “future states” of the supply chains were determined and simulations were run to determine the affects of the changes on the system.

In System Dynamics, once the problem has been articulated, there are four steps to complete an analysis such as that required in objectives 2 and 3: 1) Formulate a dynamic hypothesis, 2) Formulate a simulation model, 3) Test the simulation model, and 4) Identify alternate policies and evaluate them (Sterman 2000). Details of each of these steps are shown in Figure 2-7.

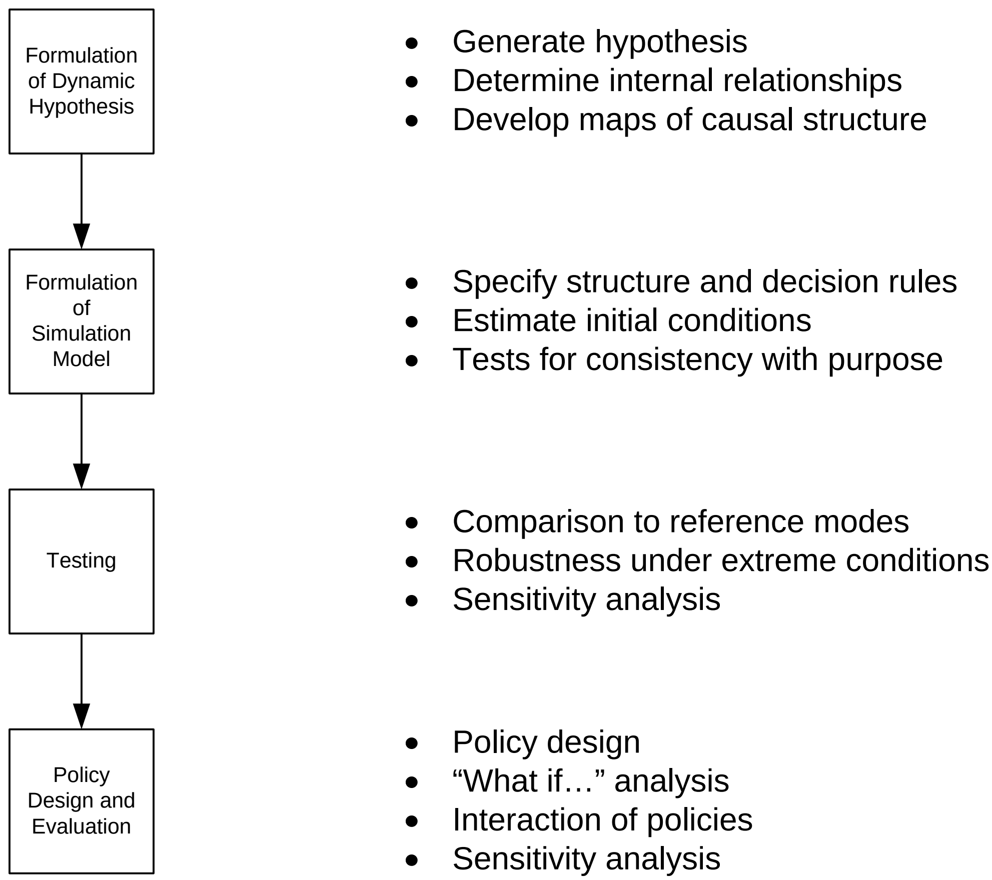

Figure 2-7 Methodology for System Dynamics Modeling

In completion of the first step, the Formulation of the Dynamic Hypothesis, the hypothesis was determined through relevant literature and presented in Chapter 1. The internal relationships of the case study supply chain were determined in the completion of objective 1. The System Dynamics models of causal structure were built utilizing data collected from the members of the case study supply chain through interviews with personnel along the flows of information and material determined also in the completion of objective 1. The data collection required investigation of both the interaction between supply chain members and internal to each member. Specific data collected is presented in Table 2-4.

Table 2-4 Data Collection for System Dynamics Modeling

Between Supply Chain Partners	
Purchasing	Drivers of purchases, Procedures for purchasing, Communications internal/external, information reporting
Receiving	Procedures for reception of goods, Paperwork requirements, Processing times, information reporting
Sales/Marketing	Customer relation procedures, Product development
Shipping	Order processing procedures, Information process, Processing times
Other	Information as required
Internal	
Management/ Supervision	Source of information, inventory levels, lead times, cycle times, information reporting
Planning	Source of information, transformation process, information reporting
Other	Information as required

The second step in System Dynamics Modeling was to formulate/develop the simulation model. The models created in the first step were translated into (discrete-event) simulation code which required development of decision rules (assumptions) by which the simulation would emulate the case study supply chain. The initial conditions were estimated based on data collected in the completion of objective 1 and the previous step. Tests were then performed to verify that the simulation model performs as related to the purpose of the research requirements.

The third step is to test the simulation model. The simulation model was tested against the System Dynamics models in step one to verify that the simulation model reproduces the relationships in the flows of information and material defined in that first step. The simulation was then stressed to determine if the model behaves realistically under extreme conditions. Finally, a sensitivity analysis was performed to identify how the simulation performs under varying levels of uncertainty.

The final step was to test the affects of changes in policy on the case study supply chain through the simulation model. Specific changes in policy were determined based on an analysis of the System Dynamic Models in the first step and the Value Stream Mappings of material flow and information flow. These were translated into “what if...” scenarios, the simulation model was altered to communicate these scenarios one at a time, and the results determined. The different scenarios were then analyzed together to determine the interaction of the changes in policy on the case study supply chain.

With the completion of the methods outlined in this chapter, the objectives of the research were completed. The pathways of information and production flow through the Hardwood supply chain and benchmark current lead times for both were determined utilizing a variation of Value Stream Mapping. The inter-relationship between supply chain information and the managerial decision-making process for production within the supply chain was determined utilizing System Dynamic modeling. Finally, the impact of increased information sharing on the hardwood supply chain was completed utilizing simulations. These were done to determine that increased sharing of the right information between individual companies within the Hardwood supply chain can address the lack of customer-focus of the Hardwood supply chain.

Chapter 3 The Supply Chain

3.1 Introduction

A case study supply chain is typically defined by a specific or focal company and its products. For this research, the focal company is a manufacturer ("Manufacturing Company") of solid wood and engineered panel kitchen cabinets. The Manufacturing Company has a number of manufacturing facilities across the United States and supplies kitchen cabinets in most states through a number of different sales and distribution channels.

The selection of the Manufacturing Company for the research was based on a number of criteria:

1) The Manufacturing Company was representative of a hardwood manufacturing company in its methods of production which includes drying lumber, processing lumber into dimension stock in a rough mill, manufacturing parts on standard woodworking equipment, as well as gluing and finishing stages.
2) The Manufacturing Company manufactured products that were representative of the hardwood industry's "high-grade market segments" which include the furniture, cabinets, flooring and millwork industries (Sinclair et al. 1992). This "high-grade" designation was because the use of the higher quality hardwood lumber utilized by these segments creates more value for wood fiber (Luppold et al. 2007).
3) The Manufacturing Company maintained on-going relationships with its immediate customers and suppliers as one of the criterias of a supply chain is that there is some form of collaboration between its members (Beamon 1998).

With the selection of the focal company, the next step was the selection of the specific supply chain that the Manufacturing Company was a part. Since it is regarded that a company is not part of just one supply chain but many supply chains, a company typically has a number of different suppliers and a number of different customers (Lambert et al. 1998). A specific chain within this network must therefore be selected that meets the requirements of the system defined in the objectives. Figure 3-1 shows the focal company, the Manufacturing Company, set amongst its various suppliers and customers. Since the primary product of the Manufacturing Company is kitchen cabinets, the two most utilized supplies are the solid wood and panel products that make up a majority of the product by volume. Other external suppliers would be made up of providers of veneers, hardware, adhesives, and finishes. The primary customers of the Manufacturing Company were builders and contractors who purchase directly from the Manufacturing Company's service centers or retailers who sell to the builders and contractors AND ultimately the final customers, the home owners.

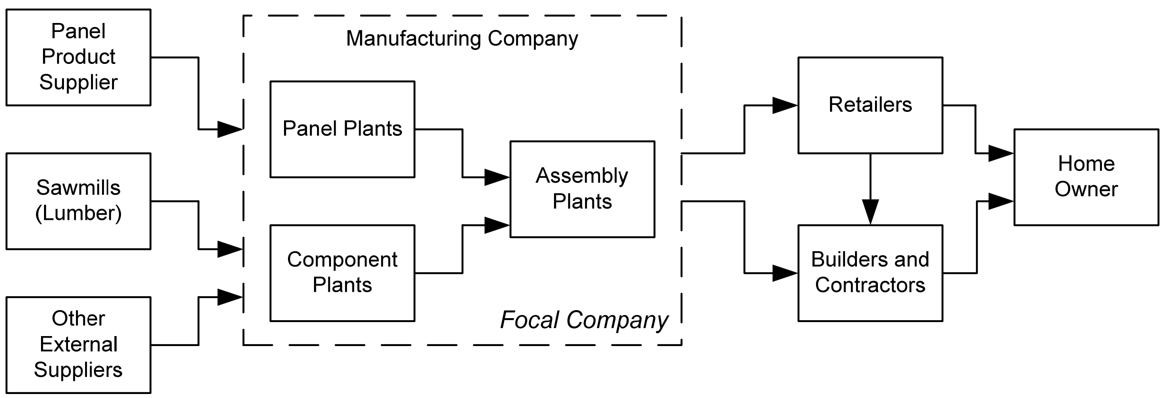

Figure 3-1 Focal Manufacturing Company and its Relationship with Suppliers and Customers

In addition to the external suppliers and customers of the company, the Manufacturing Company is not a stand-alone manufacturing facility, but a conglomerate of a number of different divisions of manufacturing facilities, as well as the headquarters and a number of service centers. Thus, the Manufacturing Company's divisions can have suppliers and customers that are internal to the conglomerate. Figure 3-1 includes a depiction of the internal customer/supplier relationships that exists within the Manufacturing Company (inside the dashed box). The three internal divisions of the Manufacturing Company (Panel Plants, Component Plants, and Assembly Plants) are operated as individual profit centers with managers who are in charge of each division's activities, production, inventories, purchasing, etc. Thus, for the research supply chain case study, the individual divisions within the focal company must also be considered.

The selection of the specific members of the supply chain to include in the case study was determined based on the requirements of the research. The objectives of the research (Section 1.4) state that case study supply chain must be representative of a Hardwood supply chain. Kaplinsky and Morris (2001) have identified the members of a hardwood supply chain as:

forestry/logging operations, a sawmill, a secondary manufacturer, buyers (wholesalers/retail), and finally consumers (detailed in Section 1.7.2).

Internal to the Manufacturing Company (secondary manufacturer), the supply chain must follow the flow of the hardwood lumber through the facilities that make up the Manufacturing Company. Since the only solid hardwood components in the final product are used in the making of the doors and drawer fronts (the remaining wood components being made from veneers and panel products), the facility that makes the doors and drawer fronts, termed "Component Plant," was included in the case study supply chain, as well as the "Assembly Plant" - the facility that takes those components and assembles them into the final product.

The Component Plant produces doors from four different species of lumber. For the research, red oak was followed for several specific reasons, to be discussed in Section 3.3.1. The external supplier to the Manufacturing Company (Component Plant) in the case study supply chain was one of the suppliers of red oak lumber. As are most of the sawmills that supply lumber to the Manufacturing Company, the specific supplier in the case study supply chain combined both the forestry/logging operations and the sawmill in one organization. This organization will be identified from this point forward as the Raw Material Supplier.

The immediate external customer to the Manufacturing Company was selected as part of the case study supply chain based on the volume of products the customer obtained from the Assembly Plant (approximately 30% by volume) which is the largest customer for the Assembly Plant. The "Retailer," as it will be identified in the research, is one showroom for a company that operates showrooms throughout the mid-Atlantic region and who was the largest customer in the region the Assembly Plant operates.

The final customer or consumer to the Manufacturing Company for the case study supply chain was a home owner who purchased the final products of the Manufacturing Company through the Retailer. This "Final Customer" does not represent the majority of business conducted by the Retailer (building contractors would), however the home owner 1) represents the second largest customer of the Retailer, 2) is the absolute final customer of the case study supply chain, 3) is not necessarily part of the decision-making process when the purchase is made by a building contractor.

The case study supply chain is narrowed down from the original scenario (Figure 3-1) and defined in this research as the four facilities (Figure 3-2) that connect the raw material, trees, with the final customer, the home owner. They are a forestry/sawmill company (Raw Material Supplier), a door manufacturing division of the Manufacturing Company (Component Plant), a final assembly plant division of the Manufacturing Company (Assembly Plant), and an independent retail store (Retailer). The Raw Material Supplier transforms trees into lumber; the Component Plant manufactures the lumber into cabinet doors; the Assembly Plant combines the cabinet doors with other components to make finished cabinets; and the Retailer combines the cabinets with other products such as countertops, sinks and appliances which were to be installed as a completed kitchen in the home of the Final Customer.

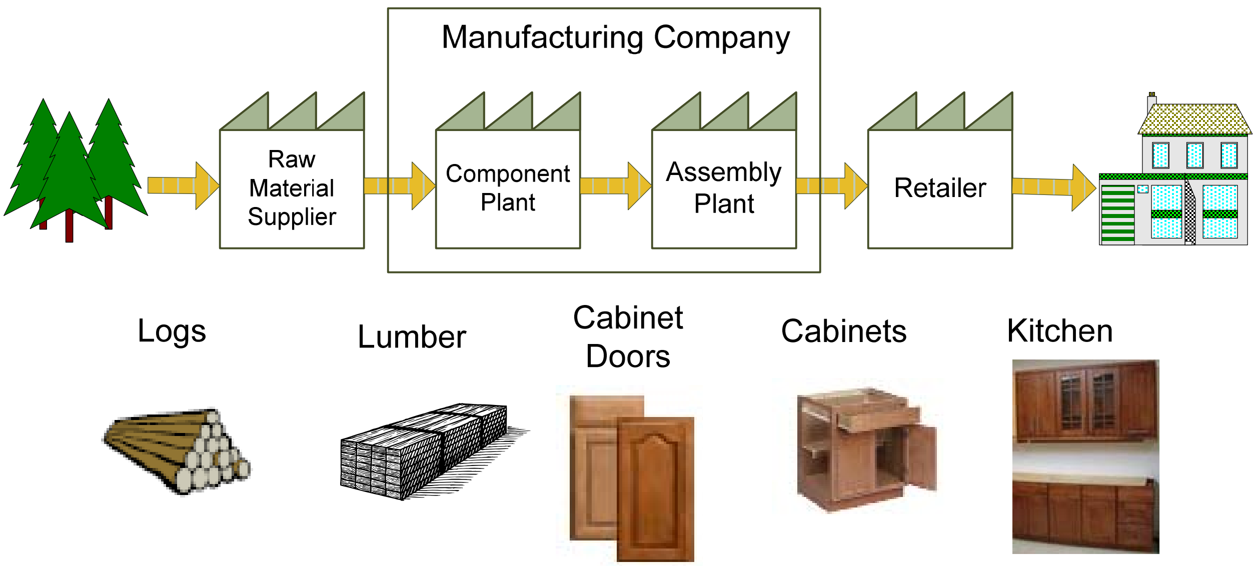

Figure 3-2 Case study supply chain

3.2 Raw Material Supplier

The Raw Material Supplier role in the supply chain is to obtain the resource (trees), transform the resource into a product that is easy to utilize in a manufacturing setting (lumber) and deliver the lumber to the Component Plant. To accomplish this role in the case study supply chain, trees are harvested and manufactured into logs in the forest and these logs are manufactured into lumber at the factory (sawmill).

The Raw Material Supplier operates in the central Appalachian hardwood forestland. The species of trees that grow within that region are desired by companies such as the

Component Plant that offer traditional solid-wood products to customers in the United States. The species found in the region that the Raw Material Supplier sells to the Component Plant include red oak and soft maple. Due to regional species distribution in the forest, the Raw Material Supplier cannot offer all of the species required by the Component Plant. Therefore, the Component Plant must fulfill gaps in their species requirements through distribution networks and lumber brokers that are able to provide raw materials from a larger geographic region.

In addition to species limitation, the Raw Material Supplier cannot produce the volume of any one species of lumber that the Component Plant requires. Thus, the Raw Material Supplier is not the sole supplier of lumber of any of the species that it does cut and must vie for the opportunity to supply the Component Plant with other sawmills. The relationship between the Raw Material Supplier and the Manufacturing Company is controlled predominantly with the purchases and purchasing conditions dictated by the Component Plant.

The Raw Material Supplier sells un-dried, “green,” lumber to the Component Plant. The Raw Material Supplier does have the resources to dry the lumber however the Component Plant prefers to dry their own lumber when possible. Larger manufacturing facilities, such as the Component Plant prefer drying lumber on-site, as it reduces the cost of the raw material and can better control variability in lumber quality for the target value stream due to more precise and consistent control of the drying process which can increase the yield of parts from the lumber (Wengert et al. 1994).

Orders for lumber are made to the Raw Material Supplier by the Component Plant on a monthly basis, with delivery to be made within 30 days, though earlier delivery is accepted especially for orders that require multiple shipments. Since the lead time for harvesting the trees and manufacturing lumber from those trees is less than one month (generally two weeks), the production manager of the Raw Material Supplier will balance what is currently being cut in the forest with what it can supply to the Component Plant and its other customers, with little inventory or holding requirements.

There are a number of different sources of timberland that the Raw Material Supplier has available to procure trees. In addition to the 75,000 acres of timberland owned by the Raw Material Supplier, contracts are made with local landowners for timber rights.

The Raw Material Supplier operates both the harvesting operation and the sawmill operation. The harvesting operation fells the trees and converts them to merchantable products (i.e. logs). At the sawmill, the logs are processed into lumber under the specifications of customers and graded based on the standards and rules developed and overseen by the National Hardwood Lumber Association as defined in their guidebook (NHLA 1998). The Raw Material Supplier processes approximately 300,000 board feet[1] per week (five business days) of Appalachian hardwoods and eastern pine.

3.3 Manufacturing Company

The Component Plant and the Assembly Plant in the case study supply chain are two divisions or facilities of a larger company. The "Manufacturing Company" is a supplier of mass customized kitchen cabinets. The business strategy of mass customization means that their customers have a limited selection of customizable product designs from which to choose, and the cabinets are assembled to a specific customer order from a standard inventory of part sizes, styles, species and finishes. Mass customization is common among kitchen cabinet manufacturers as it allows for a large range of finished products without the need of maintaining large finished goods inventories.

The Manufacturing Company is a national supplier of kitchen cabinets with approximately 5,000 employees throughout the organization and annual sales of 550 million dollars. The Component Plant and the Assembly Plant are only two of the Company's eight manufacturing facilities - five regional assembly plants and three component plants located throughout the continental United States. The assembly plants supply the customers, such as the Retailer, with completed cabinets, and the component plants supply the assembly plants with specific parts for the cabinets.

The Manufacturing Company has strategically located component plants near the raw materials utilized in the production of its particular components. The purpose is to minimize the transportation of the raw material in order to reduce the costs of shipments and thus reduce overall cost of manufacturing. The Component Plant produces doors from hardwood lumber, and it is located in the heart of the Appalachian Mountains, which is known for its hardwood

[1] *Board Feet* is a measure of lumber volume. It is equivalent to 144 cubic inches. 1000 bdft = 2.36 cubic meters

forests. Lumber is purchased from nearby raw material suppliers (sawmills), dried of excess water, processed into cabinet doors and shipped to the Assembly Plant without the added weight and volume of residuals.

The various assembly plants for the company are strategically distributed throughout the continental United States to serve regional markets. By doing so, the average distance that a finished cabinet must travel to the final customer is much smaller than if there was only one assembly plant serving the entire market. This strategy has two major effects: 1) it minimizes order delivery times to the customers, and 2) it minimizes shipping cost because, in its final form, a kitchen or bath cabinet is a large empty box which is inefficient to ship on a per ton basis over great distances. For this research, the particular assembly plant is the one that serves the mid-Atlantic region of the United States.

The Manufacturing Company offers a range of product styles and quality to their customers. There are three levels of quality. Within each quality group, one can choose from up to five hardwood species or a laminate and up to 20 door styles. The Assembly plant will produce all of the cabinet styles offered by the Manufacturing Company within its regional market. However, the Component Plant produces doors manufactured from hardwood lumber obtained only from the region; doors made of other species or composite materials are produced by other component plants.

3.3.1 **Component Plant**

The Component Plant manufactures approximately 16,000 components per day. All of the components are made exclusively for the assembly plants of the Manufacturing Company. Approximately 80 percent of the components' production is made to maintain standard parts inventory levels of the facility. The remaining 20 percent of the production is made to meet specific on-demand orders for the final customers. The 20 percent of on-demand production is for components that are in low demand which the company has deemed uneconomical to hold inventory or they are special orders for sizes that are not standard to current component dimensions.

The lumber utilized for manufacturing into the components comes from between 35-40 sawmills including the Raw Material Supplier in this study. In addition to sawmills, lumber also comes from brokers (15%) which are used primarily for obtaining a certain species of lumber.

Other than these brokers, the Component Plant maintains preferred suppliers and does not search out new suppliers. The Component Plant utilizes four species of lumber – red oak, hard maple, soft maple and cherry (Figure 3-3). Due to inherent discoloration issues, the hard maple lumber is purchase pre-dried to appropriate specified moisture content. Since red oak, soft maple and cherry do not have the same coloration issues within the process, the lumber is purchased "green" (un-dried) and the drying processes are performed at the Component Plant. For the purpose of drying lumber, the Component Plant maintains two pre-driers, which perform the initial drying and six steam-heated dry kilns for completing the drying process.

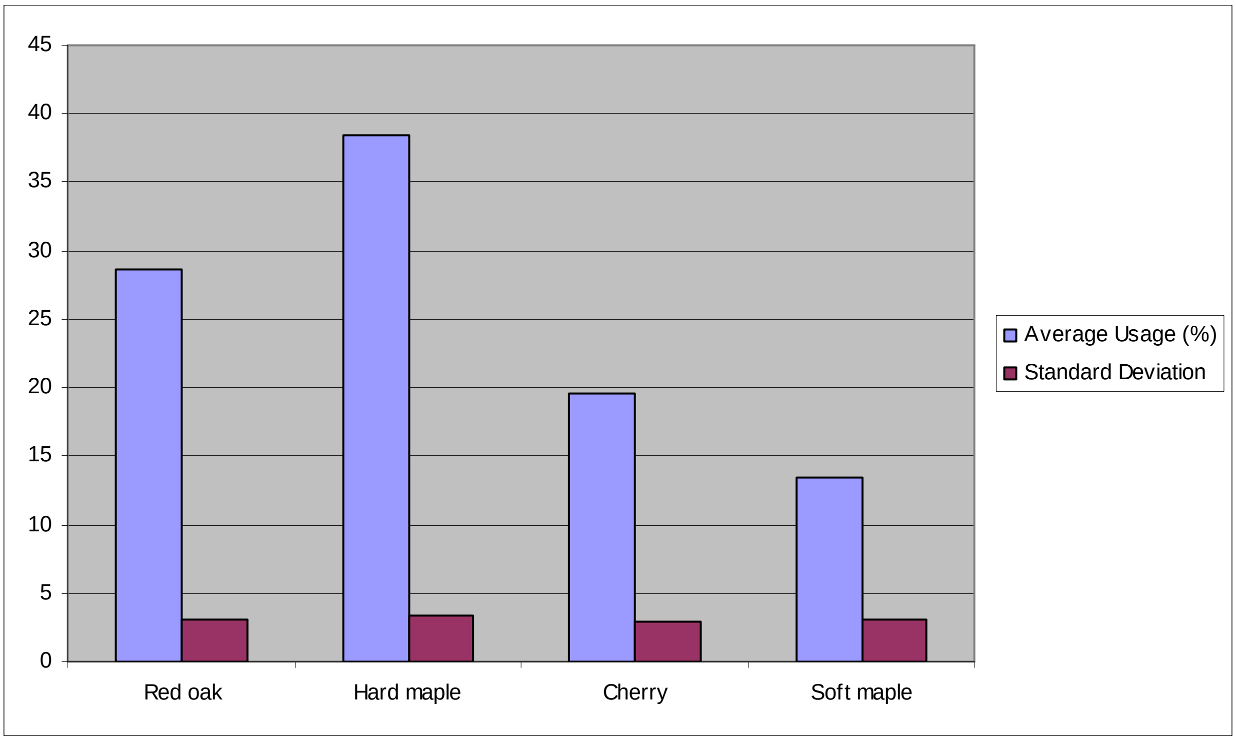

Figure 3-3 Distribution of Species Usage at the Component Plant

The Component Plant maintains approximately 500,000 board feet of dry lumber in inventory until needed by the processing plant. The individual quantities of the four species of lumber held in inventory vary to account for production fluctuations and lead times for obtaining and drying the lumber.

The processing of the dried lumber to a finished component which is ready to be delivered to the assembly plant occurs in five stages as shown in Figure 3-4. Minimal inventory is held between these stages and the total time it takes from the beginning of the first stage to the completion of the final stage is five days. The lumber is first planed, ripped (cut to width), moulded, and chopped (cut to length) in the dimensioning stage. Additional machining and shaping is performed in the second stage. The pieces are combined during the glue-up stage to form the component. The component continues through one more shaping process (at a double end tenoner) and sanded to smooth on all surfaces. The final stage is the application of finish (including color) to all surfaces.

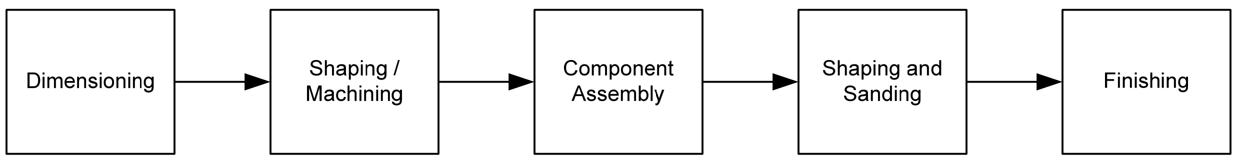

Figure 3-4 Component Plant - Manufacturing Process

Upon the completion of the manufacturing process, the components are delivered to their appropriate destination – either finished goods inventory at the Component Plant or shipped directly to an assembly plant that requires the components immediately. The Component Plant maintains an inventory of approximately 175,000 parts which have a high to medium demand that can be shipped to the assembly plants immediately. The inventory represents about 14 business days of demand or 15 inventory turns per year. Low usage items are made-to-order and shipped directly to the assembly plant that ordered them upon completion in the manufacturing process.

3.3.2 **Assembly Plant**

The Assembly Plant is one of several assembly plants operated by the Manufacturing Company. Each assembly plant serves a specific regional United States market with strategic overlapping markets when required due to changes in market demand or product changes. Each assembly plant manufactures all of the final products offered by the Manufacturing Company.

The Assembly Plant is a simple two-stage facility (assembly and shipping) as shown in Figure 3-5. Since all of the components that make up the final product created at the Assembly

Plant are obtained from suppliers, either internal or external to the Manufacturing Company, the Assembly Plant maintains a large inventory (20 days worth of inventory) of which parts from the Component Plant number approximately 65,000.

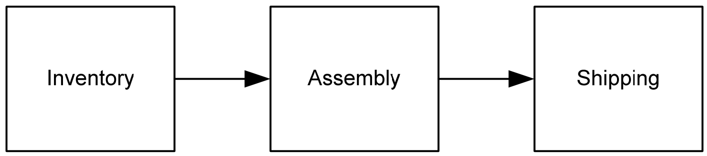

Figure 3-5 Assembly Plant – Manufacturing Process

All products manufactured at the Assembly Plant are made-to-order. There is no inventory held for final products. Instead, the finished products are transferred directly from the production area to the trucks that are destined for their customers. By producing to customer orders and not to inventory, the Manufacturing Company can offer a larger selection of final products and minimize the costs of inventory; this is known as one type of Mass Customization (Gilmore et al. 1997).

Though the Assembly Plant makes products to order, the customer (Retailer) still requires a fast delivery of products from the Assembly Plant. Thus, the Assembly plant must manufacture the final products quickly, and maintain a large inventory of components on-site. To sustain minimal assembly lead times, the Assembly Plant utilizes cellular manufacturing techniques which reduce production time due to the lack of work-in-progress inventory and can be balanced against a variable demand for the final products. There are numerous assembly cells for manufacturing the final product, which can produce an average of 3,800 final products in an 8 hour shift, or about 500 final products per hour.

Each assembly cell is made up of all of the steps required to make the final product from the components. All components are taken from inventory and placed in an ordered queue at the production workers' stations. A short conveyor system is utilized to move through the production process. Upon completion, the final product is put in its box and is transported to the loading docks. The total assembly time of the final product is less than one minute and the transportation to the loading dock is another 5 minutes – ready to be placed on the Retailer's truck.

3.4 **Retailer**

The Retailer is a business that sells components of kitchens (cabinets, countertops, appliances, and fixtures) in addition to bathrooms and specialty cabinetry for the home offices and entertainment rooms. Their main customers are contractors and home owners. The Retailer differentiates itself from other retailers, such as home improvement stores, by offering only mid- to upper-quality products, including custom cabinetry and by offering its customers more service options than would be expected at home improvement stores.

The Retailer is one of 18 stores operated by a privately held company, which, as a whole, is one of the Manufacturing Company's largest customers. Its headquarters and all of its stores are located in the mid-Atlantic region. Though the privately held company dictates the supplier brands that the stores must carry, operation of each store is independent of the privately held company. The stores purchase directly from the suppliers and deal directly with local contractors for installation without having to go through intermediate steps.

At the Retailer, 80% of purchases are made by contractors/builders and the remaining purchases are made through sales directly to final customers (typically home owners). The Retailer in the case study works with 15 contractors/builders with six of these being responsible for most of the purchases.

The Retailer and the other stores owned by the privately held company are designed around a showroom in which the various product lines are displayed. The showroom displays resemble kitchens and other rooms displaying the product lines that they represent.

For kitchen cabinetry, the Retailer offers a selection of products from four main manufacturers. Three of the manufacturers can be identified as mass customization because standard cabinets are assembled in a factory to order specification. The remaining manufacturer is a custom cabinet contractor who manufactures the cabinets specifically for the Final Customer's kitchen.

The Retailer maintains a minimal inventory with products that are stored at the facility representing three categories: short-term holding, accessories, and returns. The short-term holding is any product that has been ordered for its customers that has been delivered from the supplier or distributor and has yet to be picked up by the customers. Accessories are mouldings, panels, and other components that may be required for installation and are kept in stock so that installation will not have to be delayed due to delivery lead times from the suppliers. Returns are products, including cabinets that do not meet the specifications of the Final Customer or installation and must be reordered. In some cases, the suppliers do not require them to be returned and are held by the Retailer until suitable re-use can be determined, or they are disposed.

To reduce costs associated with holding inventory (warehouse rent, heating, management, etc.), the Retailer minimizes inventory held at the store, especially the inventory associated with the short-term holding of cabinets for the final customers. To minimize inventory holding costs, the Retailer orders products from the suppliers and distributors based on lead times of delivery. If a customer orders cabinets for delivery in four weeks, but the lead time for delivery from the supplier is seven days, then the Retailer will not place the order to the supplier until the end of the third week. In addition, the Retailer maintains a "pick up" clause in the contract which states that if the customer does not pick up the order within 10 days of the date that they requested the cabinets be available, a daily fee for storage of the cabinets is added to the bill.

3.5 The Final Customer

The driving force of any supply chain is the final customer. Without the demand of the final customer for the product that a supply chain makes, there is no reason for manufacturing the product or any of the components or materials along the supply chain. Any product that is manufactured that is not demanded by the final customer has no value and must be stored in inventory until a final customer or end-use can be found.

The Final Customer of the case study supply chain is identified as homeowners who are remodeling a kitchen or installing a kitchen in a new home. The Final Customer has a number of possible sources to purchase the cabinets: home improvement stores, discount centers, cabinet shops, and the Internet, but has chosen a retailer specializing in mid to high-end kitchens. The Retailer in this supply chain has identified its customers as people who consider the "look" of the finished kitchen as their main priority, followed closely by construction and functionality and after these, price.

3.6 **Summary**

The case study supply chain was selected for this research based on a number of criteria. It had to be representative of a supply chain in the hardwood industry which means that it manufactured a product that is typical of the hardwood industry and that all of the companies within the supply chain manufacture, process, and transport the product in a manner similar to other companies in the hardwood supply chain. Like most supply chains, each member of the supply chain has any number of suppliers and customers. The supply chain chosen for the case study followed the predominant products of each company in the supply chain by volume.

The focal company was chosen as the company that manufacturers the finished product within the supply chain. This manufacturing company is a national supplier of kitchen cabinets in the continental United States.

Specific products and components were selected that could be followed through the supply chain of interest. The components utilized solid hardwood lumber (red oak) as its primary material so that the supply chain would include the lumber manufacturer required by the study constraints. The selected products and components dictate that two facilities within the focal company be analyzed – the one that manufactured the components and the one that utilized the components to assemble the finished product.

The customer of the focal company selected for the case study supply chain was one retail store that belonged to a larger retail company that was a major purchaser of finished products from the focal company. The retail store obtained the finished product directly from the manufacturing company and sold directly to the final customer (the homeowner).

The supplier to the focal company selected for the case study supply chain was one of four suppliers of the specific lumber of interest in the research. This supplier is a company that harvests trees and manufactures lumber from the trees requiring no other companies between the raw material and the focal company.

Though the case study supply chain represents only one potential supply chain by which each company included could be a part, the individual company selection was based on a particular focus of product lines centered around the red oak solid wood cabinet door frame manufactured by the focal company. This focus makes the subsequent analysis much more manageable and rich in data. The product focus is based on a “high-volume” pathway which revealed key material and information flow constraints that impacted overall supply chain performance. Analysis of these constraints leads to recommendations for improvements for the overall system that they represent.

This case study supply chain was utilized to perform the required analysis for completion of the goals and objectives defined in Chapter 1 and outlined in Chapter 2. The flow of material and the flow of information were determined for this supply chain as well as an analysis of the role of information from supply chain partners in the decision-making process within the individual companies that make up the supply chain. Finally, an analysis of the impact of increased information sharing within the supply chain was performed.

Chapter 4 Material and Information Flow

4.1 Introduction

To determine the extent that information from the supply chain is utilized by individual companies within the supply chain, it is first important to determine the pathways in which the information flows both within a company and between companies (the first objective of the research). In Chapter 3, the supply chain of interest was defined and the general flow of material and processing steps through the case study supply chain were identified. This chapter will be devoted to precisely identifying the material (or production) pathway through the supply chain and identifying the pathways in which information passes along the supply chain to create and manage the flow of material. In doing so, the first objective of this research, to determine the pathways of information and production flow through the Hardwood supply chain and benchmark current lead times for both, will be addressed.

4.2 Material Flow in the Supply Chain

As defined in Chapter 2, Value Stream Mapping is a tool to analyze production flow within a company or supply chain. This section defines the material flow of the case study supply chain (Figure 4-1) as prescribed in texts for Value Stream Mapping (Rother et al. 1998; Jones et al. 2003). Information flow will be included as it is defined by these methods as non-linear flow. The following section (Section 4.3) analyzes the information flow of the case study in greater detail utilizing the same tools and techniques, but follows the final customer demand as it flows through the supply chain in a linear fashion in the opposite direction of the material flow.

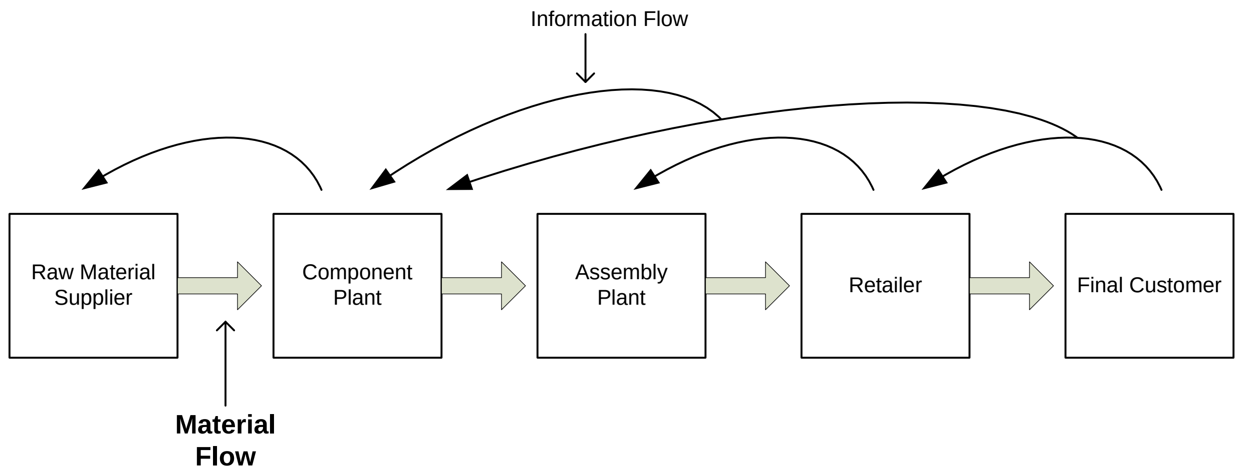

Figure 4-1 Flow of Material in the Case Study Supply Chain

4.2.1 **Data Collection - Walking the Supply Chain**

When following the flow of material through a supply chain, an important attribute of this process is the *lead time*. The lead time is the total time that it takes for material to travel from its origin to the destination. For a simple process, such as machining, the lead time is the time that it takes for a part to be processed by a machine. In the case of a supply chain, the total lead time is the time it takes from the point of initiation of extraction of the raw material to the point at which the product is delivered to the final customer.

For the case study supply chain, material was followed from the point at which the raw material was extracted to the point at which the finished product was delivered to the final customers (a more detailed discussion on data collection for Value Steam Maps can be found in Appendix A – Data Collection Methodology for Material and Information Flow). The data collected from this "walk" was utilized in the understanding of material flow modeled using Value Stream Mapping in Section 4.2.2. In addition, the individual companies/stages that are identified will be mapped in the subsequent sections. The following is the pathway of material flow through the supply chain:

Raw Material Supplier

The supply chain begins with the tree in the woods. The extraction crew for the Raw Material Supplier harvests the trees and prepares them for the production at the main facility (the sawmill). A tree is cut down and limbs and top removed from the main stem. The stem is conveyed by a winch to the access road where it is combined with other stems and is dragged to an intermediate processing area. The stems are stacked with other stems to await their second processing step, which is to cut the stem to merchandisable log segments based on length and quality. After being processed, the log segments are held in queue until they are loaded onto a truck and transported to the main facility of the Raw Material Supplier.

At the main facility, the raw material is converted from log segments to lumber. The log segments are placed in piles based on species and grade to await the processing in the sawmill. When it is time (typically processed first-in-first-out) the log segment are placed on the entering conveyor to the sawmill where the bark is removed from the log, the log sawn into lumber, and the lumber is graded and stacked. The completed stacks of lumber are held until transported to the customer - the Component Plant.

Component Plant

Once delivered to the Component Plant, the stacks of boards are converted into doors that will be used in the production of kitchen and bath cabinets at the Assembly Plant. There are two stages that the boards must go through to become the finished components – the preparation stage and the production stage.

Before the boards can be processed, they must be dried, as trees maintain large quantities of water that must be removed before the lumber can be made into wood products for a home (Simpson 1991). From the receiving queue, the boards are re-graded by the Component Plant to verify grades and restacked for the drying process. The new stacks are placed in the large environmental chambers (predryers) which remove most of the water from the boards. The stacks are then transferred to a large drying oven where the remaining water in the boards will be reduced to the required level and drying stresses relieved. Both of the drying steps can be considered value-creating time as they are required for a quality finished product. After this drying process, the wood is cooled and placed in a queue until required by production.

During the second stage of production at the Component Plant, the dried boards are converted into finished doors through a series of processing steps. The boards are first processed by the “rough mill,” the portion of the facility that converts the boards into specifically sized and shaped pieces. This process involves four steps with a total value creating time of approximately two minutes. Four of these pieces that are created at the rough mill are combined with a central panel (which was manufactured at another facility) to form a cabinet door. The doors are shaped, sanded, and coated with a finish to create the completed component. The total value-creation time for this portion of the process is approximately five minutes. Once the doors are completed, they are held in inventory until requested by the Assembly Plant where they are bundled, palletized, and shipped overnight to the next facility in the supply chain.

Assembly Plant

The final phase of the production in the supply chain is at the Assembly Plant where components are combined to produce the finished cabinets. When the doors from the Component Plant arrive in the morning, they are staged and eventually placed in the Assembly Plant’s inventory, and where they sit until needed by production. The doors are removed from the inventory and placed in queue at the production line. After a 30 minute wait they are assembled with the other components into a finished cabinet in under a minute, put into a box and transferred via conveyor to shipping. They are loaded onto a truck and when the truck is filled (all appropriate cabinets are on board), the cabinets are transported to the Retailer.

Retailer

The cabinets remain with the Retailer for a short time until the customer is ready to pick them up. This time is typically minimized by two policies of the Retailer. First, the Retailer orders from its suppliers so all orders arrive just before the Final Customer's requested pick-up date. Second, the Retailer charges a storage fee to the Final Customer if the cabinets are not picked up prior to 10 days after the agreed upon pickup-date.

Table 4-1 is a step-by-step synopsis of the stages that the material went through to be transformed from the raw material to the final product as delivered to the Final Customer. The information portrayal is as prescribed for mapping supply chains (Jones et al. 2003). The first column is the specific process, transport, or storage that the material goes through in chronological order. The second column is how many value creation steps were included in that stage (value creation step is any process that increases the value of the material or product in the eyes of the final customer (Jones et al. 1997)). The third column is the amount of time the material spent in that particular stage. The final column is the amount of time the material spent in a process that added value to the final product in the eyes of the Final Customer.

Table 4-1 Steps in the Flow of Material through the Supply Chain

Stage	Value Creating Steps	Total time	Value Creating Time
Raw Material Supplier part 1			
1. Obtain raw material		1 d	
2. Store raw material		1.5 d	
3. Load raw material for thrice daily direct ship		40 m	
Transport Link (internal)			
4. Direct ship processing plant (50 miles)		0.3 d	
Raw Material Supplier part 2			
5. Unload raw material		8 m	
6. Store raw material		9.5 d	
7. Processing		0.5 d	
8. Store raw material		1 d	
9. Load raw material for thrice monthly direct ship		30 m	
Transport Link 1			
10. Direct ship to Component Plant (100 miles)		0.25 d	
Component Plant			
11. Unload raw material		8 m	
12. Store raw materials		2.3 d	
13. Stack raw materials for next process		0.1 d	
14. Drying raw materials (predrying)	1	60d(43 d)*	43 d
15. Drying raw materials	1	6d(5 d)*	5 d
16. Store raw materials		6 d	
17. Processing of raw material	8	2 d	7 m
18. Store completed components		11 d	
19. Load truck for daily delivery		0.5 d	
Transport Link 2			
20. Direct ship to Assembly Plant (250 miles)		4.5h	
Assembly Plant			
21. Unload components and put in inventory		0.5 d	
22. Store components		20 d	
23. Processing (assembly of cabinet)	1	1 h	1 m
24. Load truck for weekly delivery		0.5 d	
Transport Link 3			
25. Direct ship to Retailer (175 miles)		3 h	
Retailer			
26. Unload truck		0.25 d	
27. Store finished product		7 d	
Total business days	11	113d 3h 32m	48d 8m

* 24/7 operation, to be consistent with other processes the number in parentheses represents conversion to business days.

From the data collected, it was determined that the time between initial extraction of the raw material and the time that the Final Customer obtains the final product, the lead time of the supply chain, is greater than 113 business days (5.2 months). Out of the hundreds of work-in-process steps observed, only 11 steps were identified as "value creating" steps. The total time for these value creating steps was 48 days 8 minutes or 42 percent of the total lead time, most of this time (48 days) was involved in the wood drying processes. Over 51 percent of this time (58 days) is inventory sitting between business segments. The products are being transported between facilities in the supply chain 1.5 percent of the time.

A break-down of where most of the time in the supply chain lead time was spent (Figure 4-2) shows that most of the time was at the Component Plant, which has two inventory steps and a particularly long processing time due to the drying of the lumber. The Assembly Plant, though fast in production, has a larger inventory, and thus a large delay. The Raw Material Supplier is the next longest time in the supply chain due to its two processing areas, the forest and sawmill and their associated queues. The Retailer maintains no inventory except that for products to be picked up from the customer, thus delays are minimal.

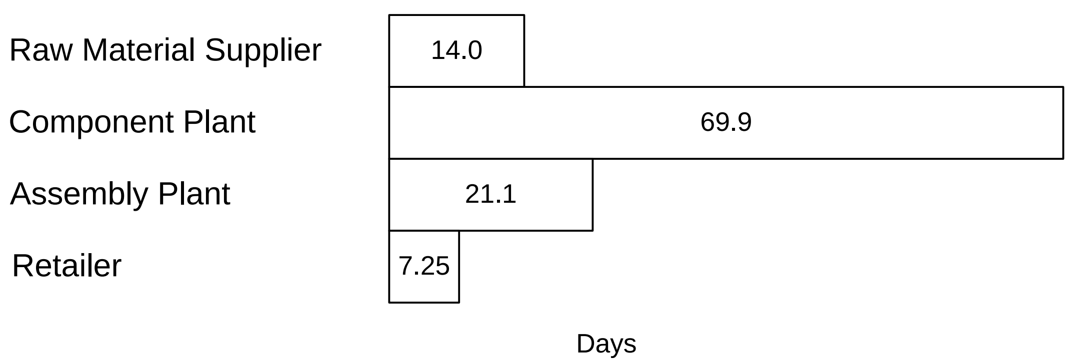

Figure 4-2 Time Spent at Stages in the Supply Chain

Figure 4-3 shows that a significant portion of the time that material flows from the Raw Material Supplier to the Final Customer is in delays relating to storing of the products along the supply chain. Note that "Value Creation" is independent of the specific steps in Table 4-1 and thus the total of the remaining categories ("storing," "Processing," and "Transport") will sum to the total processing time of 113 days. A small portion of the delays are tied to processing the material with an even smaller portion being of processing steps that can be identified as "value creation." Finally, transportation of material within a company or between companies is minimal in comparison to the other three delay categories. Relatively small transport times are a characteristic of the case study supply chain being geographically local (552 miles of total transport distance covered between segments).

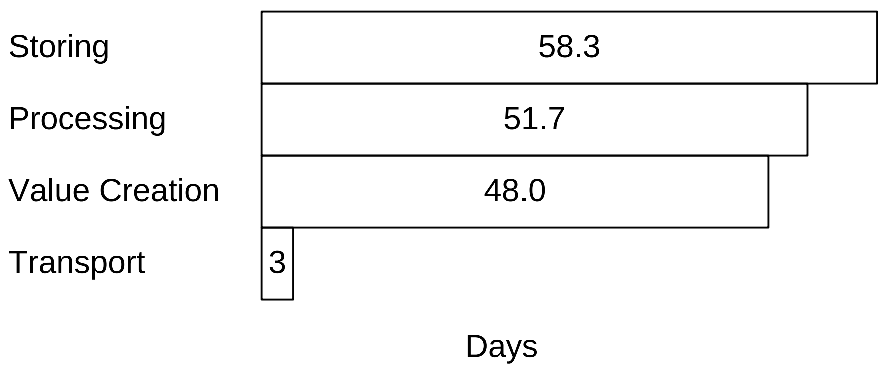

Figure 4-3 Time Spent (in Days) for Flow of Production in the Supply Chain

Drying lumber and its affect on the Hardwood supply chain

The hardwood supply chain is greatly affected by the required process of drying lumber prior to manufacturing finished parts. In the case study supply chain, the drying process makes up 48 out of a total of 113 business days (42%) for the entire supply chain. If just the Component Plant is considered, drying makes up 73% of the lead time. This number is large, in part, due to the selection of red oak as the primary species to follow in the supply chain, which takes the longest to dry of any species utilized at the Component Plant. The other species either require less drying time at the Component Plant, such as soft maple (26 days), or the drying takes place at the supplier, such as hard maple. The long drying time masks the issues of storage and the low proportion of value creation time to total supply chain lead time. For example, the value added processing time for the nine specific processing steps to transform materials specifically targeted towards final cabinet production is only 0.03% of the total lead time through the supply chain.

The drying process when accomplished in isolation of the target customer product family, causes further fragmentations in the flow of information in the supply chain that creates further lead time delays. In particular, there is a large proportion of time spent in storage of raw material, components, and final products. Large inventories are indications of supply chains that do not utilize accurate and timely information and rely more on forecasting (Forrester 1961).

4.2.2 **Supply Chain Material Flow**

Utilizing the Value Stream Mapping technique, the information collected in the previous section (Table 4-1) can be portrayed visually as shown in Figure 4-4 to better analyze the different stages of the supply chain. The figure is divided into four levels of information: information flow, material flow, production data, and steps/time. Each level portrays data that was collected during the data collection process in a concise manner for analysis.

Material Flow

Starting with the Material Flow level in Figure 4-4, the movement of material through the supply chain is similar to that shown in Figure 4-1 with a few exceptions. Most notably, the Raw Material Supplier and the Component Plant were each divided into two separate entities. The division for both was necessary for Value Stream Mapping because each of the paired subdivisions act in a supplier/customer relationship similar to the Component Plant and the Assembly Plant of the Manufacturing Company. This division was necessary for later analysis. The second difference between Figure 4-4 and Figure 4-1 in regards to material flow is the use of two different types of arrows, a striped arrow and a non-striped arrow. For Value Stream Mapping striped arrows indicate production based on forecasting downstream demand while attempting to schedule the upstream process. The non-striped arrows indicate only the flow of material (Rother et al. 1998). In the case study supply chain, the purchase of the final product by the final customer initiates the order being placed by the Retailer to the Assembly Plant, and the Assembly Plant does not make the product until that order arrives. All other production in the case study supply chain is based on attempting to meet a forecasted future demand and to keep production rates as close to capacity as possible (economy of scale).

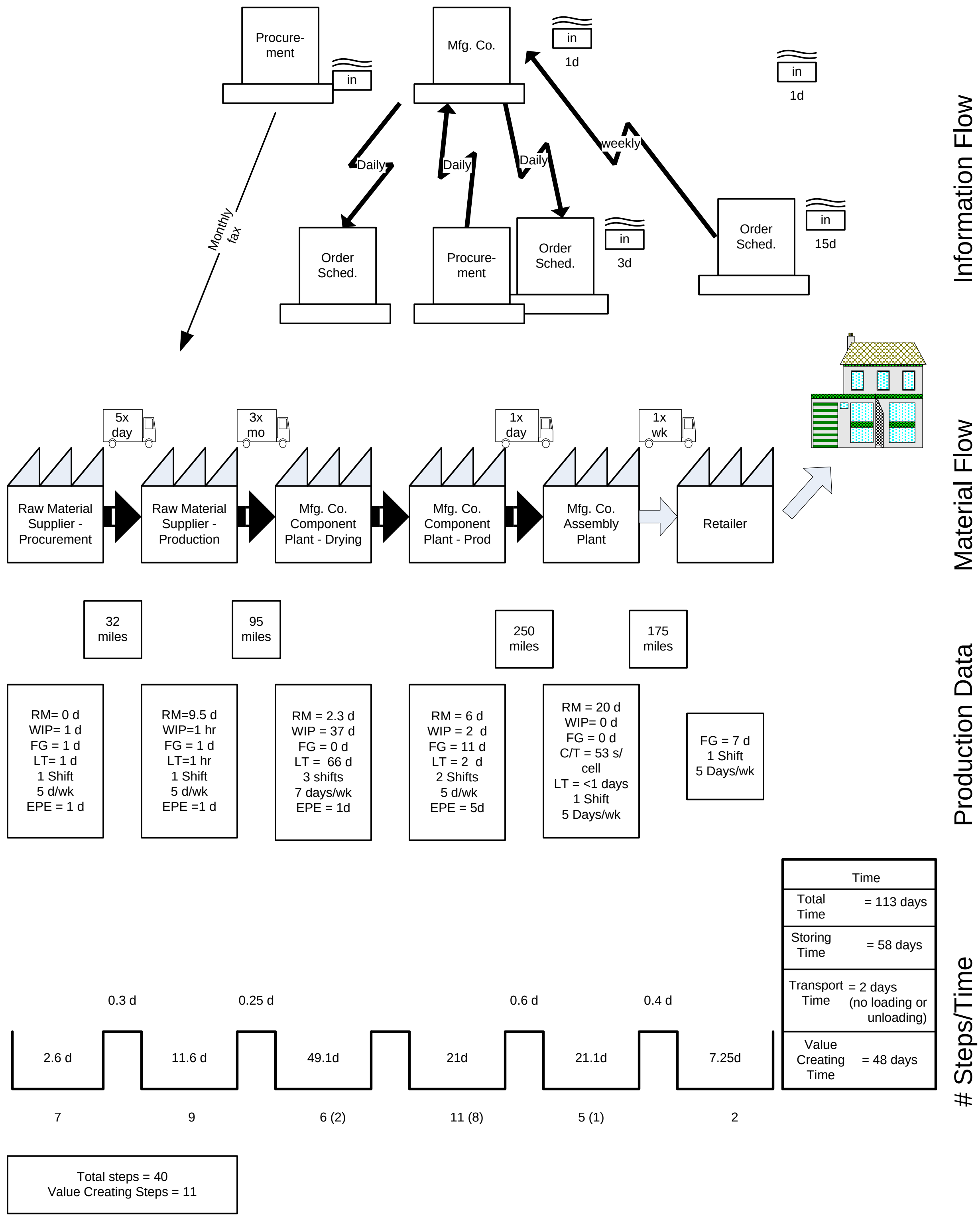

Figure 4-4 Value Stream Map of the Flow of Material through the Case Study Supply Chain

The Material Flow also depicts the rate at which the material is delivered between each member of the case study supply chain (the distances the trucks travel in the small boxes below the Material Flow level). Most material flow between facilities is done by trucking; the exception is between drying and production in the Component Plant, which is done by forklift. Since most facilities in the case study supply chain have multiple suppliers and/or customers, it is difficult to extract any specific information from the details of the rates at which material is shipped.

Production Data

The Production Data level of Figure 4-4 has data relating to inventory levels, production rates and capacities along the case study supply chain. This data assists in identifying where all the material is within the supply chain during observation and the time it will take to pass through all of the stages of the supply chain.

The inventory data in Figure 4-4 is identified as three types of inventory: raw material (RM), work-in-progress (WIP), and finished goods (FG). Raw material is the inventory of material obtained from the previous facility in the supply chain and has yet to be processed by the current holders of the material. Work-in-progress is the sum of all the material that is currently undergoing some form of processing or is at machines/workstations waiting to be processed or has just been processed. Finished goods is the inventory of material that has completed all processing by the particular facility and is awaiting shipping. The labeling of these inventories is in keeping with the format created for Value Stream Mapping. Only for this discussion will finished goods and raw material have these definitions. In the other sections of the document, raw material will remain the material supplied by the Raw Material Supplier and the finished goods/product is the final product created by the Assembly Plant.

The inventory information from Figure 4-4 is portrayed in Figure 4-5 to better visualize the location of material through the case study supply chain. The sub-divisions of the Raw Material Supplier and the sub-divisions of the Component Plant were recombined for analysis. Inventories that served as buffer stock between the sub-divisions were re-identified as work-in-progress (WIP). The work-in-progress inventory of the Component Plant dominates the numbers of days of inventory for the entire supply chain, which was earlier explained to be due to the drying process. The one important item to make note of in Figure 4-5 is the combination of the relatively large finished goods inventory at the Component Plant (11 days) and the relatively large raw material inventory at the Assembly Plant (20 days). These two inventories represent similar products and create duplication within the supply chain and result in a combined buffer stock of 31 days.   A buffer stock of this size would be important if the lead time of manufacturing the components was large or there was a large period between shipments between the Component Plant and the Assembly plant. However, the production lead time (LT) at the Component Plant is two days and there is a daily delivery between the Component Plant and the Assembly Plant which makes this excessive buffer stock an opportunity for improvement.

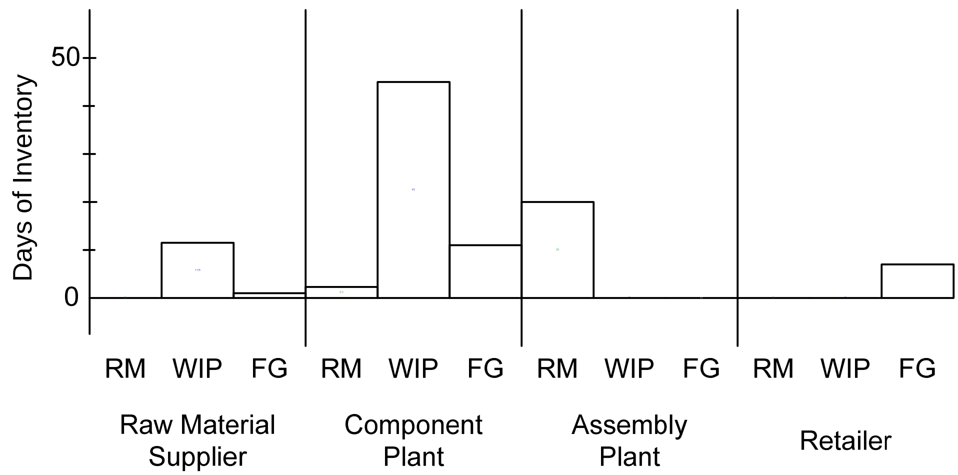

Figure 4-5 Distribution of Material in Supply Chain

There is minimum inventory at the end of the supply chain, except for the finished products awaiting pick-up by the final customer. This lack of inventory is because the finished products that are sold to the final customers are made-to-order. No inventory is held from the work-in-progress of the Assembly Plant (where the finished products are made) to the finished goods inventory at the Retailer that is not designated for a specific final customer. Thus, forecasting by the Assembly Plant or the Retailer is not required, so buffer stock (inventory) is not possible.

The combined strategies of make-to-order and lead time minimization at the Assembly Plant require that there be sufficient buffer stock (inventory) at the Assembly Plant. All components that go into the final product must be readily available to account for the variability of demand by the final customers. The *Min/Max* inventory system that is employed at the Assembly Plant for components is meant to account for the variability in demand. One of the limitations of a Min/Max system is that it can account for day-to-day variability, but does not consider cycling trends, demand growth/decline, and other longer-term trends. The result of lack of consideration of long-term demand can add to additional demand amplification which leads to larger maximum numbers for the components in the Assembly Plant inventory.

At the Component Plant, components are held in inventory to ship when the orders are placed by the Assembly Plant and the other assembly plants of the Manufacturing Company. Batching causes larger order quantities and larger delays between orders for specific components at the Component Plant than if the assembly plants ordered components as they were used. Because of these large quantities and larger delays, the Component Plant must maintain large inventories of components so that the orders from the assembly plants may be filled quickly. There are no maximum levels for components in the inventory at the Component Plant. The levels are regulated at the discretion of the production planning department and any policies from management that limit the total value (and thus quantity) of inventory held by the Component Plant.

The work-in-progress inventory at the Component Plant represents the largest inventory in the supply chain in terms of day's worth of inventory. The predominant reason for the quantity of inventory is the lead time for the drying process of the lumber prior to manufacturing of the components. Although, these drying functions are necessary, there is opportunity for improvement, especially in the pre-drying process. The raw material is dried to an approximate level in the pre-drier and is then moved to the kilns to complete the drying process. There is no prescribed time to completion or point at which the raw material is removed unless the kiln is ready to be filled. In other words, there can be a time when the raw material is dried to a point of diminishing return in the pre-drier, and it can then be considered inventory and not work-in-progress.

The final position within the case study supply chain in which significant inventory is held is as work-in-progress at the Raw Material Supplier. This is material that has been harvested from the forest and not yet manufactured into lumber. The predominant reason for this inventory is to account for weather conditions at the harvesting sites. The policy at the sawmill is to try to maintain enough sawlogs on-site to account for delays in harvesting due to inclement weather, but to also attempt to minimize that inventory so as to limit the amount of degradation that may occur to the raw material while sitting in inventory.

Other information included in the Material Flow portion of Figure 4-4 for the purpose of a fully complete Value Stream Map are the lead time for manufacturing (LT), the number of shifts per day and the numbers of days per week the facility operates, and a measure of how frequently products are made (EPE). The EPE is an abbreviation for *Every Part Every* and when put with a time such as EPE = 1d means in this case that every part (or product) is made once every day. The only facility that cannot make every part every day within the case study supply chain is the Component Plant, which has a five day cycle due to the large quantity of styles and finishes that they produce in batches (to minimize set-up time). This is important because though the lead time is only two days through the Component Plant, the rotation of products is five days. Thus, there is a delay in reaction time to the demands put upon the Component Plant by the Assembly Plant.

Steps / Time

The bottom level of the Value Stream Map in Figure 4-4 is the number of steps in the process and the pertinent times for the case study supply chain. In this depiction, the values at the top of the peaks are the transportation times between facilities. The values in the valley of the shape are the times to be completely processed by each facility immediately above the particular valley. Finally, the values under the shape are the number of processing/handling steps that the material goes through at each facility with the number of steps that are "value added" in parentheses.

As with any Value Stream Map, the amount of detail, or what is included in each step is dependent on the size of the system that is analyzed. Since Value Stream Maps are meant to be descriptive within one figure in a report, the level of detail should reflect this. A Value Stream Map that is highly detailed may include items such as breakdowns in individual machinery within a production facility or the number of stops of a truck during transportation, but the resulting Value Stream Map will be limited to a small portion of a supply chain. The analysis contained here is meant to encompass the entire supply chain, thus information is aggregated accordingly.

When the subdivided Raw Material Supplier is combined and the subdivided Component Plant is combined, the results of the total values for total processing time at each facility would be similar to Figure 4-2. The total time in the case study supply chain is 113 days. The Component Plant would contribute to the longest processing times due to the drying process (see Section 4.2.1 for additional discussion). The total transportation time is slightly different than previously reported due to the inclusion of loading and unloading times in the earlier figures. The values for transportation in Figure 4-4 are only for the actual time on the road. For this analysis, loading and unloading times were added to the processing times for the appropriate facilities.

The value creation within the case study supply chain is of importance in that, as stated earlier, value is a function of what the final customer sees as value in the final product. For instance, storing a part may be considered necessary to one facility due to policy constraints, but the final customer does not care how many times a product or component is stored and certainly would not pay extra for that. In the material flow from raw material through all of the processing steps, 11 steps were identified as ones that the final customer may consider valuable. Examples of these would be shaping a board with a particular profile or applying a finish to the final product. These 11 steps are approximately 25% of all the individual steps identified in the supply chain. From the standpoint of optimization of the supply chain, removing all non-value adding steps, such as storage (and duplicate storage), excessive delays, batching, would be beneficial in terms of better servicing the final customer at a reduced cost.

Information Flow

The top level of the Value Stream Map in Figure 4-4 is the flow of information through the case study supply chain. Dominating the movement of information is the centralized computer system of the Manufacturing Company. This system handles all of the inter-facility exchange of information as well as orders coming from customers, removing much of the need for human communication between the facilities. All of the information through the supply chain is in the form of orders and the dominant direction of flow of the communication is from customer to supplier. Any communication outside of orders is related to quality issues and those are handled on an as-needed basis with the flow being again from customer to supplier only by human communication.

One exception to the computer system in the case study supply chain is the link between the procurement at the Component Plant and the Raw Material Supplier. This link is completely separate from the computer system used elsewhere in this supply chain and relies on monthly faxes to transfer orders rather than daily computer updates.

The general portrayal of information in the case study supply chain utilizing the Value Stream Map in Figure 4-4 can limit the analysis of the flow of information with the amount of detail required in this study. The vantage point of the map is far too high to understand the flow of information between the facilities that make up the supply chain and more importantly the flow of customers' and suppliers' information within a specific facility (more detailed information flow is presented in Chapter 5). Thus, a modified Value Stream Map is utilized in the following sub-sections to analyze the supply chain information flow at each facility/company that makes up the case study supply chain.

4.2.3 **Raw Material Supplier**

The flow of material through the Raw Material Supplier (Figure 4-6) is from the forest operations through the sawmill. The large arrows represent the flow of material through the Raw Material Supplier's operations at the forest and the sawmill and out to the customer (the Component Plant). The images of the trucks represent deliveries and the numbers inside them indicate how often deliveries occur. The smaller arrows link the material movement with the manager/system administration that controls the production (in this case the Raw Material Supplier Controller/officer). Along each of these smaller arrows is the frequency that the information passes between the specific areas within the company.

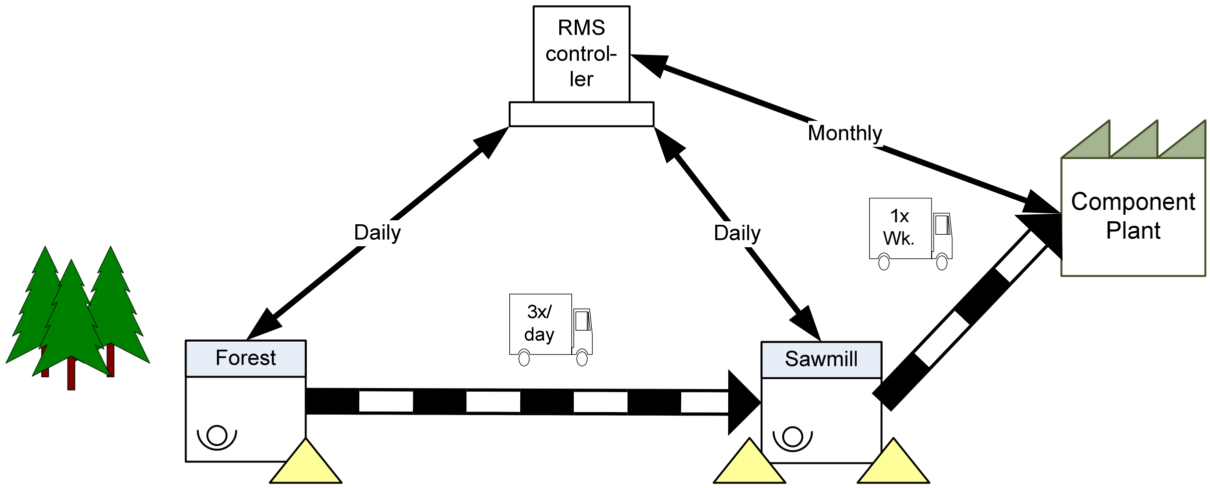

Figure 4-6 Raw Material Supplier - Product Flow Map

At the forest operations, trees are felled and then processed into saw logs. The saw logs are trucked to the sawmill where they are manufactured into lumber that will be shipped to companies such as the Component Plant. The driving force of material flow for the Raw Material Supplier is the capacity of the sawmill. The objective of the sawmill is to maximize the production and value of the lumber being produced, from which all decisions are made.

The orders from the Component Plant have minimal effect on the average production of the sawmill, as the exact distribution of species and quality of the lumber is dictated by the species and quality of the saw logs being delivered from the forest operations. The only attribute of the order that would affect production is dimensional requirements of the lumber. The product is considered a commodity product and has standards developed by an overseeing body, National Hardwood Lumber Association (NHLA 1998). Since the Component Plant buys this commodity product from a number of sources, the Raw Material Supplier being only one, it is not necessary for the Raw Material Supplier to supply all of the raw material needs of the Component Plant. Instead, procurement at the Component Plant balances purchases across a number of different suppliers with what the suppliers will have available in the coming month.

To accommodate the Component Plant (and its other customers), the Raw Material Supplier must have accurate information from the sawmill, as to what it is cutting, but, more importantly, it must have accurate information from the forest operations as to what it is cutting both now and what it will be cutting weeks into the future.

4.2.4 **Manufacturing Company Material Flow**

Component Plant

At the Component Plant, orders from the Assembly Plant are processed in one of two ways. If the components are medium- or high-usage, they are pulled from inventories that are maintained on-site (80% of the orders). If the component is not in maintained on-site inventory (due to low usage rates) or the current inventory level is not enough to fill the order, the components are then made-to-order (20%). Whether to fill an order from the Assembly Plant or to restock a dwindling on-site stock, the physical flow of material through the process is identical, although the rate of flow will be slightly faster to fill a specific order through expediting.

Once a production order has been initiated, the entire production process takes place over the course of five days. The lead time of five days includes both the production at the Component Plant and the production of complementary parts at an adjacent facility. The timeline of the production through completion of the component is shown in Figure 4-7.

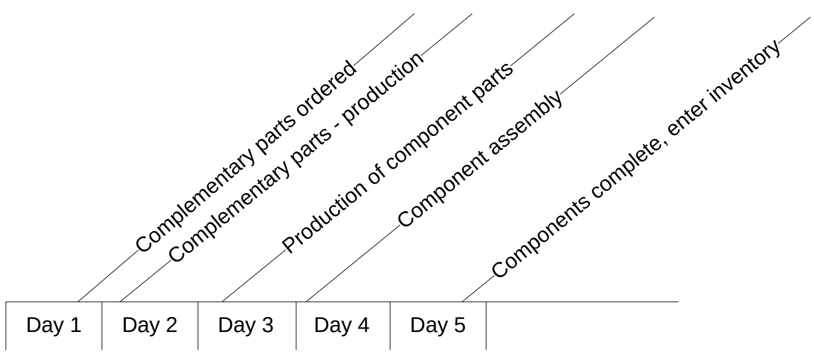

Figure 4-7 Timeline of production at the Component Plant

On Day One, the planning department schedules the assembly of the component three days into the future (Day Four). The scheduling requires that parts manufactured at this facility and complementary parts manufactured at an adjacent facility meet at the component assembly area at the same time (Day Four). The complementary parts take the longest to manufacture and are scheduled on Day One to begin the manufacturing process on Day Two.

Production begins at the Component Plant on Day Three when the orders are released to the first machine. The release time is a function of the scheduled time for assembly of the component to begin minus the time it takes for the parts to be produced. The objective in scheduling the beginning of production of parts at the Component Plant is to minimize the queue in front of the assembly area.

On Day Four, the complementary parts produced at the adjacent facility and the parts produced within the Component Plant meet at the assembly area in the Component Plant, where they are combined to create the component product in its raw form. Once combined, the component must undergo a series of additional machining and an application of stain and finishing prior to being inventoried at this facility or shipped to an assembly plant. The truck is loaded on Day Five and departs at 11:30 pm for delivery to the Assembly Plant at 5:00 am on Day Six.

Since a majority of the production (80%) at the Component Plant is performed to maintain the finished components' inventory at the Component Plant, Planning and Scheduling utilizes the current inventory levels and the rates of removal from the inventory to do most of the production scheduling. In addition, production involves large batches to fill that inventory, which creates a greater disconnect between the components being manufactured and the actual demand for the product. Batching also creates a larger lead time for specific parts as each part is made more infrequently.

The adapted Value Stream Map of the processing at the Component Plant is shown in Figure 4-8. Following the information, the orders from the Assembly Plant are received by the Planning and Scheduling department at the Component Plant (via the Manufacturing Company) each morning. If the components are in stock, the information is sent to the shipping department where the items are pulled from inventory and put on the next truck. The Production and Scheduling department creates a production order for the factory based on the remaining orders from the Assembly Plant (the ones that were not in stock) and an analysis of current inventory levels and rates of shipping.

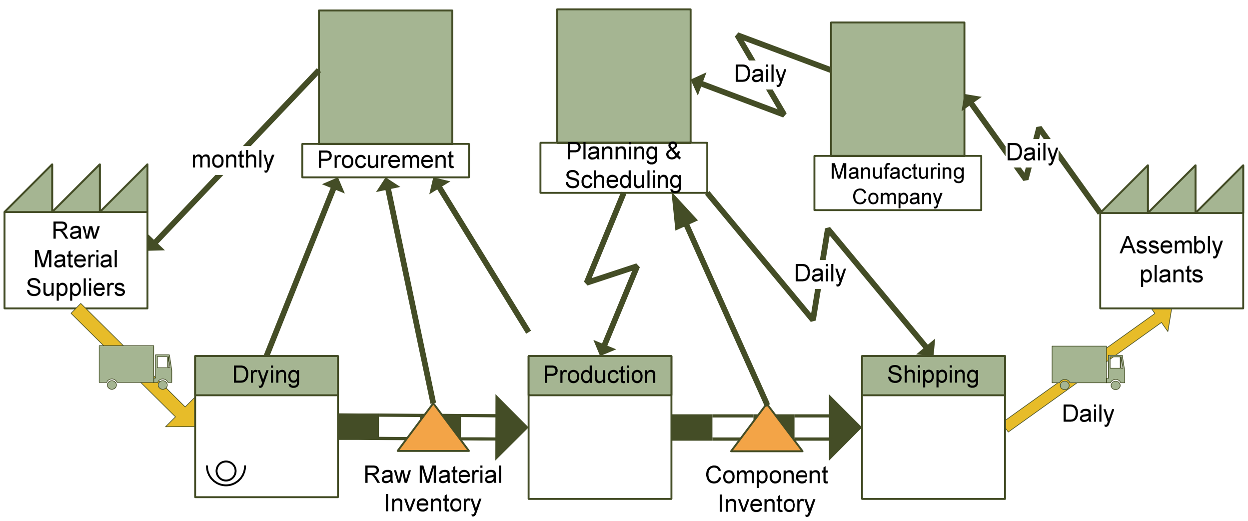

Figure 4-8 Component Plant – Value Stream Map

Of primary interest in Figure 4-8 is the disconnection between of the Planning and Scheduling for production and the Procurement of the raw materials. Though the Procurement officer gets updates on inventory and production rates (rates at which inventory is removed), the officer does not directly see the demand for the finished products. This creates a delay of information and a transformation of information to the Procurement officer through the steps of component orders, production orders, and raw material usage reports.

Assembly Plant

Unlike the Component Plant, no inventory is held for finished goods by the Assembly Plant, due to mass customization for the final product. Thus, all orders that come from the Retailer have to be manufactured to-order. The timeline for standard orders at the Assembly Plant is shown in Figure 4-9. The total lead time, 7 days, is less a function of production lead times, and more a function of component deliveries and capacity / demand management (to be discussed in later chapters).

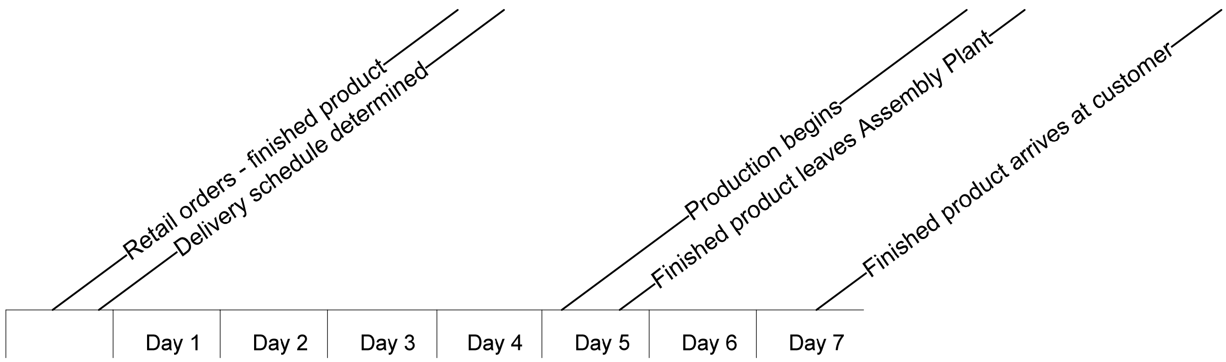

Figure 4-9 Timeline of production at the Assembly Plant

When the orders are received by the Assembly Plant, the first thing that is done is to schedule the date and time that the truck used for transporting the completed order to the customer will be at the loading dock. The start of production for the order is the time the truck is at the loading dock, minus the time to complete the order (or fill the truck, whichever is smaller). At the time of this study, trucks were scheduled to be at the loading docks approximately five days from the date of order; final assembly of the cabinets begins four hours prior to this. The lead time between customer order and truck scheduling is to account for the manufacturing of pending orders and to allow for the delivery lead times of components that are not available at the time of the customer's order.

The assembly cycle time of a single finished cabinet from its components takes just under one minute. The Assembly Plant utilizes cellular manufacturing and staged components to accomplish this cycle time with relatively stable repeatability. The components are picked out of inventories 30 minutes prior to assembly and systematically staged in their designated locations within the assembly cell. The personnel doing the assemblies do not have to worry about what part goes with what other part as the components are staged in the order of assembly. The personnel doing the assemblies simply grab the next part/component in the line. This requires good planning, visual synchronization, and excellent organization by everyone involved.

Once a cabinet is produced at the assembly cell, it is conveyed to the loading dock. It takes five minutes from the time the last part is attached to the cabinet to the time the cabinet is loaded into the appropriate truck. The total time it takes to fill a truck ranges between 3.5 to four hours. The average time it takes for the truck to reach the customer is two days.

From the adapted Value Stream Map of the Assembly Plant (Figure 4-10), the information flow shows a good link between production Planning and Scheduling and Procurement (unlike the Component Plant). This link facilitates procurement of orders from the Component Plant with minimal lead time. In this case, actual demand is quickly transferred to Procurement and thus to the Component Plant, with some information conveyed undistorted from the original order. However, if the item is in Assembly Plant inventory, which is controlled by an inventory system known as a *Min/Max* system, Procurement will not see the demand until the minimum level of the stock is met, which then combines an information delay with batching. For the *Min/Max* system, procurement of components is driven by monitoring of the inventory levels of the components at the Assembly Plant.

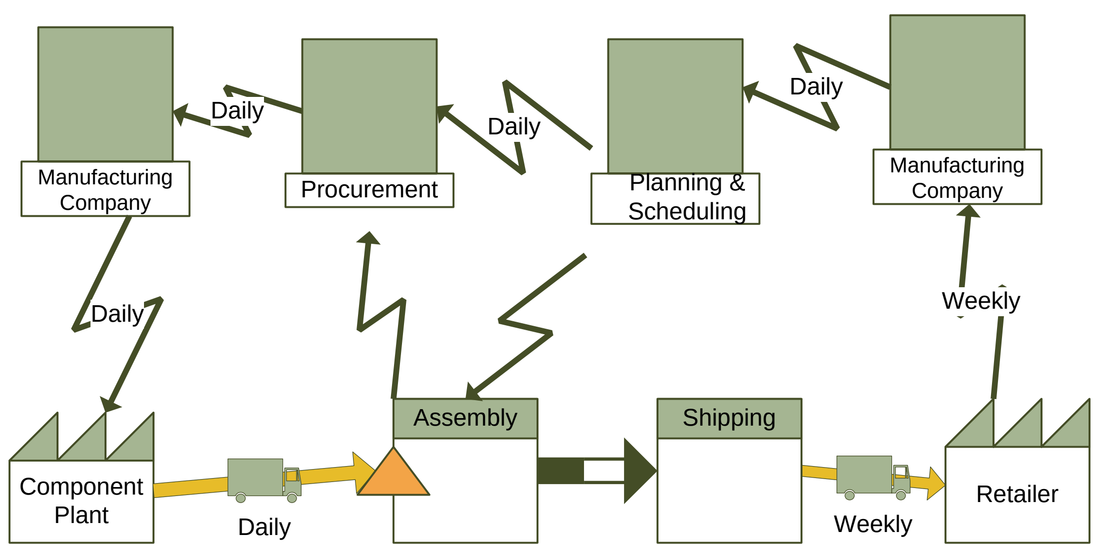

Figure 4-10 Assembly Plant - Product Flow Map

4.2.5 **Retailer Material Flow**

In its capacity as an intermediary between its customer and its suppliers, the Retailer does not manufacture any products. Instead, it accepts the finished products from the Assembly Plant and stores the products until the Final Customer picks them up. As shown in the adapted Value Stream Map of Figure 4-11, the deliveries are put directly into the finished goods inventory which is where the Final Customer will pick them up.

The Retailer does not get involved in the installation process and only orders the products as specified by the Final Customer. If issues occur in the installation process, such as improper products were ordered or the delivery from the Manufacturing Company was incomplete or incorrect, the Retailer again serves as the intermediary between the Final Customer and the Manufacturing Company to resolve all issues.

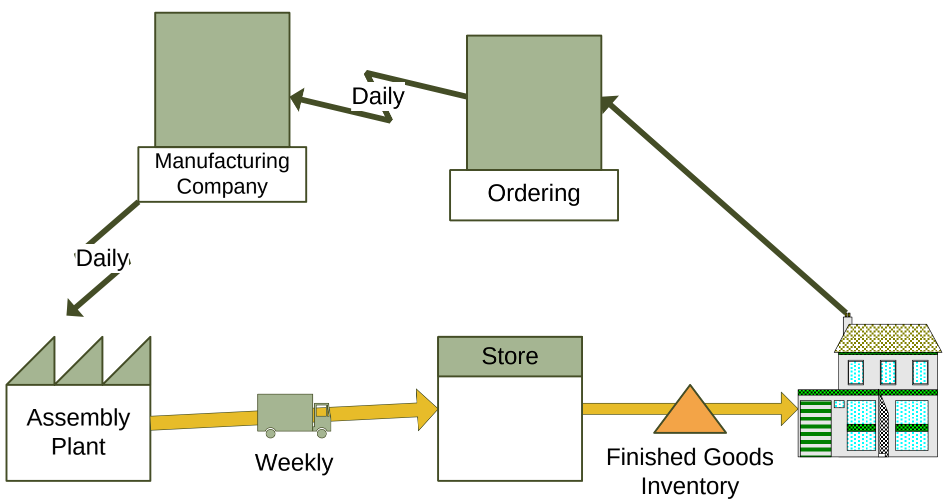

Figure 4-11 Retailer - Material Flow Map

4.2.6 **Materials Flow versus Information Flow**

Value Stream Mapping was useful in determining details about how material flows through the case study supply chain and how information is linked to the flow of material. However, the flow of the original demand by the Final Customer through the supply chain was not easily ascertainable from the traditional Value Stream Map. An analysis of the information flow within the supply chain using similar methods to that of material flow would further reveal the usage of supply chain information within individual facilities/companies that make up the supply chain.

4.3 Information Flow in the Supply Chain

Unlike material flow, which begins with the extraction of the raw material, information flow begins when a customer places an order at the Retailer (Figure 4-12). This sets off a series of events that eventually will trigger assembly of the product, the procurement of components, the manufacture of the components, etc., until a final signal for the raw material to be extracted. The path of the information flow is similar to that of the path of production/material flow but in the opposite direction. The information flow, however, is not necessarily affected by the same delays that occur for the production lead time, such as processing time and transportation time. Instead, the rate of the information flow is controlled by communication protocols, information quality, and procedural delays.

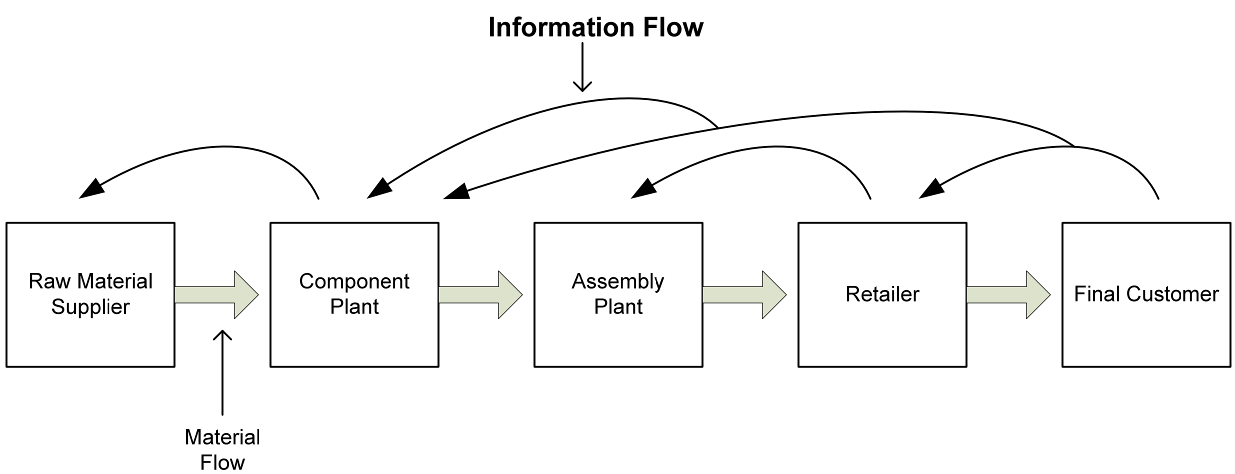

Figure 4-12 Flow of Information in the Case Study Supply Chain

One similarity between order flow and the production lead time is that they are both affected by inventory policy. For production lead time, a part is delayed in an inventory by the amount of time that it must wait for its removal from the stock. This is a function of the number of parts in the stock and the rate of removal of parts from that stock. For order flow, the time between a part's removal from a stock and a new part being ordered to replace it is a function of the number of parts in the stock, the rate of removal of the parts from the stock and the particular ordering policy for that inventory.

It is important to note that although the basic premise of the order flow is that each order triggers a chain of events, the case study supply chain being analyzed is one that is predominately driven by traditional production planning techniques and is termed a PUSH system. A PUSH system is one that produces goods and services based on a perceived future demand or forecast. In a truly demand driven system, commonly termed as a PULL system, production and ordering are closely tied together in such a manner that production does not occur until the customer (typically the immediate customer and not the final customer) requires it. The analyzed production system of the case study supply chain is a PUSH system which is based on producing goods based on a perceived future demand or forecast. In one portion of the case study supply chain, a PULL system exists. The Assembly Plant does not produce any of the final products until an order has been placed by a customer, this being indicative of a PULL system.

4.3.1 **Walking the Supply Chain**

Similar to production flow, walking the supply chain for information flow is a process of following the chain of events that lead from the initial process (in this case the Final Customer ordering a finished product from the Retailer) until it ends at the other end of the supply chain (the point where the initial raw material is extracted). Also, like production flow, the lead time for information flow can be determined for the supply chain. In this case, the lead time would be the amount of time between the initial order being placed by the Final Customer to the Retailer, the time that the information flows through the supply chain, ultimately creating a need for the raw material to be extracted. The following is the pathway of information flow through the supply chain:

Retailer

At the Retailer, the Final Customer and the service professional come to an agreement of the product and services that will be part of the purchase. The order will include the exact products and quantities required by the Final Customer, the quality expectations, and the expected date the customer needs to take the products into possession. The final customers for the Retailer typically take possession of the products in an average of 20 business days as the products 1) will be installed by a third party and it is necessary to coordinate delivery with the estimated time of a contractor and 2) are large and the Final Customer may not have adequate space for storing the products prior to installation or simply does not want to have the products taking up space when not necessary. The 20 business days (one month) seems to be the typical time to coordinate delivery, installation, and site preparation to accept installation of the final product.

The Retailer creates the necessary paperwork for the sale but delays the ordering of the products from the supplier, the Manufacturing Company. The reason for the delay is that the Manufacturing Company has a policy of completing an order in five days of the order being received and a policy of no inventory of finished products. Since the Retailer does not want to hold inventory at its own facility for excessive amounts of time due to the cost of maintaining the inventory (warehouse, personnel, etc.), the Retailer does not immediately send the order to the Manufacturing Company. Instead, the Retailer sends the order approximately one week prior to the date that the Final Customer wants to pick up the finished products. Because the five day lead time of production at the Manufacturing Company is dependable, the finished products will arrive just before the Final Customer's required date.

The Retailer is not only concerned with the cost of warehousing the finished products but also the cost of shipping. The Retailer utilizes its own shipping agent and must pay freight from the Manufacturing Company's location. To minimize shipping costs, the Retailer orders in batches with the assumption that they will all be manufactured and delivered together on a single truck. By ordering for multiple customers at one time, they can have all of these orders shipped in one truck from the facility where they are manufactured to the Retailer's facility.

Manufacturing Company (I)[1]

Once the Retailer has determined the optimal time to order for their needs, the order is placed through a business-to-business network directly with the Manufacturing Company. The Manufacturing Company is the headquarters for the Assembly Plant and the Component Plant, which is not in the same facility as where manufacturing is done. The Manufacturing Company is a centralized information system that is used to coordinate a group of regional assembly and manufacturing facilities. The orders are received throughout the day by the central computing system and delivered to the appropriate assembly plant, at set times, for the customer's region and product needs. This process typically causes the Assembly Plant to receive orders up to a full business day after the Retailer places the order.

Assembly Plant

At the Assembly Plant, the order must be processed to determine what the production schedule will be, which is based on a number of factors including current production status and component assessments. The current production status is made up of production capacity and queue. The order, unless rushed based on a customer premium, will be placed at the next available slot, typically four days out, which is based on current queues for production. The component assessment may cause a deviation in this schedule if components are not currently in stock. If the components are not available, there might be additional delays of a day or two depending on the lead time of the respective supplier.

Thirty minutes prior to the assembly of the product, the components are removed from the stocks and the computerized inventory system is updated utilizing a portable bar code reader. This event will trigger an event further upstream only if the number of components reaches a specific minimum quantity level. If the minimum trigger quantity for a component is not met, then no

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[1] Information is processed by the Manufacturing Company at two points in the case study supply chain. The first incident is identified as Manufacturing Company(I), and the second incidence is identified as Manufacturing Company(II).

information is passed upstream until the trigger level is met in future removals of components from the stock. When the minimum trigger level is met for a component, a signal is sent to the procurement personnel via the computerized inventory system.

The maximum amount of time that an order would be delayed in this inventory would be the time between signals, assuming the component is removed from the stock immediately after the component that triggered the signal and a constant rate of removals from that stock. On average, this time can also be defined as the inverse of the number of turns in inventory, which is the number of times per year inventory is completely replaced.

Once a day, the procurement personnel at the Assembly Plant identify components that are in need of replenishing (minimum triggers have been met) and orders are placed to the respective suppliers. All inventories are automatically updated in the computer inventory system when components are added or removed from the bins. UPC Scanners are utilized to enter the necessary changes immediately in the computer at the time of the change. The procurement personnel must then compile this information and send this information to the Manufacturing Company which will disperse the orders to the appropriate suppliers.

Manufacturing Company (II)

The Assembly Plant order is placed with the Component Plant utilizing the Manufacturing Company's procurement computer system. At the end of each business day, the procurement personnel send a report via this system. The information is then compiled with orders from other similar assembly plants and the orders are directed to the appropriate component plants at a time in the early hours of the following day prior to regular business hours.

Component Plant

At the Component Plant, a member of the scheduling department obtains the information sent from the Manufacturing Company hours before production begins. This is done in the case that there are any components being ordered that are not in stock and must be rushed through production. The component of interest represents a high use item that, like most of the SKUs are maintained in stock. Orders of these components are transferred to the shipping so it can be processed for delivery.

A trucking system is used to transport stock daily from the Component Plant to the Assembly Plant and leaves at a fixed time each day. During the day the shipping department pulls stock, palletizes it, and loads the truck. When the components are removed from inventory, the computerized inventory system is automatically updated utilizing a bar code reader.

The inventory replenishment policy at the Component Plant is different from the Assembly Plant. Since the Component Plant replenishes inventory, not from another inventory like the Assembly Plant, but from production, the controller's staff at the Component Plant must balance priorities of inventory levels with production capacities. The criticality of the particular component and/or component group is determined based on current inventory levels, the rate at which the components are being drawn from the inventory, and what is currently being produced or scheduled to be produced. This information is combined with production information such as production rate, schedules, and raw material rotations to determine priority levels for production. When this information is combined and analyzed in a spreadsheet computer program, a schedule is determined with approximately a one-week lead time and is relayed to production.

The order sits in queue with the production supervisor until the style and raw material specifications cycle through the many combinations of each to be processes; this is the approximate one-week of lead time. When production begins on the order, the necessary raw material is removed from the stocks. Information on what material and how much of the material was utilized is tallied at the end of the day by the controller and emailed to the raw material purchaser.

Ordering of the raw material is a monthly process. The person in charge of purchasing utilizes information gathered throughout the month from production and inventory to determine how much of what type of raw material should be purchased. The ordering process begins with a fax to the appropriate suppliers to identify how much of the raw material, in the required specifications, each one can deliver in the following month at the price determined by the purchaser.

The Component Plant maintains a number of suppliers for each type of raw material that it needs for a number of reasons. First, none of the suppliers have the capacity to produce enough to be the sole supplier (while maintaining its other customers). Second, the raw material is a commodity product so that keeping multiple suppliers has benefits in keeping a competitive price while ensuring a relatively stable price and supply. Third, suppliers have multiple customers, so it is possible that the product of a raw material supplier can be diverted away from the Component Plant. Finally, obtaining the raw material by the supplier can be variable due to sources, weather, or other conditions.

The production manager at the Raw Material Supplier reviews the request from the Component Plant and reviews supply information to determine the quantity of raw material that is available to ship in the coming month. The decision by the Raw Material Supplier is based on current information which includes 1) current inventory, 2) current production, 3) promised deliveries to customers, and 4) what raw material will be available in the following month. Within a day, the production manager faxes back the form with the quantities of raw material and the expected delivery date(s) to the purchaser at the Component Plant.

The purchaser evaluates all of the information from the potential raw material suppliers and decides how much raw material will be ordered from each of the suppliers. Within a day, a fax is sent to the Raw Material Supplier which indicates the amount of the raw material the Component Plant will be purchasing from the company.

Raw Material Supplier

At the Raw Material Supplier, the manager develops the schedule for obtaining the raw material. There is some variability in the source which may require scheduling of extraction, for example size or species requirements, but in general the extraction is done on a “next available” schedule. If scheduling for extraction (timber harvesting) is necessary, it is generally two weeks between an order coming in from the Component Plant and the information being relayed to the extracting team due to the lead time in order processing.

For analysis purposes, four types of delays that occur during the flow of information up the supply chain are classified - *Process delay*, *Transport delay*, *Manufacturing delay,* and *Policy delay*. These categories are defined as follows:

Process delay – Any step that transforms information accumulated during the previous step(s) for the purpose of ease of use or understanding at following steps in the flow of information. Examples of this would include steps that transform incoming component orders into production schedules, steps that transfer production numbers into daily reports, and steps that transfer inventory shortages into orders to suppliers.

Transport delay – Any step that transfers the orders from one member or sub-member in the supply chain to another member or sub-member in the supply chain. Transport delays for email, business-to-business networks, intra-webs, faxes and similar electronic systems would be zero or so close to it in respect to other delays that it can be considered zero (0). Transport delays that involve mail or other similar courier systems would have delays that would be significant respective to the other delays.

Manufacturing delay – Any step that is tied directly to production. An example of this is when an order is placed to a specific machine or process which has a queue of other orders already waiting to be manufactured. In this case, the order does not trigger information to continue through the supply chain until the raw material is removed from inventory. This means that the order must be delayed until all orders in the queue prior to the order are complete.

Policy delay – Any step that creates a delay due to the policies or procedures of a company. Examples of this would include inventory policies which call for the batching of orders for replenishment or policies that are based on predetermined time increments such as monthly orders.

Table 4-2 is a synopsis of the stages that the information went through to be transformed from the initial order by the final customer to the extraction of the raw material. The information portrayal is as prescribed for mapping supply chains (Jones et al. 2003) with a slight variation – no “value-added.” The first column is each step the information takes in the flow. The second column is the amount of time the step takes. The final column is the type of delay that the step is classified, as defined previously in the section. Unlike the material flow, there are no categories for value-added steps or value added time as information delay is not defined as value added from the perspective of the final customer.

Table 4-2 Steps in the Flow of Information through the Case Study Supply Chain

Step	Delay	Delay Type
Retailer		
1. Final Customer places order with Retailer	30 m	Process
2. Order processing for bill of materials	30 m	Process
3. Held for optimal delivery of finished product	15 d	Policy
Transport Link 1		
4. Order sent via B2B network to Mfg. Co.	-----	Transport
Manufacturing Company		
5. Order held for optimal delivery	0.5 d	Policy
Transport Link 2		
6. Order sent to Assembly Plant via corporate network	-----	Transport
Assembly Plant		
7. Order processing for scheduling assembly	1 d	Process
8. Order held for manufacturing lead time delay	4 d	Manuf.
9. Component removed from stock/Inventory system updated	-----	Transport
10. Information delayed until minimum level reached	20 d	Policy
11. Order processing for stock replenishment	1 d	Process
Transport Link 3		
12. Order sent to Mfg. Co. via corporate network	-----	Transport
Manufacturing Company		
13. Order held for optimal delivery	0.5 d	Policy
Transport Link 4		
14. Order sent to Component Plant via corporate network	-----	Transport
Component Plant		
15. Order processing for scheduling component delivery	1 d	Process
16. Component removed from stock/Inventory system updated	-----	Transport
17. Order held for Controller decision	15 d	Policy
18. Order processing for scheduling component replenishment	0.25 d	Process
19. Order sent to production via daily reports	1 d	Process
20. Order held for manufacturing lead time delay	5 d	Manuf.
21. Raw Material removed from stock/Inventory system updated	-----	Transport
22. Information sent to Purchaser via daily tallies	1 d	Process
23. Order held until monthly lumber supplier order request scheduled	30 d	Policy
Transport Link 5		
24. Preliminary resource assessment form sent to Raw Material Supplier via fax (preliminary)	-----	Transport
Raw Material Supplier		
25. Order Processing to bid on request	1 d	Process
Transport Link 6		
26. Information sent to Component Plant via fax	-----	Transport
Component Plant		
27. Order Processing for purchase order	3 d	Process
Transport Link 7		
28. Order sent to Raw Material Supplier via fax	-----	Transport
Raw Material Supplier		
29. Order Processing schedule lumber production	1 d	Process
30. Sent to Raw Material harvester via daily reports	1 d	Process
31. Orders held due to manufacturing lead time	5 d	Manuf.
Raw Material obtained in Forest		
Total	106.4 Days	

From the data collected, it was determined that the time between initial order being placed by the final customer and the time of the extraction of the raw material, the information *lead time* of the supply chain, is 106.4 business days or approximately 21 weeks. The largest percentage of information delay occurred at the Component Plant where 50 percent of the total information dwell time takes place (Figure 4-13). However, the delays that occur early in the flow of information, such as the information delay at the Assembly Plant (24% of the total delay) and especially the Retailer (10% of the total delay) can initiate large demand amplifications.

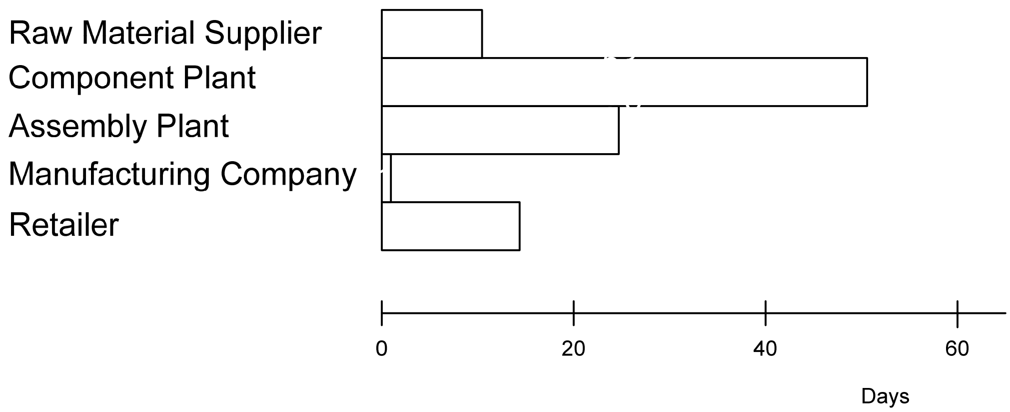

Figure 4-13 Information Delay at Each Facility along the Supply Chain

Differentiating the total informational delay of the case study supply chain based on the classification of the delay type, (Figure 4-14) shows that a significant portion of the time that information flows from the Final Customer to the Raw Material supplier involves delays relating to policies of the individual companies that make up the supply chain. A much smaller portion of the delays are tied to processing the information. A little more than processing is manufacturing which ties the delay of information flow into the actual manufacturing of the product. Finally, transportation of information within a company or between companies is minimal in comparison to the other three delay categories.

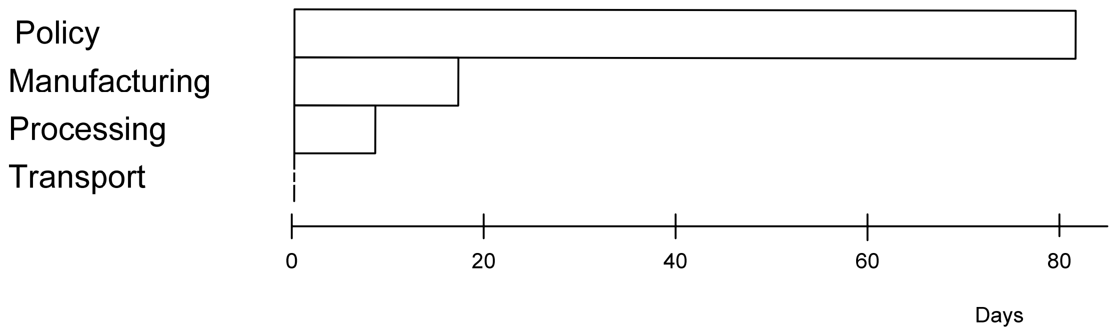

Figure 4-14 Information Flow in the Supply Chain by Classification

Of the 106 days that it takes for the Final Customer's order to cause raw material to be obtained from the forest, 75 percent of that time is associated with policies. The monthly orders placed at the Component Plant to the Raw Material Supplier were the largest policy delay. Another large delay was that of the Retailer Placing the order with the Assembly Plant. The other policy contributing to the long delay was that associated with inventories. Demand information is delayed at several points in the supply chain due to inventory policies which create a buffer until some minimum level is created. The largest demand and information delay is associated with the component inventories between the Component Plant and the Assembly plant because there are two inventories – 1) an outgoing finished components inventory at the Component Plant that feeds 2) the incoming finished components inventory at the Assembly Plant. Between these two inventories, the demand at the assembly lines is delayed for 35 business days (or seven weeks).

An analysis of the distribution of four types of delays at each of the members of the case study supply chain (Figure 4-15) shows that the delays are distributed across the members of the supply chain. The major delay, due to policy, occurs predominately at the Component Plant but also at the Assembly Plant and the Retailer. Relatively little delay is caused by policy at the Raw Material Supplier, or the Manufacturing Company, although it is important to note that policy is the primary form of delay at the Manufacturing Company. Delays due to the process of moving orders throughout a facility are equally distributed among the Raw Material Supplier, the Component Plant and the Assembly Plant with minimal process delays at the Retailer and the Manufacturing Company. The delays due to manufacturing also take place at the Raw Material

Supplier, the Component Plant with no manufacturing delays occurring at the Retailer and the Manufacturing Company.

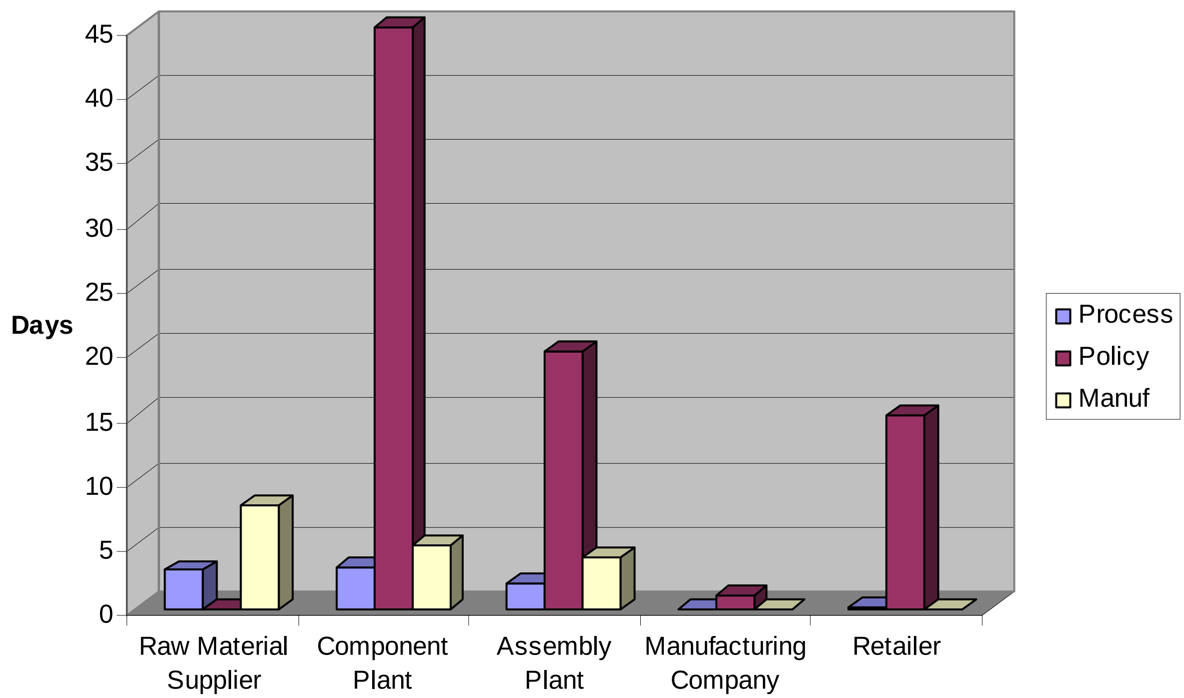

Figure 4-15 Information Delay at Each Stage in Supply Chain by Type of Delay

Information processing delays are relatively small in the case study supply chain when compared to policy delays and manufacturing delays and only take up to seven percent of the total time information flows through the supply chain. However, 8.4 days of information processing may significantly contribute to demand amplification due to the delay that the processing creates. Such information processing delays increase the need for forecasting and increased inventory sizes to act as buffers.

With the usage of advanced communication devices such as emails, business servers, business-to-business networks, and even faxes and telephone, the transportation of information is practically instantaneous. For the case study supply chain, all information transference utilizes one of the above mentioned forms of communication to transport information between companies and within companies. However, all of this technology does very little good if information is critically delayed by wasteful organization policies and information processing.

4.3.2 Mapping the Supply Chain Information Flow

Utilizing Value Stream Mapping, the information collected in the previous section can be portrayed in a visual summary as shown in Figure 4-16. The flow of information is identified with the large arrows pointing right and show the source flow from supplier to customer. Since this is a flow of information and not material, the additional smaller arrows found in maps of material flow, which indicate information flow, are not included due to redundancy.

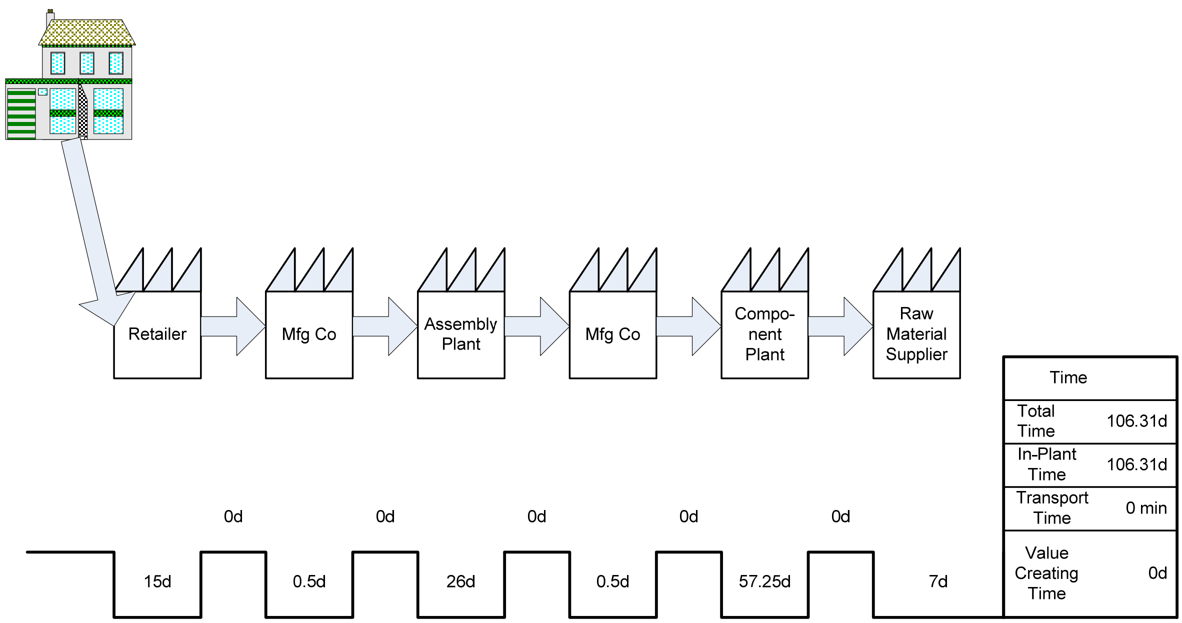

Figure 4-16 Extended Value Stream Map of Information through the Supply Chain

The depiction of information flow in Value Stream Mapping format does little to show the intricacies of the information flow. Although the process by which the data was obtained (walking the information flow) revealed important information about where and how information was delayed, the important attribute that can be viewed in Figure 4-16 is the assigned time to the Value Creating Time. In the analysis, no value was designated for any steps within the information flow. There are numerous steps that can be identified as necessary but of no value. Debate might exist as to the value associated with the Retailer placing the orders for the Final Customer and dealing with any issues that may arise in the order.

4.4 Summary

Both the flow of material and the flow of information in the case study supply chain have been found to have total lead times from start to finish (in their respective directions) of over 100 business days, or about five months. For the material flow, the lead time is the time that it takes for the raw material to be harvested, manufactured into components, assembled into a final product and then delivered to the Final Customer. For the information flow, lead time is the time it takes for the Final Customer's order to ultimately trigger the need for the harvesting of raw material.

The similarity in lead times for the material flow and the information flow (Figure 4-17) in the case study supply chain is partially justifiable. In many instances, such as production and inventories, both material and information must wait in queue until there is a trigger that allows them to move onto the next stage in the flow. For material flow, the wait is associated with the component(s) or product(s) in front of it to be processed or there is a particular lead time to process (or both). For information flow, the wait is associated with policies such as an inventory reordering policy in which a portion of the material must be utilized before the order (or information) is passed to the next stage.

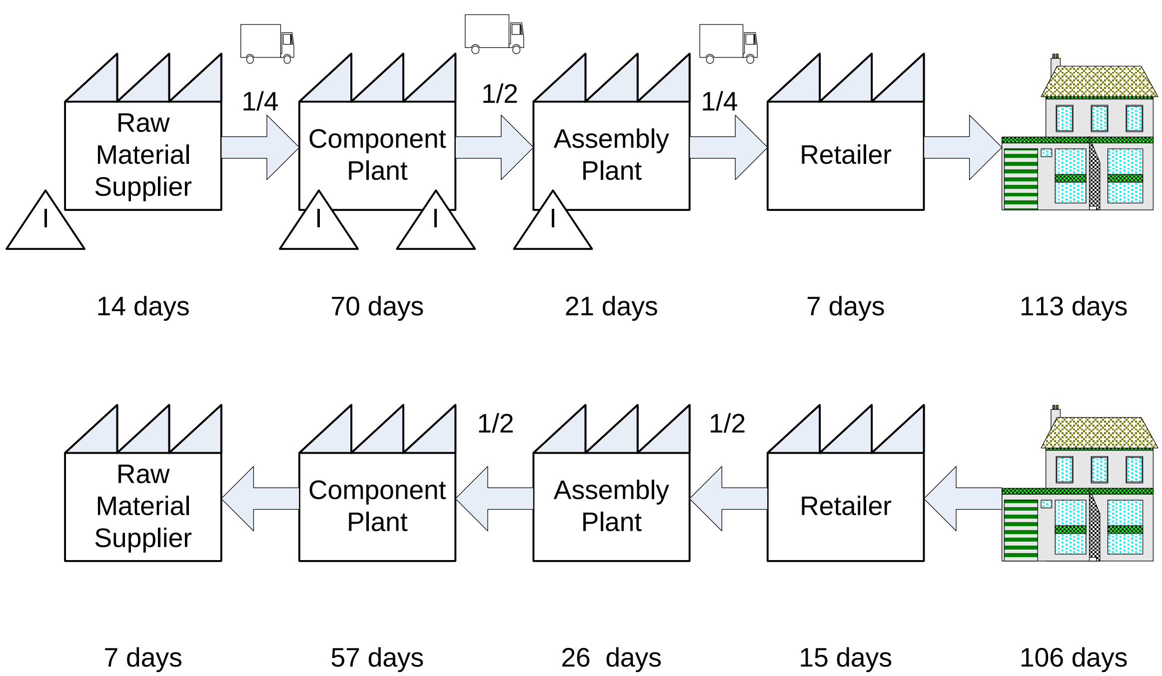

Figure 4-17 Comparison of Material Flow and Information Flow

The interaction between supply chain partners within the case study supply chain appears to be limited primarily to the processing of orders (Chapter 5) with order information flowing from customer to supplier and products flowing from supplier to customer. Policies have been developed, such as inventory systems and order processing policies, which appear to benefit the individual company only if viewed within the confines of the individual company's walls. Delays both in information and in material flow have been identified between each company and/or facility along the cases study supply chain. These delays lead to demand amplification, inventory buffers, and the need for forecasting, all of which make a supply chain slow to respond to customer needs, and more importantly inflexible to long-term trends. This means that the supply chain will not be able to cope with major changes or shifts in customer demands over a long period of time (Forrester 1961).

Between the Retailer and the Assembly Plant, there is minimal delay in material flow due to the make-to-order policy at the Assembly Plant. However, the flow of information between these two members of the case study supply chain is delayed further due to an additional member of the supply chain being included in the flow of information that was not included in the flow of material, the Manufacturing Company. The corporate organization of the Assembly Plant adds an additional step in the flow of information and thus additional delays.

Between the Assembly Plant and the Component Plant, both the material flow and the information flow are delayed by inventory policies. Both of these facilities maintain duplicate inventories which cause large delays between when a component is used in a final product at the Assembly Plant and a component is manufactured at the Component Plant in response to the usage. In addition, the Manufacturing Company (like in the link between Retailer and Assembly Plant) adds an additional step in the passage of information through the supply chain between the Assembly Plant. This causes additional delays in the information flow of the case study supply chain.

Between the Component Plant and the Raw Material Supplier, information flow has decreased immensely with orders batched and sent from the Component Plant to the Raw Material Supplier on a monthly schedule. Material flow, too, has become erratic with delivery schedules of raw material being at the discretion of the Raw Material Supplier, as long as it is delivered within a month of the original order.

In this chapter, the depiction of the flow of material and particularly the flow of information in the case study supply chain begins to show the inter-relationship between supply chain information and management decisions. Long lead times in the material flow are tied to the rate and quality of information that flows from the initial source, the final customers. How the supply chain information is utilized by management and the information triggers production and material flow will be addressed in the next chapter.

Chapter 5 Information and the Decision-Making Processes

5.1 Introduction

The purpose of this chapter is to identify the inter-relationship between supply chain information and the managerial decision-making process of production in the supply chain. To assist in accomplishing this purpose, models were created utilizing *Causal Loop / Stock and Flow* diagrams (System Dynamics) from the data collected during the investigative portion of the research. These diagrams were utilized to aid in the analysis of how information from supply chain partners is utilized in the internal decision making by personnel in the individual companies along the supply chain. Each segment of the case study supply chain (Retailer, Manufacturing Company, Assembly Plant, Component Plant, and Raw Material Supplier) was analyzed in three specific areas: material flow, information flow, and informational content.

The first analysis, material flow, was required to identify what factors affect the flow of material into each specific segment and out of each specific segment. In general, it could be assumed that material flow is driven by order rates and delivery rates. However, other factors can and do affect the rate at which material flows through a particular segment in the case study supply chain. Within a specific segment, material flow is controlled by production and inventory procedures and policies that create deviations from original order rates and delivery rates.

Information flow was then analyzed to determine what factors affect the rate at which information is passed through the supply chain. As determined in the previous chapter, some factors that affect the delay of information include company policies and methods of information transference. In addition, there is information transformation (altering of information) that can affect what information flows between supply chain segments and within each segment.

The specific supply chain information that is utilized at each segment was then analyzed to identify how the information was transformed. As information flows through the supply chain, it can be transformed to accommodate the needs at each segment. The information that was collected from the final customers by the Retailer was changed as it progressed through the supply chain. For the case study supply chain, those changes were identified and analyzed.

As discussed previously, the general information flow and product flow are opposite in direction as they proceed through the supply chain. The products flow from the Raw Material Supplier, through the facilities of the Manufacturing Company, to the Retailer, and end at the

Final Customer. The information flow predominately flows from the Final Customers' demands, through the Retailer and the Manufacturing Company to the Raw Material Supplier. The material flow and information flow can and do meet at specific points within the case study supply chain, specifically when company policy and/or procedures dictate.

5.2 Retailer

If it is assumed that the driving force of any supply chain is the demand put on it by the final customers, then the Retailer in the case study supply chain is the first member of the supply chain to capture the information which is to drive the supply chain. It is the Retailer that collects all of the information from the Final Customer and passes that information to the next segment, the Manufacturing Company, upstream in the supply chain.

In essence, the Retailer serves as an intermediary between the Manufacturing Company and the Final Customer. From a production standpoint, the Retailer does not add any value to the product as delivered by the Manufacturing Company except in its ability to combine the product with products from other manufacturing companies. Thus, the Retailer's main task is to assure that the products the Final Customer wants are available at the Retailer's store when the Final Customer wants the products

5.2.1 Material Flow at the Retailer

The material flow (or product flow) at the Retailer is a relatively simple process (Figure 5-1). The amount of inventory the Retailer holds at its facility (represented in the figure as a box) is related to the rate at which the final products are delivered to the Retailer by the Assembly Plant (represented in the figure by the arrow on the left coming from outside the system indicated as a cloud) and the rate at which the final customers pick-up the final products from the Retailer (represented in the figure by the arrow exiting the box and leaving the system again indicated by a cloud). If the rate of deliveries exceeds that of the rate of pickups, the Retailer's inventory will grow. Inversely, if the rate of deliveries is less than the rate of pickups, the Retailer's inventory will shrink. For a short time horizon, it would be expected that these two rates would fluctuate so that the Retailers queue would swell and subside. As the time horizon increases, the rate at which material flows into the Retailer's inventory will approach that of the rate at which material flows out of the Retailer's inventory.

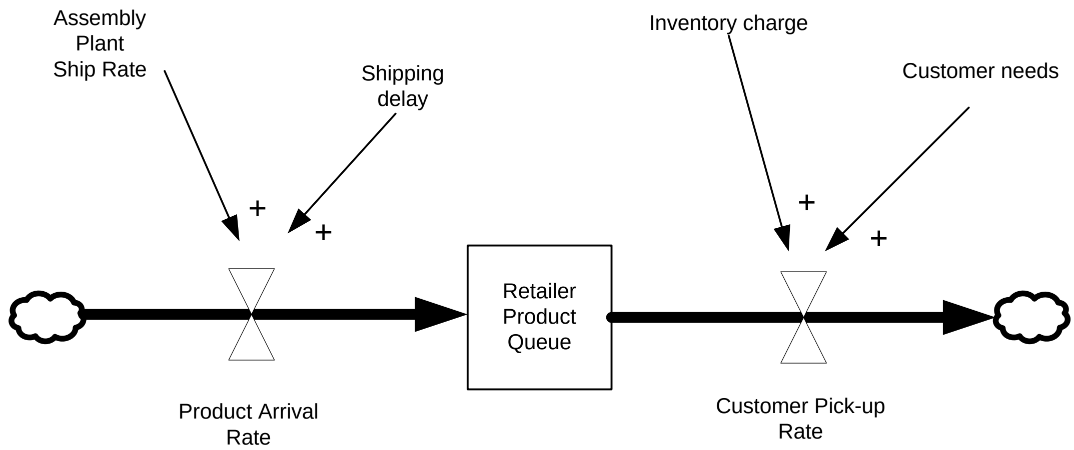

Figure 5-1 Material Flow at Retailer

The rates of flow in and out of the inventory queue are controlled by a number of factors as shown by the smaller arrows to each of the rates. The positive signs are Causal Loop Diagramming indicators of a positive influence on the rates which means as the factor increases so would the associated rate. The Production Arrival Rate is influenced by the Assembly Plant Shipping Rate and the delay in transportation (Shipping) to the Retailer. The Customer Pick-up Rate is influenced by the charge that the Retailer imposes on the Final Customer for holding the inventory and the specific delivery needs of the Final Customer.

The rate of flow of products out of the Retailer Product Queue is a function of the Customer Pick-up Rate. However, in this case, the Retailer realizes that the Final Customer may not need the products when they originally designated their delivery due date. Thus, the Retailer influences the Customer Pick-up rate by introducing an inventory charge to any orders that remain in the Retailer's inventory that are more than 10 days past the Final Customer's original delivery requirements. Whereas the rate of flow into the Retailer Product Queue (Product Arrival Rate) is a function of the rate at which the products are shipped at the Assembly Plant and the delay in shipping.

The Retailer does not maintain an inventory for the purpose of "off-the-shelf" purchases by the Final Customer. The Retailer only places an order to the supplier (the Manufacturing Company) when the Final Customer places an order with the Retailer. This is due to the fact that each product is made "to order" by the Manufacturing Company meaning that no inventory of final products are held by the Manufacturing Company. The only inventory the Retailer does maintain is caused by the delay between the receiving of the final products from the Manufacturing Company and the pick-up by the Retailer's customers.

5.2.2 Information Flow at the Retailer

When the Final Customer places the initial order with the Retailer, the Retailer needs only to transfer the order to the supplier, the Manufacturing Company. However, the Retailer in most cases chooses to delay that transference keeping the orders in a queue (Figure 5-2). Instead, the order rate of the Retailer to the Manufacturing Company is dependent on Final Customer order rate and four additional factors: 1) risk of missing customer's delivery needs, 2) perceived inventory costs, 3) perceived shipping costs per unit, and 4) policy of ordering on a specific weekly schedule. Both shipping and inventory costs are considered perceived as no actual value has been measured for either cost.

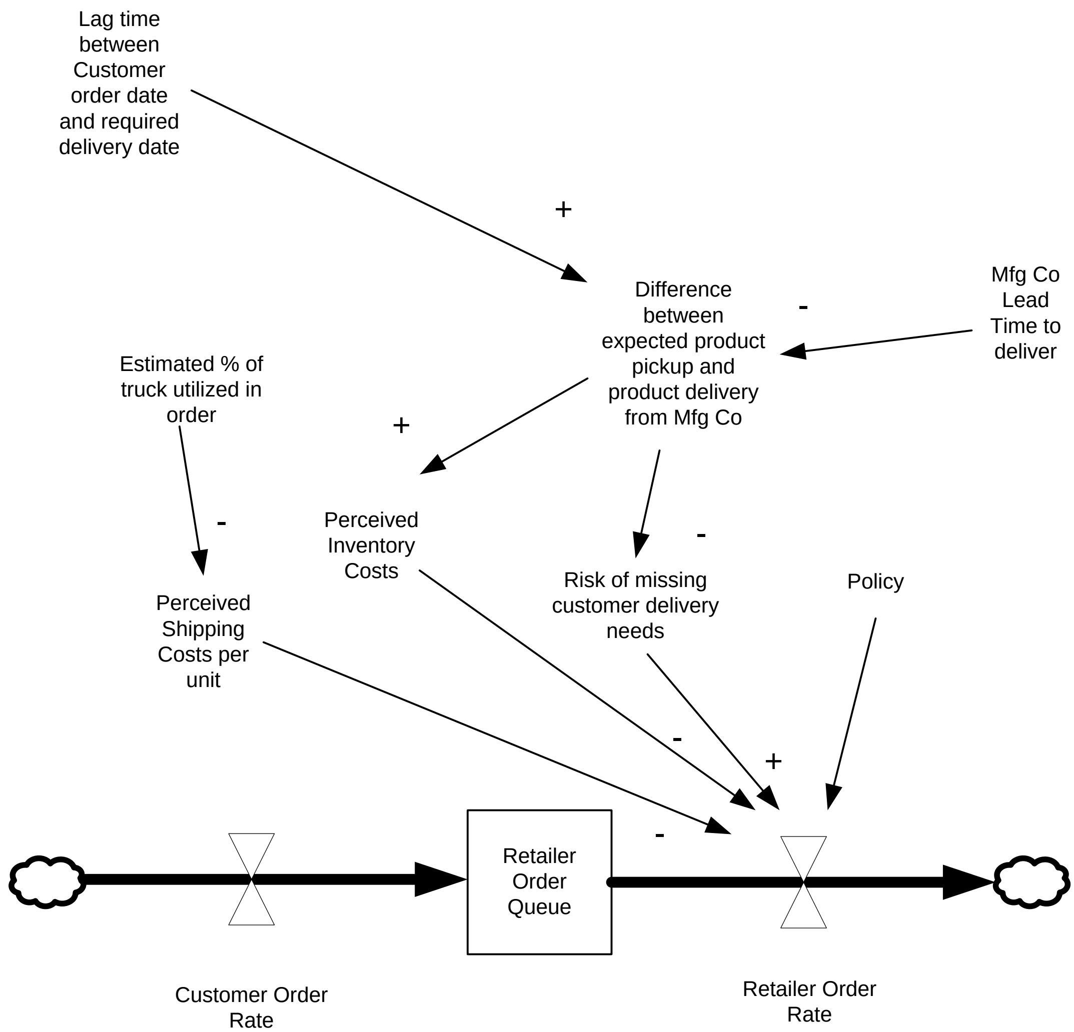

Figure 5-2 Information Flow from the Retailer to the Manufacturing Company

To guarantee customer satisfaction, the Retailer must make sure that the products are available at the Retailer's facility when the customer asked for them to be there, as defined by the purchase contract (Risk of Missing Customer Delivery Needs). The only constraint to meeting this requirement is the time it takes for the products to be delivered to the Retailer once the order has been placed. As long as the date the Final Customer wants the products is farther in the future than the estimated delivery date, the Retailer just needs to promptly pass the Final Customer's order to the Manufacturing Company to guarantee customer satisfaction.

The second factor of the Retailer order is to minimize the cost of storing inventory at its facility (Perceived Inventory Cost). Since the Retailer maintains a warehouse of limited size, the Retailer attempts to minimize the amount of inventory that it needs to store, though no specific costs are calculated. This is done by delaying the ordering process with its suppliers, such as the Manufacturing Company, until the last possible moment and still having the products available to the customers on time. Based solely on this factor, the order date would then be a function of the date that the customer wants to pick-up the products and the time it takes the products to be delivered to the Retailer by the supplier (shown in Figure 5-2 as the Difference Between Expected Product Pickup and Product Delivery from Mfg. Co.) The date the product is ordered would be the date the customer wants to pick up the product minus the order lead time (Mfg. Co. Lead Time to Deliver). In reality, the order lead time is variable and can be a function of any number of factors in the ordering process, the manufacturing process, and/or the delivery process. In the case of the Manufacturing Company, they have maintained a consistent lead time for the Retailer, which has led to the Retailer being comfortable in delaying orders with the Manufacturing Company.

The third factor that affects the ordering process by the Retailer is the cost of shipping (Perceived Shipping Cost). Though the distance between the facility that manufacturers the finished products and the Retailer are in close proximity (160 miles), the cost of shipping individual orders is prohibitive. Thus, orders are batched by the Retailer when sent to the Manufacturing Company with the assumption that all of the orders will be manufactured together and will be shipped on the same truck to the Retailer. The cost of shipping one product would be at a fraction of the cost of the truck transportation (Estimated % of Truck Utilized in Order). The result of batching orders is that not all of the orders can be expected to arrive just in time for the customers' needs. To guarantee that all the customers are satisfied with regards to meeting pick-up needs, the Retailer will order so that one or two orders arrive just in time, while the others will be early and require storage in the warehouse.

The final factor that affects when the Retailer places orders with the Manufacturer is based on policy created by the Retailer's management (Policy). It is standard policy that, unless there is a rush order, all orders will be placed on a weekly basis, a predetermined "order day" with the Manufacturing Company. The other factors, or concerns, defined previously must then be weighed against this policy. The weekly order policy was derived from the history of ordering by the Retailer to the Manufacturing Company. It was determined that, on average, the Retailer receives nearly one truckload of products from the Manufacturing Company per week. This policy ties in with the third concern that affects the Retailer's ordering.

How information flows from the Retailer to the Manufacturing Company is a direct flow as shown in the model shown in Figure 5-2. Why that information is delayed, that is, why the Retailer Order Rate is different from the Customer Order Rate (over a short time horizon) is shown to be a function of the four factors or concerns of the Retailer previously discussed. These factors impact the minimization of operating costs of the retailer while maintaining customer service. The only input that the Manufacturing Company has to influence the process is indirectly through the Order Lead Time that is set by the Manufacturing Company.

Although, over a long time horizon, the average Customer Order Rate will equal the Retailer Order Rate. However, in a short time horizon delays in information flow from retailer to manufacturer can have significant effects on production and inventory practices of the manufacturer (Forrester 1961). In addition to the delay, the aggregation of orders/information also masks the true demand of the final customers from the manufacturer creating the need for the manufacturer to make assumptions leading to higher variations in demand. This, in turn, leads to increased safety stock in inventories that must be maintained (Fransoo 2000).

5.2.3 **Information Obtained by the Retailer from the Final Customer**

When the Final Customer places an order with the Retailer for products made by the Manufacturing Company, certain information is obtained from the Final Customer by the Retailer. This information can be separated into three categories: customer information, product information or specifications, and pertinent dates to the transaction (Table 5-1).

Table 5-1 Information Collected by Retailer

Information Type	Specific Information
Customer information	Final Customer • Name • Address • Phone Number • Billing information
Product Specifications	Cabinets • Product identification codes • Quantities • Species • Style • Finish • Upgrades Specifications of complementary products
Dates	• Final Customer initiated order • Final Customer delivery date

The customer information contains information that is necessary to keep in contact with the final customers as well as billing information. The contact information is limited to name, address, and phone number. No other information relating to the final customers' demographics is collected and/or disseminated to the suppliers, which may be useful in market research of current and future products and services.

Product specifications are the information required by the Manufacturing Company, and the other suppliers, to manufacture the exact product the Final Customer desires. Since the Manufacturing Company is a mass-customization manufacturer, there are pre-determined specifications from which the Final Customer can choose. This information is supplied to the Retailer and is utilized in the consultation between the Retailer and the Final Customer in selecting the details of the products.

The final category of information is based on pertinent dates in the transactions. The Retailer records the date of the transaction between the Retailer and the Final Customer. In addition, the date the Final Customer wants to pick up the products at the Retailer's facilities is recorded.

5.2.4 Information Sharing - Retailer to Manufacturing Company

The Retailer and Manufacturing Company utilize a business-to-business computer networking program to standardize and facilitate transactions. All orders are entered into a computer by a representative of the Retailer at the Retailer's location. Once the orders are submitted (after being delayed by all of the factors in Figure 5-2) to the Manufacturing Company, the information is transferred immediately to the Manufacturing Company's main database where it is to be processed and disseminated to the appropriate assembly plants for production.

The specific information that the Retailer shares with the Manufacturing Company is shown in Table 5-2. This information is similar to that of the information collected from the Final Customer except for a few differences. First, the Final Customer's information is replaced with the Retailer's information. Second, the Retailer does not pass on information on complementary products (such as countertops, appliances, etc.) that the Final Customer may be purchasing from the Retailer in conjunction with products to be obtained from the Manufacturing Company. Finally, the date that the order was initiated by the Final Customer is not included with the order to the Manufacturing Company.

Table 5-2 Information Shared by the Retailer to the Manufacturing Company

Information Type	Specific Information
Customer Information	Retailer • Name • Address • Phone Number Final Customer – none
Product Specifications	Final Customer requirements • Product identification codes • Quantities • Species • Style • Finish • Upgrades
Dates	Final Customer delivery date

5.2.5 **Information Usage at the Retailer**

The Retailer role in the supply chain is to predominately serve as an intermediary between the Final Customer and the Manufacturing Company. All information collected by the Retailer from the Final Customer serves to facilitate the particular sale. The Retailer passes information onto the Manufacturing Company in the format and medium designated by the Manufacturing Company.

Internally, the Retailer does little with the information collected from the Final Customer, except as a resource to place orders with the Manufacturing Company, to verify against the bill of lading from the Assembly Plant, and to bill the Final Customer. Most of the information collected has been designated by the Manufacturing Company as a requirement of filling orders; no additional information is collected for the purpose of marketing, such as demographics of the Final Customer.

Information flow is predominately from the Retailer to the Manufacturing Company in the form of orders, with limited communication in the other direction. Any communication from the Manufacturing Company to the Retailer comes in the form of policy, process, and product changes. Examples of changes that would be conveyed to the Retailer by the Manufacturing Company would include changes in lead time at the Assembly Plant. Specifically changes that would affect delivery times or changes in product lines that would create a discontinued product or new products or accessories that are available for sale by the Retailer to the Final Customer. This information occurs on a need-to-know basis and is typically directed to the Retailer's parent company.

5.3 Manufacturing Company (I)[1]

The Manufacturing Company receives, processes, and distributes all orders at corporate headquarters. Those orders originating at the Retailer are sent directly to the Manufacturing Company and then sent to the appropriate assembly plant for processing. At the corporate headquarters, no manufacturing takes place. Thus, there is only information processing and flow and no material flow.

5.3.1 Information Flow at the Manufacturing Company (I)

The flow of information from the Retailer through the Manufacturing Company to the Assembly Plant is a very transparent and simple model (Figure 5-3). All information (orders) sent from the Retailer is held by the Manufacturing Company (Mfg. Co. Order Queue) for the scheduled delivery times (Scheduled Releases). No other factors affect the rate at which the orders enter the queue except for the rate that they arrive from the Retailer. The flow out of the queue is controlled only by the scheduled releases of the orders to the Assembly Plant. The delays in the orders from the Retailer being transferred to the Assembly Plant are equal to the difference in time of the arrival and the scheduled release. Though the purpose of the scheduled release in the case study was not clarified, it is assumed that the benefit of the scheduled release was for the sake of a batch daily report out to the Assembly Plant which minimizes assembly

[1] Manufacturing Company (I) is to denote the Manufacturing Company's role between the Retailer and the Assembly Plant. Later reference to Manufacturing Company (II) denotes the Manufacturing Company's role between the Assembly Plant and the Component Plant.

load imbalances that may occur if individual orders were sent randomly first-in/first-out throughout the day.

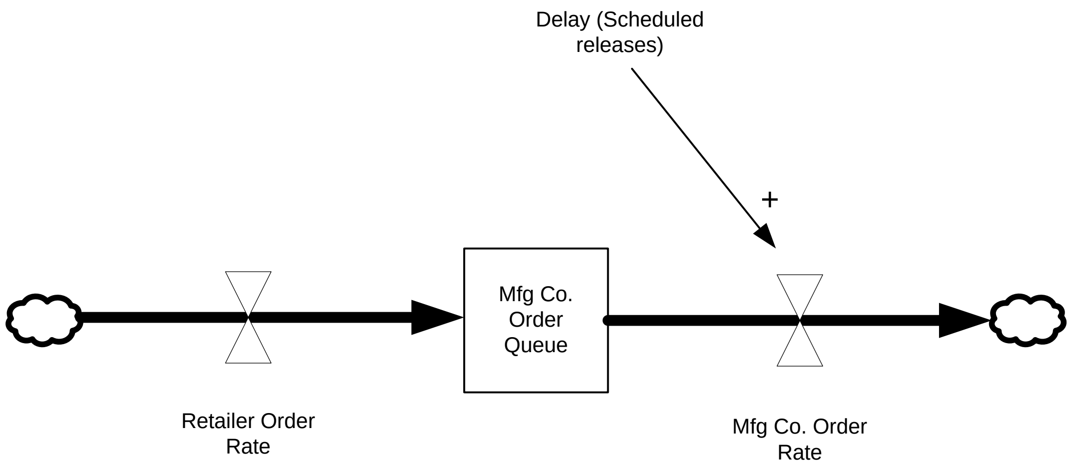

Figure 5-3 Manufacturing Company (I) Order Flow – Final Products

5.3.2 **Information Sharing - Manufacturing Company (I) to Assembly Plant**

The information from the Retailer is only slightly transformed by the Manufacturing Company prior to it being sent to the Assembly Plant (Table 5-3). The customer information (the Retailer) and the product specifications remain the same. However, the Retailer order initiation date is now included with the information.

Table 5-3 Information Shared by the Manufacturing Company to the Assembly Plant

Information Type	Specific Information
Customer	Retailer identification
Product Specifications	Final Customer requirements • Product identification codes • Quantities • Species • Style • Finish • Upgrades
Dates	Retailer order initiation date Final Customer delivery date

5.3.3 Information Usage at the Manufacturing Company (I)

The primary flow of information at the Manufacturing Company is wholly unidirectional. The Final Customer's orders are transmitted from the Retailer through the automated systems of the Manufacturing Company to the Assembly Plant. All communication between the Retailer and the Assembly Plant is assumed to be completely contained within this system.

Informal secondary communication between the Retailer and the Assembly Plant does exist, bypassing the Manufacturing Company. Direct person-to-person contact through telephones and emails occur when irregularities in the delivery process occur. These would include delays at the Assembly Plant due to inventory shortages, as initiated by the Assembly Plant, and issues with the products upon reception by the Final Customer, as initiated by the Retailer.

Other than the automated process of transferring orders from the Retailer to the Assembly Plant and the informal secondary communication associated with those orders, there are no specific channels of communication between the Retailer and the Assembly Plant for supply chain management. Changes in policies within the individual companies that affect their supply chain partners have a minimal mechanism for transference to the partners. At a minimum, the Manufacturing Company will inform the Retailer of changes in product lines or ordering processes. However, the Retailer and Assembly Plant work in isolation for the most part with regards to individual company policies which may affect the other company.

5.4 Assembly Plant

The Assembly Plant is a make-to-order facility. This means that finished goods are only produced to meet the orders from the Manufacturing Company. There is no inventory of finished goods except for those loaded in a truck that are awaiting shipping to the customers. To minimize lead time for delivery to the customer, however, the Assembly Plant maintains a large level of standard components so that orders can be met without waiting for deliveries from suppliers.

In regards to orders, both from customers and to suppliers, the Assembly Plant relies on the Manufacturing Company which filters all orders (information transference) coming into the Assembly Plant from the Retailer and exiting the Assembly Plant to the Component Plant. This may assist in the organization and efficiency of the facility, but creates a buffer (and consequently a delay) of communication between organizations and may limit supply chain effectiveness.

5.4.1 Material Flow at the Assembly Plant

The material flow through the Assembly Plant is a two-stage system (Figure 5-4) with a buffer or inventory in the middle (Assembly Plant Component Queue) and a minimal finished goods inventory (Assembly Plant Finished Goods Queue). The production rate is directly influenced by the rate that orders arrive to the Assembly Plant, since it is a make-to-order facility. As the final products are produced, the components are removed from inventory as required which diminishes the inventory supply. To compensate for the removal of components from inventory, new components are added to the inventory through shipments from the Component Plant and other suppliers.

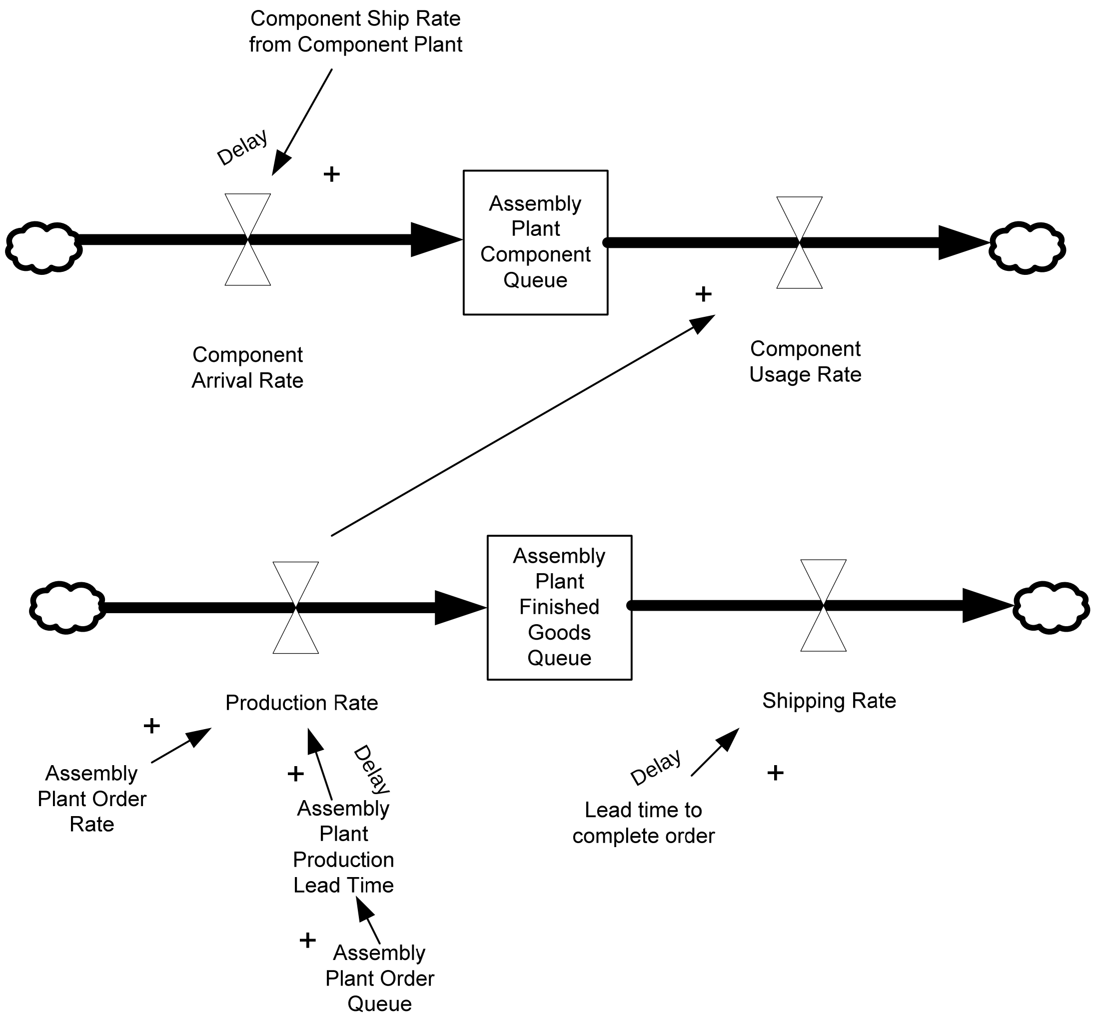

Figure 5-4 Material Flow at the Assembly Plant

Though the actual production rate is fast (53 seconds per unit), there is a delay between the arrival of the order to the Assembly Plant and the initiation of production (five days). This delay is based on two factors. One, there are already orders in the system and the arriving orders must wait in queue (Assembly Plant Order Queue) for the next available scheduling opportunity. Two, the Assembly Plant maintains that delay to account for orders that include low-use components that are not held in inventory and must be ordered from the appropriate component plant. The time it takes for the specially ordered/low usage components to arrive from the component plant and be available for the production line at the Assembly Plant is five days.

The component arrival rate is simply the rate at which the components are shipped to the Assembly Plant from the Component Plant (daily deliveries). There is a delay between the orders being placed with the Component Plant and the components being shipped based on the lead time at the Component Plant. In most cases, the components at the Component Plant are in-stock and most are just pulled from stock and placed on the next truck destined for the Assembly Plant. In a few cases, specifically low-usage components or special order components, the lead time must be increased to accommodate the production of the component at the Component Plant. This delay is rare, and in most cases, the Assembly Plant's component inventory is restocked with the Component Plant's component inventory within a day.

5.4.2 **Information Flow at the Assembly Plant**

In regards to information flow from the Final Customer up the supply chain, information passes from one member of the supply chain to the next. Minor changes have been made from the original information supplied by the Final Customer. The predominant factors that play a part in the information flow are the delays created due to policy decisions, first at the Retailer to accommodate deliveries and second at the Manufacturing Company to batch orders. Information Flow at the Assembly Plant must now face delays due to production, as well as policy, and the information is transformed as orders for final products must become orders for the components that make up the final product.

Like the material flow, the information flow at the Assembly Plant is a two-stage system based on final product manufacturing and component stocking (Figure 5-5). The incoming orders from the Manufacturing Company drive the production line at the facility, and then the production information must be transformed to create the orders for the components. The transformation is more a function of policy than of decision-making.

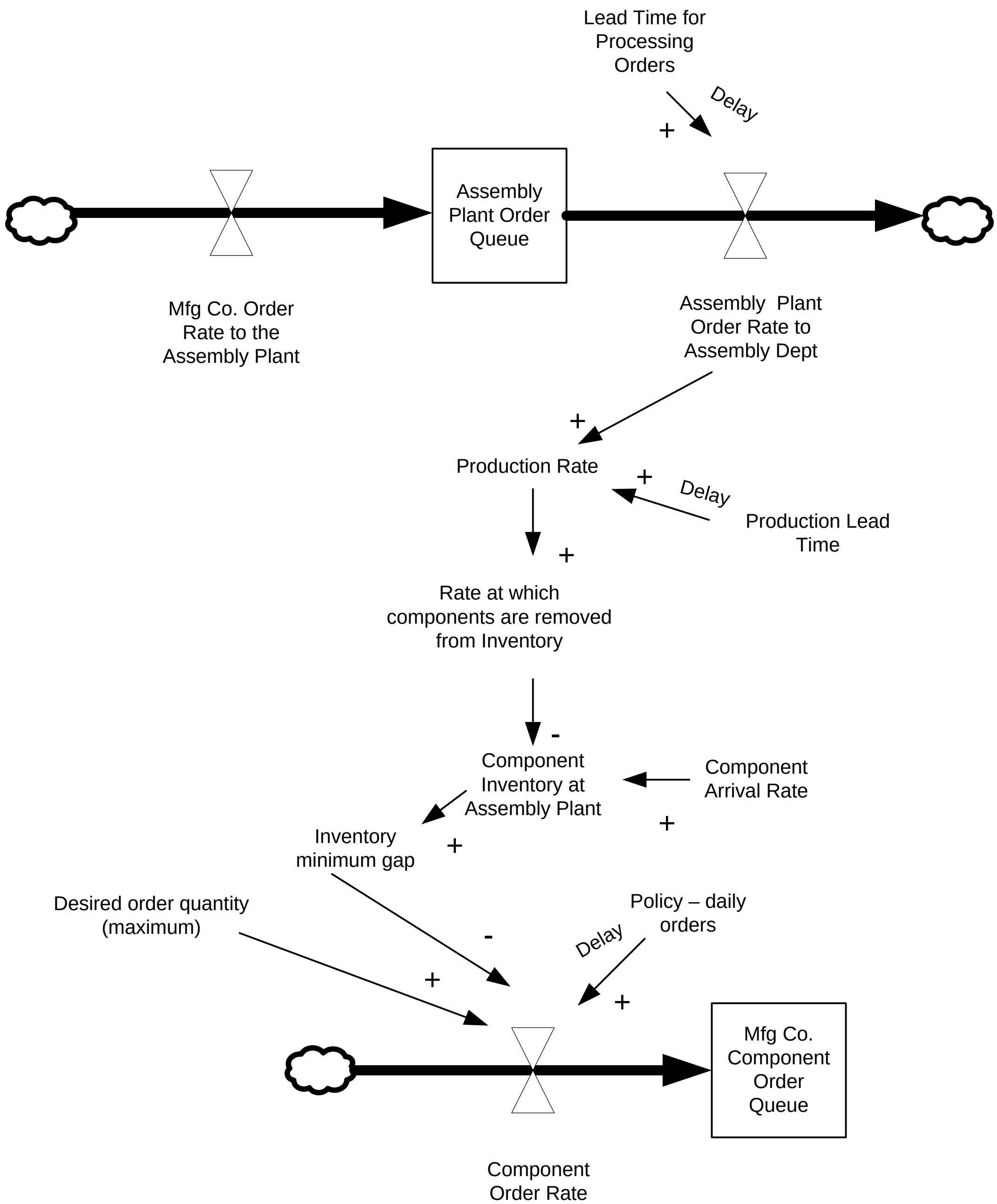

Figure 5-5 Information Flow at Assembly

Between the order arriving from the Manufacturing Company and the production at the Assembly Plant, the information maintains all data. The only difference is in time, as the information was delayed for various policy reasons. First, the information is utilized by the scheduling personnel to determine production scheduling, which is not an instantaneous process (it must wait for the scheduling process and then go through the process of scheduling). Once the scheduling is determined, the information must wait until the appropriate time slot, as determined by scheduling, for the order information to be used to build the final products for the Retailer and thus the Final Customer (Production Lead Time). At this key point, the information (demand pull), that started from the Final Customer, through the Retailer, through the Manufacturing Company to the Assembly Plant ends and the information that the Assembly Plant transfers up the supply chain to its suppliers is now information pertaining to the components that have been utilized in the production of the final products. The information for use to suppliers is now generated by the Assembly Plant from inventory data. Although the rate at which the components are removed from inventory are correlated to the production rate, that connection is lost in the transference.

The rate at which components are ordered by the Assembly Plant is based on the utilized inventory system. Most of the components are maintained on a *Min/Max* inventory system, meaning that each component has a prescribed minimum level, at which point, an order will be placed to a components' supplier with a prescribed quantity that replenishes the inventory level to the maximum level.

Each day, the purchasing personnel review the computerized inventory system to determine what components have met or fallen below their minimum levels. Those components that have met this criterion are ordered that day. For the orders of components that come from other facilities owned by the Manufacturing Plant, like the Component Plant, the orders must first be sent to the Manufacturing Company through the internal network to then be sent to the appropriate component plants.

5.4.3 **Information Sharing - Assembly Plant to Manufacturing Company**

With the transformation of information from that relating to the final product to that of components, the specific information that the Assembly Plant shares with the Manufacturing Company is much different than that of the original orders sent to the Assembly Plant (Table 5-4). All links to the Final Customer are lost, as the Manufacturing Company now sees the Assembly Plant as the customer. The orders are now for standard components (instead of final products) which includes species, styles, finishes, and quantities (these are aggregated based on the *Min/Max* inventory system.

Table 5-4 Information Shared by the Assembly Plant with the Mfg. Co (II).

Information Type	Specific Information
Customer	Plant Identification
Product Specifications	Assembly Plant requirements • Component identification codes - Species - Style - Finish • Quantities
Dates	Current date

5.4.4 **Information Usage at the Assembly Plant**

With the predominant flow of information from the Final Customer up the supply chain towards the Raw Material Supplier, the Assembly Plant is the first member of the supply chain to utilize the information supplied by the Final Customer and not just pass it on to the next member in the chain.

Since the Assembly Plant is a make-to-order facility, production planning personnel develop production schedules based on the arriving orders. At the time of production, the necessary components are removed from inventory. This removal is both the trigger for information flow up the supply chain as well as the source of information. The inventory level is monitored continuously, and when the inventory level reaches a critical level, an order is placed for a specific quantity of the particular component. The order to the supplier is how demand for the component (aggregated) is passed from Assembly Plant to Component Plant.

In addition, the make-to-order nature of production does not allow for forecasting by the Assembly Plant for production purposes. The only forecasting that is done is in the development of the *Min/Max* inventory system for the components. The maximum level of any component is derived from the expected rate of removal of that component by the production department. The transformed information (component usage) is then utilized by the purchasing/procurement personnel to order new components.

5.5 Manufacturing Company (II)[1]

Similar to its role between the Retailer and the Assembly Plant, the Manufacturing Company receives, processes, and distributes all orders at corporate headquarters. Those orders originating at the Assembly Plant are sent directly to the Manufacturing Company and then sent to the appropriate component plant for processing. At the corporate headquarters, no manufacturing takes place. Thus, there is only information flow and no material flow.

5.5.1 Information Flow at the Manufacturing Company (II)

The flow of information from the Assembly Plant through the Manufacturing Company to the Component Plant is also a simple model (Figure 5-6) and is similar in structure to the flow of information from the Retailer through the Manufacturing Company to the Assembly Plant (Figure 5-3). All information sent from the Assembly Plant has a direct access to the Manufacturing Company Order Queue. No other factors affect the rate at which the orders enter the queue except for the rate that they arrive from the Assembly Plant, as each component has only one supplier. The flow out of the component queue is controlled only by the scheduled releases of the orders to the Component Plant. The delays in the orders from the Assembly Plant being transferred to the Component Plant are equal to the difference in time of the arrival and the scheduled release. Though the purpose of the scheduled release was not clarified, it is assumed that the benefit of the scheduled release was for the sake of a batch daily report out to the Component Plant which minimizes oversight that may occur if individual orders were sent randomly through the day.

[1] Manufacturing Company (II) is to denote the Manufacturing Company's role between the Assembly Plant and the Component Plant. Earlier reference to Manufacturing Company (I) denotes the Manufacturing Company's role between the Retailer and the Assembly Plant.

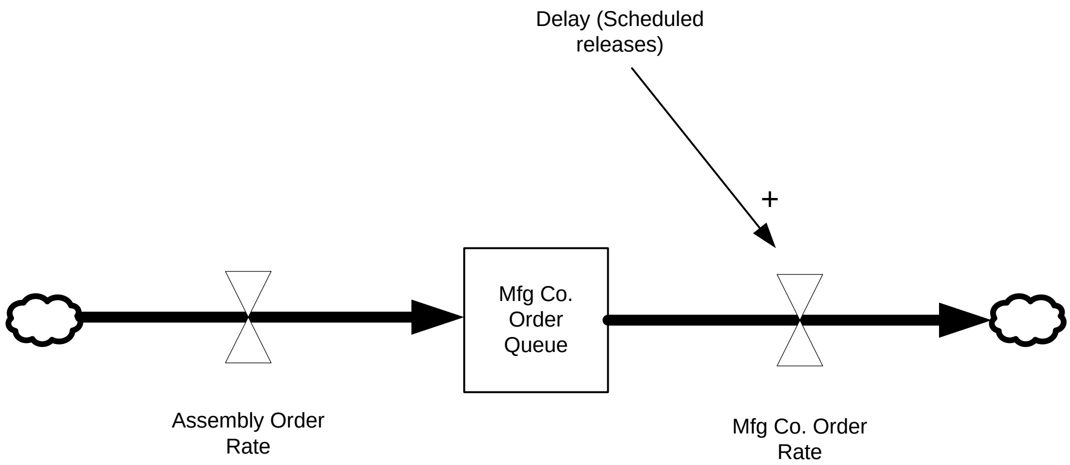

Figure 5-6 Information Flow at the Manufacturing Plant – Components

5.5.2 **Information Sharing – Manufacturing Company to Component Plant**

The information from the Manufacturing Company is not edited in any manner as it arrives from the Assembly Plant and is simply sent with a slight delay to the Component Plant (Table 5-4). The customer information (the Assembly Plant) and the product specifications remain the same.

Table 5-5 Information Shared by the Mfg. Co. with the Component Plant

Information Type	Specific Information
Customer	Plant Identification
Product Specifications	Assembly Plant requirements • Component identification codes - Species - Style - Finish • Quantities
Dates	Current date

5.5.3 **Information Usage at the Manufacturing Company (II)**

The flow of information at the Manufacturing Company (II) is wholly unidirectional like Manufacturing Company (I). The automated process of transferring orders from the Assembly Plant to the Component Plant does not serve as a medium for dialog between the Manufacturing Company and either the Component Plant or the Assembly Plant. Like the role of the Manufacturing Company in the communication between the Retailer and the Assembly Plant, this arrangement serves to create a barrier that limits transparency between the Component Plant and the Assembly Plant in communications.

5.6 **Component Plant**

The primary concern of the Component Plant is to supply the required components to the Assembly Plant in a timely manner. To accomplish this supply requirement, most components are stored in inventory until the Assembly Plant orders them, whereby the components can be shipped quickly with minimum delay. Thus, most of the production at the Component Plant is triggered by a need to replenish internal inventories.

The materials needed to produce the components are purchased from external suppliers, like the Raw Material Supplier. Since the raw material needs to be processed (dried) before it can be used in production, adequate quantities of the raw material must be kept in stock to account for both the fluctuation in demand in the production of the components and the lead time required to procure and process the lumber prior to production.

5.6.1 Material Flow at the Component Plant

The flow of material through the Component Plant is determined by the planning and scheduling personnel who determine the production order rate for internal manufacturing (Figure 5-7). An order is delayed before it is manufactured based on the amount of orders that are queued up in front of that particular order. Once the production of an order begins, material is released from the raw material inventory (Raw Material Queue). The orders are processed at the Production Rate of the facility with a lead time of approximately 16 hours. Upon completion of the production process, the finished components are held in inventory until orders from the Assembly Plant arrive.

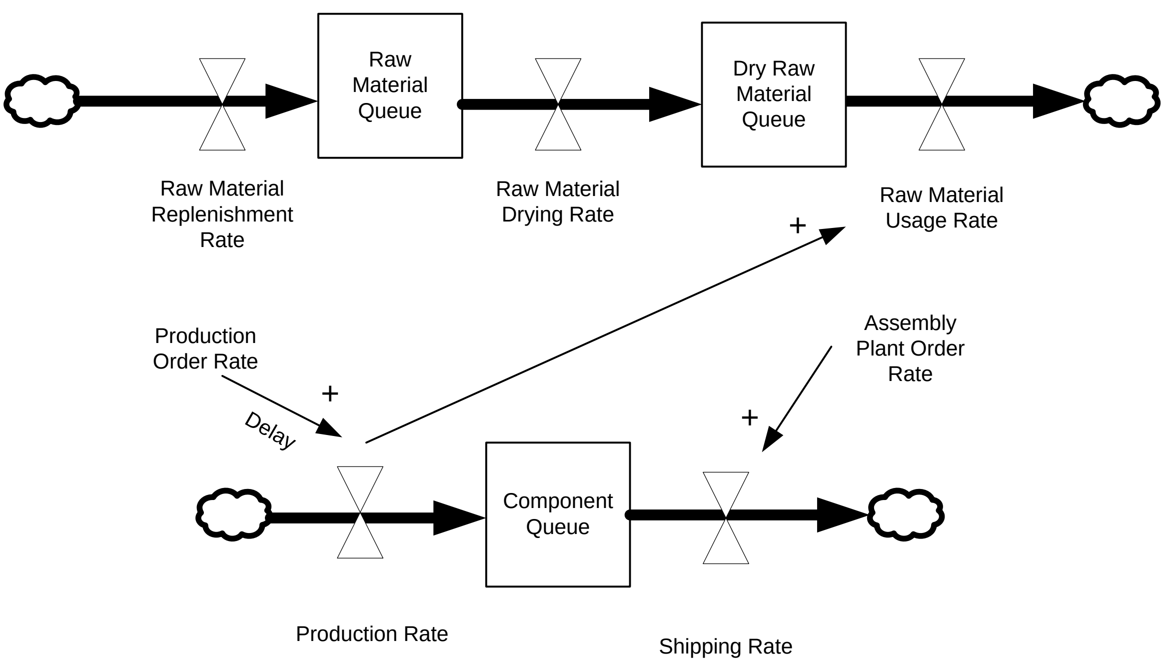

Figure 5-7 Material Flow at the Component Plant

In regards to the raw material, the drying personnel attempt to balance the rate at which the raw material is dried with the rate at which the raw material is utilized in production. The ultimate goal is to minimize inventory of raw material in the dry inventory while maintaining enough material so that a stock-out does not occur. Likewise, the purchasing personnel attempts to balance the incoming shipments of raw material from the suppliers with the rate at which the raw material is dried and at the rate the raw material is used by production.

5.6.2 **Information Flow at the Component Plant**

The flow of information in the Component Plant is far more complex than that at the Assembly Plant. The production of components is not made-to-order, but is based on company policies, forecasting, and scheduling decisions. In addition, the ordering processing of the raw material prior to production requires an even heavier reliance on forecasting as the entire process, from order initiation to raw material in inventory waiting for production, can be over two months (as shown in Figure 4-4).

Figure 5-8 shows the information flow through the Component Plant with the many steps and transformations that the information goes through in the process. The supply chain information first enters the Component Plant as component orders from the Assembly Plant in the form of the Manufacturing Company Order Rate. These orders gradually work their way through the shipping department (Component Shipping Rate), the production planning and scheduling department (Production Order Rate), production (Production Rate), the raw material department (Rate of Raw Material Usage), and finally end at the raw material purchasing department where the information flow becomes the Raw Material Order Rate.

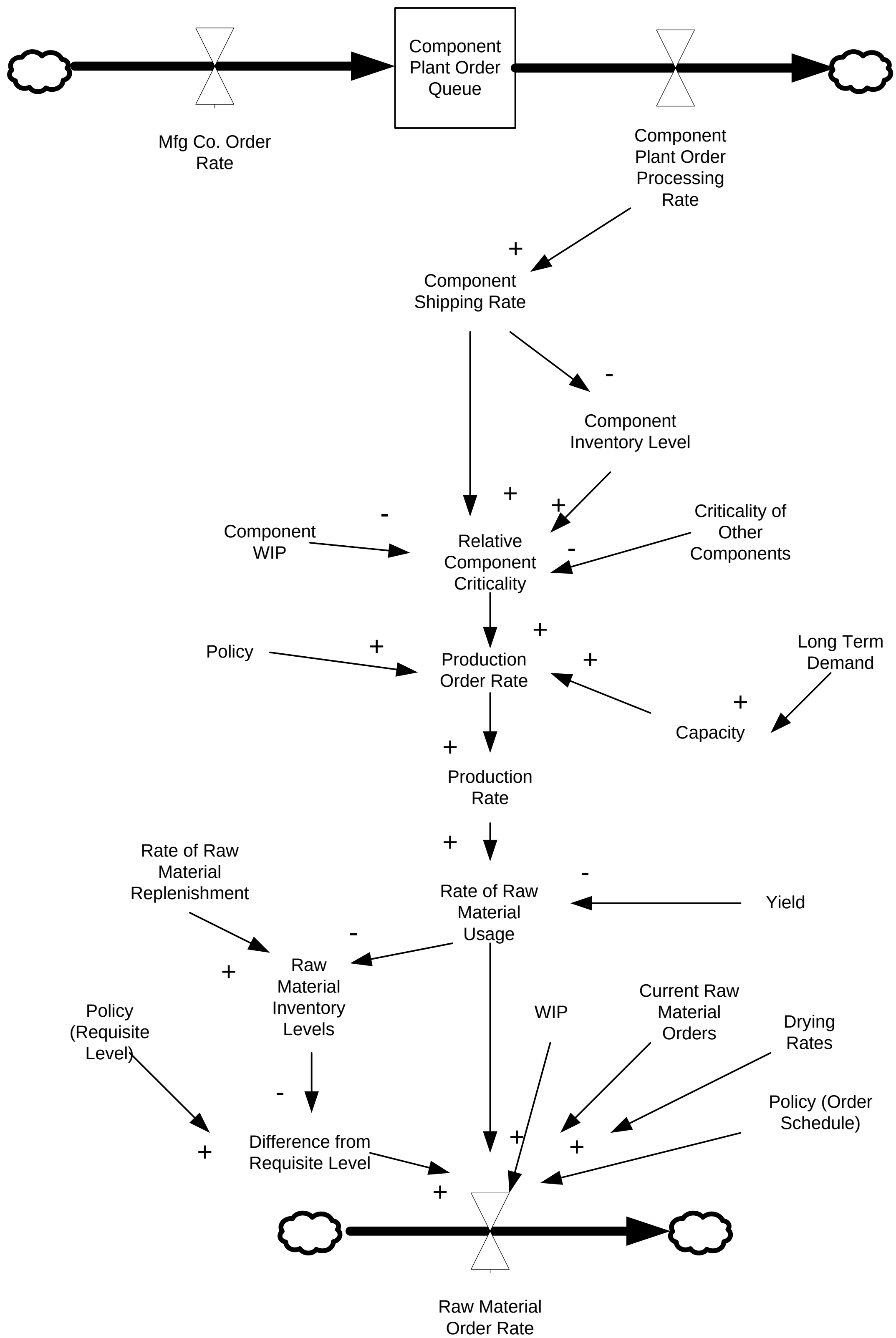

Figure 5-8 Information Flow at the Component Plant

Incoming orders from the Manufacturing Company for finished components are sent to the shipping department for processing. The required components are pulled from the inventory shelves and loaded on trucks for delivery to the Assembly Plant (Component Shipping Rate). At this point, the information from the order is no longer utilized creating another decoupling point in the case study supply chain. Instead, the information of inventory levels (Component Inventory Level) and rates of removal from inventory (Component Shipping Rate) are utilized for production planning purposes.

Unlike the Assembly Plant, the Component Plant does not use a Min/Max inventory system for the determination of restocking needs. Instead, the production planning and scheduling department utilizes a number of different bits of information to balance inventory needs with production capacities based on the previous experience of the manager who utilizes spreadsheets to identify the individual component criticality and schedule based on the level of criticality of components to each other (Relative Component Criticality). The specific information reviewed for each component is current inventory (Component Inventory Levels), previous production rates, previous shipment rates (Component Shipping Rate), current production (Component Work-in-Progress or WIP), and how important the inventory levels of a component are to other components (Criticality of Other Components). With this information, a relative criticality of production needs is determined for the components (Relative Component Criticality) and a production order (Production Order Rate) can be issued based on the higher priority components, the current production capacity (Capacity) of the facility, and the current policy (Policy) for production ordering within the production department.

Production orders are issued to the production department and are sub-divided based on species of raw material as each of the four species is cut in rotation with consideration of concurrently produced styles of the parts of components and finishing of the final components (Policy). There is approximately a five-day cycle of production scheduling between production of components of the same species/style/finish. As the production at this facility is coordinated with another facility that has a longer lead time for manufacturing, the production orders 1) have very specific start times/dates and 2) will be sitting in queue waiting for the start time/date. The specific information that the production department receives is start date, part numbers and descriptions, quantities, and estimated raw material usage.

Each day, the amount of raw material that is used during that day (Rate of Raw Material Usage) is reviewed and reported. The purchasing department utilizes this and other information to determine how much raw material should be purchased. The additional information required (as shown in Figure 5-8) is 1) production rates, 2) drying rates by species, 3) work-in-progress, 4) current raw material orders pending or shipped and 5) current policy on inventory levels. The purchasing department contacts the Raw Material Supplier to determine how much raw material it can supply in the following month. Since the Raw Material Supplier can only supply a fraction of the total raw material required by the Component Plant, the purchasing department divides the total order amongst multiple suppliers each of similar size to the Raw Material Supplier. Each supplier gets part of the order based on individual supplier's expected quantities of production in the following month and the total requirements for raw material by the Component Plant.

5.6.3 Information Sharing - Component Plant to Raw Material Supplier

The original information obtained from the Final Customer, which was completely decoupled by the previous members of the supply chain, has now been further transformed numerous times through the Component Plant. Delays, policies, batching, and forecasting have made it impossible to link information sent to Raw Material Suppliers to the information obtained from the Final Customer (or even the immediate customer), the Assembly Plant. Information has been aggregated into a monthly ordering policy, and such aggregation increases demand amplification higher than at any other previous point in the supply chain before.

The specific information sent to the Raw Material Supplier from the Component Plant (Table 5-6) includes the type and quantity of raw material that is required to be delivered within the next 30 days. Thus, the purchasing order contains the Component Plant name, the quantity and quality specifications for each species of raw material, and the expected delivery deadline date(s).

Table 5-6 Information Shared by the Component Plant to the Raw Material Supplier

Information Type	Specific Information
Customer	Name, Component Plant
Product Specifications	Raw material requirements broken down by • Species • Quantity • Quality specifications
Dates	• Expected delivery date

5.6.4 **Information Usage at the Component Plant**

Of all the members of the case study supply chain, the Component Plant utilizes the information from external sources the most. Production, finished goods inventory and shipping all utilize the information from the customers. In addition, the purchasing personnel work much closer with the supplier than at any other point in the supply chain. Within the case study supply chain, the Component Plant is the member that must attempt to adjust long-term demand with production and inventory without the knowledge of the true demand. Although the Raw Material Supplier is even further from the true demand, it is less affected by the lack of the true demand than the Component Plant, as discussed in section 5.7.

At the Component Plant, incoming information, in the form of orders, from the Manufacturing Company is immediately reviewed by the production planning and scheduling personnel. This is done to identify components that may not be in stock or may not have enough in stock, so as to expedite production orders. As most of the components are held in inventory, the orders from the Assembly Plant are sent to the shipping department.

With components that are in stock, the shipping department fills the customer's orders within the day that the order arrives. The appropriate inventory is pulled from the component racks, palletized and put on the appropriate truck designated for the Assembly Plant. Once the components are removed from the shelves the inventory is immediately updated for usage by production planning and scheduling personnel.

To determine production, the usage rate of components by shipping as well as the current inventory levels is utilized. Thus, it is critical that the production planning and scheduling personnel have daily updates from the shipping department which are correlated with orders from the Assembly Plant. This information is combined with production capacity and current production orders to determine the future production schedule for the Component Plant.

With regards to information from the Raw Material Supplier, the purchasing personnel at the Component Plant work with the sales/production personnel at the Raw Material Supplier to determine the optimal quantity of raw material that the supplier can ship in the coming month. This quantity is based on a number of factors from both the Component Plant and the Raw Material Supplier.

The purchasing personnel at the Component Plant must replenish the raw material inventory utilized in the production of components. The information utilized is from inventory levels, usage rates and production trends. It is all transformed from the original orders placed by the Assembly Plant. However, the Component Plant utilizes more raw material than one supplier can deliver. Thus, the production personnel work closely with the Raw Material Supplier to determine what they are able to deliver in the coming month and to distribute the total amount of raw material required by the Component Plant across its main suppliers, which includes the Raw Material Supplier.

5.7 Raw Material Supplier

The Raw Material Supplier role in the case study supply chain is based in part on the product that it manufactures and the relationship it maintains with the focal company (the Manufacturing Company). The product that the Raw Material Supplier produces is, for the most part, a commodity that is manufactured by numerous other companies. Since, the production levels of the Raw Material Supplier (as with other suppliers) are less than the total requirements of the Component Plant, the Raw Material Supplier must accept that it cannot be a sole supplier to the Component Plant.

5.7.1 **Material Flow at the Raw Material Supplier**

For the Raw Material Supplier, the product goes through three transformations before the natural timber resource becomes the product(s) required by the Component Plant, as shown in Figure 5-9. The tree length logs are removed from the forest (Tree-length log removal rate) where they are bucked (cut) into log segments (Processing Rate). The log segments which were manufactured (Log Segment Production Rate) are trucked to the mill (Trucking Rate) where they remain in queue (Log Segment Mill Queue) until required by the mill (at the Usage Rate). At the mill, the log segments are processed into lumber (Mill Production Rate) which will be shipped to the Component Plant (Shipping Rate).

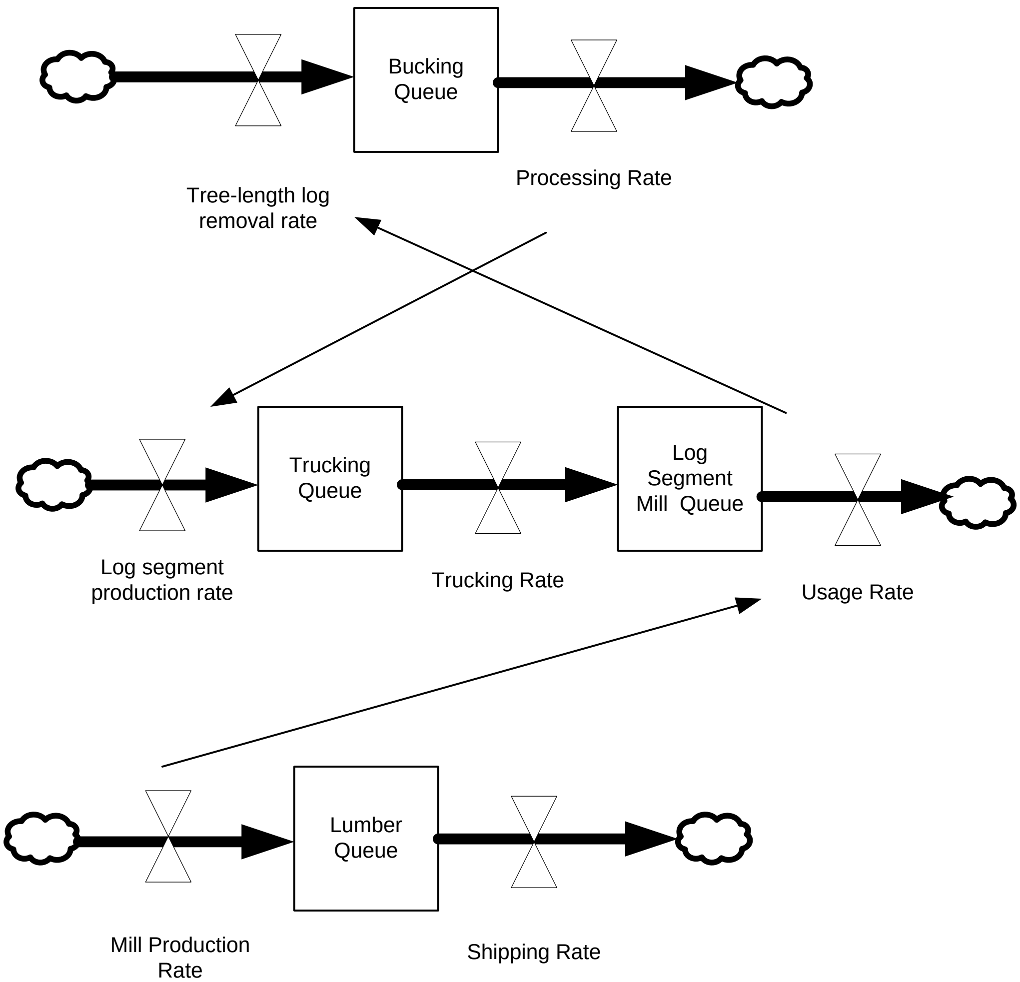

Figure 5-9 Material Flow at the Raw Material Supplier

In general, the production of sawmills, such as the Raw Material Supplier is closely tied to the distribution and quality of the available species within the region of operation (Luppold et al. 2008). The Raw Material Supplier, like other hardwood sawmills, harvests most of the trees on-site so as to increase the return on investment of having the equipment in the woods. The premise is that the trees have value as logs even if the value may be low due to quality; any logs not processed at their mill can be sold to other manufacturers.

For material flow, the controlling factors for the Raw Material Supplier are related to the capacity of the sawmill. Since the end-products for the Raw Material Supplier are considered commodities, maximization of profit, in part, occurs by maximizing the output of the manufacturing facility. Thus, the sawmill is kept producing as much as possible and all the scheduling of raw material for the sawmill must be done so as to maintain a continual flow of material into the facility and to the customers. The usage of log segments at the mill directly influences the procuring of logs in the forest (similar to a PULL system).

5.7.2 **Information Flow at the Raw Material Supplier**

Unlike the flow of information between other segments of the case study supply chain, the orders that the Component Plant place with the Raw Material Supplier minimally affect the production at the Raw Material Suppliers facilities. The Raw Material Supplier is constrained in its production of its final product by the capacity of the manufacturing facility and the distribution and quality of the species attainable from the raw material sources. Instead of purchasing from inventories of final products at the Raw Material Supplier, the Component Plant purchases from the expected production of the Raw Material Supplier in the following month. The only effect that the Component Plant orders have on the production of the final products at the Raw Material Supplier is the size requirements of raw material, which does not affect the volume of logs that are processed at the sawmill. It is important to note that prior to sawing the log segments into lumber, the Raw Material Supplier wants to already determine the customers for the lumber.

Any direct effect of the Component Plant on the Raw Material Supplier’s production rate occurs due to the specification of dimensions, primarily thickness. Production rate at the Raw Material Supplier is typically measured by the quantity (in board feet) of lumber that is produced. With the design of sawmills such as at the Raw Material Supplier, cutting lumber of larger thicknesses correlates to a higher production rate due to less passes through a saw. Thus, the orders from the Component Plant can have some effect on the production rate of the Raw Material Supplier.

The information flow at the Raw Material Supplier that is created by orders from the Component Plant is shown in Figure 5-10. As stated previously, the rate at which the Component Plant orders raw material from the Raw Material Supplier is influenced by the estimated production of the species of wood in the following month by the Raw Material Supplier. This estimate of production is based on the timberland that is currently being harvested and scheduled to be harvested in the coming weeks, and the quality, species, and quantity of timber on those lands.

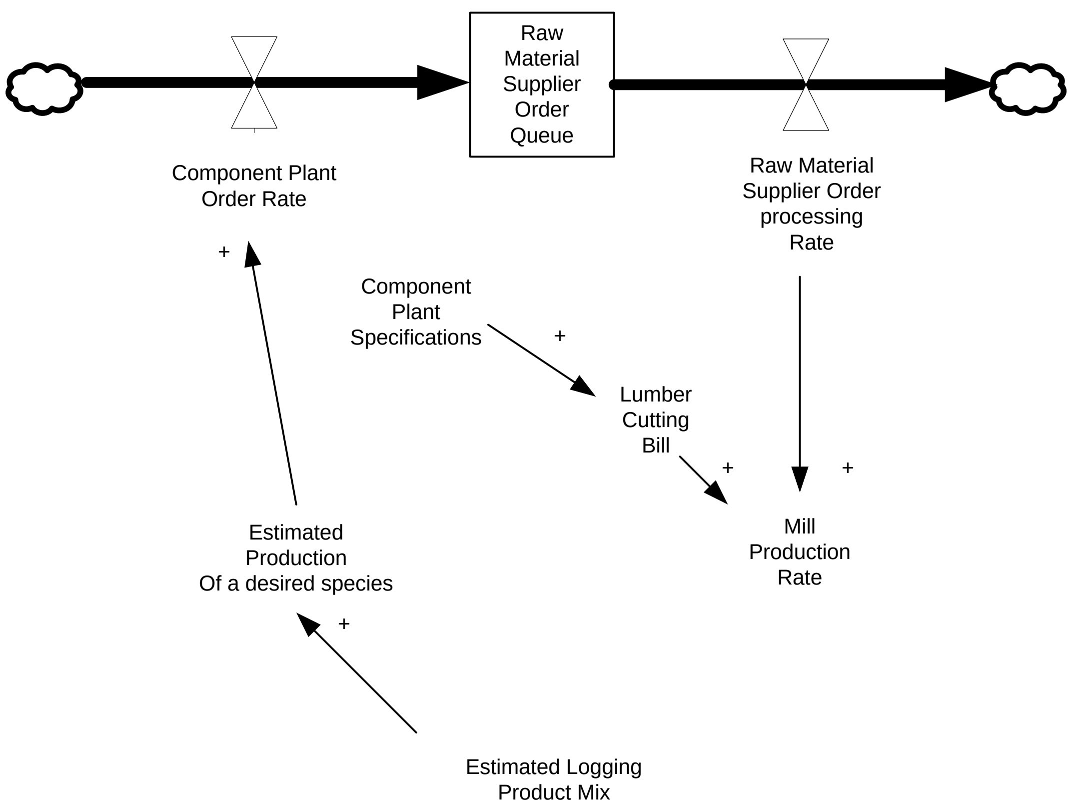

Figure 5-10 Information Flow at the Raw Material Supplier

The rate that material is ordered by the Component Plant (Component Plant Order Rate) from the Raw Material Supplier is affected not only by the needs of the Component Plant, but also the capabilities of the Raw Material Supplier. The Raw Material Supplier informs the

Component Plant of the estimated production at the sawmill of the material that the Component Plant desires so that the Component Plant can decide the quantity to purchase from the Raw Material Supplier. The estimated production at the Raw Material Supplier is based on the current logging information (Estimated Logging Product Mix), which is based on the timber inventories where the loggers will be for the month.

The production at the Sawmill (Mill Production Rate) is then affected by the orders as they are placed by the Component Plant by two means. First, the Component Plants orders affect the priorities of production at the sawmill as to the quantities to produce over the short-time horizon. Second, the Component Plant orders have specifications of raw material sizing (specifically thickness) that is required within the Component Plant. These specifications affect the way in which the raw material is cut within the sawmill (Lumber Cutting Bill).

5.7.3 **Information Usage at the Raw Material Supplier**

The information utilized by the Raw Material Supplier from the Component Plant was presented in Table 5-6 (Section 5.6.3). The amount of product of a specific species, thickness and grade specifications and the expected delivery date for the Component Plant are utilized to adjust the scheduling within the sawmill. The quantity of log segments entering the sawmill are adjusted so as to complete full orders or partial orders (truckloads) to be delivered to the Component Plant.

The Raw Material Supplier will typically deliver the raw material to the Component Plant in partial orders, each partial order associated with a full truckload. Each of these truckloads is shipped immediately after being loaded during the month leading up to the expected final delivery date defined by the Component Plant. This arrangement is beneficial to both the Component Plant and the Raw Material Supplier.

For the Component Plant, early delivery of product reduces degradation of the raw material at the site. When the raw material arrives at the Component Plant, it is unloaded and kept outside in the elements until it can be graded and restacked for placement in the climate controlled pre-drier. If large quantities of raw material arrive at one time or relatively close in time, the queue for the grading process will be much larger. As the stacks of lumber sit outside, they are susceptible to the degradation that can occur from sun, rain, and wind. Thus, partial orders delivered throughout the month are beneficial to the Component Plant.

For the Raw Material Supplier, delivering partial orders to the Component Plant is beneficial due to the rate at which species of log segments are delivered to the sawmill by the logging crews. Since the proportion of each species cut by the sawmill is determined by the make-up of the forest being harvested by the logging crew, the sawmill must cut the species in rotation so as not to create large inventories of any particular species in the log yard. The ability to deliver to customers such as the Component Plant in partial orders, gives the Raw Material Supplier the ability to meet the needs of the customers while minimizing inventories of their raw material (log segments) and finished goods inventories (lumber).

Since the products manufactured by the Raw Material Supplier (species/quantities and grades) are driven by the forest diversity currently being harvested, the sawmill cannot adjust the product as much as it must adjust the sales. The Raw Material Supplier utilizes both forest land that is owned by the company and contracted tracts of land. For the contracted tracts, timber is purchased based on expected yields from the tract and all timber is cut. Over a short time horizon, the Raw Material Supplier can and does select scheduled harvesting based on expected species and yields from the tracts available to it as based on current production needs. However, with the contracted tracts, short-term contracts (typically two years) do not allow for long delays of harvesting. In addition, selective harvesting on the tracts based on actual demand can be cost prohibitive due to setup and operation costs of logging crews.

5.8 Summary

Information obtained from supply chain partners can be an important part of the decision-making process within a company. Although the demand of the final customer in the supply chain is of utmost importance, a manager must estimate from the orders of his/her immediate customers to determine what the true demand of the final customers are, and from that extrapolate what future demand of the product(s) will be. While doing this, the manager must balance the capacities of production and inventory to keep the factory effective and efficient and to minimize stock outs of the products. At each stage in the supply chain, managers perform these estimations, which cause true demand to become more blurred the further a business segment becomes from the final customers.

In the case study supply chain, the flow of materials and the flow of information may take similar paths, but in opposite directions within these paths there are differences in the micro-structure within each organization that make up the supply chain. The flow of material, probably due to years of efficiency experts, is a very linear path with minimal number of steps and with a minimal number of influences, both between companies in the supply chain and internally. The flow of information, however, has numerous complex steps and more opaque influences than material flow, with company policies, managerial heuristics, and less concern for efficiency than the flow of material. These information flows can lead to significant delays and ultimately, costs.

Material Flow

The flow of material through the case study supply chain was as to be expected for a supply chain in that the material flow was highly linear through all of the business segments. The individual flows within each segment of the case study supply chain were controlled by a number of factors, the two most common were production orders and production rates. Production orders are derived by managerial decision-making or direct from the customer (as discussed in the following on information flow). Production flow is based on the rate at which other production is occurring directly prior to or after the particular flow of interest, such as when transportation rates are a function of log segment production at the Raw Material Supplier.

Inventory has been utilized throughout the supply chain to buffer against variation in demand and to allow production to take advantage of scale by optimizing production batching material and transportation logistics. Inventory buffers compensate for delays in information along the supply chain, and as a result, they can also add to the amount of delay in information that does occur in the supply chain.

Information Flow

The flow of information in the case study supply chain is traced from the Final Customer through all of the upstream business segments to the Raw Material Supplier. Unlike the material flow, information flow has many more decision-making processes that affect its flow. The Final Customer’s order rate is only the initial factor at the Retailer and does not directly flow through the entire supply chain. For the upstream segments, many other factors creep into the business system to drive and govern information flow, including: supplier order rates, inventory systems/policies, transportation rates, lead times, and company policies. As more factors are used, the original demand by the Final Customer is altered and distorted either by information delays, batching of orders, or transforming a demand for a final product to demand for intermediate components and raw materials.

Buffer inventory is a method by which managers deal with the uncertainty of demand, especially when there are large production lead times; however, the buffer inventory itself creates an opportunity for further delays in information that increase the uncertainty of demand. If the demand information has been distorted through the supply chain, either through delay, batching, or other transformation, a manager will have to utilize multiple sources of information to try to keep track of actual demand and to forecast what the demand will be in the future. The manager then must combine the newly transformed information to meet the criteria of the production, transportation, or inventory systems for which he/she is in charge.

It is not clear as to which came first, the inventory or the uncertainty, as one feeds off of the other in the relationship. The uncertainty does arise due to the minimal amount of information that suppliers have from their customers. In the case study supply chain, suppliers obtain information from the customers in the form of orders only after the information has been batched and delayed. This information can be very misleading due to distortions that are created based on long lead times and buffer inventory (Li et al. 2001). In most instances, within the case study supply chain, the lead times have been minimized with continuous improvement programs, but buffer inventories remain.

Of particular interest in the case study supply chain, is that the Component Plant and the Assembly Plant are sister companies within the same organization, and yet they communicate using a fragmented ordering strategy, typical of separate organizations. Perhaps because of this decoupled communication, both facilities maintain buffer inventories of the identical components. In this chapter, it was shown that the Component Plant does more than just communicate orders with the Raw Material Supplier. The Component Plant works with the Raw Material Supplier to balance the capacities of the Raw Material Supplier with the requirements of the Component Plant. Because of this relationship there is only one buffer inventory between these two members of the supply chain versus the relationship between the Component Plant and the Assembly Plant which yields two buffer inventories.

<u>Information Usage</u>

Information transformation is the change in information from its previous characteristics. A change in information as it flows through the supply chain is a distortion of the original final customer demand signal. Each new transformation as the information moves through the supply chain can increase the discrepancy between the current information characteristics and the original final customer demands.

In this chapter, it was found that information transformation occurred at three places: from Assembly Plant to Component Plant, from Component Plant to Raw Material Supplier, and internal to the Component Plant. In all three cases, there were two issues that were occurring. First, there was a physical transformation of the material. Second, single material flow was altered due to batching.

The physical transformation of material in the case study supply chain occurred when the components were being transformed into final products, logs were being transformed into lumber, and lumber was being was transformed into components. In all three cases, transformations had to occur because there was not a one-to-one relationship between original material and the final material in each stage of production. One log does not yield one piece of lumber, one piece of lumber does not yield one component, and each final product does not use the same component or the same number of components. The variability requires a transformation of the original demand information as well as a certain amount of buffering inventory to minimize stock-outs.

Transformation of information can also occur due to batching of products or orders. In the case of batching, the characteristics of the specific order or product are not changed, but the order or product is combined with others of similar characteristics. Batching is required to use scale to minimize production cost. However, in this transformation, there is one characteristic that is changed dramatically, which is time. When orders or products are batched, the original need for each of those order or products is lost and a new time is created for the entire batch. Over a large time horizon, the average for the original demand times of the order or product should equal the average demand of the batched orders or products. However, the batching process increases the distortion of the original demand and each incident of batching along the supply chain increases the amount of distortion of the final customer demand.

Some of the information transformation is unavoidable; however there are some transformations that occur that can be minimized. The transformation of material (manufacturing) through the supply chain is unavoidable as it is the purpose of the supply chain. Distortion of demand through information transformation caused by batching of orders and products can be minimized through changing the way that information passes through the supply chain.

In many customer/supplier relationships, the ordering process proceeds in two general steps. The first step occurs at the customer's facility, where orders are created based on the criticality of inventory levels against production or sales needs. During the second step, these orders are given to the supplier, who must manage their own inventories or production to accommodate the needs (both short-term and long-term) of all their customers. In this second step, the customer can create distortion by hiding actual demand through holding and batching orders to minimize costs subject to business capacity constraints. This leads to the supplier creating more distortion by batching their own inventory and forecasting because actual demand is unknown. The more customer/supplier relationships in the supply chain, these distortions can ripple through the supply chain to create unnecessary and often times costly responses to such complex distortions in demand.

To minimize the amount of distortion, additional information could be relayed to the supplier by the final customer. In addition to orders, the customer can inform the supplier every time one of the supplier's products is utilized. The supplier will then have a better sense of trends in usage of its product and be able to adjust its own production accordingly, possibly reducing sizes of batches, and reducing the amount of buffer inventory in its own facility.

The question is then, "why must there be buffer inventory at both the supplier and customer?" One buffer would be necessary to account for demand fluctuations when lead time for production is long. Two buffer inventories, one at the customer and one at the supplier, create a situation in which information is delayed due to inventory policies at both facilities, actual demand is distorted due to each inventory, and lead times of both material flow and information flow are extended (both of which increases information distortion).

A one inventory system in which the inventory is held by the customer but the level of the inventory is controlled by the supplier is familiarly called a Vendor Managed Inventory (VMI). A VMI system is an inventory system in which the supplier accesses the demand information of the customer, through incoming orders to the customer or through inventory information of the customer and it is the supplier's responsibility to guarantee that the inventory is replenished and that stock-outs do not occur (Kaipia et al. 2006). A commonly used and studied, VMI is in the grocery industry in which stocks at the grocery store are maintained by the distributors and/or manufacturers of the product, giving the manufacturer a better control of their product demand (Cachon et al. 1997).

Within this chapter, issues pertaining to the flow of material and flow of information through the case study supply chain have been identified. Potential improvements through reduced inventories, increased communication between customer and supplier, and changes in policy to increase the rate of flow of information through the supply chain have also been highlighted. How and where these changes should be applied and the effects that these changes have on the supply chain require that a measurement system be devised for further evaluation. The following chapter describes a performance measurement system based on literature and the attributes of the case study supply chain. In addition, the case study supply chain is evaluated with these performance measurements both as individual segments of the supply chain and the supply chain as a whole.

Chapter 6 Evaluation of the Case Study Supply Chain

6.1 Introduction

In the previous chapter, the flows of information and material were determined through the case study supply chain. With this data, it is possible to determine the particular causes that affect the rate at which information and material flow. In addition, inventory stockpiles and delays in the system are explained. However, to evaluate the segments of the case study supply chain as they relate to the supply chain as a whole requires further investigation and evaluation.

In this chapter, the individual segments within the case study supply chain and the supply chain as a whole were evaluated with the purpose of determining opportunities for improvement at each segment that can positively affect the overall supply chain's performance. The evaluation of this supply chain was completed utilizing the five performance measurements identified in literature (section 1.7.5) as being required for supply chain evaluation. These measures were 1) Information Integration, 2) Visibility and Trust, 3) Flexibility, 4) Functional Duplication, and 5) Final Customer Satisfaction. Specific metrics of performance (Table 6-1) were determined within these measures based on the characteristics of the case study supply chain as revealed in Chapter 4. Any special adaptation of metrics specific to this particular supply chain are discussed in this chapter and justified in relation to metrics specified in the literature for the evaluation of other supply chains.

Table 6-1 Performance Measures and Metrics

Performance Metric	Definition
Information Integration • Information Transformation • Age of Information • Information Aggregation	 • Change in informational content (0 = no transformation; 1 = transformed) • Time that information is held by a member of the supply chain (days) • Amount of time orders are held before release to supplier (days)
Visibility and Trust • Separation • Direction of Visibility • Method of Communication	 • Number of steps that an order must pass between pertinent supplier/customer to supply chain member • Appraisal of direction of information flow and the direction of the information; "1" = one direction; "2" = both directions "+" = towards supplier; "-" = towards customer. • Method by which information is communicated between supplier and customer "0" = no dialog (ex. database forms); "1" = delayed dialog (ex. Email and fax); "2" = direct dialog (ex. Phone conversation)
Flexibility • Short-Term Turn Around • Long-Term Turn Around	 • Measure of a company's lead time to deliver product once order is placed (days) • Measure of a company's lead time to change a product line based on usage of inventory in stock (days)
Functional Duplication • Order Process Duplication • Production Duplication	 • Number of processes that are duplicated in the flow of information • Number of processes that are duplicated in the flow of material
Final Customer Satisfaction • Delivery Date Contribution	 • Measure of a supply chain member's contribution to the delivery date of the finished product to the Final Customer. "2" directly connected with meeting delivery date "1" indirectly connected with meeting delivery date "0" no connection with meeting delivery date

Information Integration

Information Integration is a measure of the degree in which the data retains its original characteristics when transferred from supply chain member to supply chain member as it relates to the original information supplied by the final customers. Three metrics of *Information Integration* that were identified from analysis are: *Information Transformations*, *Age of Information*, and *Information Aggregation*.

To identify changes to information along the supply chain, *Information Transformation* was utilized. *Information Transformation* was specifically the changes that occurred in the information at each segment of the supply chain from when it was obtained by that segment to when it was transmitted to the next segment of the supply chain. It was measured as a percentage of the original information remaining intact.

The delay of information is an important factor impacting demand amplification in a supply chain and *Age of Information* was used to evaluate this delay. *Age of Information* was the amount of time that passed in the transfer of information from one member of the supply chain to the next segment of the supply chain. It was measured as the total time (in days) between a member obtaining the information and the information being obtained by the next member of the supply chain.

Finally, information was compiled by supply chain segments for many purposes including production batching and ordering policies. *Information Aggregation* was the quantity of information (orders) gathered and held by a supply chain member prior to passing the information onto the next member of the supply chain. It was measured (in days) by the total time between orders (the total amount of orders batched would be appropriate except for other suppliers and customers to supply chain partners were not incorporated in the research).

Visibility and Trust

Visibility and Trust is a measure of the openness of information that one member of a supply chain has with other members of the supply chain. Three metrics for this measure were identified and defined based on previous results: *Separation from Pertinent Customers/Suppliers*, *Direction of Visibility*, and *Method of Communication*.

Separation from Pertinent Supply Chain Partners is a measure of unnecessary segments in the supply chain which only serve to move (or delay) information adding to the lead time of information without affecting production. A Pertinent Supply Chain Member was defined for this research as a member of the supply chain that added value to the final product through manufacturing. A non-pertinent member of the supply chain is a member of the supply chain that passes material or information through its organization without changing the information or material.

Figure 6-1 illustrates the relationships between supply chain members as to the separation. In this case, the On-line Retailer acts as an intermediary for the Final Customer and the Factory, simply passing the orders from the Final Customer to the Factory. The Final Customer is two steps away from its pertinent supplier (the Factory) and the Factory is two steps away from the pertinent customer (the Retailer). For the On-line Retailer, its pertinent customer (the Final Customer) is one step away, and its pertinent supplier (the Factory) is one step away.

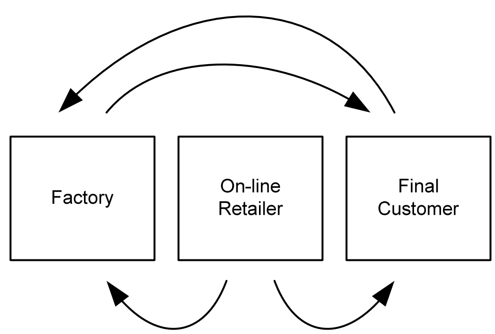

Figure 6-1 Example of Separation of Pertinent Supply Chain Partners

Information in the form of product orders can flow in both directions depending on the policies between a customer and supplier. *Direction of Visibility* is a measure of how information flows between supply chain partners. If the information flows only from customer to supplier, the flow would be identified as *unidirectional* (1) and *up* (+) the supply chain versus down (-) the supply chain. If the information flows equally between the supplier and the customer, the flow would be identified as both directions (2) and without a sign.

As a measure of visibility in a supply chain, it is also important to identify how information is passed between supply chain partners. *Method of Communication* was used to evaluate how each segment shares information with its partner (specifically orders). Categories of Methods of Communications were based on the types of interaction that companies utilize to communicate information to the supply chain partners: 1) direct dialog through face-to-face meetings or phone conversations (identified as “2”), 2) delayed dialog such as emails (identified as “1”), and 3) no dialog which occurs in situations when information is sent through computer forms and databases (identified as “0”).

Flexibility

The flexibility of a supply chain is the ability of the supply chain to make changes. A supply chain is more flexible when it can quickly respond to the desires of the customer (final customer). Thus, a measure of the flexibility of a supply chain is based on the time it takes to complete production of an order from the time that the order was placed. There are two separate factors associated with this: *Short-Term Turn Around* (STTA) and *Long-Term Turn Around* (LTTA). *Short-Term Turn Around* is the time between an order arriving to a supply chain member and the product being shipped to the customer measured in days. *Long-Term Turn Around* is the time it takes to clear out the inventory associated with a product, which would be critical if the supply chain member or the entire supply chain are required to replace a given product with another, also measured in days.

Functional Duplication

Functional Duplication is repetition of processes that occur in the flow of information and material flow through the supply chain. Of primary concern are duplications that occur at adjacent members in the supply chain, with a supplier and its customer performing identical processes before and after transport of the material or information. An example of a duplication of process would be a supplier counting the number of items on a pallet prior to shipping and the customer repeating that process to verify the suppliers count. Duplication of processes, whether in the flow of information or in the flow of production, causes unnecessary delays which can contribute to long lead times and large inventories. Two metrics were identified for evaluating the case study supply chain: *Order Processing Duplication* and *Production Duplication*. In both cases, the duplication relates to duplication that occurs between supply chain partners and not wholly internal to any one supply chain partner. In both the Order Processing Duplication and the Production Duplication, the number of duplications was identified for both separately in regards to each supply chain linkage between partners.

Final Customer Satisfaction

The satisfaction of a final customer can encompass many different factors relating to the quality of the product and services provided. In the case study supply chain, there is only one factor that is studied that can be evaluated for the measurement of the *Final Customer Satisfaction*, meeting the final delivery date required by the final customers. For this metric, the degree to which a supply chain member affects the delivery of the finished product to the final customer was evaluated.

The individual segment will be given a rating based on its contribution as outlined in

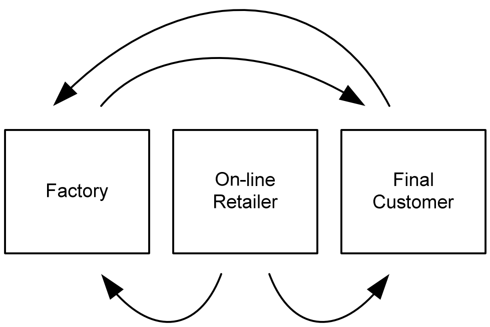

Table 6-1

Figure 6-1. A rating of “2” means that the segment of the supply chain directly affects the delivery date based on current policies and procedures and that by its actions can cause the delivery of the final product to be later than that defined by the final customer, and by the product being late can cause the final customer to potentially be dissatisfied with the customer service. A rating of “1” in this category is given to a segment that can affect the delivery date only if the policies and/or procedures currently in place were to be altered. An example of this would include the changing of procedures which cause an increase the delay of production or information flow and in turn, lengthens the lead time for delivery. A rating of “0” in this category is given to a segment that has no direct affect on the delivery of the finished product to the final customer. If changes occurred in these segments (non-calamity), the assumption is that other segments would have ample opportunity to adjust to maintain the ability to meet the delivery date defined by the final customer.

6.2 The Segments of the Case Study Supply Chain

Utilizing the performance measures and metrics defined, the case study supply chain was evaluated. The individual segments of the supply chain were evaluated and then findings from those evaluations were utilized to evaluate the entire case study supply chain. The results of these evaluations used later used to compare potential changes to the case study supply chain to the original.

6.2.1 **Retailer**

The role of the Retailer in the case study supply chain is to serve as an intermediary between the Final Customer and the Manufacturing Company. In some ways, the Retailer is a representative of both the Final Customer and the Manufacturing Company. The Retailer represents the Final Customer by delivering to the Manufacturing Company the specific product needs of the Final Customer. The Retailer represents the Manufacturing Company by offering to the Final Customer the production lines that the Manufacturing Company has available. In addition, the Retailer must also act as the intermediary when issues arise with the Final Customer's satisfaction with the Manufacturing Companies Products, passing the quality assurance policies of the Manufacturing Company (and any internal policy of the Retailer) onto the Final Customer. From the perspective of product flow, the Retailer receives the products from the Manufacturing Company and holds the products until the Final Customer picks them up.

The *Information Integration* of the Retailer (Table 6-2) shows that information obtained from the Final Customer by the Retailer is passed to the Manufacturing Company almost exactly as it was collected by the Retailer, except that the due date was removed. The removal of the due date is because the Retailer chooses to take responsibility for the date that the product will be delivered to the Retailer by the Manufacturing Company instead of passing on the responsibility to the Manufacturer. (This lack of passing of responsibility is due to the current policy of the Manufacturing Company that all products must be made as quickly as possible – five-day lead time.) Since the Retailer insists on delaying the delivery of the orders to the Manufacturing Company, the orders (information) are, on average, 15 days old before the Manufacturing Company sees them. In addition, orders are delayed (aggregated) to allow for a once-a-week ordering that reflects a once-a-week delivery schedule.

Table 6-2 Retailer Supply Chain Performance

Performance Metric	**Observed or Measured Value**
Information Integration • Information Transformations • Age of Information • Information Aggregation	 • 0 • 15 days • 5 days (business days)
Visibility and Trust • Separation • Direction of Visibility • Method of Communication	 • 1 Customer / 2 Supplier • 2 (multidirectional with the Final Customer) • 1 + (Unidirectional with Manufacturing Company) • 2 (Face-to-Face with Final Customer) • 0 (Computer forms to Manufacturing Company)
Flexibility • Short-Term Turn Around • Long-Term Turn Around	 • 0 • 0
Functional Duplication • Order Process Duplication • Production Duplication	 • 1 (duplication Final Customer Order and Manufacturing Company) • 0
Final Customer Satisfaction • Delivery Date Contribution	 • 2 (large contribution to delivery date)

In regards to *Visibility and Trust*, the Retailer works closely with the Final Customer but has minimal contact with its supplier. The Retailer and the Final Customer work together, face-to-face, to define the needs of the Final Customer. This relationship involves understanding the customer's needs and developing a detailed list of products that will be ordered from the necessary suppliers. When the Retailer places the order with the Manufacturing Company it is done through a unidirectional computer form. In addition, when the Retailer sends the order to the Manufacturing Company, the order is relayed with a delay to the Assembly Plant which is the true supplier to the Retailer.

Since the Retailer only passes information from the Final Customer to the Manufacturing Company, the Retailer is very flexible. If a rush order is required, the Retailer can place the order to the Manufacturing Company immediately upon obtaining the product information from the Final Customer; the Short-Term Turn Around would be zero (0). From the stand-point of a Long-Term Turn Around, the Retailer holds no inventory of finished goods, so it does not have to clear out any inventory before it can sell a totally different product to the Final Customer (LTTA = 0 hours). Other supply chain segments would contribute to the delay in turn around, but not the Retailer.

The Retailer does not duplicate any of the production of its supply chain partners but there is both internal and external duplication. Since the Retailer does not do anything with the products after they are delivered, other than pass them on to the Final Customer, the only production duplication that could occur would be in duplication of inventories with the product supplier. However, in this case, the supplier (the Assembly Plant) makes all products to-order and does not maintain an inventory, which means the only inventory of finished products is at the Retailer. In terms of order process duplication, there is one duplication that occurs in the supply chain at this segment - the retailer enters the Final Customer's order into its internal order database, and then enters it into a separate database belonging to the Manufacturing Company. This is the means of passing orders between the two segments.

Finally, the Retailer takes most of the burden of keeping customers satisfied. This is done by making sure that the orders placed with suppliers such as the Manufacturing Company are done so that the respective lead times for delivery guarantee that the orders arrive at the Retailer prior to the contracted pick-up date.

Overall, the Retailer's role as the interface between the Final Customer and the Manufacturing Company is a necessary component of the supply chain, primarily as a means of bringing together two components of the supply chain that would not otherwise meet. For material flow, the Retailer performs the desired task of holding the finished products until the Final Customer is ready for them and to minimize total delivery cost by batching multiple customers' orders for shipping between the Assembly Plant and the Retailer. However, the flow of information through the supply chain is immediately delayed at the Retailer by the policies of the Manufacturing Company to maintain a short production lead-time, and the Retailer's desire to minimize inventory on its site. This delay of information (and batching of information) causes demand amplification at the start of the supply chain which can create the need for excessive forecasting and inventory levels.

6.2.2 Manufacturing Company (I)

Like the Retailer, the main purpose of the Manufacturing Company (I) is to relay information from its customer, the Retailer, to the next member of the supply chain, the Assembly Plant. Unlike the Retailer, the Manufacturing Company (I) as defined here, does, at no time during the process, retain possession of any of the supply chain products. Instead it serves to distribute the orders from the various customers to the appropriate suppliers within its group of assembly plants, including the case study's Assembly Plant. Table 6-3 contains the evaluation of the Manufacturing Company (I) based on the supply chain performance measurements.

Table 6-3 Manufacturing Company (I) Supply Chain Performance

Performance Metric	**Observed or Measured Value**
Information Integration • Information Transformations • Age of Information • Information Aggregation	 • 0 • 1 day • 1 day
Visibility and Trust • Separation • Direction of Visibility • Method of Communication	 • 2 Customer / 1 Supplier • 1 +(Unidirectional from the Retailer) • 1 +(Unidirectional towards Assembly Plant) • 0 (Computer forms from Retailer) • 0 (Computer forms to Assembly Plant)
Flexibility • Short-Term Turn Around • Long-Term Turn Around	 • 1 day • 1 day
Functional Duplication • Order Process Duplication • Production Duplication	 • 1 (duplication Retailer) • 0
Final Customer Satisfaction • Delivery Date Contribution	 • 1 (indirectly associated with delivery date)

The Manufacturing Company (I) has little affect on the information (*Information Integration*) as it is passed from the Retailer to the Assembly Plant. All of the information sent to the Manufacturing Company by the Retailer is maintained when sent to the Assembly Plant.

However, in the process, the information is delayed by one day due to the Manufacturing Company's (I) policy of sending orders once per day to the Assembly Plant. This policy creates up to a full days delay in information passing from the Retailer to the Assembly Plant.

In regards to *Visibility and Trust*, information travels unidirectionally through the Manufacturing Company (I) from the Retailer to the Assembly Plant in the form of computer forms (order reports). In addition, if one considers just the flow of orders, the Retailer which serves as an information relay from the Final Customer to the Manufacturing Company, becomes an unnecessary intermediary of information flow.

Since the Manufacturing Company (I) maintains no inventory of product, nor does it play a part in the material flow of the supply chain, the flexibility of the Manufacturing Company (I) is very high. The turn around times, both short- and long- term are one day. This means that the Manufacturing Company (I) can abruptly change the product lines that it deals with a minimal delay.

Due to the lack of material flow through the Manufacturing Company (I), there is no production duplication; however, there is duplication in the order processing. Since, the Manufacturing Company (I) only serves to relay the information that was created at the Retailer to the Assembly Plant, the need to place the order again to the next member of the supply chain (Assembly Plant) is a repetition of what the Retailer did to the Manufacturing Company (I).

Finally, the Manufacturing Company has minimal affect on the Final Customer satisfaction with regards to its contribution to the delivery date to the Final Customer. The effect it does have is due to the creation of additional variation in the overall lead time of an order being processed, product manufactured, and product delivery. Depending on the time of day that the order is placed, the order can be delayed in the Manufacturing Company's (I) order queue for minutes or a business day before it is transmitted to the Assembly Plant. If the lead time at the Assembly Plant is five days, the additional wait could be as much as 20% of the Assembly Plants lead time.

The questions that arise are 1) is the Manufacturing Company's (I) centralized role in the case study supply chain necessary, especially since the information is computer to computer? and 2) if it is necessary to schedule through the Manufacturing Company due to the number of assembly plants that the company retains, is it necessary for the Manufacturing Company (I) to batch the orders and send them to the Assembly Plant once per day? The one day of delay in information can cause some need for forecasting and result in increased inventory needs. If the Manufacturing Company (I) information delay was reduced from a maximum of one day to instantaneous via computer linkages, the delay would be zero.

In addition, there is the potential that the time that it takes for information to travel from the Final Customer to the Assembly Plant could be instantaneous. The removal of the delay caused by the Manufacturing Company (I) can be combined with the Retailer sending the information from the Final Customer's order when it is determined.

6.2.3 **Assembly Plant**

The Assembly Plant is the first member along the flow of information that utilizes the Final Customer's order to create the flow of material in the supply chain. The necessary components are removed from internal inventories to manufacture the Final Customer's product on a make-to-order arrangement.

Unlike the previously discussed members of the supply chain, information integration (Table 6-4) sees a large transformation from the original information created by the Final Customer's order. Once the finished product is built at the Assembly Plant, the Final Customer's order stops being transmitted along the supply chain. Instead, the information is decoupled, transformed into component part depletion, and then sent along the supply chain in the form of component replenishment requirements. The Assembly Plant maintains inventories of components which are replenished when the amount of each component reaches a minimum level. Thus, demand for the components are not immediately transmitted to the next member of the supply chain but held (average of 20 days) and the demand is aggregated based on the batching quantity for each component. Orders are placed with the Manufacturing Company (II) every day, and since it is done on a predetermined schedule, it is possible that maximum level was met almost one day previously. Thus, the total time that information has from arrival to departure is the five days of production lead time, 20 days of parts inventory held, and one day of ordering, which equals 26 days.

Table 6-4 Assembly Plant Supply Chain Performance

Performance Metric	Observed or Measured Value
Information Integration • Information Transformations • Age of Information • Information Aggregation	 • 1 • 26 days • 1 day
Visibility and Trust • Separation • Direction of Visibility • Method of Communication	 • 3 Customers / 2 Suppliers • 1 + (Unidirectional from the Mfg. Co. (I)) • 1 + (Unidirectional towards Mfg. Co. (II)) • 0 (Computer forms from Mfg. Co. (I)) • 0 (Computer forms to Mfg. Co. (II))
Flexibility • Short-Term Turn Around • Long-Term Turn Around	 • 5 days • 26 days
Functional Duplication • Order Process Duplication • Production Duplication	 • 0 • 1 (Inventory duplication with Component Plant)
Final Customer Satisfaction • Delivery Date Contribution	 1 (indirectly affect delivery date)

In regards to *Visibility and Trust*, the Assembly Plant deals directly with the Manufacturing Company for the incoming orders (Manufacturing Company (I)) and for placing orders with the suppliers (Manufacturing Company (II)). In each case, the flow of information is unidirectional, with the flow of information from the customer to the supplier. In addition, the information transmitted is in the form of orders entered by the customer into a computer and received by the supplier in the same format. The most interesting fact within Visibility and Trust is the separation between pertinent supplier and pertinent customer for the Assembly Plant from the standpoint of information flow. If it is considered that the Retailer and the Manufacturing Company (I) simply transmit the information originating from the Final Customer up the supply chain, then the Assembly Plant is three steps away from its pertinent customer, the Final Customer. As for the Assembly Plant supplier, the Manufacturing Company (II) (to be discussed later) only serves to pass the Assembly Plant's order information to the Component Plant, which means that the Assembly Plant is two steps away from its supplier.

Because of production lead time, the Assembly Plant has less flexibility than the previously discussed supply chain members. From the point at which an order is placed with the Assembly Plant, it takes five days (Short-Term Turn Around) to turn that order into a finished product. If the demand for products were to change, the Long-Term Turn Around would be 26 days; the time it would take to clear out the entire inventory of components and replace it with new component requirements for the new production specification.

Since the Assembly Plant processes orders to be completed into finished products and initiates orders for components, no duplications of order processing take place, however, there is duplication in production. Both the Assembly Plant and the Component Plant maintain inventory of the same components. In most cases, the components are simply transferred from the Component Plant's inventory to the Assembly Plant's inventory when an order is placed by the Assembly Plant.

The Assembly Plant does contribute partially to the satisfaction of the Final Customer. The fixed lead time of transforming orders from Retailer into finished products (five days) allows the Retailer to create firm schedules for the orders. If the lead time at the Assembly Plant was to fluctuate due to component problems or mechanical downtime in the manufacturing process, this could directly affect the delivery of the product and potentially arrive at the Retailer past the date required by the Final Customer. However, it is the Retailer who schedules orders based on the fixed delivery of five days (Assembly Plant delivery time) that is the determining entity of Final Customer satisfaction of deliveries.

Overall, the Assembly Plant is efficient in converting incoming orders to finished products, though it must contend with information that is not up-to-date due to delays in information transmission by the Retailer and the Manufacturing Company (I). If information was transmitted to the Assembly Plant immediately from the Final Customer, and the Assembly Plant removed its five day lead time policy for a policy of meeting the Final Customer's needs in terms of delivery date, there is a potential for a tighter control of inventory (lower quantities) because future demand in the coming weeks will be known. In addition, the policy of maintaining inventories at both the Assembly Plant and the Component Plant is redundant. However, if inventories are needed at both facilities because a) they need to be at the Assembly Plant to be close to production and b) they need to be at the Component Plant due to batching requirements, and c) the Component Plant is supplying multiple assembly plants, there is the potential of minimizing inventories through a change of inventory policy. Since the inventory at the Assembly Plant is kept electronically and updated whenever parts are added or removed, a vendor managed inventory system (managed by the Component Plant) would allow the Component Plant direct access to replenish component usage at the Assembly Plant. This would give the Component Plant accurate usage rates for the components and reduce the time to order products (one day at the Assembly Plant and one day with the Manufacturing Company (II)) which, if managed properly, is hypothesized to reduce inventories and ultimately lead time at both the Assembly Plant and the Component Plant.

6.2.4 **Manufacturing Company (II)**

Manufacturing Company (II) is very similar to Manufacturing Company (I) except that Manufacturing Company (II) processes transactions between the Assembly Plant and the Component Plant, whereas Manufacturing Company (I) is between the Retailer and the Assembly Plant. In this case, Manufacturing Company's (II) role in the case study supply chain is to transmit order information from the customer to the supplier.

The performance of Manufacturing Company (II) in the case study supply chain is shown in Table 6-5. The integration of information is identical to Manufacturing Company (I) with a no transformation of information occurring within Manufacturing Company's (II) process of obtaining orders from the Assembly Plant and delivering them to the Component Plant. There is only a delay of up to one day due to the accumulation of orders to the Component Plant being released at one set time daily.

Table 6-5 Manufacturing Company (II) Supply Chain Performance

Performance Metric	Observed or Measured Value
Information Integration • Information Transformations • Age of Information • Information Aggregation	 • 0 • 1 day • 1 day
Visibility and Trust • Separation • Direction of Visibility • Method of Communication	 • 1 Customer / 1 Supplier • 1 + (Unidirectional from the Assembly Plant) • 1 + (Unidirectional towards Component Plant) • 0 (Computer forms from Assembly Plant) • 0 (Computer forms to Component Plant)
Flexibility • Short-Term Turn Around • Long-Term Turn Around	 • 1 day • 1 day
Functional Duplication • Order Process Duplication • Production Duplication	 • 1 (duplication with Assembly Plant) • 0
Final Customer Satisfaction • Delivery Date Contribution	 • 0 (does not affect delivery date)

In regards to *Visibility and Trust*, Manufacturing Company (II) reduces the visibility by only allowing orders to flow in one direction from the Assembly Plant to the Component Plant in the form of automated computer reports. Unlike Manufacturing Company (I), Manufacturing Company (II) is closer to its customers by one step (the Assembly Plant) and is just as close as Manufacturing Company (I) to its supplier (the Component Plant).

Since no manufacturing occurs at this segment of the case study supply chain, the flexibility of the Manufacturing Company is limited to the time it takes for the order to be passed from the Assembly Plant to the Component Plant. In a short- and long-term horizon, the value for order turn around would both be one day, which is the maximum time that it would take for an order to be processed.

Manufacturing Company (II) is not involved in any material flow, and thus has no production duplication with the Assembly Plant or the Component Plant. However, since the Manufacturing Company (II) is an intermediate step between the Assembly Plant and the Component Plant, the process of delivering the order to the Component Plant is a duplication of the Assembly Plant's delivery of the order to the Manufacturing Company (II) with an additional delay of up to one day.

At this point in the case study supply chain to the Raw Material Supplier, the members, including the Manufacturing Company (II), have no affect on the satisfaction of the Final Customer for the delivery date. The buffer stock of components in the Assembly Plant acts as a disconnect in the case study supply chain, which creates the need for batching orders and disconnects the demand for components with the demand for the final product.

Like Manufacturing Company (I), Manufacturing Company (II) delays information flow between other members of the case study supply chain. In addition, the separation of the Component Plant and the Assembly Plant by the Manufacturing Company (II), creates a barrier of communication that limits the two segments of the supply chain from potentially increasing the effectiveness and efficiency of the supply chain as a whole. Elimination of the Manufacturing Company (II) segment and increased multidirectional information flow between the Component Plant and the Assembly Plant could serve to minimize inventory levels at one or both facilities. This increased communication could include the implementation of a vendor (Component Plant) managed inventory at the Assembly Plant which is hypothesized to reduce information flow delays and decrease inventory at one or both facilities. Ultimately, reduction in inventory and information delays would reduce overall lead time in the supply chain.

6.2.5 **Component Plant**

The Component Plant is the first stage in the production of the finished product when the commodity raw material purchased from the Raw Material Supplier is formed into a part (component) that will be a portion of the finished product. As such, the Component Plant must keep the Assembly Plant stocked with the necessary components so that the Final Customer can obtain the finished product in the five day lead time policy of the Assembly Plant that is relied upon by the Retailer. The overall performance of the Component Plant in the case study supply chain is shown in Table 6-6.

Table 6-6 Component Plant Supply Chain Performance

Performance Metric	**Observed or Measured Value**
Information Integration • Information Transformations • Age of Information • Information Aggregation	 • 3 • 53 days • 21 days (monthly raw material order schedule)
Visibility and Trust • Separation • Direction of Visibility • Method of Communication	 • 2 Customer / 1 Supplier • 1 + (Unidirectional from the Manufacturing Company) • 2 (Multidirectional with the Raw Material Supplier) • 0 (Computer forms from Manufacturing Company) • 1 (fax with the Raw Material Supplier)
Flexibility • Short-Term Turn Around • Long-Term Turn Around	 • 1 day • 53 days
Functional Duplication • Order Process Duplication • Production Duplication	 • 0 • 2 (Duplication of inventory with Assembly Plant / duplication of grading raw material with Raw Material Supplier)
Final Customer Satisfaction • Delivery Date Contribution	 • 0

The integration of the information at the Component Plant is similar to that of the Assembly Plant. The incoming orders for components are transmitted through the facility to the Raw Material Supplier. They are transformed three times within the Component Plant due to a number of different policies. First, the orders are pulled from a finished goods inventory whereby the finished goods inventory are replenished on a batch production policy not tied to outgoing demand. Second, the incoming raw material requires a long drying process prior to usage. Finally, the raw material is purchased on a monthly basis. These all create a situation in which demand for components cannot be tied to purchase of raw materials. Due to all of these different policies, the age of the information from the point at which orders for components are placed and raw material is purchased (lead time) is 53 days (Section 4.3.1).

In regards to *Visibility and Trust*, the Component Plant is limited in its communication with orders arriving from the direction of the Final Customer by the computerized reports that are passed unidirectionally from Manufacturing Company (II), which creates an additional step from communicating with the actual customer, the Assembly Plant. However, the link between the Component Plant and the Raw Material Supplier is the only other relationship in the case study supply chain that maintains one-on-one communication (the Final Customer and Retailer being the other). The Component Plant works with the Raw Material Supplier to determine the specific quantities of raw material that will work for both companies (as discussed in section 3.2).

Due to daily deliveries from the Component Plant to the Assembly Plant, orders that are placed by the Assembly Plant to the Component Plant are removed from the Component Plant's inventory and placed on the next day's delivery truck to the Assembly Plant arriving before manufacturing hours on the following day. This makes the Component Plant relatively flexible (one-day Short-Term Turn Around) to the needs of the Assembly Plant. However, the inventories of finished goods and raw materials, as well as the relatively long drying time of the raw materials, makes the four-day production lead time for the components inconsequential when orders are not "rush" or expedited orders. The overall lead time to clear out current stocks for the purpose of changes in production that may occur due to changes in product demand would be 53 days, making the Component Plant the least flexible of the members of the case study supply chain.

The Component Plant does not have any duplication of order processing with any other members of the case study supply chain; however there is duplication of production with these other members, specifically with inventories. The Component Plant does not have a duplicate inventory with the Raw Material Supplier as the Raw Material Supplier delivers the raw material when a truckload has been accumulated. The Component Plant does maintain a duplicate inventory with the Assembly Plant as discussed previously. The purpose of the inventory is to have components ready for next day delivery to the assembly plants that it supplies, including the Assembly Plant. The additional inventory assists in guaranteeing that the Assembly Plant does not stock-out on components. However, the additional inventory can result in lead-times to manufacture the finished product that would exceed the five-day lead time that is accepted by the Retailer.

Duplication does occur between the Component Plant and the Raw Material Supplier for one manufacturing process, which is evaluation of the raw material. At the Raw Material Supplier, the lumber is graded, stacked, and the volume is recorded, all prior to being loaded on a truck and shipped to the Component Plant. At the Component Plant, the lumber is unstacked, re-graded, the volume calculated, and restacked. With the amount of raw material processed at the Component Plant and the Raw Material Supplier, small discrepancies can equate to large sums of money. Since the Component Plant purchases raw material from a number of different sources other than the Raw Material Supplier, including some through third-party brokers, it would seem uneconomical for the Component Plant to trust all of its suppliers and not re-grade the lumber.

Since the Assembly Plant is in charge of maintaining its own component inventory, the Component Plant is not responsible for stock-outs of components at the Assembly Plant that may cause delays in finished products being delivered to the Final Customer. As a result, the Component Plant does not have any control over the satisfaction of the Final Customer with regards to the meeting of the required delivery date of the finished product to the Final Customer.

Overall, the Long-term Turn Around associated with the Component Plant can be reduced by minimizing the requirements of maintaining a duplicate inventory with the Assembly Plant and allowing the Component Plant direct access to the Assembly Plants inventory levels so that the Component Plant can manage and replenish (i.e. vendor managed inventory system) the Assembly Plant inventory. Reductions in inventory levels are hypothesized to minimize the lead time by removing the Manufacturing Company (II) and delays associated with managing the inventory levels at two facilities.

With regards to the raw material inventories, the 30-day ordering period by the Component Plant, along with the multiple transformations of actual Final Customer demand, may cause demand amplification in the ordering process with the Raw Material Supplier. The end result of this amplification would be excessive levels of inventory in the Component Plant of raw material, as well as a hindrance on the Raw Material Suppliers' ability to develop long-term planning. The potential for minimizing inventory of raw material at the Component Plant would then be for the rate at which deliveries are made by the Raw Material Supplier to be correlated with the rate at which the raw material is utilized by the Component Plant. With long-term contracts between the Component Plant and Raw Material Supplier, the Raw Material Supplier can be contracted to supply raw material at a rate that correlates more precisely to the usage rate with adjustments made by the Component plant as necessary. Such contracts or policies that facilitate demand-driven need, if created and managed properly, would lead to inventory reduction and eliminate duplication of grading and sorting steps. Policies and contracts leading to inventory reduction are hypothesized to minimize the lead time of the Component Plant while allowing more production scheduling flexibility for the Raw Material Supplier. The theorized results would be that the Component Plant and the Raw Material Supplier could be more reactionary to the demands of the Final Customer.

6.2.6 **Raw Material Supplier**

The Raw Material Supplier is the last member of the case study supply chain. The Raw Material Supplier harvests trees from its own tracts of forestland and from landowners under specific timber contracts. Although some logs obtained from these trees are sold to other manufacturers, for the most part, the Raw Material Supplier's production is dictated by the particular species and quality of the currently harvested timberland. Due to regional similarities in timberland, the variation at a given mill, such as the Raw Material Supplier, is not so large as to make it impossible to maintain a relatively constant flow of similar products from one month to the next. Thus, the Raw Material Supplier can maintain long-term contracts with some customers, such as the Component Plant. The performance of the Raw Material Supplier in the case study supply chain is presented in Table 6-7.

Table 6-7 Raw Material Supplier Supply Chain Performance

Performance Metric	**Observed or Measured Value**
Information Integration • Information Transformations • Age of Information • Information Aggregation	 • 1 • 11 days • Not applicable
Visibility and Trust • Separation • Direction of Visibility • Method of Communication	 • 1 Customer • 2 (Multidirectional with Component Plant) • 1 (fax with the Component Plant
Flexibility • Short-Term Turn Around • Long-Term Turn Around	 • 11 days • 11 days
Functional Duplication • Order Process Duplication • Production Duplication	 • 0 • 1 (Grading of raw material)
Final Customer Satisfaction • Delivery Date Contribution	 • 0

The integration of the information as it passes from the Component Plant, through the Raw Material Supplier, and ending at the timber source, is transformed greatly.   This transformation is due to the demand by the customer (the Component Plant) having minimal affect on the production at the Raw Material Supplier (as described in section 5.7.2). Any information that has the potential of being passed through the Raw Material Supplier would take approximately 11 days. This would also be considered the flexibility of the Raw Material Supplier (Short-Term and Long-Term Turn Around).

The *Visibility and Tru*st and the *Functional Duplication* have already been discussed in the previous section regards to the Raw Material Supplier's relationship with the Component Plant. In addition, since the Component Plant has no affect on the Final Customer satisfaction in terms of the delivery dates of the finished product, the Raw Material also does not contribute to the delivery dates because of the separation created by the Component Plant (and the Manufacturing Company (I) and (II)).

In regards to *Flexibility*, the information flow from orders received to harvesting may take 11 days to travel, but minimal changes can occur in harvesting during the short-term horizon that will affect the distribution of production at the sawmill on a day-to-day basis. The distributions of species and grades may be altered slightly by relocation of harvesting at a particular site or slightly more by changing sites entirely.

Over a longer time horizon, there is a potential that customer orders may affect the management decisions at the Raw Material Supplier, more specifically those relating to timberland. If long-term contracts existed between the Raw Material Supplier and the Component Plant (and other customers), the Raw Material Supplier would have a clearer vision of the types of forest distributions required to produce the output needed at the sawmill. A more constant demand structure for orders coming into the Raw Material Supplier has the following possible affects: 1) more accurate valuation of standing timber when developing contracts, 2) better scheduling of harvesting rates to meet demand, 3) better long-term site selection of harvesting sites to minimize overcut species. However, the short- and long-term effects of decreasing the demand fluctuation between the Component Plant and the Raw Material Supplier on the Raw Material Supplier are difficult to analyze within the parameters of this study.

Increased information sharing between the Component Plant and Raw Material Supplier does have the potential of reduction in inventory at the Component Plant if the Raw Material Supplier can balance the rate at which it delivers the raw material with the rate at which the raw material is used by the Component Plant. To do this, the Raw Material Supplier needs to be able to have access to the current inventory levels of raw material at the Component Plant. If this information can be used to better match selection of timber harvesting sites to the demand of the

Component Plant, then it is hypothesized that necessary inventory can be reduced at the Component Plant.

6.3 The Case Study Supply Chain

The determination of a supply chain's ability to serve the Final Customer can be divided into three criteria – alignment, agility, and adaptability (Lee 2004). The ability of the members of the supply chain to work together towards the one goal of serving the Final Customer is the alignment of the supply chain. The ability to quickly meet the current needs of the final customer is the agility. Finally, the ability to make large changes to meet the future needs of the final customer is the adaptability.

Within the performance measurements that were utilized in this study, the supply chain's alignment, agility, and adaptability were measured. Agility is measured with the *short-term turn around time* within the category "Flexibility." Adaptability is measured with the *long-term turn around time* also within the category "Flexibility." Alignment is measured with all of the other categories as a function of how well the members of the supply chain communicate both short-term and long-term goals with each other.

6.3.1 Information Transformation in the Case Study Supply Chain

The flow of information through the case study supply chain undergoes five transformations during its movement from the Final Customer to the Raw Material Supplier (Table 6-8). The transformation of information is caused by changes in the form of product along the material flow and batching of products in inventory and production. In all five transformation cases in the supply chain, it was observed that a significantly sized inventory buffer is involved in the transformation in each case. The buffers themselves are not the cause of the transformation of information; instead it is the policies that are utilized in conjunction with those inventories. Companies choose to minimize information flow to orders, even among facilities within the same company (Assembly Plant and Component Plant).

Table 6-8 Supply Chain Evaluation

Performance Metric	Final Cust.	Retailer	Manuf. Co. 1	Assembly Plant	Manuf. Co. 2	Comp. Plant	RMS
Information Integration							
Transformation		0	0	1	0	3	1
Age (days)		15	1	26	1	53	11
Aggregation (days)		5	1	1	1	21	NA
Visibility and Trust							
• Separation		1/2	2/1	3/2	1/1	2/1	1
• Direction of Visibility		2/1+	1+/1+	1+/1+	1+/1+	1+/2	2
• Method		2/0	0/0	0/0	0/0	0/1	1
Flexibility							
• Short-Term Turn Around		0	1	5	1	1	11
• Long-Term Turn Around		0	1	26	1	53	11
Functional Duplication							
• Order Process Duplication		1	1	0	1	0	0
• Production Duplication		0	0	1	0	2	1
Final Customer Satisfaction							
• Delivery Date Contribution		2	1	1	0	0	0

In the case study supply chain, all of the inventories are managed (regardless of the company or manager in charge of the inventory) by a reordering system in which the levels of the inventories are monitored and orders are placed based on the levels. In one instance (the Assembly Plant) inventory levels are monitored with a strict *Min/Max* system by which orders are triggered based on a specific minimum level of inventory being obtained. The order quantity is then based on the maximum level determined; each component having its own minimum and maximum level based on usage rate and lead time for replenishment. With the other inventories in the supply chain, the managers of each inventory attempt to keep their respective inventories between a maximum level and a minimum level without a formalized ordering process. The managers utilize past experience to develop a non-standardized inventory policy and set of heuristics. The result: if one of the managers leaves so does the exact inventory policy of the inventory he/she was managing

Even though the five inventory buffers are observed to be managed differently, one thing they have in common is that the suppliers do not know the true demand rate of the customers' finished product. The suppliers only know the customers raw material needs which are orders for the suppliers' products (a transformation of product-type). These inventory buffers become a significant decoupling point for actual downstream demand. That is, the suppliers do not know what the original customer demand is and must use some form of heuristic based on past orders to anticipate and determine short- and long-term needs of the customer so as to schedule production in their own facilities.

6.3.2 **Information Age in the Case Study Supply Chain**

The number of information decoupling points and the time duration that information spends at each segment of the case study supply chain increases the amount of forecasting required by the members waiting for the information to reach them. The information age (or the time it takes to pass through a segment in the supply chain) is shown in Table 6-8. As previously discussed (section 4.3.1), the delay in information flow at the Component Plant, Assembly Plant and Retailer relate directly to policies that are maintained by each member such as inventory policies, ordering policies, or a combination of both. In the case of the Component Plant and the Assembly Plant, the age of the information can be attributed to the inventory policies of resources. With the Component Plant, there are three separate inventory buffers within the facility that cause this delay (component, dry lumber, green lumber).

If information flow is tied to the replenishment of an inventory, the information will not continue in the supply chain until the inventory levels reach a predetermined minimum level. In addition, the Component Plant and the Retailer have policies in which orders are not released to suppliers until certain criteria are met, such as a specific date of ordering. Reduction in the time it takes for information to pass through each of these supply chain members based on policy change to the areas of inventory and ordering procedure is hypothesized to reduce the need for inventory by decreasing the demand amplification (section 6.3.1).

In the case of the Retailer, the policy of delaying orders being sent to the Assembly Plant (via Manufacturing Company (I)) is due primarily to the policies of the Assembly Plant. The Assembly Plant has created a policy of minimizing lead time from order reception to delivery of the product (five days). The Retailer, based on its own requirement to minimize inventory at its own facility, delays the orders until the delivery day from the Assembly Plant coincides with the delivery date that the Retailer's customer, the Final Customer, requires. Thus, in its own policies, the Assembly Plant has created a delay in information which makes their information older and amplifies demand creating an artificially perceived need for more inventories.

Though small in comparison, the time that is spent at the Manufacturing Company (I, II) creates what may be assessed as unnecessary delay in the flow of information through the supply chain. If the Manufacturing Company can transmit the information immediately from each of its respective customers to its suppliers, it is hypothesized that demand amplification will be reduced.

If current policies, such as inventory/order policies, can be altered within the case study supply chain so that information flows freely, up to 80 days of information flow could be eliminated which would be 75 percent of the total time it takes for information to flow through the case study supply chain (values found in section 4.3). Delay of information is one of the factors that causes demand amplification, which can increase the need for inventories (Forrester 1961). Thus, the information delay is creating a need for increased inventories (Figure 6-2). It is the policies for inventory that keep the loop from growing which typically define some cap based on physical limitations or capital restrictions.

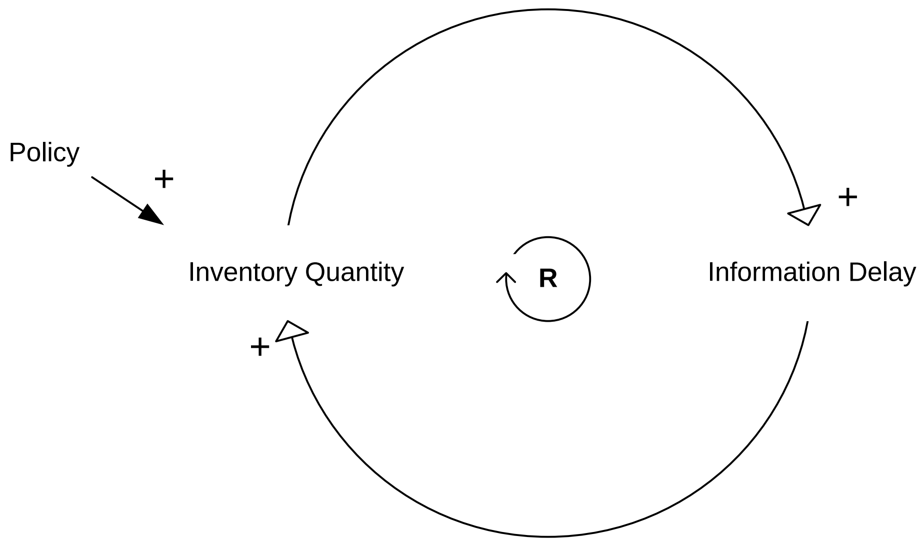

Figure 6-2 Information and Inventory Reinforcement Loop

The Inventory/Information reinforcement loop can better be controlled, not from the side of policy towards inventory quantities which can be set arbitrarily by upper management, such as in the Component Plant component and raw material inventories, but from the information delay. Policies which reduce the delay in information will then reduce the quantities of inventory for a company. It is hypothesized that the reductions in both the information delay and thus the inventory quantities should reduce the lead time of material flow through the supply chain.

6.3.3 **Information Aggregation in the Case Study Supply Chain**

Each member of the case study supply chain has their own unique method or policy when it comes to conducting orders with their supplier. Whether they are company policy or managers' decisions, orders are placed based on a specific schedule. For the Retailer, orders are placed weekly (five business days) which is based, in part, on the accumulation of a full truck of product. Within the focal company, that includes the Manufacturing Companies (I&II), the Assembly Plant, and the Component Plant, information is passed on a daily basis. Orders between the Component Plant and the Raw Material Supplier are based on a monthly ordering schedule (21 business days).

Like the buffer inventories, the holding of information until a specific time or date adds unnecessary delay in the movement of information through the supply chain. Though the aggregation of orders may be beneficial to one or both of the members in the transaction, it is also detrimental in that the added delay of information can lead to the need for increased buffer inventory.

Although aggregation such as for the Retailer to the Manufacturing Company (I) or from the Component Plant to the Raw Material Supplier can be seen as enough to create a level of amplification in the demand, the daily ordering delays can cause unnecessary issues within the members of the Manufacturing Company. The Component Plant and the Assembly Plant are both utilizing continuous improvement strategies to improve their respective lead times, in some cases trying to shave minutes or seconds off of one particular area of the production process. Yet, within their corporate policy, information is delayed in flow by up to a day between each entity due to daily order processing policies. In addition, the requirement of all information having to be routed through the corporate network and aggregated for a day there, means that there is potentially another day delay between the Retailer and the Assembly Plant and between the Assembly Plant and the Component Plant.

6.3.4 Separation in the Case Study Supply Chain

The determination of the separation between supply chain partners is based on the origination of information and products that an individual member of the supply chain utilizes. In the case of products and product flow, the separation is the same as what was determined in Chapter 4 – Raw Material to Component Plant to Assembly Plant to Retailer to Final Customer. However, if we look at information flow and identify specifically where information comes from and who specifically utilizes the information, it becomes more unclear than for products. In Table 6-8, the distance between these pertinent members is shown for each member of the case study supply chain. Presenting this information in a different form, Figure 6-3, a better understanding of these distances can be ascertained. Between the Raw Material Supplier and the Component Plant, arrows are shared in opposite directions, which mean that the two companies need information originating from each other. From this depiction, it is seen that the Manufacturing Company (both I and II) which serves as an intermediary between the Component Plant and the Assembly Plant and between the Assembly Plant and the Retailer serves no purpose to these members of the supply chain. The Manufacturing Company (I and II) only serve as an additional step in the flow of information.

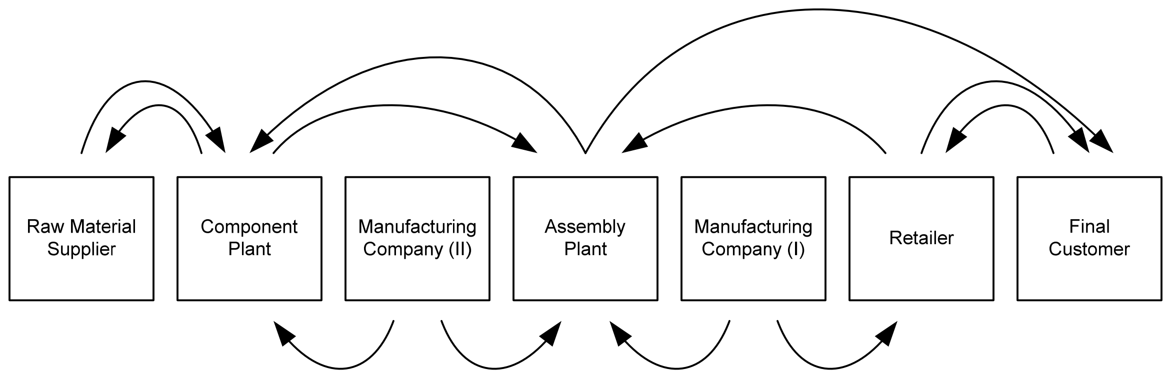

Figure 6-3 Location of Closest Pertinent Supply Chain Member for each Segment of the Supply Chain

Also from the figure, it can be noted that the Assembly Plant does not need information from the Retailer. All of the information required by the Assembly Plant comes directly from the Final Customer – product type, style, accessories, etc. The Retailer only delays the information that the Assembly Plant requires to meet the needs of the Final Customer.

Thus, to improve the flow of information through the case study supply chain, three proposed changes would be necessary. First removing the delay at the Manufacturing Company (I) or increasing the efficiency of the Manufacturing Company (I) would increase the flow of information between the Retailer and the Assembly Plant. Removing the delay at the Manufacturing Company (II) would increase the flow of information between the Assembly Plant and the Component Plant. Finally, removing or increasing the efficiency of the Retailer would increase the flow of information between the Assembly Plant and the Final Customer.

6.3.5 Visibility and Communication in the Case Study Supply Chain

The last two metrics of the *Visibility and Trust* performance measure are utilized to determine the degree of cooperation between adjacent members of the case study supply chain; the assumption being made that non-adjacent members of the supply chain have little or no interaction. The Direction of Visibility indicates the direction of information flow and the Methods of Communication details how that information is shared.

The predominant communication of information through the case study supply chain is orders that flow unidirectionally from the customer position to the supplier position. The orders are passed in these cases by means of computer ordering protocols which limits the interaction between adjacent members of the case study supply chain to specific order inputs in a larger networked program. The computer network allows for an exacting level of detail in the flow of information; however it restricts communication between members of the supply chain to very specific information and only in one direction.

The two segments of the case study supply chain that utilize multidirectional communication are at the beginning and the end of the supply chain. The Retailer works one-on-one with the Final Customer to determine the needs of the Final Customer and the products that the Final Customer wishes to obtain, which helps to assure that the information (in the form of orders) being sent through the case study supply chain are accurate with minimal returns. At the other end of the case study supply chain, the Component Plant and the Raw Material Supplier work together through fax and telephone to develop an ordering strategy that benefits both of these members of the supply chain; the reasoning was described previously (Section 6.2.5).

6.3.6 **Flexibility in the Case Study Supply Chain**

The *Flexibility* of the case study supply chain is a measure of the supply chain members' (and the supply chain as a whole) ability to react to changes in demand over short-term and long-term horizons. In the short-term, the supply chain is limited by the production lead time and the necessary transportation of products between the members of the supply chain. For the case study supply chain, this would be 19 business days with most of that delay coming from the Raw Material Supplier (Figure 6-4). Short-term delays, though, only reflect the ability of a supplier to meet the orders of the immediate customer (or agility of the supply chain) and do not necessarily reflect the ability of the entire supply chain to react to the needs of the Final Customer.

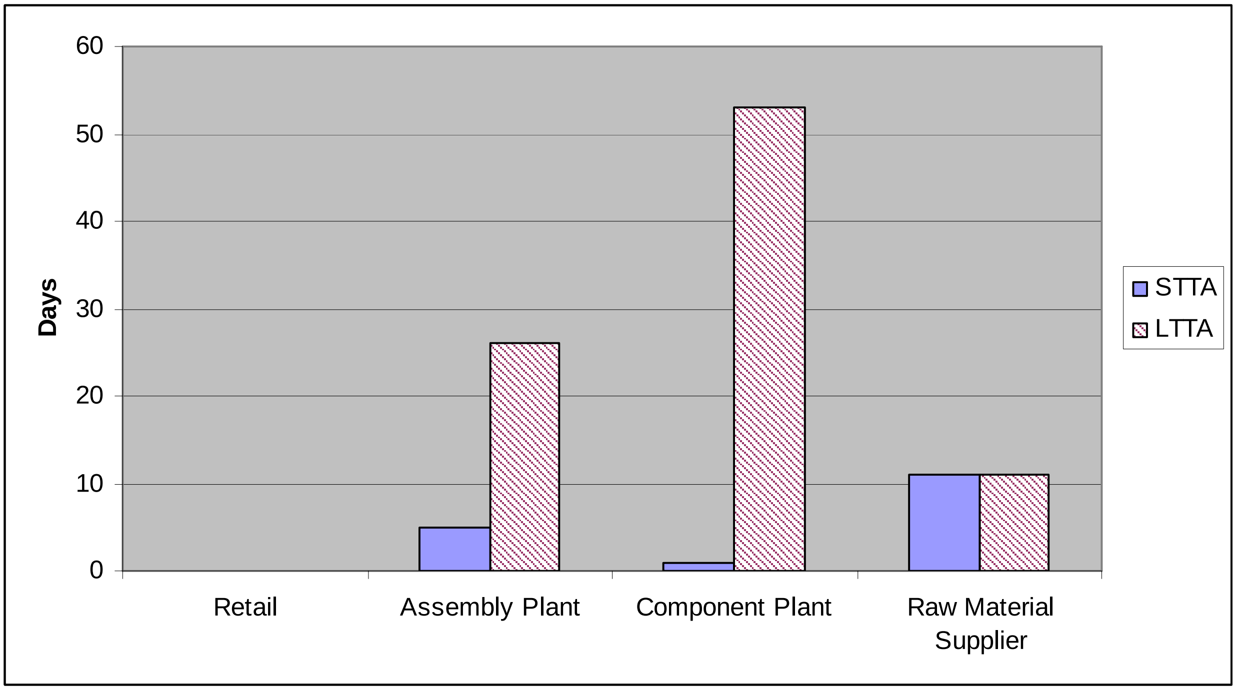

Figure 6-4 Flexibility in the Case Study Supply Chain

The Long-Term Turn Around is a measure of the adaptability of a supply chain to the changing needs of the Final Customer. If a totally new product/raw material was to be incorporated into the supply chain and it required clearing out the current inventory and work-in-progress, the entire process would take 92 business days (or 4 ½ months). The chief component of the length of time in the long-term turn around is the amount of inventory held throughout the case study supply chain. The Long-term Turn Around length is primarily due to the inventories held at the Assembly Plant and the Component Plant. Thus, it is the inventories that are one of the key factors in making the supply chain unresponsive to the needs of the Final Customer.

6.3.7 **Functional Duplication in the Supply Chain**

Duplication of processes and procedures occurs throughout the case study supply chain (Table 6-8) and was discussed in detail within section 6.2. There were two main types of duplications of interest – order process duplication and inventory duplication.

Order duplication occurred primarily due to the requirement of information to pass through a secondary facility/organization not directly related to the production of products in the cases study supply chain. The specific facility/organization is that which is described in this research as the Manufacturing Company (I and II). The process that information goes through at the Manufacturing Company is not simply a routing of the customer orders to the necessary supplier, but a delay and organization of the information to be passed on. In essence, an order is placed by the customer with the Manufacturing Company and then the order is placed by the Manufacturing Company with the supplier - a duplication of the ordering process. The duplication of orders occurs between the Retailer and the Assembly Plant, and between the Assembly Plant and the Component Plant. In both cases, the duplicate ordering adds demand amplification due to added delays and information transformation (batching).

The second type of duplication that is of interest in the case study supply chain is the duplication of inventories. It may be typical for a supplier and a customer to have duplicate buffer inventories because of large differences in the objectives and operations of the two organizations. The interesting item about the duplication of inventories in this case is that the supplier (the Component Plant) and the customer (the Assembly Plant) are essentially part of the same company's production line only in two facilities (the Manufacturing Company). There is exclusivity in the usage of component made by the Component Plant by the Assembly Plant. Though other component plants owned by the Manufacturing Company supply other components to the Assembly Plant, and the Component Plant supplies other assembly plants owned by the Manufacturing Plant, the components made by the Component Plant are not obtained by the Assembly Plant through any other suppliers external or internal to the Manufacturing Company. Include with this that there is a daily delivery between the two facilities, and 30 business days worth of inventory between the two buffering inventories of components has resulted.

6.3.8 **Delivery Date Contribution in the Case Study Supply Chain**

For the sake of this research, Final Customer Satisfaction in the case study supply chain was measured based on the contribution of the individual members of the supply chain to their part in guaranteeing that that the Final Customer receives his/her product(s) on the date requested by him/her. What was observed in this research was that the closer a member of the case study supply chain was to the Final Customer, the more the member was responsible for the meeting of that deadline. The Retailer was ultimately responsible for delivery of the product on-time (a rating of "2"). However, over a short time horizon (the ordering horizon) both the

Manufacturing Company (I) and the Assembly Plant had the potential of directly affecting the delivery to the Final Customer by operating outside of the standard procedures, such as raw material stock-outs, loosing an order, production break-downs, etc.

The significance of the Retailer taking the largest responsibility for the delivery date to the Final Customer is that it leaves further members of the supply chain with less flexibility in production scheduling that makes for a less agile supply chain. In this particular case, the Assembly Plant has created the situation, in part, due to the policy of minimization of lead time between orders arriving from their customers and deliveries of the finished product. This lead time of five days is far less than the delivery times required by the Final Customer which can exceed one month. This discrepancy of deliveries (in and out) at the Retailer requires that either a) the Retailer holds large inventories due to the discrepancy or b) the Retailer delays ordering to make the deliveries coincide better. Thus, the flexibility of the Assembly Plant (and potentially further members) is partially limited by not understanding the needs of the Final Customer of the supply chain who does not necessarily want the finished product fast, but rather on-time for a specified delivery date.

6.4 Summary

The case study supply chain was evaluated utilizing supply chain performance measures that were defined by the literature and metrics that were created based on specific detailed observations of the case study supply chain and the criteria of interest in the supply chain. From the evaluation, it was found that there are opportunities within the case study supply chain to improve the flow of information and the flow of material. Opportunities center on minimizing or removing buffering inventories of product and information which delay information and production that when in place, create long lead times in production. With the purpose of the research being to increase the competitiveness of the Hardwood Industry through increased agility to better address the Final Customer’s needs, it is necessary to determine if these buffer inventories can be reduced and better managed thereby increasing agility in meeting the Final Customer’s needs for the entire supply chain.

Literature defines five performance measures for supply chain management: 1) *Information Integration*, 2) *Visibility and Trust*, 3) *Flexibility*, 4) *Functional Duplication*, and 5) *Final Customer Satisfaction* (Section 1.7.5). Within each performance measure, metrics identified that buffer inventories were one of the major causes of low ratings amongst these performance measures with regards to information and production flow.

The buffer inventories, as they are utilized within the case study supply chain, increase the lead times of production flow and information flow, which affects both the agility and the adaptability of the supply chain. Removing the inventories would greatly decrease the lead times for production and production changeovers which would increase the supply chain's ability to meet the changing needs of the final customers, especially in the long-term turn around (adaptability). However, the inventories serve an important purpose in the supply chain, which is to accommodate lead time in manufacturing and to buffer against changes in demand. Not all changes in demand are caused by the final customers. Demand amplification, change in demand from the final customers' demand, can be caused by the decoupling and delay of information through the supply chain.

The larger the fluctuations in demand the more need there is for the buffering of an inventory. If the large fluctuations are not caused by actual demand but by the demand amplification, then we see that demand amplification causes the need for a buffering inventory which in turn further reinforces demand amplification – a cycle which without other policies or heuristics utilized by management or some mechanisms to balance this cycle (e.g. physical space limitation or production capacity limitations) - would create mammoth inventories.

Inventories do not necessarily lead to delays in information. It is the policies that companies utilize to synchronize information flow in the management of the inventories which do and affect the alignment of the supply chain. With the polices of the case study supply chain, demand of the customer initiates production and leads to inventory being depleted. However, it is the order policies that release information to the suppliers of the inventory, not the pull from inventory. Any delay in information flow and batching as a result of these policies creates demand amplification.

The following chapter endeavors to answer the hypotheses identified within this chapter. Through discrete-event simulation, the case study supply chain is analyzed for the effects of increased information flow on the inventory levels and lead times within specific companies, segments and through the supply chain as a whole.

Chapter 7 Increased Information Flow

7.1 Introduction

The hypothesis of this research was that increased sharing of the right information between individual companies within the Hardwood supply chain can address the lack of customer-focus in the Hardwood supply chain. The final customers' needs which drive the supply chain are delayed as they flow through the supply chain by the policies and processes of the companies that make up the supply chain (section 4.3.1). Delays in final customers' demands can create a supply chain that is slow to respond or unresponsive to the needs of the final customer.

As information flows through the supply chain, there are unique challenges that each company or facility within the supply chain must face with regards to what information is available and how it is presented. In the case study supply chain, the Retailer to Assembly Plant segment's production and inventory policies are controlled by the demand of the Final Customer. The Component Plant to Raw Material segment is far removed from the Final Customer demand and must use forecasting methods to extrapolate past aggregated demand into current and future needs for production and inventories. The central segment, the Assembly Plant to the Component Plant, combines aspects of the other two segments.

A prevalent form of information delay found throughout a supply chain is the inventory buffers (section 6.3.6), which affect the adaptability of the supply chain to the final customers needs. Information delays and inventory buffers share an integral relationship. Information delays can create the need for inventory buffers and inventory buffers can create informational delay, and this reinforcing relationship can be controlled with the policies of a company (section 6.3.2).

Simulation models were developed to investigate the affects of increased information flow on the inventory levels throughout a supply chain, utilizing the case study supply chain. The purpose of the simulation models was to determine the potential benefits through reduced inventories by increasing information flow. Of particular interest in the investigation were the positions of policies that determine the quantities of inventory in stock as they create the forecasts by which the inventory accumulates.

There were three major inventory buffers in the case study supply chain which were analyzed. Since the Retailer orders the finished product as the Final Customer requires, the Assembly Plant holds an inventory of components prior to the manufacturing cells so that the Final Customer's delivery requirements can be met. The Component Plant holds the remaining two inventories. The first inventory is of components required by the Assembly Plant so that orders from the Assembly Plant can be delivered quickly, so as to not create a stock-out for the Final Customer. The other inventory is that of the raw material from the Raw Material Supplier which the Component Plant orders on a monthly basis.

7.2 Retailer/Assembly Plant

In the first segment of a supply chain, represented by the Retailer to the Assembly Plant in the case study supply chain, inventory is accumulated for the purpose of getting the finished product to the Final Customer when the Final Customer desires. In the case study supply chain, no finished products are held by the Retailer or Assembly Plant. Components are held by the Assembly Plant until the Retailer sends the Final Customer's order to the Assembly Plant and then the finished products are made-to-order. The passage of Final Customer demands up the supply chain may not be instantaneous, which combined with production delays may cause increased inventory of components at the Assembly Plant. For this particular segment, the inventory in the case study supply chain happens to occur at the component inventory buffer in the Assembly Plant.

One of the primary concerns in the flow of material between the Retailer and the Assembly Plant is that the Final Customer is satisfied with regards to the delivery of the finished product meeting their requirements. The short lead time to manufacture and deliver the final product by the Assembly Plant, combined with much longer lead time requirements by the Final Customer for delivery of the final product, has created a situation in which there is no perceived need for information flow to be increased. The build-to-order by the Assembly Plant meets the needs of the Final Customer without the need for an inventory buffer of finished products. However, increased information flow has implications for improvements at the Assembly Plant in the area of component buffer inventories which must be maintained in large quantities to keep the production times of the finished product to a minimum.

At the Assembly Plant, production efficiency is of high concern. Production lead times are constantly being analyzed to determine new methods by which the production process can be minimized. Since everything is made-to-order there is minimal finished goods inventory, and since the production lead time is short, the work in progress inventory is also minimum in the factory. To be able to guarantee short lead times to the customers, the Assembly Plant must hold a large inventory – approximately 500,000 stock-keeping units (SKUs). In dollars, the inventory represents $6.2 million and the components of interest are between $2 and $3 million.

In this case, increased information flow between the Retailer and the Assembly Plant may not be required for satisfying the Final Customer satisfaction in delivery, or increase the efficiency of the Assembly Plant manufacturing process, but having more information about demand through increased information flow may affect the inventory by minimizing the quantities held for each component.

Min/Max Inventory System

The Assembly Plant component inventory is managed with a *Min/Max* inventory system (Section 5.4.2). The inventory is so named because ordering policies for components are based on a predetermined minimum level and maximum level for each component. Components are ordered when the quantity of the components meet a certain level (minimum level) and the number that is ordered is enough to bring the quantity to another level (maximum level).

The minimum level is based on the time that it takes for a shipment to arrive from a supplier (lead time to order) and the rate at which the components are removed from stock (Usage Rate). The specific quantity for the minimum level is calculated by multiplying the rate at which the stock is being used by the lead time it takes for an order to be filled by the supplier and the quantity of stock at the arrival of the order is zero (Figure 7-1). As an example, if demand for a component is such that 10 parts are removed from the inventory per week and it takes two weeks for a delivery to replenish the components, the order must be placed when the inventory level reaches 20 (10 components/week x 2 weeks to replenish).

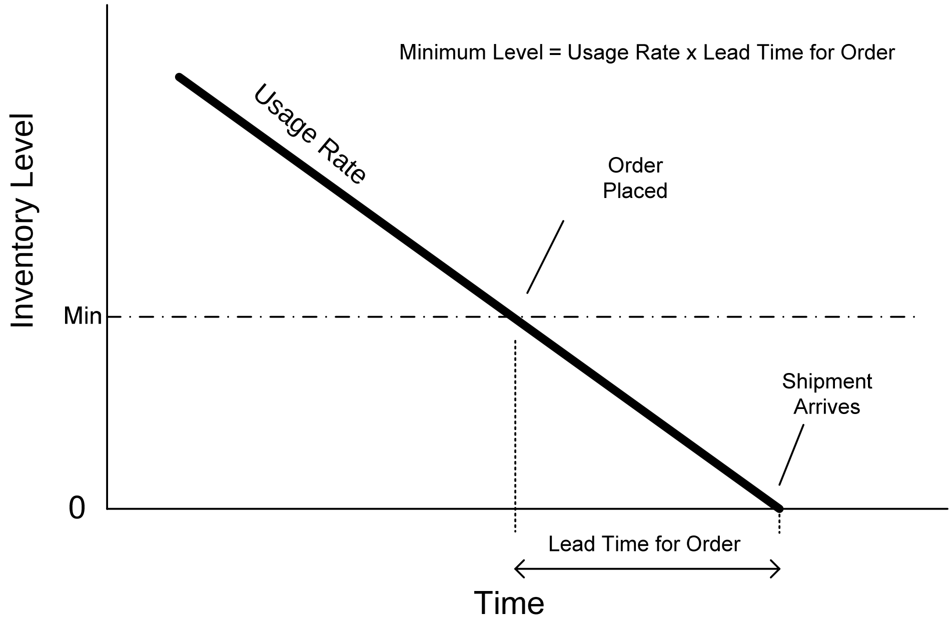

Figure 7-1 Explanation of Minimum Level of Min/Max Inventory System

In reality, both the Usage Rate of a component and the lead time for an order are estimated values. Variability in the short-time horizon of the usage rate and the lead times can make a strict adherence to the Minimum Level result in stock-outs (parts not being available when needed). Thus, the minimum quantity for a part is increased to account for the variability so as to minimize the likelihood of a stock-out. This additional quantity is called a safety stock and is shown in (Figure 7-2).

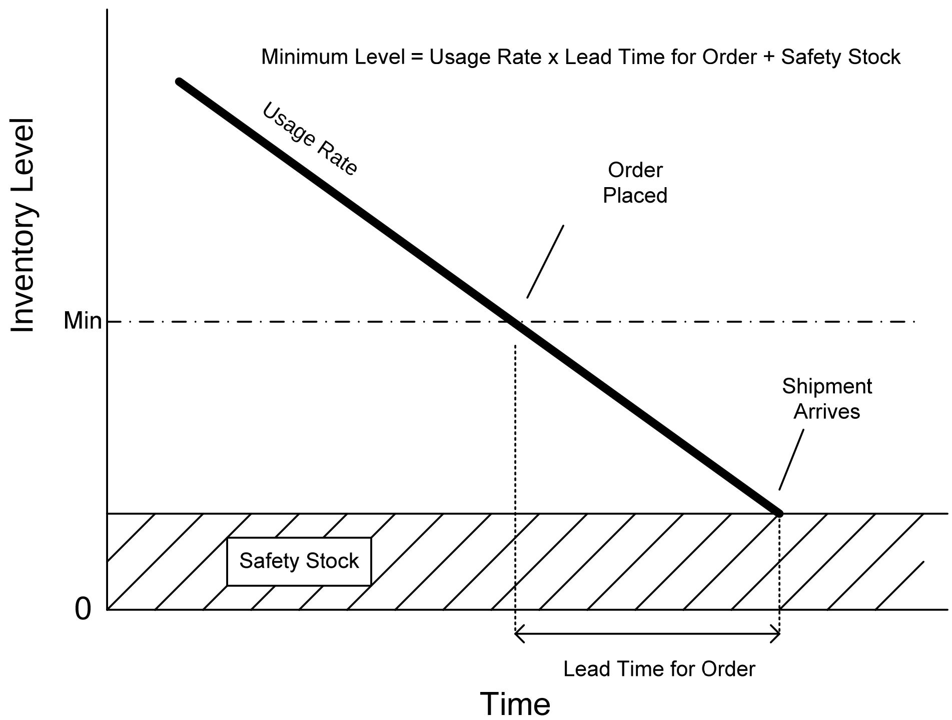

Figure 7-2 Safety Stock in a Min/Max Inventory System

In the previous example, if a safety stock of five units is utilized, the point at which the order with the supplier should be placed is when the inventory level reaches 25 (10 components/week x 2 weeks to replenish + 5 units for safety stock). The determination of the quantity of the safety stock for any one part can be calculated utilizing formulas that take into consideration the variability in usage rate, the variability in the lead time to replenish the part, and the acceptable probability of a stock-out occurring as shown in Equation 1 (Shim et al. 1999; Atkinson 2005).

Equation 1

$$\text{Safety Stock} = z \times \sqrt{LT \times (\text{stdev}(DU))^2 + (\text{avg. }DU)^2 \times (\text{stdev}(LT))^2}$$

Where:

z = z value

LT = Lead time for Order

DU = demand usage of inventory

In a *Min/Max* inventory system, the maximum level for replenishment of a particular inventory stock is typically determined based on the number of times that the inventory is reviewed and the usage rate. If the inventory level is reviewed monthly, the maximum level needs to be large enough to account for the time between reviews. However, in the Assembly Plant, the inventory is constantly reviewed by utilizing bar code inventory systems that track real-time usage and replenishment for all components in the inventory. Because of the range of products produced and the quantities of products manufactured in a day, the result would be a large quantity of orders of one unit for many of the components. Such a small replenishment quantity is not efficient or logistically possible for the Assembly Plant.

The Assembly Plant does not utilize a maximum level for ordering components as is typically prescribed within a *Min/Max* inventory system. Instead, a specific order quantity (batch size) for each component is determined by the Manufacturing Company for the Assembly Plant. The assumption is that this order quantity is based on some form of Economic Order Quantity (EOQ). An EOQ is an order quantity that is determined by minimizing ordering and carrying costs of an inventory. Having an inventory may be beneficial for reducing lead times to customers however there is an inherent cost of maintaining the inventory. The costs of an inventory typically include the costs of placing an order and the costs of holding the inventory. A common formula for determining the EOQ is Equation 2.

Equation 2

$$EOQ = \sqrt{\frac{2 \times CD}{H}}$$

Where:

EOQ = Economic Order Quantity

C = Fixed cost per order

D = Annual demand quantity of the product

H = Annual holding costs per unit

A representation of the *Min/Max* inventory system utilized by the Assembly Plant for the components is shown in Figure 7-3. Following the darker line from the left, the inventory is reduced based on its usage by production. When the quantity reaches the minimum level that was determined for that component, an order is placed (t_{min}). The order is expected to be replenished by a certain time (t_{Repl}); the difference between t_{min} and t_{Repl} would be the suppliers lead time. The quantity that is ordered is based on the modified EOQ and the level that the inventory should be at when the order is replenished. The safety stock is the predetermined quantity from the Manufacturing Company that is utilized to minimize stock outs due to demand usage that exceeds the average.

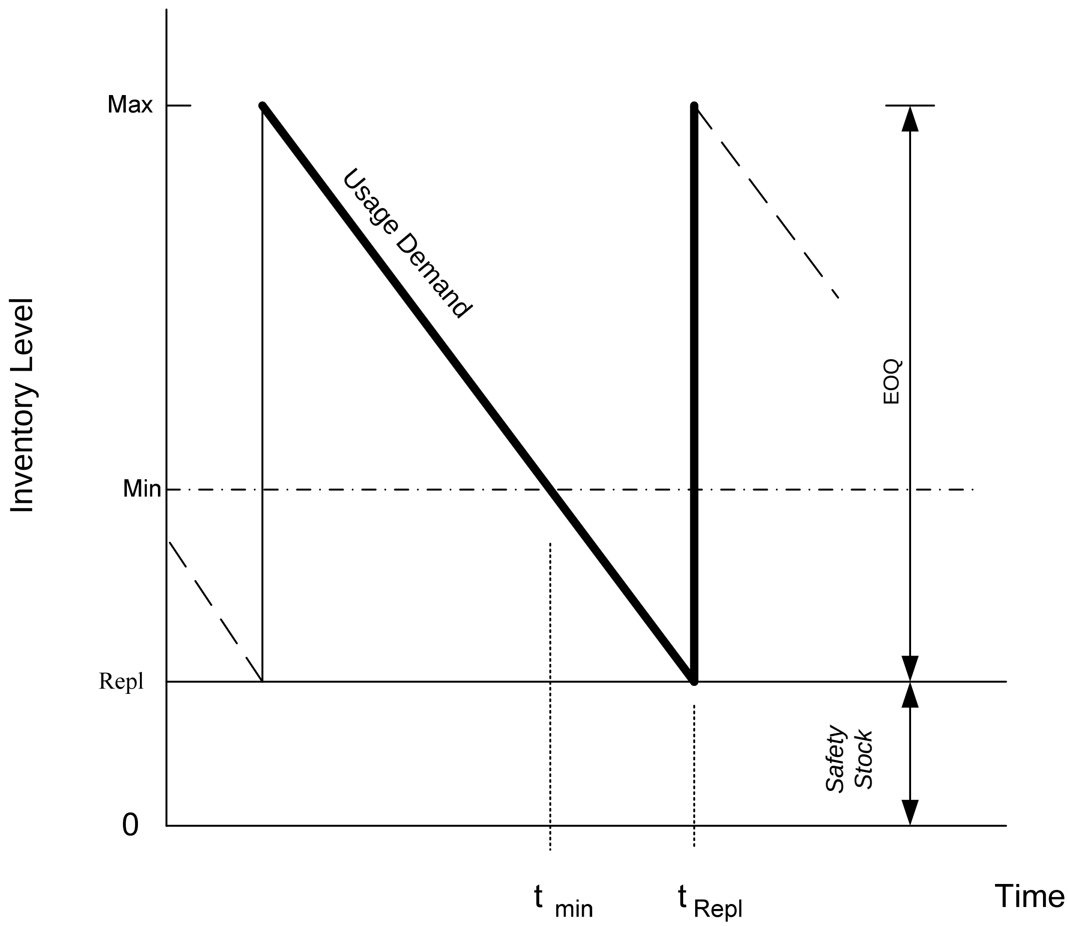

Figure 7-3 Min/Max Inventory System at the Assembly Plant

The *Min/Max* inventory system of the Assembly Plant in the case study supply chain utilizes current information of inventory levels in the management of the inventory. If information was available for the future levels of the inventory, the variability of the demand usage would decrease causing a reduction in safety stock and thus inventory costs. The EOQ does not take into consideration daily variability and in the calculation would not be affected by an increase in the flow of information.

Knowledge of Future Demand

In the case study supply chain, the Assembly Plant information is 21 days old. This is the difference in time from when the Final Customer placed the order with the Retailer and when the production of the finished product at the Assembly Plant began. The Retailer delayed the original order information for 15 days, the Manufacturing Company held it for a day, and the

Assembly Plant held it for five days. For the inventory manager at the Assembly Plant, this delay of information is an opportunity for determining more precisely the future removal of components from inventory and reducing the inventory costs by reducing safety stock requirements.

An example of the lack of future knowledge of demand on a *Min/Max* inventory is shown in Figure 7-4. At the time when the inventory level of a component reaches the minimum level, the inventory manager knows what the previous usage rate of the component was and estimates the future usage based on the average usage rate. If the actual usage rate deviates from the estimated usage rate, the safety stock can reduce the likelihood of a stock-out before the component inventory is replenished from the supplier.

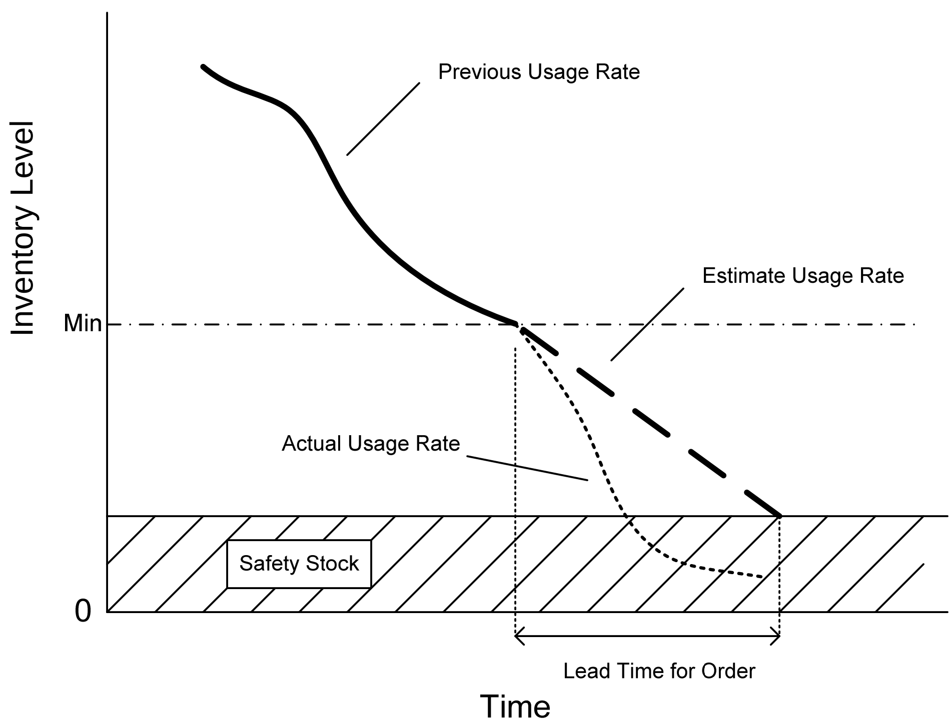

Figure 7-4 Example of Min/Max Inventory System with Non-linear Usage Rate

With an increase in the information flow to the inventory manager pertaining to future production, the manager could potentially place the order in advance of the minimum level being met, in this case. The result would be that the safety stock would not be necessary for this order. With a known future usage rate, the order policy could then be defined not by a minimum quantity but a time. The time that an order is to be made (the time that the inventory will reach a certain level safety stock quantity) minus the lead time for an order to be filled (i.e. the components put into inventory). Figure 7-5 illustrates the shift in ordering time associated with advanced knowledge of demand. If the future usage rate was fully known by a manager, the exact time that the inventory would meet the minimum safe quantity (in this case assuming a safety stock is still required for variation in replenishment). The manager need only place the order at the correct point in time to account for replenishment (future point in time of meeting minimum safe quantity minus time of replenishment).

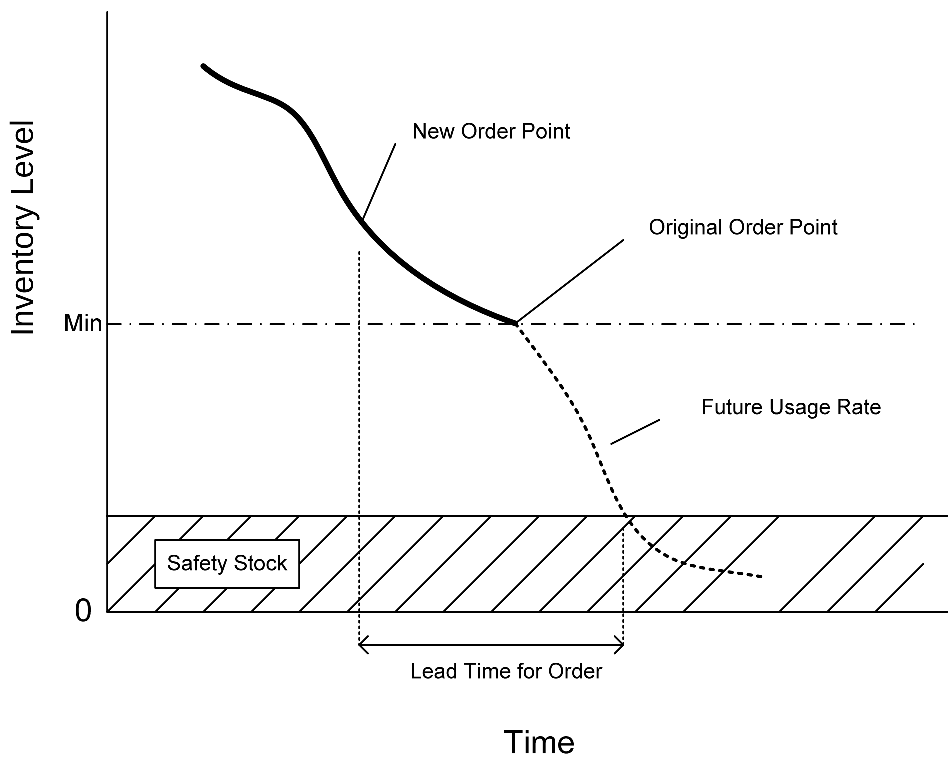

Figure 7-5 Min/Max Inventory System with Knowledge of Future Usage

The objective of the simulation model is to determine how the increased knowledge does affect the inventory of the Min/Max system utilized within the Assembly Plant. If inventory can be reduced through increased information flow, what specifically is the relationship between information flow increases and inventory level decreases? The purpose of identifying this relationship is to determine a method by which potential cost decreases can be associated with information flow gains. The return on investment of changes to an inventory system can then be determined for anticipated costs in increasing the information flow such as implementation of information systems.

7.2.1 **Introduction to Model**

A model was developed for the purpose of evaluating the effects of increased information flow (knowledge of future demand) in inventory systems such as that of the Assembly Plant component inventory system. Of specific concern is how changes in information flow will affect the system's ability to satisfy customer demands for delivery and affect the cost of inventory required to maintain high customer satisfaction levels. The ability to satisfy customer demands was measured as a function of component inventory being available when required to manufacture the final product in time to meet the customer's delivery requirements; if the product was available when the customer requested it, the customer was satisfied. The cost to maintain the inventory was measured as a function of the relative quantities of inventory required under the different rates of flow of information– reduction in quantities within the inventory would equate to a reduction in cost of the inventory.

The simulation model[1] was based on the affect of increased knowledge on the need for components inventory by a company utilizing a *Min/Max* inventory system to control the ordering of components (Figure 7-6). The minimum level of the inventory system reflected the number of days of knowledge of the future demand. The model centers on the component inventory which is buffering the differences in production rate and replenishment rate. The production rate was based on the retailer order rate (with a production scheduling delay), and the replenishment rate is based on the orders placed by the company (with a delivery delay from the supplier). The orders were determined based on the minimum level for each component. As knowledge of demand increases, the need for inventory should be reduced because of the reduction in the variation in the inventory system.

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[1] The full code for the simulation model is located in Appendix C - Retailer/Assembly Plant Simulation

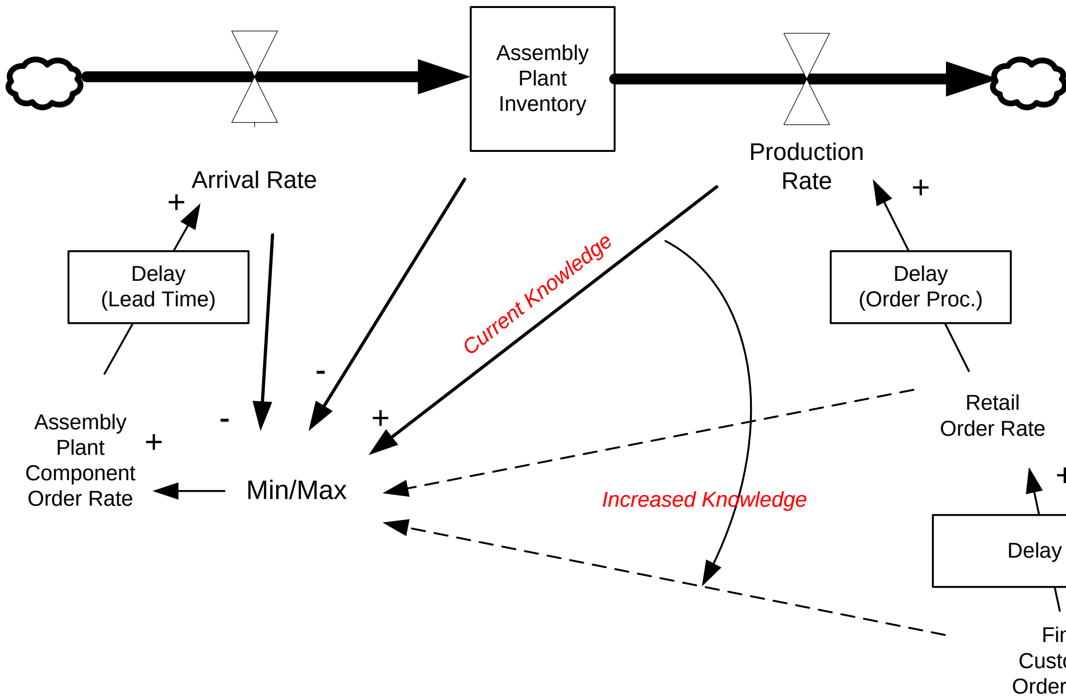

Figure 7-6 Retailer/Assembly Plant – Model: Current and Future States

The inventory level of a component was controlled by three factors: delays in the system, production rate for the component, and replenishment rate (Figure 7-7). The delays in the system are based on information flow and production flow of the Assembly Plant. The production rate is based on the demand for component and the required scheduling. Finally, the replenishment rate is based on the *Min/Max* inventory system utilized by the Assembly Plant. The first two factors (delays and production) were held constant for the simulation runs. The simulation model was programmed so that the inventory level could be monitored over time to identify stock-outs and average inventory levels. The specific inventory variable of interest was the residual inventory level, which is the amount of inventory that was remaining when the replenishment occurs. Optimally, the residual inventory would be zero at the time of replenishment, since remaining inventory would be excessive of need. However, variation in the demand and replenishment makes this scenario unlikely, and if customer satisfaction through timely delivery is a requirement of the system, the minimum level defined for the inventory system must incorporate these factors. The knowledge of future demand will be increased in the model through minimum level reduction (as discussed previously) to determine its affect on the lead time for delivery of the final product to the customer and the average inventory required to keep the customers satisfied.

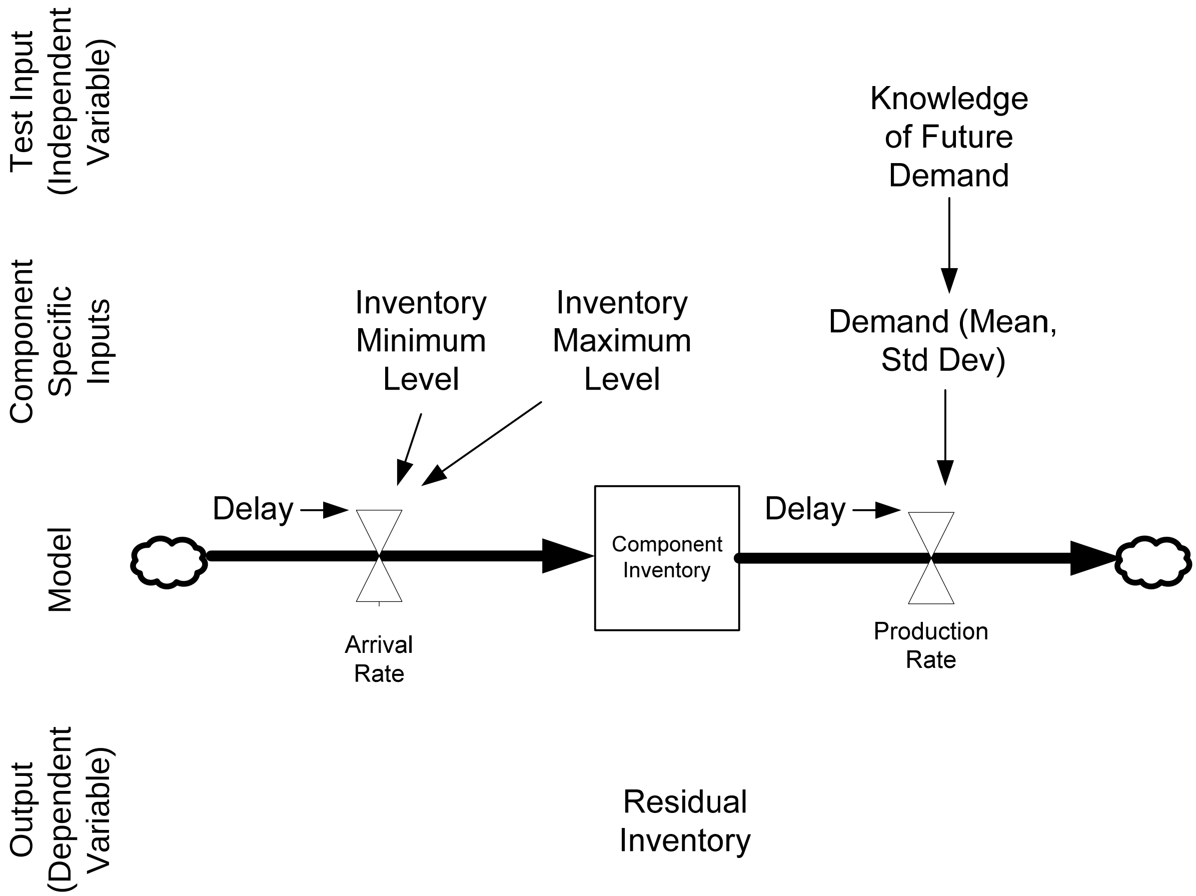

Figure 7-7 Retailer/Assembly Plant - Simulation Model

The variables utilized in the simulation model are found in Table 7-1. Each variable is defined as to what units and values were utilized as well as the source of the values. The Production Delay and the Arrival Delay were determined in the analysis of material flow presented in Chapter 4. The Production Delay is a set lead time defined by the Assembly Plant, whereas the Arrival Delay is an assumed value by the procurement officer in the planning of orders. The demand in the simulation model was determined from the Assembly Plant order records, and was broken down into specific component demands which are presented in Table 7-2 (as were Inventory Minimum Level and Inventory Maximum Level).

Table 7-1 Variables for Retailer/Assembly Plant Model

Variable	Units	Values	Source
Knowledge of Future Demand	Days	1,2,3,…	Test Input (Independent Variable)
Demand	Units per day	See Table 7-2	Company Order Records
Inventory Minimum Level	# of units	See Table 7-2	Company Inventory Records
Inventory Maximum Level	# of units	See Table 7-2	Company Inventory Records
Production Delay	Days	5	Section 4.2.1
Arrival Delay	Days	5	Section 4.2.4
Residual Inventory	# units		Test Output (Dependent Variable)

From the Component Plant, the Assembly Plant obtains just over 5000 component types, differentiated by size, style, finish, and species of wood. The break down of these components into the components of interest for the simulation modeling is shown in Figure 7-8. Thirty-five percent of the total components from the Component Plant are made of the species of interest in the research (Red Oak). Of these species, approximately 750 are maintained in inventory by the Assembly Plant through the *Min/Max* inventory system. The remaining components, approximately 1050, have extremely low demand and are not maintained within the *Min/Max* ordering protocol. The components of interest from this point forward would be those that are of the 750 components that are of the species of interest and maintained in the Min/Max inventory system.

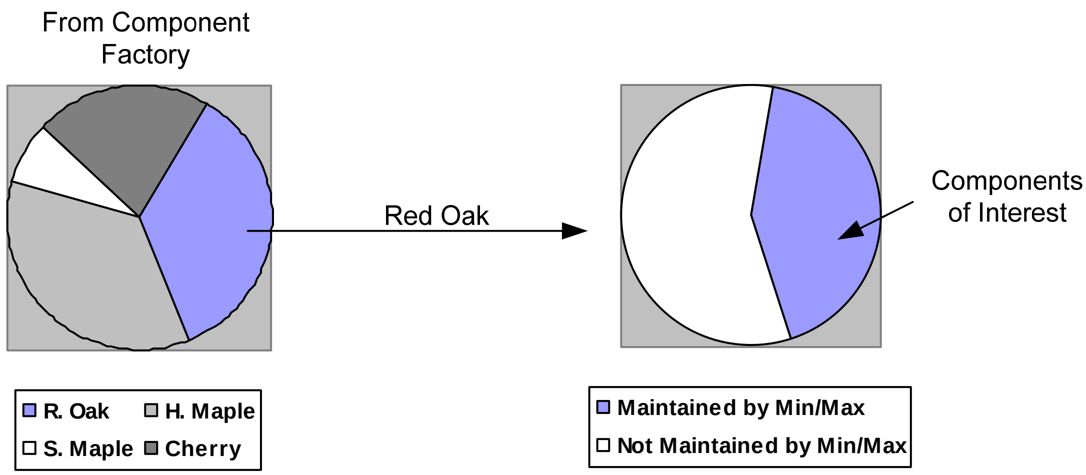

Figure 7-8 Determination of Components of Interest

For the components of interest, there is a broad range of demand usage at the Assembly Plant – between 0.1 to 59.2 components per day. In the determination of minimum and maximum levels for these components, the Manufacturing Company has chosen to group many of the higher demand components into specific ordering batch sizes (Figure 7-9). The larger batch sizes, which would represent components that are used frequently, are grouped at specific quantities (40, 60, 80, and 120). These four batch sizes are utilized for 41% of the number of components of interest held in inventory and 69% of volume of the total production by the Assembly Plant. Although most occurrences of component types are grouped into batch sizes of 20 and below, the production utilizing these components is only 22% of the total production.

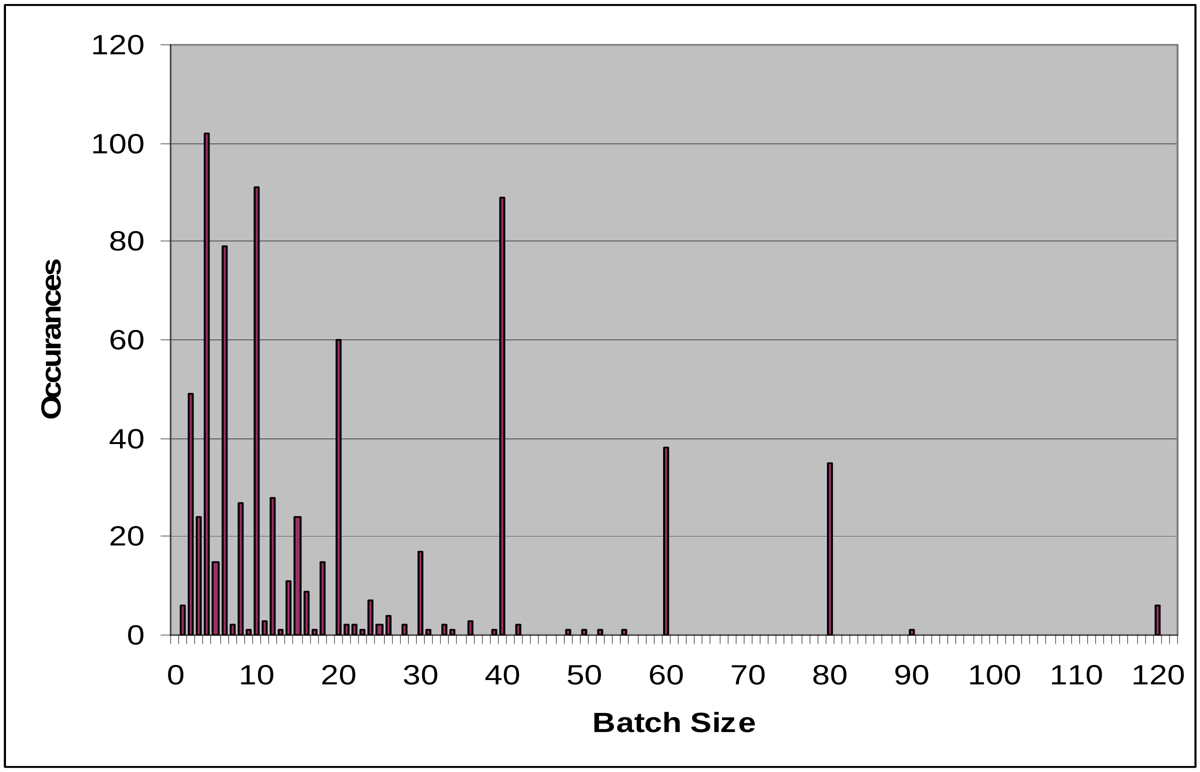

Figure 7-9 Order Batch Sizes of Red Oak Components from Assembly Plant to Component Plant

Six of the components of interest were selected from the original 750 to represent the range of demand that occurs within the Assembly Plant. One component was selected from each of the four previously defined batch sizes. Two additional components were chosen from the lower demand components based on the level of occurrences within the particular batch size and representative of the range of total batch sizes. Within each of the six batch sizes selected, a representative component was selected based on its average daily usage. The median component was chosen based on being representative of the most components without being affected by an outlier. The attributes of the selected components as obtained from the Assembly Plant are presented in Table 7-2. These attributes include the average and standard deviation of daily demand for the component by the Assembly Plant in production, the batch size for replenishment orders, the minimum quantity of the component's inventory to trigger a replenishment order, and for reference.

Table 7-2 Components Used in Simulations

Average Daily Demand[1]	Std. Dev. of Avg. Daily Demand[2]	Batch Size[1]	Minimum[1]
10.5	0.439	120	67
5.6	0.483	80	38
4.3	1.119	60	36
2.3	0.791	40	21
1.0	0.329	20	9
0.5	0.219	10	5

1 = supplied by Assembly Plant, 2 = calculated

The model required knowledge of the variability of the average daily demand. Detailed data necessary to calculate the standard deviation was not available for this research, so an alternative method was utilized. The assumption was made that the Manufacturing Company utilizes an equation similar to that of Equation 1 (page 178) for the determination of minimum level to initiate the replenishment process. By making this assumption, the standard deviation for the daily demand usage of each part can be solved utilizing Equation 1. To calculate the daily demand usage, the following additional assumptions were made: 1) the components will arrive and be shelved no later than six days from the date of the order, with no contingency for variability of that time (i.e. Lead Time = 6 and Standard Deviation of Lead Time = 0) and 2) all values were normally distributed. The resulting values are shown under "Std. Dev. Of Avg. Daily Demand" in Table 7-2.

For the simulation model (Appendix 2), the lead time of replenishment was not assumed to be deterministic (e.g. six days as in the calculation for the standard deviation for the daily demand usage), but instead a random variable since the actual arrivals varies. The entire processes of ordering, processing, transporting, and restocking can take between four days and six days as defined by the Assembly Plant. For the simulation model, a normal distribution with an average of 40 hours (five working days) and a standard deviation of 3.11 hours was utilized. This distribution is based on a 99% probability that all values would fall between four days (32 work hours) and six days (48 work hours). Each condition was run for the equivalent of ten years and each run was replicated 30 times for normality.

The practice of batching of orders was understood to be a necessary practice for the Assembly Plant. The logistics of moving the quantities required for so many different ranges of products from the Component Plant to the Assembly Plant and the storage at the Assembly Plant would be outside the realm of the organization's current capabilities. In addition, since the exact methods for determination of the batch sizes are not available, all of the batch sizes remained as designated by the Manufacturing Company.

7.2.2 **Model Verification and Validation**

Since the purpose of the simulation model is to determine the relationships between inventory management policy and those factors that affect the costs associated with having an inventory (e.g. managing both stock-outs and all inventory items held), the model must be verified in its ability to accomplish this task. A series of simulations were performed to identify what percentage of stock-outs would occur given specific minimum levels for replenishment. The results of these simulations were compared to the calculated values utilizing the equation for determining the minimum level with a safety stock (Equation 1). For the calculations, the known customer service failure rates (utilizing z-values) in the equation were used to determine at what minimum level those failure rates would occur. In both cases, the demand was 10.5 units per day with a standard deviation of 0.439 and a lead time of five days with a standard deviation of 3.11. A comparison of the results of the simulation runs (individual marks) and the calculations (solid line) are shown in Figure 7-10. The simulations are presented as a form of the Box-and-Whiskers approach which allows for the visual evaluation of the symmetry or skewness of a data set (Law et al. 1991). The top and bottom marks represent the outer range of data. The center mark is the median value, and the remaining two marks are the quartile results of values for the stock-out percentages. This approach shows that the simulation's results center around the values based on the calculations.

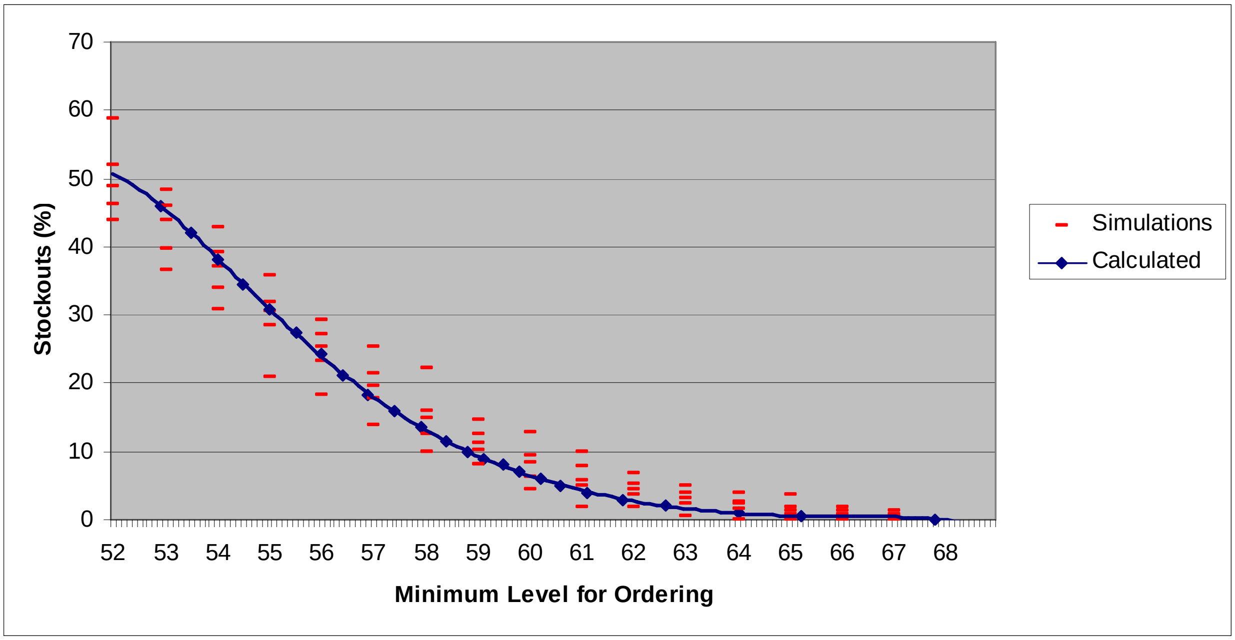

Figure 7-10 Verification of Simulation Model Utilizing Minimum Level Calculation

To validate the simulation model to that of the case study's Assembly Plant, the average number of replenishments in a year was utilized (Figure 7-11). For the simulation runs, the average number of replenishments per year for each component ranged from 13.0 to 22.7 with an average of 16.7 for all components. The exact number of inventory replenishments per year for each component was not available from the Assembly Plant, so the total average replenishment rate was determined for all components as the total inventory level divided by the total average daily usage which estimates the total average replenishments per year as 19.2. The value for the components of interest was estimated in the same manner and determined to be 17.8 replenishments per year. For the components of interest in the case study Assembly Plant, 90% of all components replenishments/year fell between 3.5 and 30.1. The number of replenishments per year for the simulations fell within that range (12.9 – 22.4) which indicates that these replenishments are valid results.

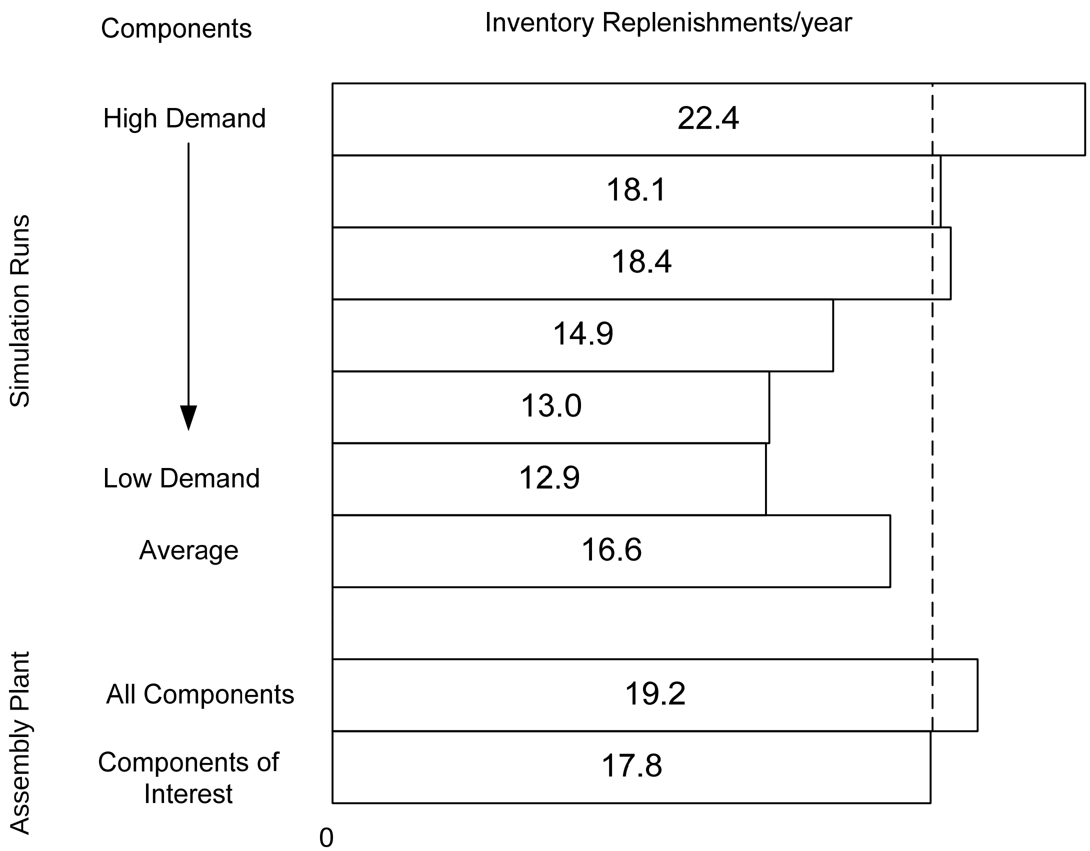

Figure 7-11 Validation of Simulation Model through Inventory Replenishments per Year

7.2.3 Simulation Protocol

The simulation model was designed to identify the possibility of stock-outs and the inventory levels under specific conditions. These conditions are the number of days of increased knowledge of demand and the designated minimum level for replenishment. Knowledge of demand is identified as the numbers of days into the future a manager can see true demand (i.e. if a manager's knowledge of demand is one day, the manager knows what the actual demand will be through tomorrow). Simulations were run for the six different components described in Section 7.2.1 to obtain a cross-section of results across the range of demands occurring in the case study supply chain (see Table 7-2).

There are typically two costs associated with inventories - the cost of holding and managing physical inventory and the cost of not having the inventory when required. Thus, two important variables within this costing structure iare the amount of inventory that is on hand and the amount of stock-outs that occur. The simulation output reflects these two variables through percent stock-outs and residual inventory quantities.

For each simulation, the amount of knowledge of future demand was controlled in the form of days of advanced knowledge of demand as well as the minimum level of replenishment to see how those two affect the residual inventory level. The future demand is based on a daily evaluation of the inventory levels by the management of the Assembly Plant. Future knowledge was then the knowledge of what the inventory levels would be on future days. For example, if future knowledge had a value of two days, the manager would know what the exact inventory level of the inventory would be up to two days from that point and thus if the minimum level for replenishment would be met on that day. The future knowledge of the levels of inventory has a direct affect on the amount of safety stock required therefore the minimum level for replenishment was also controlled with future knowledge to determine the combined affect on overall inventory levels.

7.2.4 **Results**

Simulation replicates were run to determine the relationship of information flow and the current methods by which inventory is maintained by the Assembly Plant to gain a deeper understanding of how increases in information flow can affect current inventory practices. The hypothesis was that increased information flow would reduce the cost of inventory through a reduction in the average amount of inventory that is maintained while sustaining an appropriate level of customer service.

For the case study Assembly Plant as with other companies, the inventory systems is a balance between quantities of components and the possibility of shortages of components when required. In the *Min/Max* inventory system, the minimum level for replenishment is the method by which to keep the inventory balanced as desired. Figure 7-12 shows the results of simulation runs for one of the components, with a demand of 10.5 components/day. For the minimum inventory level of 67 (and above), the number of stock-outs is virtually zero (once every 86.6 days). To keep stock outs at this level, inventory safety stock must be quite high, which results in an average of 16 units remaining in inventory when the inventory is restocked with the replenishment order (residual inventory). To reduce the excessive inventory, the minimum inventory for replenishment can be decreased but will cause more stock-outs to occur.

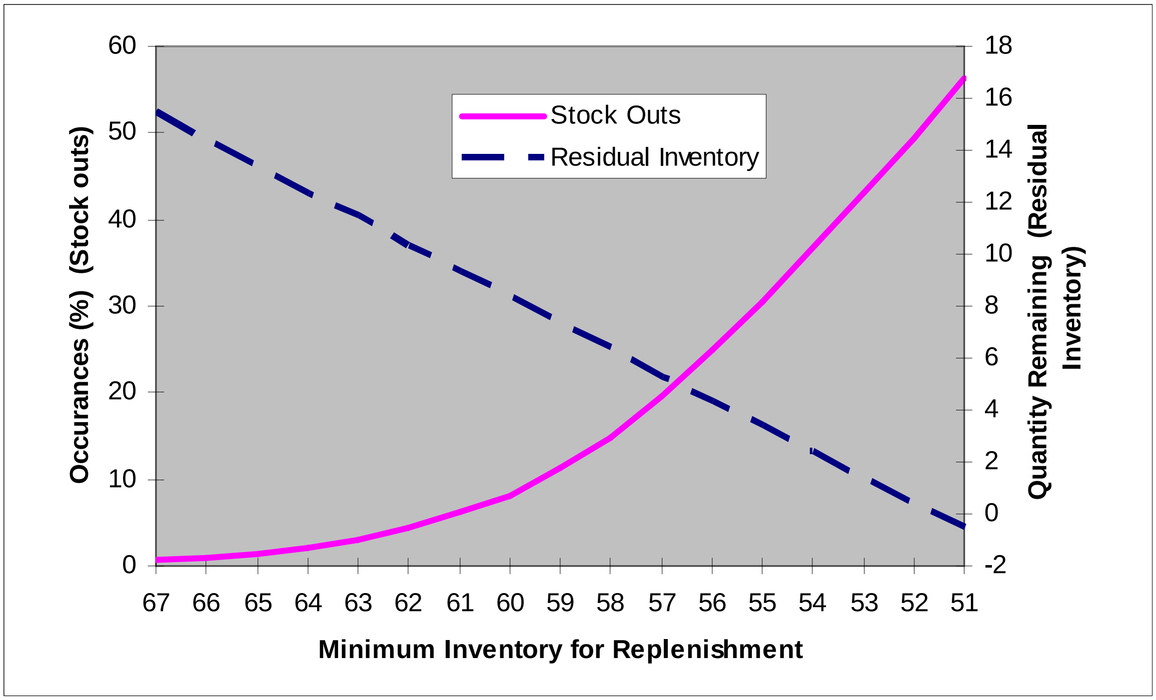

Figure 7-12 Relationships between the Minimum Inventory for Replenishment and Stock Outs/Inventory

For the *Min/Max* system in its current state, there is no information about what the customer actually has demanded. This system simply replenishes when a minimum level is reached. The next step would be to use the model to determine if knowledge about actual downstream demand could be used to more precisely manage inventory levels. Increased information in the simulation runs for the component with demand of 10.5/day was found to reduce the minimum inventory requirements for the same likelihood of stock-outs (Figure 7-13). This finding was based on the minimum level not being managed to maintain minimum prescribed inventory levels, but rather managed to satisfy known future demands. If information flow allowed for knowledge of exact inventory levels required to meet future demand, the minimum levels could reflect the lower inventory levels of that future day. It was determined that the minimum level could be reduced with the increase in information flow (the solid line in Figure 7-13). This reduction reached zero at six days. Information flow would not see any benefit beyond the sixth day as this is the maximum lead time for replenishment. Even if information flow could be increased to exceed six days, there could be no benefit as at six days, orders would be made with 100% assurance that the replenishment order would arrive exactly when the inventory level is known to reach zero. This holds that all variability is in the process of replenishment and that the variability in demand is removed due to the lack of variability in future demand.

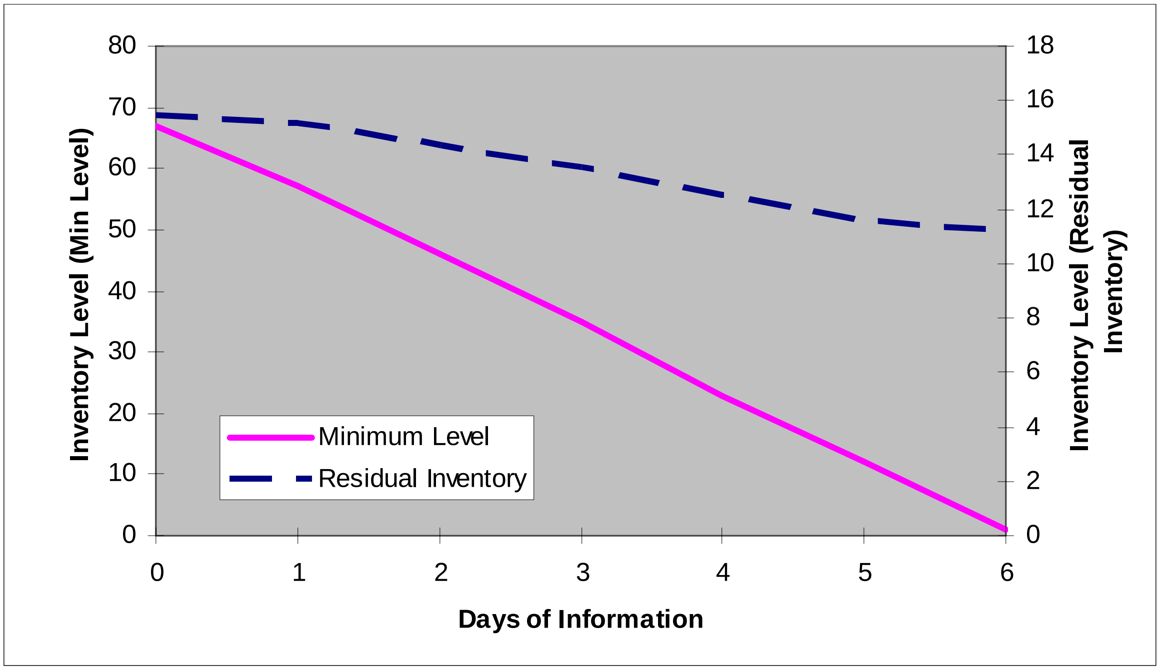

Figure 7-13 Affect of increased Information Flow on Inventory System

The dashed line in Figure 7-13 represents the average inventory levels that remain when the replenishment order arrives (Residual Inventory). These values are based on the percentage of stock-outs being equivalent to that of the initial percentage determined in Figure 7-12 at the original minimum level. The variability in the system is maintained in the simulations (i.e. usage and replenishment) however some of the variability is removed as the certainty of information increases with the increase in the knowledge of demand. The result of the decrease in variability is a decrease in the required amount of inventory necessary to maintain the original stock-out percentage. In the case of this particular component, the required residual inventory is reduced from 15.5 to 11.2 components (28% reduction). Utilizing regression analysis, the residual inventory is linear with a slope of -0.78 (a reduction of 0.78 units per day of knowledge) with an R-squared of 0.984.

For all of the components simulated, there was a reduction in the average amount of inventory remaining at replenishment with the increase in information flow. In Figure 7-14, the residual inventories (inventory remaining at replenishment) are presented for the system with no information (Current State) and with six days of information for the six components. Due to discrepancies between components in the current state, an adjustment to those inventories to best reflect the true change in residual inventory was required. It was determined that in the current state, the components did not have the same probability of stock-out with the given minimum level of replenishment. It was assumed that a component with the highest probability of stock-out in the current state (that with a demand of 10.5 units/day) was a probability which is acceptable to the Assembly Plant and that all other components tested were probabilities of stock-out that are too "safe." The "Current State w/ Adjustments" is a shift of the minimum level of replenishment for the other components to meet the same probability of stock-out as that with the demand of 10.5 units/day. For instance, the component with the demand of 4.3 units/day had a minimum level, as determined by the Manufacturing Company, of 36. However, as identified in the simulations, the minimum level should be 30 to meet the same stock-out probability as the component with the demand of 10.5 units/day. From Figure 7-14, if all of the original values for inventory level at replenishment were utilized, the simulations would determine a reduction of 54% in the inventory level at replenishment. However, with the adjustment, the average reduction of inventory level at replenishment was found to be 31% across all components (10.5 = 27%, 5.6 = 24%, 4.3 = 49%, 2.3 = 18%, 1.0 = 20 %, and 0.5 = 51%).

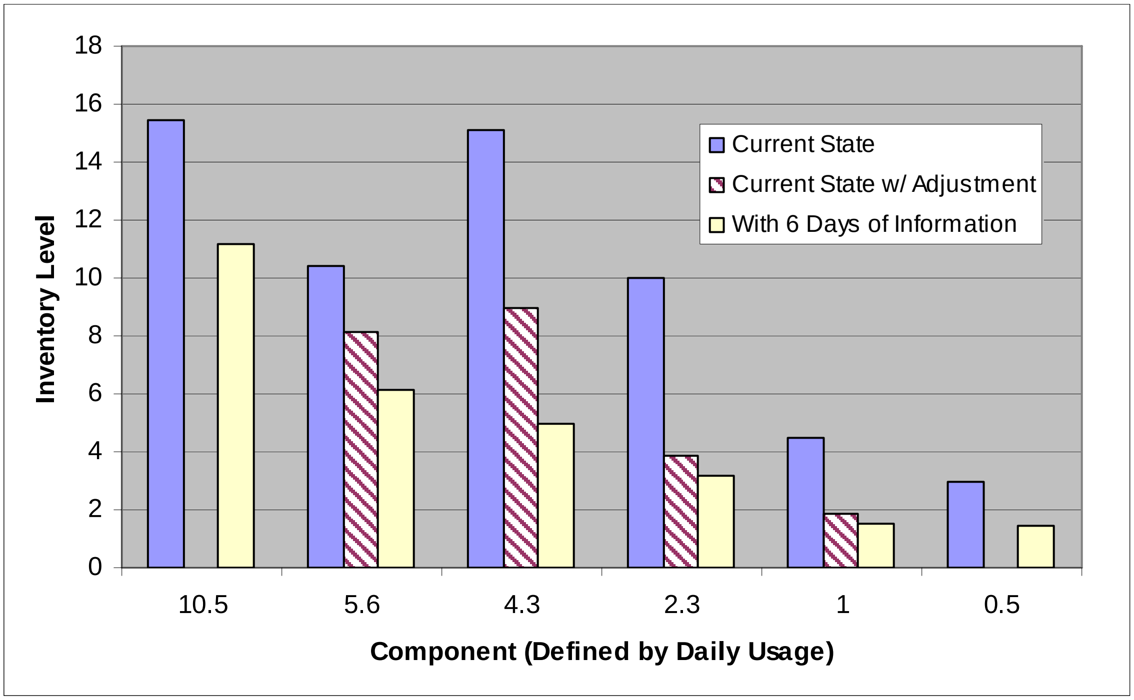

Figure 7-14 Inventory Level at Replenishment (Residual) with and without Increased Information Flow

To determine the cost savings of the reductions in inventory level at replenishment, the overall change in inventory must be determined. The average inventory for any one component would be a factor of both the amount of inventory when replenished and prior to replenishment (assuming a linear demand). Thus average inventory equals:

$$\frac{(\text{Batchsize} + \text{Average Residual Inventory}) + \text{Average Residual Inventory}}{2}$$

Where the *Batchsize + Average Residual Inventory* is the maximum quantity of inventory and the *Average Residual Inventory* is the smallest quantity of inventory. The percent of reduction in inventory due to information flow would then be:

$$\frac{(\text{Average Inventory with no knowledge - Average Inventory with knowledge}) \times 100}{\text{Average Inventory with no knowledge}}$$

The resulting reduction of inventory due to increased information flow (six days of information) for all of the components modeled is shown in Figure 7-15. All components had a reduction in inventory levels with a range of 3 – 19% and an average of 7.5%. As shown in Figure 7-13, the reduction is linear from zero to six days, thus the reduction in inventory for each day of information known in advance would be 7.56 or 1.25%.

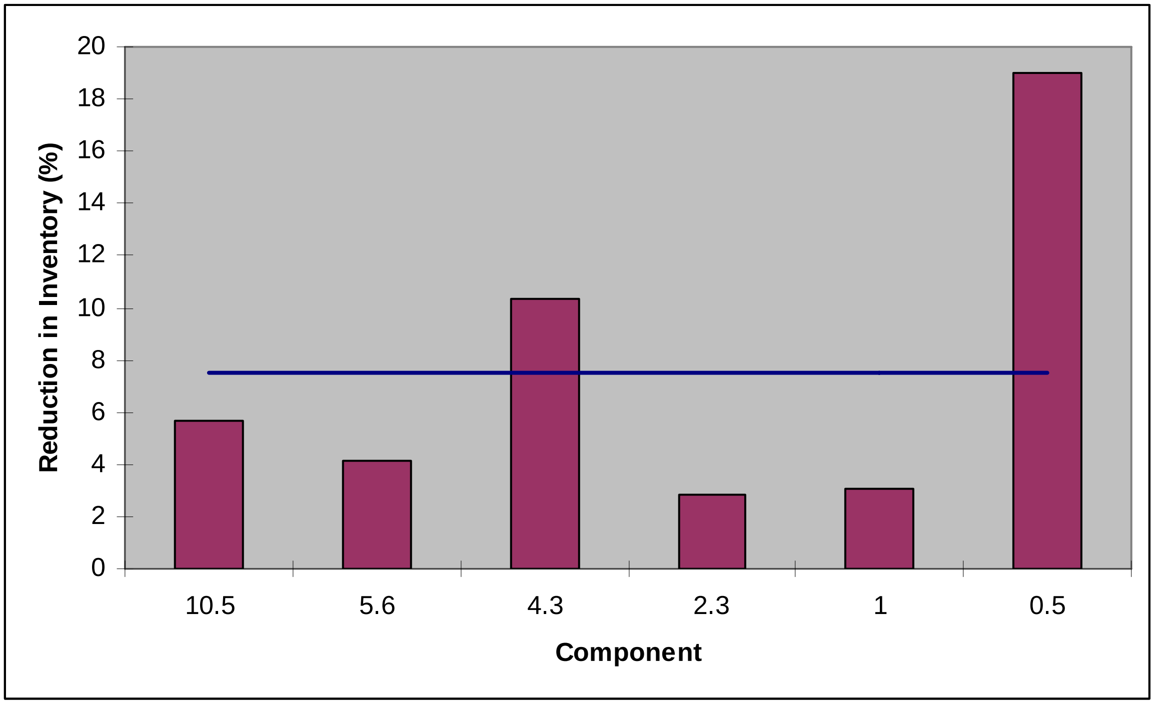

Figure 7-15 Average Reduction in Inventory from Increased Information Flow

The analysis of the flow of information (Section 4.3.1) shows that most of the six days in advanced information would come from internal to the facility, some from internal to the Manufacturing Company, and some from the customer (Retailer). The first five days of information is obtainable from the scheduling delay and production queue between the time that the order arrives to the Assembly Plant and when the components are pulled from inventory. Another half day is obtainable from the delay from the Manufacturing Company which could ship orders immediately to the Assembly Plant instead of batching orders. The half day of the six potential days of advanced information would have to come from the Retailer, who already holds orders for an average of two weeks.

7.3 Assembly Plant / Component Plant

In the case study supply chain segment that includes the Assembly Plant and the Component Plant, the Component Plant must efficiently supply the Assembly Plant with components as they are ordered. This is accomplished by maintaining an inventory buffer at the Component Plant from which the Assembly Plant's orders are filled. The component inventory at the Component Plant is not managed based on a *Min/Max* system (as the Assembly Plant). Instead the inventory buffer is used to manage discrepancies between the rate at which orders come from the Assembly Plant and the scheduling of production of the component at the Component Plant.

The inventory buffer of components at the Component Plant is larger than that of the inventory buffer of components at the Assembly Plant. This is initially contradictory with the given facts: The Component Plant maintains 11 days of finished components in inventory and the Assembly Plant maintains 20 days of finished components in inventory. This would mean that the Component plant holds almost half as much inventory as the Assembly Plant, however this is false. The Component Plant supplies multiple assembly plants and the demand of components at the Component Plant is higher than that of the order rate of the Assembly Plant (approximately four times). The daily demand for components by the Assembly Plant is approximately 4,300 components per day, whereas the Component Plant must manufacture 16,000 components per day to meet the demand of all of the assembly plants. Because of this difference, 11 days of inventory for the Component Plant is 173,000 finished components, nearly three times that of the Assembly Plant.

Inventory buffer levels at the Component Plant are managed by monitoring inventory levels and inventory flows daily so that the production rate of each type of component can follow that of the order rate of the Assembly Plant (and the other assembly plants of the Manufacturing Company). Production schedules for different species and styles are determined daily based on the latest data on inventory flow for these groups. This data includes current orders, work-in-progress inventory, inventory buffer, and monthly/yearly averages for production and shipping (Section 5.6.2).

Production scheduling for each type of component at the Component Plant is balanced with the demand placed on the inventory buffer by the orders from the individual assembly plants. The replenishment rate for each type of component is based on the delays associated with production (13 hours) and scheduling/order queue (six days), as well as the batch sizes for each run. The buffer inventory would then be based on the variability in the demand of the incoming orders and the time between replenishments. To guarantee that there will be enough stock, an average inventory level is chosen based on previous experiences with stock-outs. In the case of the Component Plant, the average inventory holding is 11 days.

For an inventory system such as the Component Plant's component inventory buffer, the addition of advanced knowledge of incoming orders has the potential of reducing that inventory by reducing the scheduling/order queue delay, like that in the Assembly Plant. With the Assembly Plant, advanced knowledge of inventory usage made it possible to work with a reduced minimum level in the *Min/Max* by identifying when the individual inventories will meet the "minimum" level for the *Min/Max* inventory system in the future, causing a reduction in the average inventory. The Component Plant was expected to have reductions in the average inventory levels with increases in future knowledge of demand, like the Assembly Plant, but the exact reduction should be different due to the differences in policies and inventory management systems of the two facilities.

In the inventory management system used by the Component Plant, production orders are based on reductions in the inventory buffer caused by the Assembly Plant's (and the other assembly plants') orders being filled. The advanced knowledge of orders should minimize the required inventory by reducing variability caused by delays in information. Figure 7-16 shows the hypothesized effect of increased knowledge on the distribution of inventory levels over time. Increased knowledge of future demand should reduce the variability of the inventory buffer. The curve labeled as "0 Days of Knowledge" would represent the current state of inventory variability in the Component Plant. By increasing knowledge, the variability of the inventory levels should decrease as depicted for one and two days of knowledge of future demand.

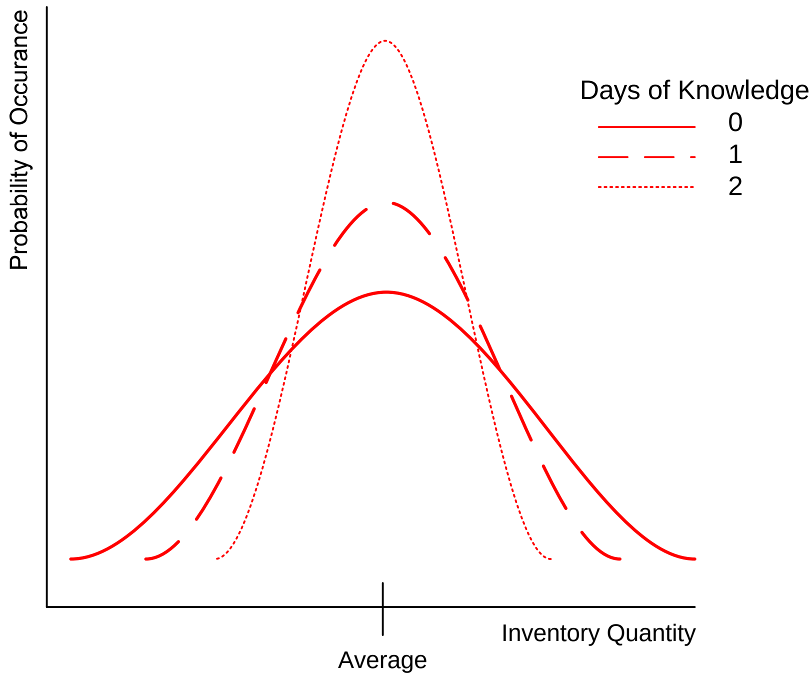

Figure 7-16 Distribution of Inventory Levels – Different Advanced Knowledge

The decreased variability due to increased knowledge of future orders would decrease the probability of stock-outs. Management could then decrease the designated average inventory while maintaining the probability of stock-out based on the ordinal probability of stock-out with no advanced knowledge of demand. This reduction in inventory would be based on the change in variability from there being no knowledge of future orders to the variability based on the amount of knowledge of future orders (Figure 7-17).

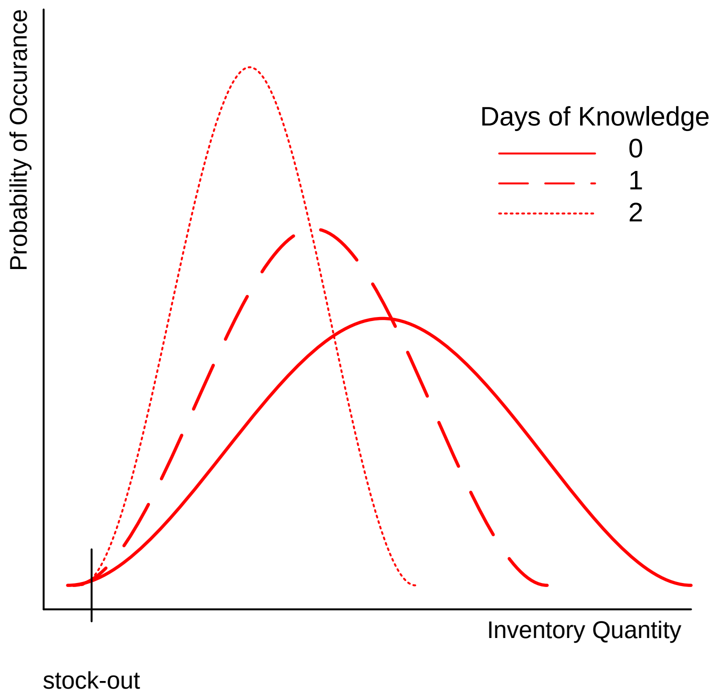

Figure 7-17 Shift in Average Inventory Based on Change in Inventory Distribution

The objective of the simulation model was to determine how the increased knowledge influences the inventory levels of the management system such as that utilized within the Component Plant for the component inventory. If inventory can be reduced through increased information flow (reduction of variability of inventory), what is the relationship between the amount of knowledge of future orders and the reduction of variability of the inventory? The purpose of identifying this relationship was to determine a method by which potential benefits can be determined for reduced inventory buffers while sustaining responsiveness to customers. In addition, the return on investment of changes to an inventory system can then be determined for anticipated costs in increasing the information flow such as implementation of information systems.

7.3.1 **Introduction to Model**

The model for the Component Plant's component inventory[1] is a variation of the model used for the Assembly Plant. The primary difference in regards to inventory management is that replenishment occurs, not by a *Min/Max* system at the Assembly Plant, but as a daily replacement of quantities removed from inventory through assembly plant orders. Figure 7-18 shows the current and future states of the model. Under the current state, the component inventory is controlled by the Production Rate and the shipping rate with delays in information flow due to scheduling and production queues. Under the current conditions, the amount of knowledge that the management of the Component Plant production is based solely on the shipping rate.

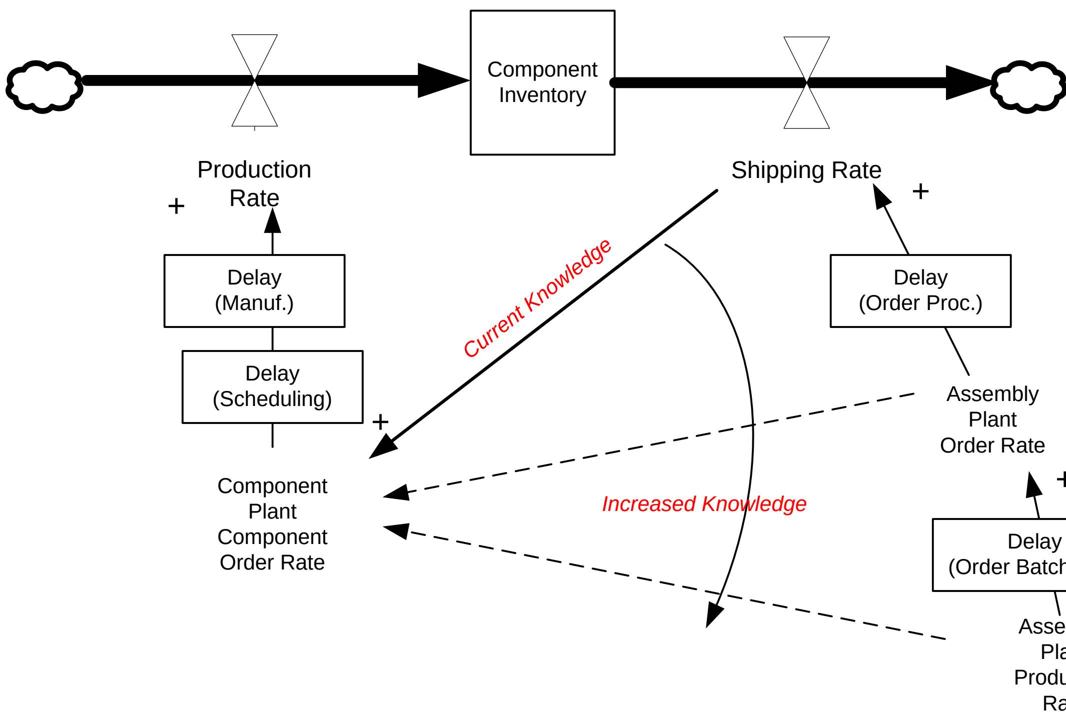

Figure 7-18 Assembly Plant/Component Plant – Model: Current and Future States

[1] The full code for the simulation model is located in Appendix D - Assembly Plant/Component Plant Simulation Model

The model used in the simulations was similar to that of the model used for the Assembly Plant except for some adaptations necessary to more appropriately match that of the functioning of the Component Plant's component inventory (Figure 7-19. As with the Assembly Plant, the inventory system of the Component Plant was evaluated based on the tolerable stock-out rate and the minimum necessary inventory to carry to obtain that stock-out rate. The ability of maintaining that allowable stock-out percentage was utilized to compare increased knowledge of demand on the Component Plant's component inventory system.

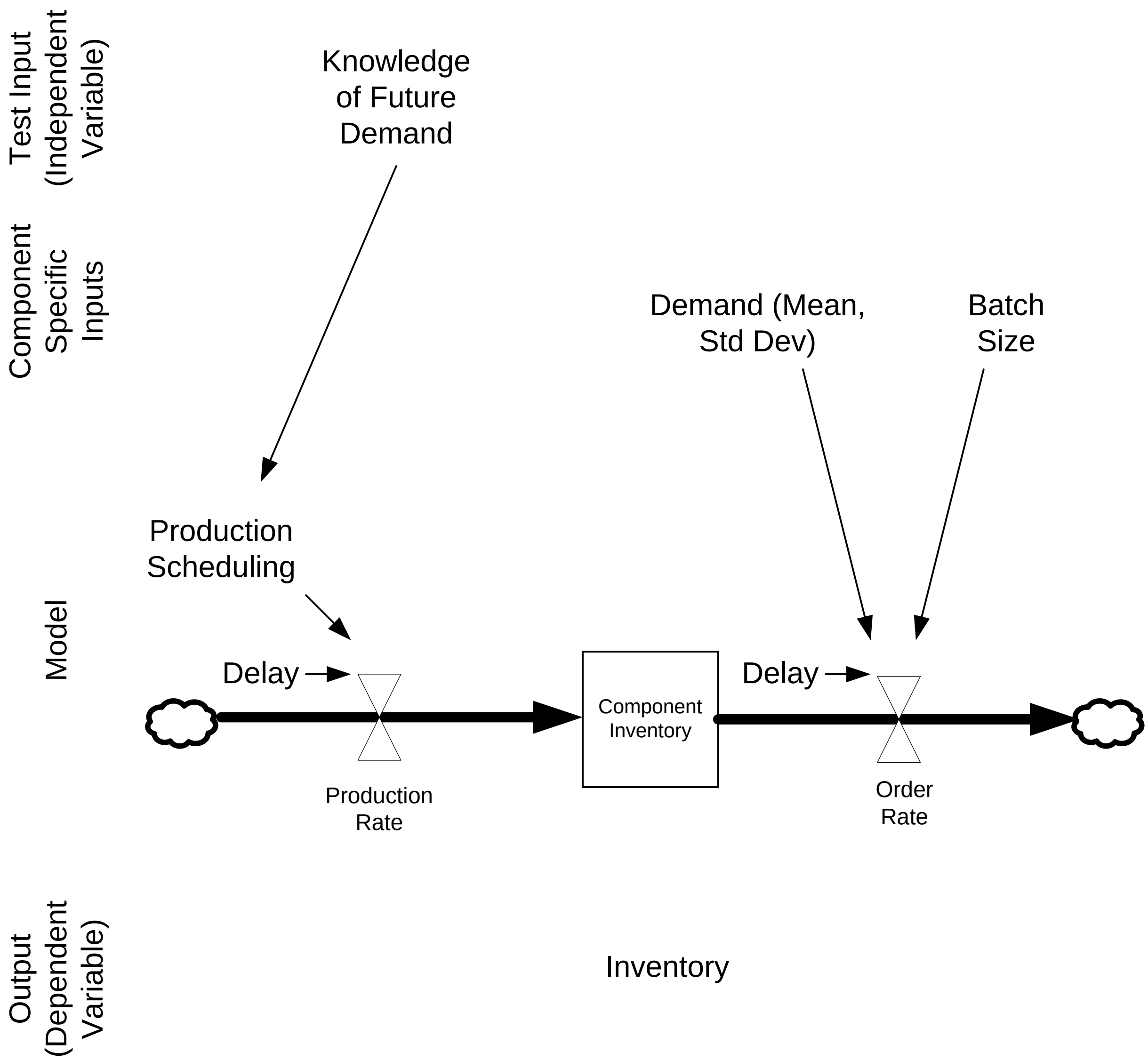

Figure 7-19 Assembly Plant/Component Plant - Simulation Model

The variables utilized in the simulation model are presented in Table 7-3. Like the previous model, the Knowledge of Future Demand is the independent variable and is measured in whole days. The Demand and the Batch Size for components were the same as utilized for the Retailer/Assembly Plant but modified for multiple Assembly Plant demand (see following discussion). Order Delay and Production Delay were both defined based on data presented in Chapter 4. Unlike the previous simulation, the entire inventory was considered for the dependent variable and not just the inventory residuals due to the difference in inventory management. The Production Scheduling in Figure 7-19 is not a variable but a programmed function based on the order that components are produced (defined in Section 5.6).

Table 7-3 Variables for Assembly Plant/Component Plant Model

Variable	Units	Values	Source
Knowledge of Future Demand	Days	1,2,3,…	Test Input (Independent Variable)
Demand	Units per day	See Table 7-2	Company Order Records
Batch Size	# of units	See Table 7-2	Company Inventory Records
Order Delay	Days	1	Section 4.2.1
Production Delay	Days	6	Section 4.3.1
Inventory	# of units		Test Output (Dependent Variable)

A number of changes were made to the Assembly Plant simulation model to account for differences between the Assembly Plant and the Component Plant. First, all delays were changed to reflect the processing of information and material in the Component Plant. Second, the order rate was changed from the retailer order rate to the Assembly Plant order rate which includes the batching of orders of components as described in the previous analysis (Section 7.2.1). Third, multiple assembly plants were included in the Component Plant simulation to copy that of the actual conditions of demand that occur in the Component Plant. Finally, inventory management procedures were changed for the Component Plant simulation. The Component Plant does not utilize a *Min/Max* system like the Assembly Plant, but a system based on scheduled manufacturing in which replenishment times are fixed and quantities are based on the relative rate of reduction of the inventory.

7.3.2 **Model Verification and Validation**

The production of components in the simulations was evaluated against the production output of the actual assembly plant in the case study. In the simulations, the average yearly production of each component was determined (Figure 7-20). The average value for the six components is 7.68 units per day per component. There are 769 components made of Red Oak at the Component Plant, which means that total production per day for oak components is 5903. Red Oak components make up 35% of all of the components made by the Component Plant which makes the total production of the Component Plant based on the simulations equal to 16,867 components per day. Production at the actual assembly plant was determined to be 16,000 components per day (detailed information on variation not available). The simulation average daily production is 5.4% larger than the actual average daily production. From other data, the daily production can vary with as much as 25% high and 24% low from its average. Thus, 5.4% difference in averages would be within tolerances.

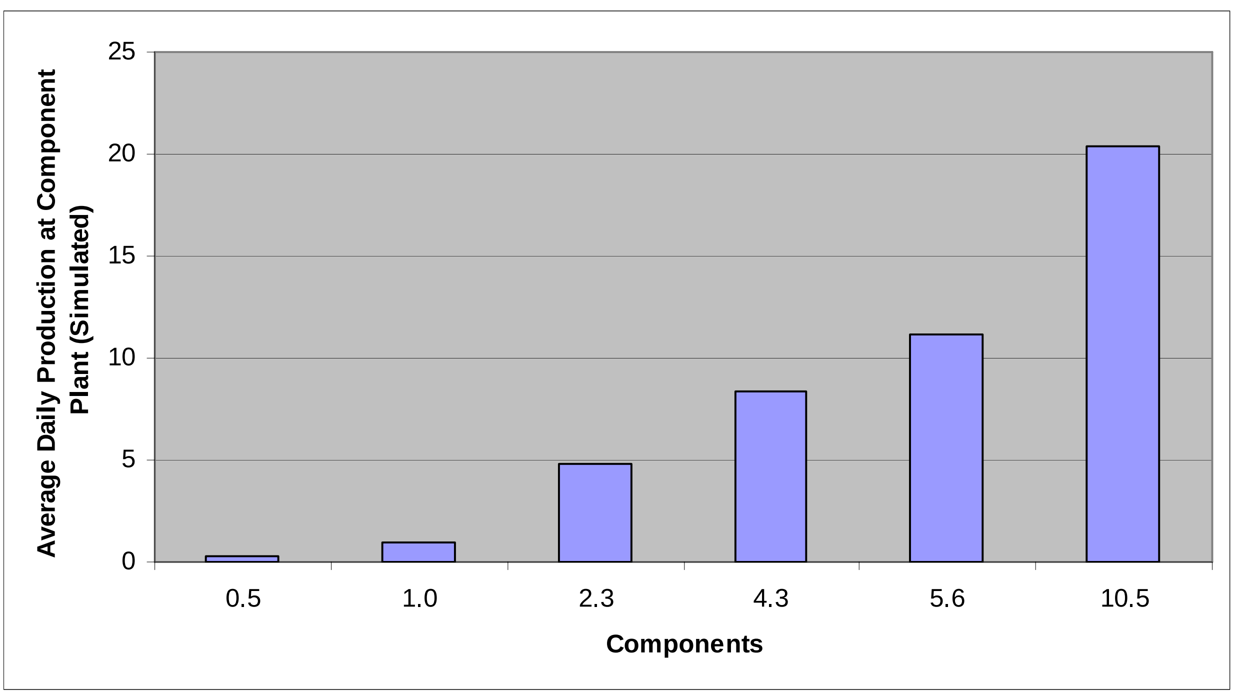

Figure 7-20 Simulated Average Yearly Demand for Components

The analysis required that the standard deviations of the inventory levels through the course of the simulation be compared. Since the standard deviations themselves vary, it is required that the simulation be run multiple times to obtain a distribution of standard deviations. To then analyze if the standard deviations within each control group of days of knowledge were statistically different, t-tests were utilized. However, before that could be completed it was necessary to determine if the variation of the standard deviations of the inventory levels was indeed normally distributed.

The distribution of standard deviations was analyzed utilizing a chi-square test, with the null hypothesis that the resulting standard deviations were normally distributed (failure to reject the null hypothesis ($p>0.05$)). The original conditions were analyzed, that is no advance knowledge of demand was included in the simulations. With a chi-square variance test, it was determined that for the components of larger demand (10.5 and 5.6 units per day), that the distributions of standard deviations of inventory was normal (10.5 - test statistic 0.999 and p value = 0.619 AND 5.6 - test statistic 2.11 and p value = 0.369). The results of chi-square tests of the lower demand components (4.3, 2.3, 1.0, and 0.5) were found to be inconclusive due to limitations in the simulation software. For the purpose of analysis, the normality of the standard deviations determined for the two higher demanded components was extrapolated to the remaining components.

7.3.3 **Simulation Protocol**

The simulation model was designed to identify the variability of the inventory levels of components at the Component Plant under specific conditions of advanced knowledge of demand. As with the Assembly Plant simulation, knowledge of demand is identified as the numbers of days into the future a manager can see true demand (i.e. if a manager's knowledge of demand is one day, the manager knows what the actual demand will be through tomorrow). Simulations were run for the six different components described in section 7.2.1 to obtain a cross-section of results across the range of demands occurring in the case study supply chain (see Table 7-2).

For each of the components, the variation of the inventory levels at the Component Plant was determined. From this data, the minimum average inventory was calculated, taking into consideration acceptable stock-outs of the components. The Probabilities of stock-outs evaluated were 0.0001, 0.001, 0.01, and 0.05 which translate to a 99.99%, 99.9%, 99.0% and 95% order fill rate, respectfully.

For each simulation, the amount of knowledge of future demand was controlled. The future demand was based on a daily evaluation of the inventory levels by the management of the Component Plant. Future knowledge was then the knowledge of what the inventory levels would be based on the same time in future days. For example, if future knowledge had a value of two days, the manager would know what the exact inventory level of the inventory would be in two days and thus if the minimum level for replenishment would be met on that day. The future knowledge of the inventory levels had a direct affect on the variability of the inventory and thus the minimum level necessary for the inventory.

7.3.4 **Results**

The Component Plant simulation was run for each of the six components representing the range of demands previously determined (See Section 7.2.1). The number of days of knowledge in the planning of the production/inventory control was increased in one day increments to determine the effect of advanced knowledge on inventory variation and thus on inventory requirements to meet demand. The results of the simulations are found in Table 7-4. The average standard deviations of inventory for each of the components/daily knowledge are the top value in each box. The other values in the boxes (in parentheses) are standard deviations of the other values for the multiple simulation runs.

Table 7-4 Standard Deviation of Inventory Quantities for Simulation

	Components (Identified by Daily Demand)					
Days of Knowledge	10.5	5.6	4.3	2.3	1.0	0.5
0	131.1 (10.6)*	80.6 (8.4)	61.9 (3.9)	37.0 (4.5)	10.0 (0.2)	4.5 (0.5)
1	128.3 (9.7)	73.2 (6.6)	56.2 (3.2)	33.2 (3.5)	9.7 (0.5)	3.7 (0.4)
2	114.6 (7.5)	66.7 (4.7)	51.2 (2.3)	30.3 (2.7)	8.7 (1.1)	3.3 (0.9)*
3	98.5 (5.0)	57.3 (1.7)	44.0 (1.6)	25.9 (1.9)	7.1 (1.8)*	2.9 (1.1)*
4	87.3 (2.9)	50.4 (1.7)	38.5 (1.0)	22.7 (1.1)	7.0 (1.6)*	2.8 (0.8)*
5	82.5 (2.4)	48.0 (1.4)	36.4 (1.0)	21.3 (0.9)	7.0 (1.0)*	2.9 (0.3)
6	88.7 (3.8)	50.0 (2.4)	37.7 (1.5)	22.0 (1.3)	6.8 (1.2)	2.2 (0.9)
7	105.5 (5.4)	61.3 (3.7)	46.6 (1.9)	27.5 (2.1)	8.1 (1.1)	2.7 (1.2)
8	118.8 (7.8)	69.5 (5.5)	53.1 (2.7)	31.5 (3.0)	9.1 (0.6)	3.2 (0.8)

Values in parentheses are the standard deviation of values across simulation runs

* failed to reject at alpha = 0. 05 when value was tested with next value in column

A statistical analysis of the results was performed to determine if values of the standard deviations (top value) were significantly different for changes in days of knowledge of future demand. T-tests (for samples of unequal variance) were performed with a one tail alpha level of 0.05. For values that are not significantly different with the following value in the column, an asterisk was added next to the value in parentheses. For example, there is no statistically significant difference (failure to reject the null hypothesis) between zero days of knowledge (131.1) and one day of knowledge (128.3) based on inventory variation for the component with a demand of 10.5 units per day.

For the four highest demand components (10.5, 5.6, 4.3, and 2.3 units per day), the average variation in inventory levels was the lowest when the number of days of knowledge was five. There was a gradual decrease in inventory variation from 0 days of knowledge to five days of knowledge and then a gradual increase once the five days was exceeded. For the component with demand of 1.0 units per day, six days of knowledge was the lowest, but was not statistically significant when compared to five days of knowledge. The component with demand of 0.5 units per day, six days of knowledge showed the lowest average variation and was statistically different from that of five days of knowledge[1].

Like the results of the Assembly Plant simulations, there is a maximum number of days of knowledge which when exceeded, cause decreased return. The lowest standard deviation of inventory for the Component Plant component inventory was determined to be at 5 days of knowledge. The significance of the reduction in standard deviation of inventory is shown in Figure 7-21. Each line in the figure represents the average daily inventory of a component (in this case the component with demand of 10.5 units per day) based on the number of days of knowledge. The average daily inventory is calculated as the minimum average inventory based on the standard deviation and the probability of failure (stock-out). The different lines represent different probabilities of failure – 0.05 (5 % allowable stock-out), 0.01 (1% allowable stock-out), 0.001 (0.1% allowable stock-out), and 0.0001 (0.01% allowable stock-out). From this figure, a decrease in average inventory is apparent with the increase in knowledge. Since the variation increases above 5 days of knowledge, the inventory will reflect the increase by also increasing.

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[1] The simulation software rounded all standard deviations to whole numbers. Due to the low values of standard deviation determined for the component with demand of 0.5 units/day, the affect of the rounding will greatly influence the results found in Table 7-4 for this particular component. This affect does not mask the general trends caused by the days of knowledge.

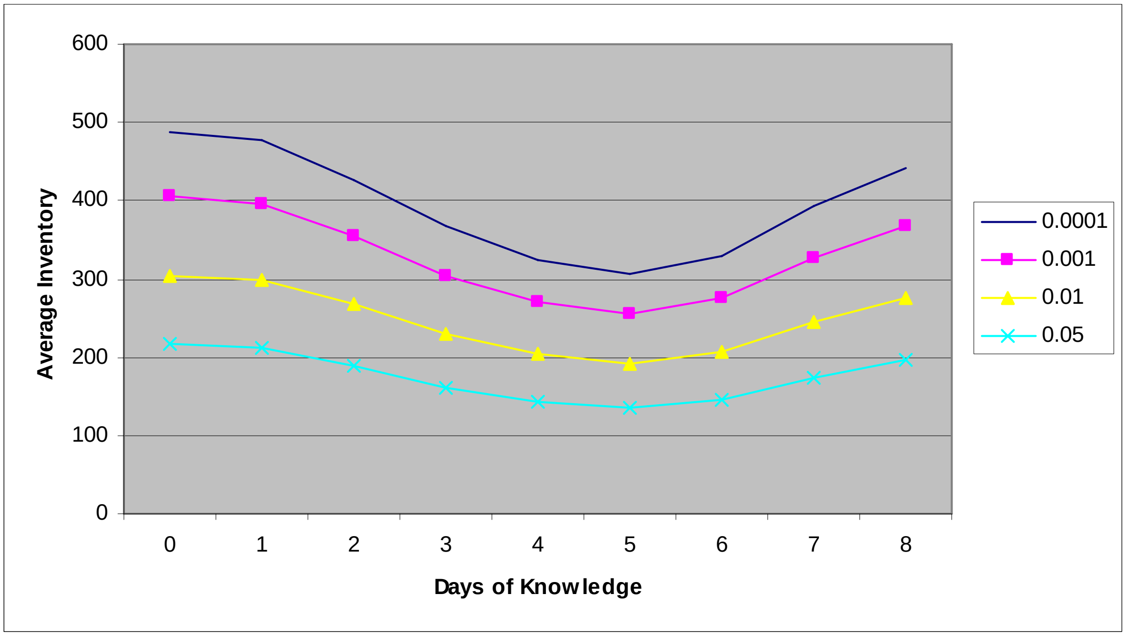

Figure 7-21 Affect of Days of Knowledge on Average Inventory Based on Different Probability of Stock-out Criteria for Component with Demand of 10.5 Units/Day

The average decrease in inventory based on days of knowledge (From zero to five days of knowledge) can be calculated as a function of the original average daily value of inventory (0 days of knowledge) for all six of the components analyzed (Figure 7-22). The six lines, each representing an analyzed component, are relatively linear especially with the four higher demand components (Average R-square of 0.980) and even more linear neglecting the tails (Average R-square of 0.995) which are affected by initial adjustments and equalizing to zero. The average decrease in inventory for all of the components per day of knowledge is 8.1% including all points and 9.9% for the middle points. Thus, an information system for the current production/inventory system at the Component Plant that can increase the advanced knowledge of demand from the assembly plants by five days, for example, can decrease the inventory requirements by 40.4% using the lesser average value. With current inventory of components at the Component Plant of $2.4 million, the amount of money tied up in inventory could be reduced by $970,000 and inventory carrying costs can be reduced by 40.4% per year.

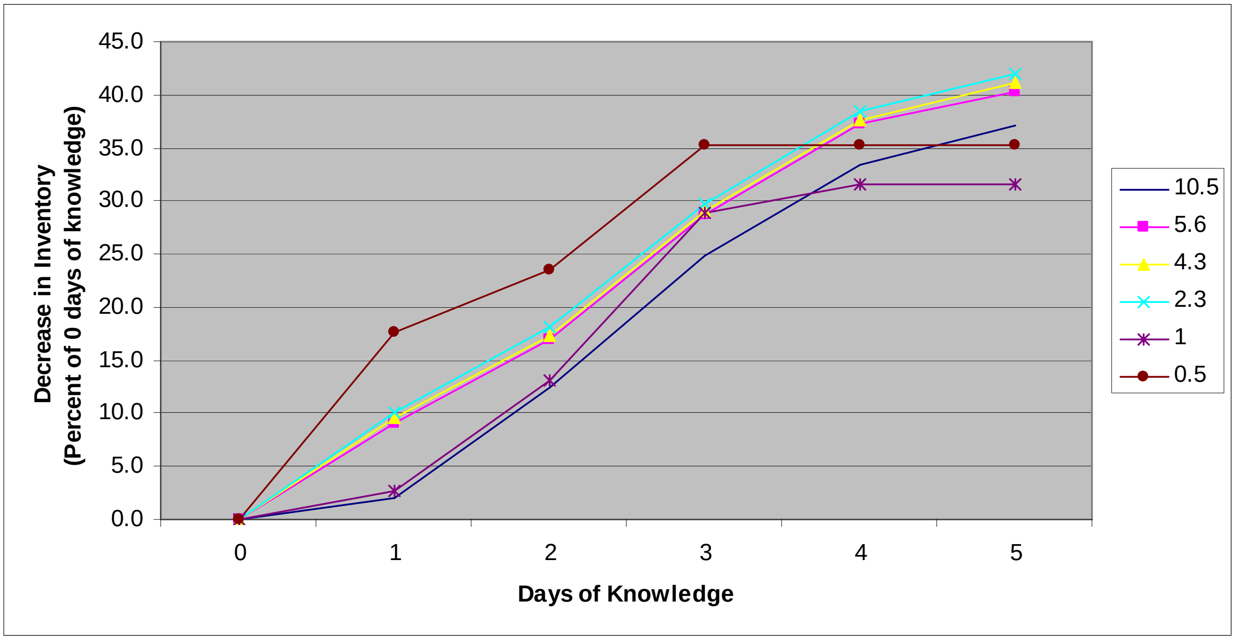

Figure 7-22 Decrease in Inventory Caused by Days of Knowledge for Different Demands

The benefits of advanced knowledge of demand, however, do not extend past five days in the case of the Component Plant. The significance of this time constraint is based in the number of days of delay between the initiation of an order at the Component Plant and the production of the component, which is five days. Essentially, the days of knowledge negate the delay in production to the point at which five days of advance knowledge creates a situation in which components are made-to-order. In Figure 7-23, scenario A shows a typical order/production policy in which production orders are made 5 days in advance (at time *x*) of production (*x+5*) with demand information known through time *x*. When production begins on that particular order, 5 days of demand have arrived since the original order was placed. For scenario B, orders are placed at time *x* with full knowledge of what demand will be up to production (*x+5*). The production orders for Scenario B would be the same at time *x* as if the production orders were placed at the time of production (*x+5*) with no advanced knowledge or make-to-order. By increasing the days of knowledge to the point at which it becomes like make-to-order, one of the two major factors which cause the need for buffer is removed which is the delay between order and production. The only remaining cause of variation that creates the need for an inventory buffer is the demand (orders from the assembly plants). An increase in knowledge beyond that of the 5 days cannot reduce the delay in the Component Plant any further and it cannot reduce the variability of the demand from the assembly plants. It does create a situation in which production occurs before the order arrives, requiring the components to be stored, thus increasing the inventory buffer.

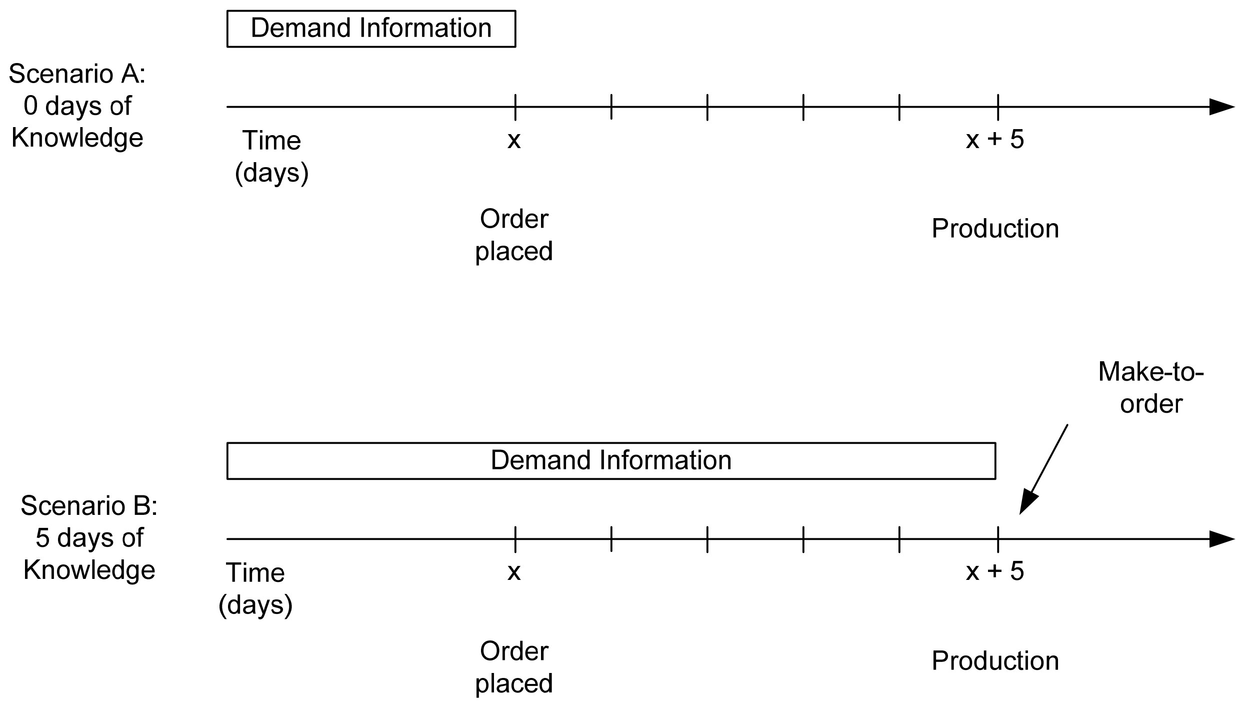

Figure 7-23 Description of Maximum Limit on Days of Knowledge

Advanced knowledge of demand in the Component Plant's finished component inventory has a positive influence on the quantity (lower) of inventory required to meet the orders of the customers and thus on the ability to react (faster) to the needs of the customers and final customers. By increasing the knowledge of demand at the Component Plant's inventory and production scheduling, a decrease in inventory levels can occur across all components of 7.6% per day while still keeping up with customer orders. The benefit of advanced knowledge of demand was maximum at five days of knowledge as the advanced knowledge reduced the variation caused by production delays which was five days. With information systems that could increase the advanced knowledge of customer demand by these five days, a reduction in inventory of components at the Component Plant could be 38.0% of the current levels.

Like the Assembly Plant, the Component Plant has internal methods by which advanced information can be obtained, but most of the five days of advanced information must come from external sources. From the information collected in Section 4.3.1, there is one day of information flow that can be reduced at the Component Plant. This day delay is caused when the order from the Assembly Plant is reviewed in the morning, but is not officially taken out of the inventory until the components are physically removed from the shelves. To reduce the information flow by a day, the component inventory can be reduced prior to the physical removal of inventory by removing it based on current orders at the time of the initial order review at the Component Plant. Like the Assembly Plant, there is an information delay due to the policy of daily information ordering through the Manufacturing Company. This can be reduced/removed through real-time order information flow between the Assembly Plant and the Component Plant. The final 3.5 days of advanced information must be obtained at the Assembly Plant and can be done through Vendor Managed Inventory (VMI) in which the Component Plant can monitor the inventory levels of the Assembly Plant for quantities and reduction rates so that the future dates of the minimum level can be calculated.

7.4 Component Plant / Raw Material Supplier

In the case study supply chain, the Raw Material Supplier supplies the Component Plant with its raw material, lumber. The Component Plant prefers freshly cut lumber, due to the degradation of lumber over time prior to drying, so the Raw Material Supplier is allowed up to one month from the initial date of the order to deliver the lumber, freshly cut (Section 3.2). In that time period, the Raw Material Supplier harvests the timber and manufactures the lumber. Because of the delays in ordering and delays in delivery, a buffer stock is required at the Component Plant to minimize the stock-outs that may occur and keep production going at the facility.

Upon arrival to the Component Plant, the raw material is evaluated and placed in the predryer where it partially dries before going into the kiln for final drying. The raw material in the predryer is not the buffer stock, not all of it. Although the predryer may be thought of as a process and not inventory, at a point in time, the drying process within the predrying is complete (the moisture content of the lumber meets the target for predrying). However, the predried raw material is not removed but remains in the predryer until it is loaded into the kiln. The loading of the kilns is not based on the raw material being ready for the kiln drying process but is based on the demand by the manufacturing facility. The raw material in the predryer that is ready for the kiln but not yet sent to the kiln acts as a buffer inventory between the demand of the manufacturing facility and the delivery rate of the raw material from the Raw Material Supplier with fixed delays for predrying and kiln drying.

Different from the prior supply chain segments studied earlier, the delivery of the raw material to the Component Plant does not have a predetermined lead time. Instead, the raw material arrives throughout the month. For the Raw Material Supplier, the raw material is produced to order. This means that there is a delay in the initial delivery based on the lead time for the Raw Material Supplier to harvest and process the raw material for the Component Plant (11 business days). Based on the Raw Material Supplier of the case study supply chain, the delivery of the raw material would occur sometime between 11 business days (earliest delivery) from the initial order and the end of the one month period (latest delivery). For modeling purposes, it was assumed that the probability of delivery was uniformly distributed between 11 and 30 days.

The specific amount of raw material ordered by the Component Plant each month is based on a number of factors (Section 5.6.2). Of primary concern is maintaining a specific quantity of raw material throughout the manufacturing facility. Management at the case study Component Plant targets 12,000,000 bdft of lumber (raw materials) to sustain their production demands.

The purchaser at the Component Plant must not only take into consideration the total amount of raw material at the facility but also the variability within the system. The location of all of the raw material at the various places in the flow of material through the Component Plant is highly important to the ordering process. Also, when ordering, the purchaser must take into consideration the variability outside of the Component Plant, specifically in the delivery schedule of the Raw Material Suppliers in the order process.

The delivery of the raw material to the Component Plant occurring throughout the month may be beneficial to the flow of material in the Component Plant by minimizing large peaks and valleys in inventory that would be created with one large delivery. However, due to the current schedule of the ordering process, most of the deliveries occur in the latter half of the month (Figure 7-24). The purchaser at the Component Plant places the order at the beginning of the month. The Raw Material Supplier completes current orders and has new logs delivered from the forest. As the raw material is processed for the Raw Material Supplier, it is delivered until the full order is complete (and the deadline of the end of the month).

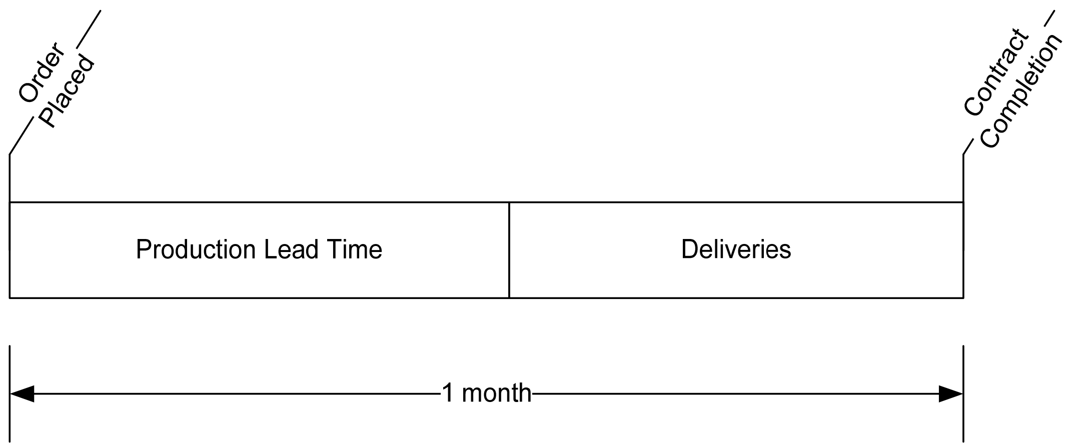

Figure 7-24 Current Schedule of Order/Delivery between Component Plant and Raw Material Supplier

The delay in initial deliveries each month by the Raw Material Supplier amplifies variation in the Component Plant which causes the need for additional buffer stock to reduce stock-out occurrences at the Component Plant. To reduce the variation in deliveries throughout the month, it would be advantageous to reduce the production lead time at the Raw Material Supplier. If little could be done to reduce raw material lead time, it still would be possible to move the start date on the production lead time forward by giving knowledge of the future order to the Raw Material Supplier sooner, thus potentially increasing the span of the delivery time.

The objective of the simulation model was to determine how the increased knowledge flow to the Raw Material Supplier from the Component Plant influenced the inventory levels of the buffer inventory of raw material at the Component Plant. If inventory can be reduced through increased information flow (reduction of variability of inventory), what is the relationship between the amount of knowledge of future orders and the reduction of variability of the inventory? The purpose of identifying this relationship was to find a method by which potential benefits can be determined for reduced inventory buffers while sustaining responsiveness to customers. In addition, the return on investment of changes to an inventory system can then be determined for anticipated costs in increasing the information flow such as implementation of information systems.

7.4.1 Introduction to Model

The model for the Component Plant/Raw Material Supplier segment of the case study supply chain focuses on the raw material inventory level that has gone through the predrying process, but has not been loaded into the kiln for final drying. This pre-dried raw material is assumed to be the only buffer that is directly managed to smooth out variations in order lead times between the Component Plant and the Raw Material Supplier. The model purpose is to evaluate the levels of the raw material in the pre-dried state as they are affected by increased information sharing between the Component Plant and the Raw Material Supplier.

The pre-dried lumber inventory is affected by two rates: the rate at which the lumber is removed from the predryer for loading in the kiln and the rate at which the lumber in the predryer meets the predried condition (Figure 7-25). The kiln loading rate is a function of the rate at which the lumber is used by the manufacturing facility and the delay associated with scheduling kiln loads (batch size / drying rate). The predryer completion rate is a function of the lumber delivery rate and the pre-drying delay which is affected by the lumber order rate of the Component Plant and the production delay at the Raw Material Supplier.

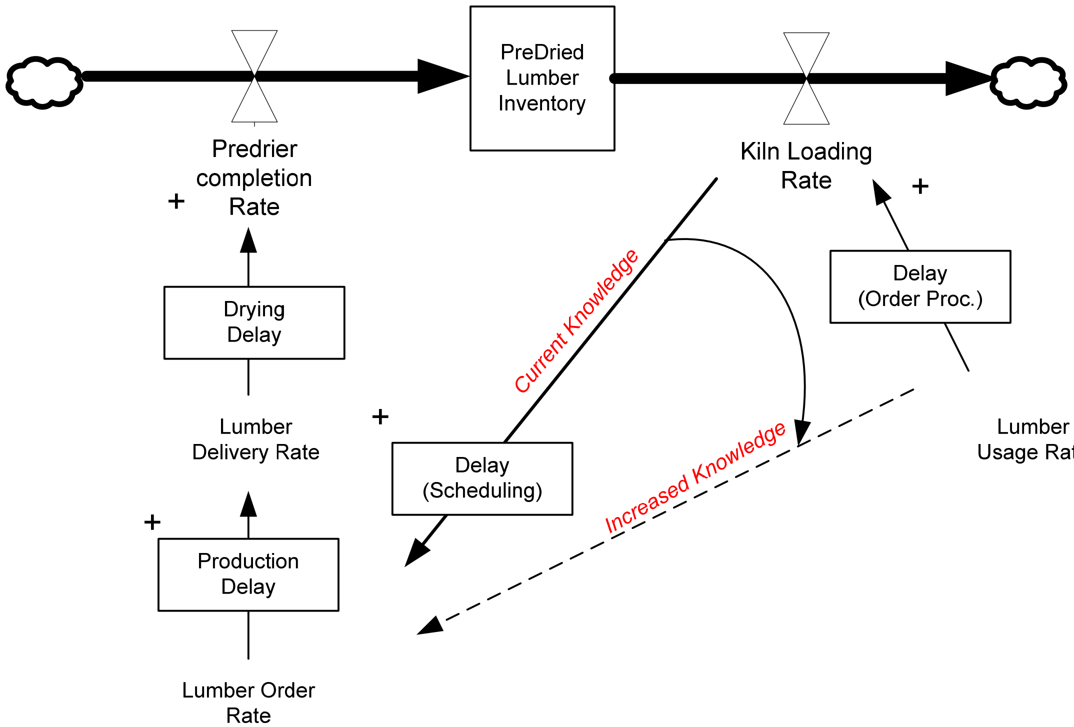

Figure 7-25 Component Plant/Raw Material Supplier – Model: Current and Future States

The simulation model[1] was constructed with a structure similar to the previous two simulation models. The amount of knowledge of future demand by the Raw Material Supplier was evaluated as to its affect on the variation of the buffer inventory of the pre-dried lumber at the Component Plant (Figure 7-24). The daily demand for lumber raw materials by the Component Plant manufacturing facility was taken from the production records of the case study Component Plant and was determined to be normal (μ = 15684 bdft, s = 3163bdft) for the Red Oak lumber of interest in the study. The kiln loading rate was based on the lumber demand, delay for kiln drying (Section 4.2.1), and kiln capacity (92,000 bdft). Utilizing delivery records of the Component Plant, the distribution of deliveries of the lumber raw material to the Component Plant by raw material suppliers was determined to be uniformly distributed (0.0118 square error) through the month. The delay in delivery between the Raw Material Supplier receiving the order and actual delivery of lumber to the Component Plant (11 days) was based on

[1] The full code for the simulation model is located in Appendix E - Component Plant/Raw Material Supplier Simulation Model

the results of walking the supply chain (Sections 4.2.1 and 4.3.1) and included the lead times for information and material flow through the Raw Material Suppliers.

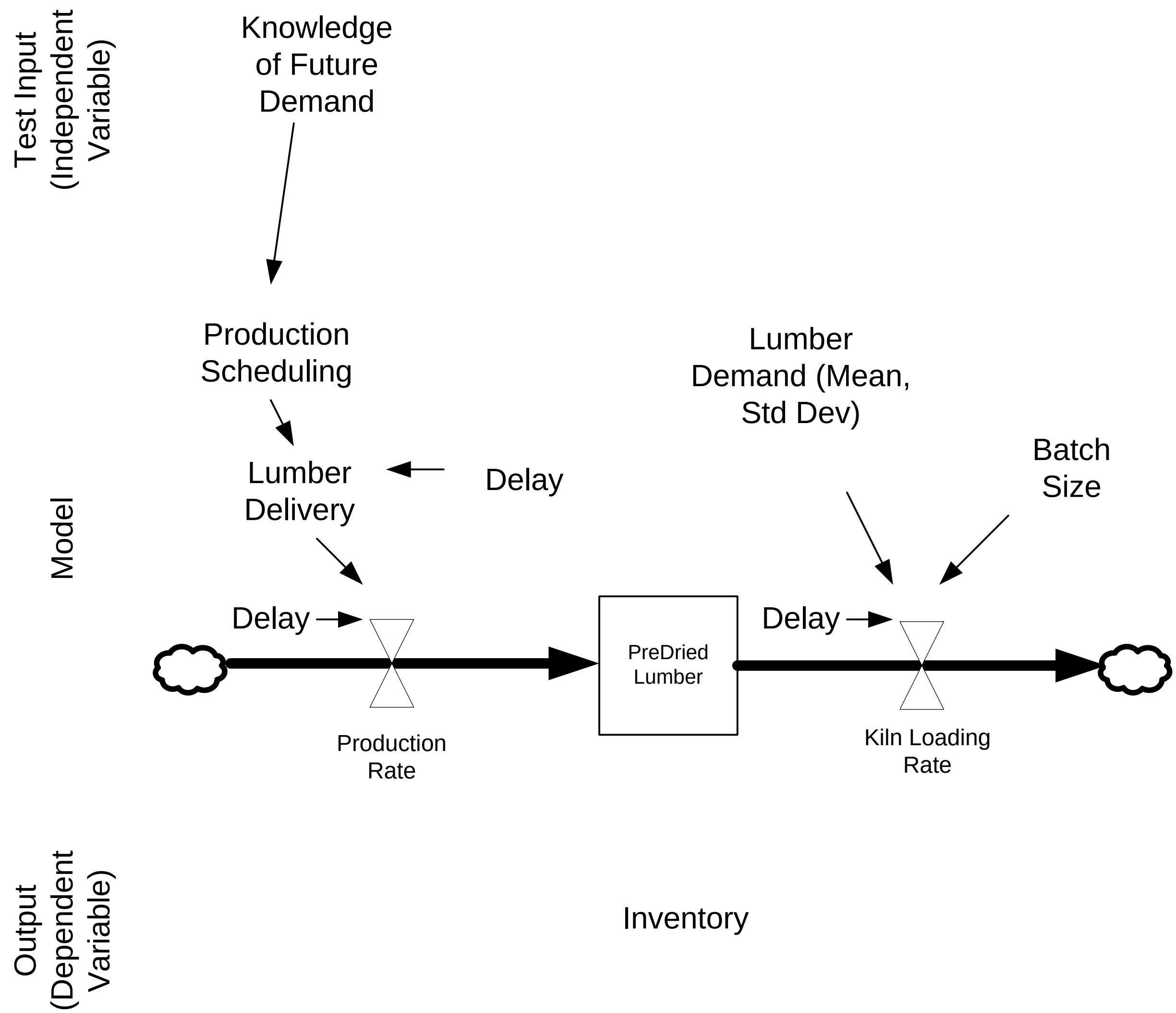

Figure 7-26   Component Plant/Raw Material Supplier - Simulation Model

The variables utilized in the simulation model are presented in Table 7-5. Like the previous model, the Knowledge of Future Demand is the independent variable and is measured in whole days. The Lumber Demand was determined from company records for lumber usage by the manufacturing facility within the Component Plant. The Batch Size for the kiln, the Kiln Delay, and the Production Delay (Predrying) were obtained from Section 4.2. The Lumber Delivery was defined previously as being uniform. The Production Scheduling (not shown in the

Table 7-5 but shown in Figure 7-7) was based on information and material flow found in Sections 5.6 and 5.7. The raw material in the predryer that is defined as the buffer inventory was the dependent variable.

Table 7-5 Variables for Component Plant/Raw Material Supplier Model

Variable	Units	Values	Source
Knowledge of Future Demand	Days	1,2,3,…	Test Input (Independent Variable)
Lumber Demand	Bdft	Normal (15684, 3163)	Company Records
Batch Size (kiln)	Bdft	92,000	Section 4.2.1
Kiln Delay	Days	6	Section 4.2.1
Production Delay (Predrying)	Days	60	Section 4.2.1
Lumber Delivery	Days	Uniform	Defined prior
Inventory	# units		Test Output (Dependent Variable)

The knowledge of future demand is designed to extend the time in which deliveries are made. In Figure 7-27, the current state of the raw material ordering and delivering processes has the one month ordering window encapsulating both the production lead time of the Raw Material Supplier and the deliveries to the Component Plant. The future state will shift the knowledge of ordering forward in time so that the Raw Material Supplier will know that the order is coming and prepare for that order by minimizing the production lead time, thus increasing the time frame for deliveries of the raw material to the Component Plant.

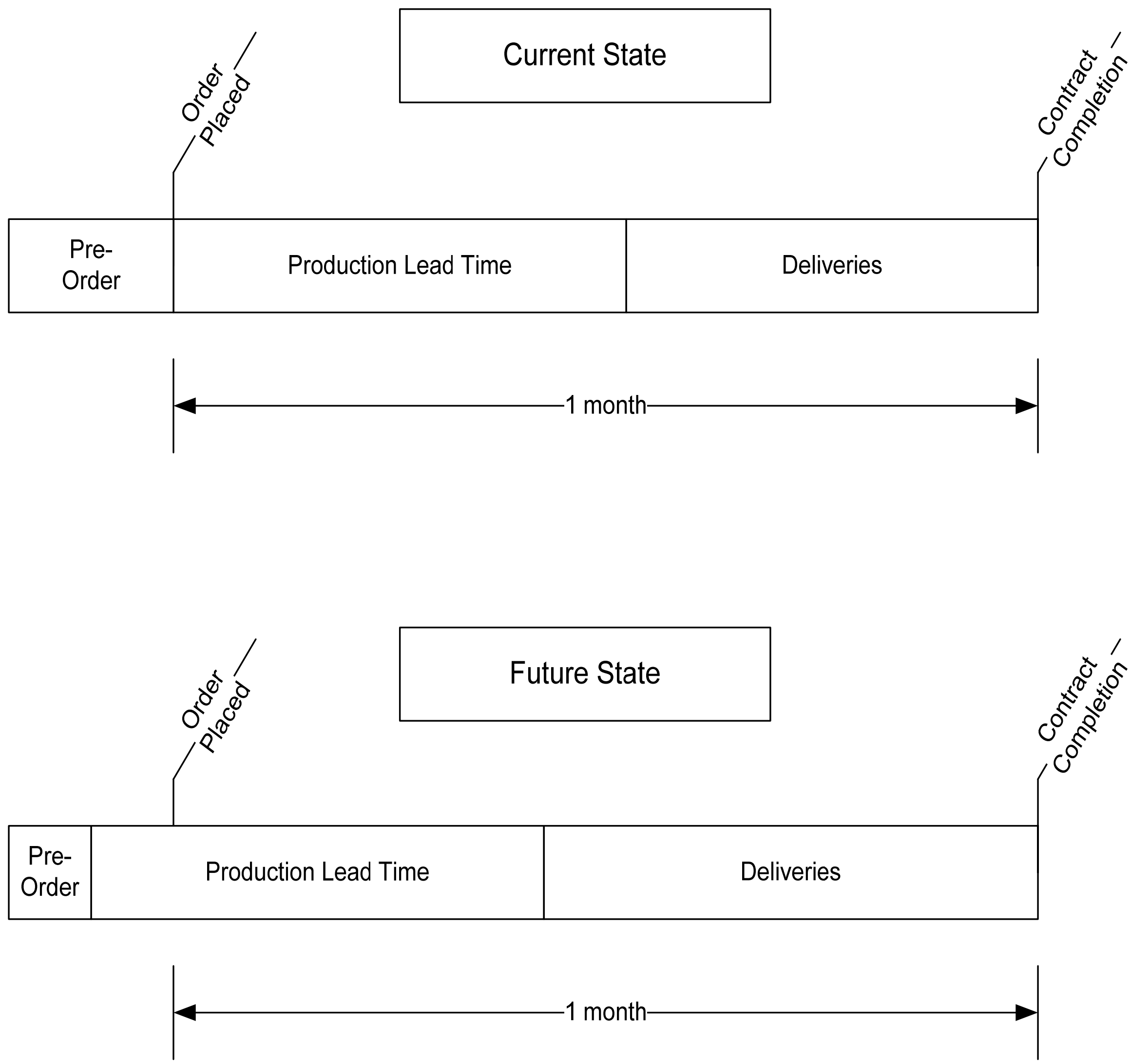

Figure 7-27 Order and Delivery Process for Lumber

The addition and increase of future knowledge of orders by the Raw Material Supplier is hypothesized to benefit the Component Plant by decreasing the variability of inventory levels of the raw material. By reducing the variability in inventory levels, the total amount of raw material inventory held by the Component Plant can be reduced because of the reduced need to buffer against the variation in deliveries of raw material by the Raw Material supplier.

7.4.2 **Model Verification and Validation**

Of primary concern in the simulation is how much inventory the Component Plant retains of the raw material (lumber) within the facility. The current state of the model was simulated to verify that the resulting inventory of the simulation was within similar tolerances of the actual system being simulated. The total inventory of Red Oak lumber at the Component Plant was targeted to be 1.2 million bdft in Current State. The company had been gradually reducing the total inventory and the last recorded amount of Red Oak lumber at the plant was 1,169,472 bdft. Utilizing regression analysis and accounting for decrease inventory over the previous 13 months, the standard deviation of the inventory was determined to be 82,431 bdft.

In the simulation model for the "current state," the total Red Oak lumber inventory was calculated to be 1,117,284 bdft with a standard deviation of 59,451 bdft. The difference of the simulation and actual Red Oak inventories is 52,188 bdft or 4.4%. A t-test was performed on the two distributions, which resulted in the failure to reject null hypothesis that they are equal at alpha = 0.05 with a p-value of 0.428.

The analysis also required that the standard deviations of the inventory levels through the course of the simulation be compared. Since the standard deviations themselves vary, it is required that the simulation be run multiple times to obtain a distribution of standard deviations. To analyze if the standard deviations within each control group of days of knowledge are statistically different, t-tests were utilized. For the t-tests it was required that the distribution of the standard deviation be normally distributed. The distributions of standard deviations were analyzed utilizing a chi-square test, with the null hypothesis that the resulting standard deviations are normally distributed (fail to reject the null hypothesis ($p>0.05$)). The original conditions were analyzed, that is no advance knowledge of demand was included in the simulations. With a chi-square variance test it was determined that for the hypothesis, the distributions of standard deviations of inventory was normal (test statistic 2.38 and p value = 0.136).

7.4.3 **Simulation Protocol**

The simulation model was designed to identify the variability of the inventory levels of raw material at the Component Plant under specific conditions of advanced knowledge of demand by the Raw Material Supplier. As with the previous simulations, knowledge of demand is identified as the numbers of days into the future a manager can see true demand (i.e. if a manager's knowledge of demand is one day, the manager knows what the actual demand will be through tomorrow).

With the simulations, the variation of the raw material inventory levels at the Component Plant was determined. From this data, the minimum average inventory was calculated, taking into consideration acceptable stock-outs (raw material not quite completely pre-dried) prior to kiln drying. The Probabilities of stock-outs evaluated were 0.0001, 0.001, 0.01, and 0.05 which translate to a 99.99%, 99.9%, 99.0% and 95% order fill rate, respectfully.

7.4.4 **Results**

Simulations of the model were run for the current state with an increasing amount of knowledge of orders by the Raw Material Supplier. The simulated system was evaluated based on the amount of raw material in the predryer that had completed the minimum amount of predrying time required by the Component Plant. The lowest average inventory of predryed lumber raw material necessary to maintain proper material flow (minimizing stock-outs) was determined.

The Component Plant/Raw Material Supplier simulation was run with the number of days of knowledge of incoming orders by the Raw Material Supplier increasing incrementally by one. The standard deviations of the buffer inventory, defined previously as the predried raw material, were determined for each of the days of knowledge (Table 7-6). The standard deviation was found to decrease with the additional days of knowledge until the eighth day of knowledge for which there was no significant change in the standard deviation.

Table 7-6 Standard Deviation of Predried Raw Material versus Number of Days of Knowledge

Days of Knowledge	Standard Deviation		Days of Knowledge	Standard Deviation
0	66969		6	52853
1	63893		7	51355
2	61076		8	49584
3	58605		9	49812*
4	56449		10	48777*
5	54260		11	49294*

* failed to reject at alpha = 0. 05 with the previous value in the column

Given the standard deviations of buffer inventory for each additional day of knowledge by the Raw Material Supplier, an average inventory level of the buffer inventory was calculated based on the probability of stock-outs (0.0001, 0.001, 0.01, and 0.05). A graph of the average inventory levels (Figure 7-28) shows a decrease in the required average buffer inventory levels until the eighth day of knowledge and then stabilization thereafter. Each additional day of knowledge by the Raw Material Supplier results in a reduction in the average buffer inventory at the Component Plant between three and five percent (through the eighth day). The flattening out of the curves around the eighth day coincides with the kiln capacity, 92,000 bdft. Thus, the advanced knowledge of the orders by the Raw Material Supplier decreases the variability in the buffer inventory so that the variability of the buffer stock is dominated by the kiln loading variability.

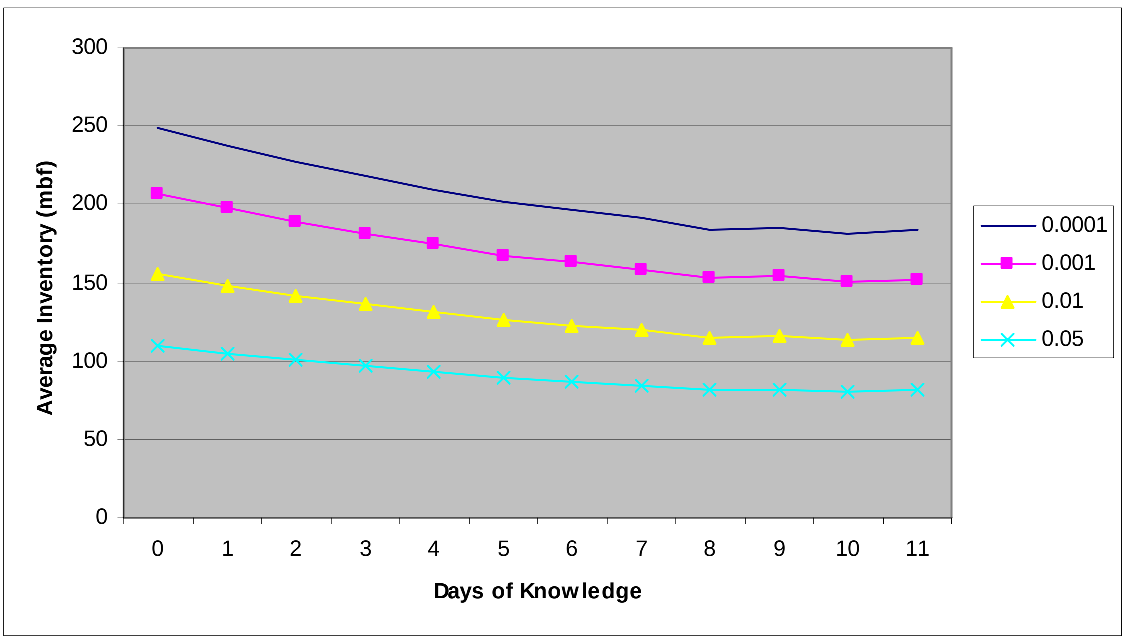

Figure 7-28 Inventory Reduction at the Buffer Inventory with Increase in Knowledge of Demand

With the reduction in variability of the buffer inventory due to increased information flow, there is an opportunity to reduce the quantity in the inventory, thus decreasing inventory costs and increasing information flow in the supply chain. If a low probability of stock-out is assumed for the system (0.0001)[1], eight days of advanced knowledge of orders will allow for a decrease in the inventory buffer of 64,653 bdft. This quantity represents a reduction of 26% of the required buffer inventory and 6% of the total bdft of Red Oak inventory at the Component Plant. The budgeted value of Red Oak lumber by the Component Plant is $0.655/bdft for a reduction in capital allocated to raw material of $42,348.

The lead time of material flow through the supply chain will also decrease with the decrease in the buffer inventory. With the production facility demand for Red Oak being an average of 15,684 bdft/day, the reduction in buffer inventory of 64,653 bdft represents a reduction of material flow of 4.1 days through the Component Plant.

Different from the Assembly Plant and the Component Plant, the advanced information flow to the Raw Material Supplier must be fully external. The delay in information comes from the purchaser at the Component Plant ordering monthly (holding demand information for a month). By passing advanced information on future need (or extending the delivery period through a one month period), the Component Plant will potentially reduce the variation in delivery and thus reduce the need for buffer inventory.

7.5 The Effect of Advanced Knowledge on the Case Study Supply Chain

If all advanced knowledge opportunities investigated in the previous sections were implemented, there could be potential decreases in both the material flow and the information flow within the case study supply chain. Table 7-7 shows the effects of advanced knowledge for each of the three segments of the case study supply chain analyzed. The first two rows are the results of the analysis of the individual segments. The second two rows are the affect of the first two rows on the material flow and the information flow of the case study supply chain.

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[1] For the simulation with zero days of advanced knowledge (current state) the amount of lumber in the predryer that had completed the predrying process had an average of 233,000 bdft. The stock-out probability for the actual system would be closest to the probability of 0.0001.

Table 7-7 Summation of Potential Gains in the Case Study Supply Chain through Advanced Knowledge

	Retailer Assembly Plant	Assembly Plant Component Plant	Component Plant Raw Material Supplier	Totals
Max. Advanced knowledge	6 days	5 days	8 days	19 days
Decrease in inventory buffer	7.5%	38.0%	26.0%	
Increase in material flow	1.5 days	5.7 days	4.1 days	11.3 days
Total increase in information flow	7.5 days	10.7 days	8.0 days	26.2 days

The maximum days of knowledge were those calculated for each segment and are the maximum amount of advanced knowledge that returns a positive gain in the reduction of the buffering inventory. For the case study supply chain, the total amount of advanced knowledge is 19 days which would reduce the information flow from its original lead time of 106.3 days to 87.3 days. The decrease in inventory buffer is the amount that the inventory buffer would be reduced if the advanced knowledge was made available in the individual segments of the case study supply chain. These values cannot be combined for a total amount as the represent different types of items in the inventories.

From the reduction in inventory buffer, the reduction of material flow can be calculated for the first two segments based on the material flow determined for each of the associated inventories in Section 4.2.1 (Walking the Supply Chain) as the total time spent in each inventory times the Decrease in Inventory Buffer. For the component inventory at the Assembly Plant, the original delay was 20 days spent in inventory. With a reduction in inventory of 7.5% there would be a reduction in time of 1.5 days in the material flow (20 days x .075). Likewise, at the Component Plant there would be a reduction in time to material flow for the same reason; the result of which is 5.7 days. For the raw material, the resulting reduction in material flow was previously calculated in Section 7.4.4 utilizing different methods (this was required due to the buffer inventory not being differentiated from the total amount of inventory in the same area), and found to be 4.1 days. Thus, the total reduction in the lead time of material flow through the case study supply chain with maximum advanced knowledge as defined is 11.3 days. In its current state, the case study supply chain has a total lead time for material flow of 113 days, so with the maximum advanced knowledge, the new lead time for material flow would be 101.7 (a 10% reduction).

There is also a residual affect of the decreased material flow on the information flow. Since the flow of information is tied to the flow of material at buffer inventories (information is not passed until inventory levels drop below some level) at the Assembly Plant and the Component Plant’s component inventory, the lead time of information flow through the case study supply chain is also reduced by the reduction in these inventory levels, in all three cases. (For the raw material inventory level at the Component Plant, the ordering interval is determined based on time and not inventory level.) Thus, the total decrease in information flow would be the sum of the advanced knowledge (previously calculated) and the reduction in material flow for those two supply chain members. The total reduction in information flow would be 26.2 days or a reduction of 25% from the original lead time.

7.6 Conclusions

From the analysis of the case study supply chain, alignment of the supply chain members through sharing of advanced knowledge of customer demand is beneficial to the material flow as well as the information flow of the supply chain. More timely information sharing by the supply chain partners reduced the need for forecasting which decreased the demand amplification within the supply chain.

The direct result of increased information flow between supply chain members was the reduction in buffer inventories that supply chain members use to account for differences in demand and replenishment. The decrease in actual delay of information from one supplier to customer reduces the need for the supplier to forecast future demand, thus decreasing the demand amplification within the supply chain. Since less forecasting is required, the buffer inventory can be reduced while maintaining the same service level to the customer.

One of the benefits of a reduced buffer inventory is a reduction of direct costs associated with maintaining an inventory. A decrease in an inventory reduces the amount of cash that a company has tied up in completed products, partially completed products or raw material. In addition, the costs of maintaining inventory, such as facilities, racks, and personnel are also reduced with the reduction in inventory.

One of the most important factors of reduced buffer inventory is the increase in adaptability of the supply chain. A reduced buffer inventory causes an increase in the material flow of the supply chain, and the faster material can flow through a supply chain, the faster changes made to the manufacturing process through the entire supply chain can reach the final customer. The adaptability of a company and a supply chain is a function of how quickly a product can go through all the steps (value added and non-value added) to be transformed from raw material to final product. Thus, by increasing information flow between customer and supplier, the long-term turn around time decreases, and the adaptability of the supply chain to the final customers' changing demands increases.

The reduction of buffer inventory in a facility has a secondary effect on information flow. Information flow was found to be integrated with the material flow at certain stages in the case study supply chain, including buffer inventories. Inventory buffers were not only found to delay material flow but also information flow. Demand information was passed onto the next stage in the flow of information in the form of replenishment orders. Thus, the information was aggregated by the time period between orders for a particular product. With the reduction in inventory buffer, there are additional increases in information flow within companies that will cause a decrease in demand amplification.

There are, however, limits to the value of increasing the information flow in the supply chain with regards to decreased buffer inventories. For each segment of the case study supply chain, a maximum number of days of advanced knowledge were identified for which more knowledge would be detrimental to the system with regards to the buffer inventory. The maximum number of days was either the point at which the known demand was equal to the actual demand (information delay is zero) or the advanced knowledge in effect neutralizes the lead time of scheduling and production (lead time is zero) so that all variability due to that lead time was removed from determination of the buffer inventory.

Chapter 8 Conclusions and Future Applications

The Hardwood Industry in the United States has been challenged by low cost competition from overseas. Many companies within the industry have sought ways to reduce their own costs utilizing strategies such as Lean Manufacturing and Six Sigma (Sabri et al. 2004; Motsenbocker et al. 2005), however countries such as China, have continually beat domestic manufacturers prices in the store even with the cost of transporting the goods across the Pacific Ocean (Houston 2003). One of the results is that United States manufacturers of hardwood goods are choosing to supplement or replace all of their current domestically manufactured products with similar low cost imported products (Bryson et al. 2003).

Price of a product is only one factor in the purchase of products such as hardwood furniture (Vickery et al. 1997). The closeness of the hardwood industry in the United States to the intended market gives the industry an edge over foreign manufacturers in the ability of the industry to be more customer-focused (Schuler et al. 2003; Gulati et al. 2005). Being customer-focused however means that individual members of the supply chain must be aligned so that they are able to meet the short-term and long-term goals of the final customers by being agile and adaptive (Lee 2004).

Traditionally, the domestic Hardwood Industry has been based on economies of scale. The large production batch sizes and large inventories of this production policy created long lead times in production which make change difficult, time consuming, and costly. For the domestic Hardwood Industry to become more customer-focused, it requires that the lead time for material flow be reduced through the individual companies that make up supply chains and the supply chains as a whole.

A large portion of the lead time through a supply chain is from buffer inventory caused by demand amplification. With the absence of effective "real-time" information, a company must rely more on forecasting, that is estimating (or perhaps even guessing) at what the true demand for their products will be. This reliance on forecasting leads to inventory stockpiling to reduce stock-outs and an artificially induced increase in demand variation along the supply chain leading to deviations and distortions in demand rates from the actual final customer demand (Forrester 1961). The difference between the forecasting and the actual demand causes the need to amass inventories.

The motivation of the study was based on the idea that the Hardwood Industry in the United States has the potential to gain market share by becoming more customer-focused, and that a significant barrier to become more customer-focused is the large lead-time in the Hardwood Supply Chain from raw material to final customer. Additionally, the large lead times of material flow through the supply chain are caused by buffer inventory created by demand amplification. By reducing the demand amplification through increased information sharing between supply chain members, the flow of material through the supply chain will increase allowing for increased opportunities to be customer-focused. Utilizing a case study approach, it was possible to determine relationships between information flow and material flow, as well as to determine the expected increases in material flow based on increased information flow between customers and suppliers.

8.1 Summary and Conclusions

The effect of information sharing on the Hardwood Industry was analyzed utilizing a case study approach on a specific supply chain which manufactures products from the hardwood resource. The supply chain was first analyzed utilizing Value Stream Mapping techniques to identify the pathways of information and production flow through the supply chain segments and to benchmark the lead times for both. A more detailed analysis of the information and material flows utilizing System Dynamics was performed to identify the inter-relationship between supply chain information and the managerial decision-making process for production for the supply chain. Finally, an investigation was conducted into the impact of increased information sharing on the supply chain

The pathways of information and material flow for the case study supply chain were found to be opposite in direction and similar in lead times. The material moved from the raw material (timber) through the Raw Material Supplier, the Component Plant, the Assembly Plant, and the Retailer until it reached its destination of the Final Customer, taking 113 days to do so. The information in the form of demand (orders) started with the Final Customer and moved through the supply chain inan opposite direction to material flow until it reached the source of the raw material (the timber), taking 106 days to do so. The information flow had two additional steps in the supply chain that the material flow did not: it was required to route the information from both the Assembly Plant and the Component Plant through the parent company's information system before it could continue. As to the similarity in total lead times of the information flow and the material flow, it was attributed in part to the commonality of delay associated with the buffer inventory. Material had to wait in inventory until used for production, and orders were not passed to suppliers until material was depleted sufficiently to a predetermined minimum level.

A detailed investigation of the material flow and the information flow throughout the supply chain found that there were far fewer factors that affect the flow of material than the flow of information. Material flow was controlled primarily by the demand for finished product, production and transportation rates, and replenishment of inventory buffers throughout the supply chain. Information flows were processed through more steps than the material flow. Policies of individual companies and the protocol of managers within the companies played an important part in the time that it took for the information to flow through the supply chain when not tied to buffer inventory.

To obtain a better understanding of information and material flow through the supply chain, the supply chain and its individual members were evaluated utilizing performance measures identified in the literature (1) *Information Integration*, 2) *Visibility and Trust*, 3) *Flexibility*, 4) *Functional Duplication*, and 5) *Final Customer Satisfaction*). Specific metrics were defined to meet the needs of the research objectives. From the analysis, it was determined that there were many opportunities for improvement in the flow of information due to aggregation, transformation, and delays (some based on specific company policies). Additionally, the material flow (through the performance measure of *flexibility*) was identified to have a low value for short-term turn around time in relation to the demand needs of the Final Customer which is indicative of an agile supply chain (i.e. meeting the immediate needs of the customer). However, the buffer inventory contributes heavily to the lack of adaptability of the supply chain (i.e. the ability to change with customer needs).

Analyses of the supply chain segments were conducted to identify the implications of increased information flow on the material flow in the supply chain. Simulation models were utilized to determine the affect of advanced knowledge of demand on the management of buffer inventory levels between adjacent members of the supply chain. It was determined that advanced knowledge of demand can cause a decrease in buffer inventory levels while maintaining the same customer service level. An optimal number of days of advanced knowledge was identified by which no more decreases in buffer inventory were determined for increased days of knowledge. Overall, the case study supply chain saw an increase in material flow of 10% with increased information sharing between the supply chain partners. In addition, the reductions in buffer inventory within the members of the supply chain created additional increases in information flow since it was determined that material flow and information flow are both tied to buffer inventories. Reductions in buffer inventories caused an increase in the total inventory flow of the case study supply chain of an additional 7%, which with the increase in information flow through advanced knowledge between the supply chain members created a total increase in information flow through the case study supply chain of 25%.

For the individual companies within a supply chain, the implication based on this research is that obtaining information on demand in a timelier manner can reduce material flow and decrease costs of operations for the company. These costs are associated specifically with the buffer inventories that are created due to the aggregated demand information of replenishment orders. Increased information from customers can only serve to reduce the buffer inventory as much as was initially caused by forecasting of demand, and cannot reduce the buffer inventory caused by discrepancies between production rate and order rate. For that to occur, production would have to go to a make-to-order production strategy which may shift buffer inventories to other parts of a company such as in the Assembly Plant of the case study supply chain.

In some cases, increased information sharing can serve to reduce or eliminate the effects of delays in material flow of a company but not necessarily reduce or eliminate the actual delays, such as in the Component Plant of the case study supply chain. Although the material delays still exist, the increased information flow aids in negating it. In this particular case, it would be important for the company to decide if (a) increasing the information flow, (b) decreasing the delay in the material flow, or (c) some combination of both would be appropriate for their current and future needs.

For companies that are researching information systems as a means of increasing information and material flow for supply chain logistics, the methodology utilized within this research could be adapted to determine the expected outcomes (future states) of increased information flow. Analyzing a company or supply chain utilizing Value Stream Mapping, system dynamics, and performance measures as was done in this research is a relatively inexpensive benchmarking and analysis methodology. However, using this methodology can be time consuming due to the time it takes to track both information and material flows in a supply chain. With the knowledge of the effects of increased information on buffer inventory (a reduction/elimination of variation for the order process), a company can determine the expected reduction of costs with increased information flow, and determine the return on investment (ROI) of the implementation of information systems that might be required to obtain the increased information flow.

Increasing information sharing without changes to production and inventory policies was found to be beneficial within the case study supply chain within the constraints of the policies and standards that are currently in place for the individual members of the supply chain. Additional opportunities exist for customer-focus through changes in the companies' policies. As an example, supply chain partners utilizing alternative material flow systems such as vendor managed inventory (Cachon et al. 1997; Waller et al. 1999) in conjunction with increased information sharing have been found to be beneficial to the supplier, the immediate customer, and the final customer.

8.2 Study Limitations

As with any case study approach to research, there is great opportunity for detailed analysis of a particular system. The problem arises on how well the case study (one supply chain) speaks to the population that it is intended to describe (Hardwood Industry). Although the specific results of the study may not be applicable throughout the Hardwood Industry, the selection of the particular supply chain for the case study based on the criteria described in the methodology, make it representative and a proper primer for future research.

The focal company was chosen based on being a manufacturer of a product that falls within one of the three top uses of high grade hardwood lumber in the United States. The degree that this company operates in a manner similar to those companies within the top three or even in the same use is unclear. Specific results determined within the research, such as the exact reduction in buffer inventory with increased knowledge of orders, are not transferable to other supply chains. What is transferable is knowledge of the relationship between information and material flow detailed in the research. With the methodology utilized in this research, results of increased information flow can be determined for individual supply chains.

It is common in research to analyze a supply chain as a single line of companies from raw material to final customer. However, in reality, companies are typically not aligned in linear fashion with each company only having one supplier and one customer. A better descriptor of the relationship between a company and its suppliers and customers would be “supply web” or “supply grid” with each company having multiple suppliers and multiple customers. When compared to a supply “chain,” the supply “grid” with its increased complexities becomes less applicable to other supply “grids.” Thus, the supply chain analysis was utilized in this research to make the results more transparent. The same analysis can be adapted and extended to more complex supply grids.

Data collected and presented throughout the research is for only one particular material flow through the supply chain, acknowledging that each company has additional products not incorporated into the research. The results are specific to the raw material, component, and final product which were chosen to be the subject in the research. In most cases, the form of material in the research was selected based on it being representative of a majority of the product that the particular company manufacturers. Individual results for each company will vary based on the amount of deviation the products and product lines have from the particular products utilized in the research.

Some of the data was historical data supplied by the companies of the case study supply chain. In most cases, the data was limited to what the companies were willing and/or able to provide. It was necessary to make certain assumptions based on discrepancies based on time-frame, units of measurement, aggregation of the information, etc. Through the course of writing the document, an attempt was made to identify the sources, the characteristics, and assumptions regarding the data as it was applied.

The research was presented to show a current state analysis of a particular supply chain and to analyze future states of the supply chain for improved performance under hypothesized changes. A current state is a snapshot of a system at a specific time or time period. The results of this research reflect the system at a specific time period from 2007 though 2009.

8.3 Recommendations for future research

Based on the research analyses and results in this study, some recommendation for future research are as follows:

- The benchmarking of the material flow and information flow conducted in this research would be of potential interest to companies for self analysis. Companies within the Hardwood Industry (and other industries) can utilize this information to identify opportunities for improvement within their own supply chains. By expanding the research of lead-times of material flow and information flow to other companies and supply chains in the Hardwood Industry, the results will be more applicable to a large portion of the Hardwood Industry.
- The analysis of information flow using System Dynamics revealed that one segment of the supply chain utilizes procurement policies that are more rudimentary than the other segments of the case study supply chain. The link between the Component Plant and the Raw Material Supplier utilize policies that make optimization in production and inventory difficult for both of these particular supply chain members. There is an opportunity to research the drivers of trade between the raw material suppliers and their customers and to develop improvement opportunities to increase efficiency and effectiveness.
- Value Stream Mapping has been utilized in companies as a tool to determine opportunities for improvement, specifically with the analysis of flow of material through a supply chain, a facility or a portion of a facility. This research utilized Value Stream Mapping for that purpose and for determining opportunities for improvement related to the flow of information through the supply chain. Research on the viability of this later usage of Value Stream Mapping would be useful to industries to determine if complicated and delayed information flow pathways exist that interfere with material flow pathways.
- As stated in the Summary and Conclusions, this research determined the value of increasing information flow for a supply chain in the Hardwood Industry under the stipulation that the specific policies of production and inventory management held by the individual companies do not change. Addition research should be performed to determine the value of information change in the presence of policy change (such as with the implementation of vendor managed inventory, *Min/Max* systems, etc.) in the Hardwood Industry.

- Duplicating this research for other Hardwood Industry product segments, such as furniture or flooring, may reveal similarities and differences with the results of this study. The advantage to such research is to identify a systemic process to identify problems of the Hardwood Industry as a whole and to determine root sources of these problems in terms of how information flow is misaligned in the various sub-functions of the Hardwood Industry supply chain.

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Appendix A – Data Collection Methodology for Material and Information Flow

The collection of information at the case study supply chain, the portrayal of data and analysis of the results (Value Stream Mapping) in Chapter 4 were based on the published works of *Learning to See: Value-Stream Mapping to Create Value and Eliminate Muda* (Rother et al. 1998) and *Seeing the Whole: Mapping the Extended Value* Stream (Jones et al. 2003)[1]. The authors present a methodology by which complex systems, such as a factory (the first) or a supply chain (the later), can be presented in an uncomplicated manner so that the underlying relationships can be exposed.

Most of what is presented in the aforementioned books relates to the presentation and analysis of the information collected from a system of interest. Specific information on data collection is not presented by the authors as it is understood that the level of detail of information to be collected is based on a "manageable field of view" (Jones et al. 2003). The level of detail is recommend by the authors to be based on the final "map" of the investigated system fitting on one piece of paper so that the entire map may be absorbable to the viewer.

Whether for one factory or an entire supply chain, the first step is the determination of what it is that will be followed through the system. It is safe to say that any manufacturing system has any number of products passing through it, with any number of sources for the components, pathways through the system, and/or destinations. The first step is then to identify the specific material, product, or group of products that follow the pathway of interest in the study. As manufacturing is a transformative process, it may be necessary to identify the specific product, component, AND raw material. For a forest product supply chain, it would be as if a specific fiber from a tree is followed through a supply chain as it is transformed to log, lumber, component, and finished product.

When creating a Value Stream Map of a supply chain, it is typical to already have a company of interest in mind. The company tends to be the manufacturer of the final product but could be representative of any stage in the supply chain. With the selection of the focal company, some preliminary investigation is suggested prior to collecting information for the

[1] For this particular appendix, the two books and their authors will be identified as "the books" and "the authors," respectively.

Value Stream Map. The investigation can be as simple as an interview with a manager within the focal company that is familiar with general knowledge of sales, production and purchasing (though additional interviews may be required with personnel who may have more details on specifics of each topic). What is hoped to be gained in this interview are:

- Identification of the product(s) of interest that will be followed through the focal company
- The supplier(s) of the material or component that are used in the manufacturing of the product(s) of interest in the focal company
- The customer(s) of the product of interest in the focal company

The selection of these three bits of information is based on the needs of the study and can be affected by any number of factors. Of primary concern for any of these are how representative they are to the focal company, to the total system (supply chain) that is desired to be analyzed, and to the industry segment. Once these three bits of information are determined, they must be repeated for the supplier of the focal company (determine product and supplier – the focal company is the customer), the supplier of the supplier, and so forth until the supply side of the supply chain has been fully identified. Likewise, the investigation should continue with the customer of the focal company, and the customer of the customer, etc., until the entire supply chain to be studied is identified. Ultimately, a supply chain should reflect the flow of material from the initial raw material (such as trees) to the final customer (such as a homeowner).

Once the individual segments have been identified, the data required for mapping the system can be collected. The authors call this step "Taking a walk" because essentially that is what is done – the person collecting the data walks through a facility following the path of the raw material, component, or product. While following this path, information is collected on what steps the raw material, component, or product goes through and how long it takes. This is not meant to be a highly detailed analysis of the individual steps in production, i.e. distributions of times is not necessary. In addition, it is accepted that there are cycles and trends that occur in any production facility. A value stream map is meant only to capture the system in the current moment, like a picture, so cycles and trends are not necessarily applicable.

With many production facilities, it is possible that the lead time for production (the time from when raw material enters the facility to the time a finished product leaves the facility) is days, weeks, or even months long, so following one specific product through a facility may not be feasible. Thus, one does not follow a specific product; instead, one follows the route that a specific part follows through a facility.

When "taking a walk," it is helpful if a representative who is familiar with production joins you. Following routing sheets on your own through a company can be overwhelming. In addition, the representative can assist in collecting data or introducing you to those that can. There may be information that is not readily available during the "walk"; the representative may be able to assist you in obtaining the information once the "walk" is complete.

The goal of "taking a walk" is to have a table similar to Table 4-1, with all of the steps in the manufacturing of the product of interest and the time it took to perform the steps. It is important to note that all of the steps include not only manufacturing steps, but also transportation, inventory, and/or other delays that occurred as the material is moved through the facility and between facilities. As an example, it may only take 1 minute to perform one task in production, but it may have to wait in a queue for 1 day before the one task, then it may have to be transported to another task in the production which takes 20 minutes. All of these are important steps in the process of manufacturing and all of these steps should be captured within the final map.

It may be convenient to aggregate some of the steps into one larger step, especially if a product goes through many small steps at one station, for instance, a cabinet may have 20 knobs that must be attached. Instead of a step being the installation of one knob, it may be more appropriate to combine all of the steps into one larger step and get the timing for that one step.

Just because a product goes through a step does not mean that it is necessarily important in the manufacturing process. Part of the analysis in Value Stream Mapping is to identify the key steps in the manufacturing processes that are "value added." That is to say they are necessary and increase the inherent value of the final product. For instance, adding knobs to a cabinet adds value to the cabinet. Whereas, the time it takes to move the cabinet to the station so that the knobs can be attached, has no value to the final customer. So, during collection of information while "taking a walk," it is important to note that a step has value. In the case of an aggregated step it is important to note how many sub-steps were performed of value and the exact time of the sub-steps that were "value added." In our knob example, the step may be defined as the assembly station that installs the knobs and also installs hinges. The station (and thus step) may delay the cabinet by 5 minutes, but the sub-sets of adding the knobs and adding the hinges (two value added steps) take 2 minutes, with moving the cabinet and set-ups taking the remaining 3 minutes. As shown in Table 4-1, columns are included in the information sheet, which identify the number of sub-sets that are value creating steps and the total time for that value creation.

If done correctly, the data collection for each facility along a supply chain should be combined to completely describe every step that material took along the supply chain from raw material to the final customer. This information can then be compiled as a Value Stream Map similar to that of Figure 4-4 utilizing the two books referenced at the beginning of this appendix.

Data Collection-Specifics

Material Flow Data Collection

Once the general flow of material was determined for the supply chain and products/material of interest, a detailed analysis of material was performed. Utilizing routing sheets for material flow, a manager direction, or some combination of both, each step in the flow of material through a facility was identified and the appropriate data was collected. Raw data included specific timings taken by researcher and interviewing pertinent personnel such as managers and laborers. The specific data collected during the step was based on the type of step and the information required. The following is a listing of the steps and the type of information that was collected:

Transportation between facilities/supply chain members

- Batch/cargo size
- Distance between facilities
- Time for transportation
- Frequency of delivery
- Loading time
- Unloading time

Individual work centers - timings performed to identify averages and range of lead times

Batch size

Lead time through work center

Queue size

Storage – Raw Material, Work-in-Progress, and Finished Goods

Average size of inventory

Number of inventory turns

General Production

Number of shifts per day

Days per week of production

Frequency of production of the part/component/product of interest

For Value Stream Mapping, the data collected must represent an average value for a reasonable production and usage. In most cases, these values only represent the material flow of a portion of production, transportation, and storage at a supply chain member and extrapolation to the entire production of a supply chain member may misrepresent actual production values for the individual facility.

Information Flow Data Collection

Key management positions in the material flow were identified based on preliminary analysis of the flow of material through the individual members that make up the case study supply chain. These include production managers, inventory/material managers, sales/marketing representatives, and purchasers. Interviews with these personnel were conducted in order to obtain the following information:

- Specific information utilized in decision-making process for position (production demand, inventory needs, orders)
- Source of information (customer, database, sales, other manager)

- Method of information transference from source
- Portrayal of information
- Transformation of information by manager
- Time between original reception of information and action on information
- Specific delays that occur and reasons for occurrences
- Frequency of update of information
- Policies that affect information usage/transference
- Next location of information/decision based on information

Due to the variation in positions and the need to identify specific factors that affect the flow of information and material through the supply chain (as presented in Chapter 5), the questioning required detailed discussions of the above to explore how and why information was utilized. Copies of reports, databases, production orders, and any information sources utilized by the interviewees were obtain when possible as well as reports, production orders, etc that were produced by the interviewees for own use or disseminated to other members of the company and/or supply chain partners.

During the individual interviews it was necessary to identify the individual's role in the overall evaluation of the supply chain member's performance based on the metrics identified and analyzed in Chapter 6. The performance measures and specific metrics are as follows:

Information Integration

Information Transformations	______
Age of Information	______
Information Aggregation	______

Visibility and Trust

Separation	______
Direction of Visibility	______
Method of Communication	______

Flexibility

Short-Term Turn Around ______

Long-Term Turn Around ______

Functional Duplication

Order Processing Duplication ______

Production Duplication ______

Final Customer Satisfaction

Delivery Date Contribution ______

Simulation Data Collection

The simulation analysis of the current and future states of the case study supply chain required a more detailed collection of production information from the individual members of the supply chain. Reports for production and demand were obtained from the key personnel throughout the supply chain. Distributions of production timings, material utilizations, and material/product demand were determined based on these reports.

Reports included, but were not limited to:

- Raw Material Supplier delivery schedules to Component Plant
- Inventory Status report at Component Plant
- Production Schedules for components
- Rough Mill production orders
- Production report for finishing department at Component Plant
- Dashboard of performance measures at Manufacturing Company
- Lumber Storage at Component Plant
- Daily Production Reports at Component Plant
- Component Inventory at Assembly Plant
- Component Demand at Assembly Plant
- Sales Report at Retailer

Appendix B - Furniture Supply Chain Material Flow

For the purpose of validating the results of the case study supply chain material and information flow analysis, a second supply chain was analyzed. The second supply chain was selected based on it being within the hardwood industry, but being of a different sector, furniture. The focal company within this second supply chain was also chosen because it manufactures case goods (wardrobes, buffets, dressers, etc.) which are similar in structure to kitchen cabinets, and more importantly have components similar to those that were followed in the cases study supply chain.

A preliminary analysis of the general structure of these two supply chains (Table B-1) shows that there are a number of similarities, though manufacturing different products for a household. Each supply chain is three components, a Raw Material Supplier, Manufacturing Company (focal companies), and a Retailer. The raw material suppliers both maintain logging crews. The focal companies are large enough that they require multiple lumber suppliers to accommodate the production needs. The focal companies in both supply chains dry the lumber at their own facilities. The retailers for both supply chains do not maintain inventory at their stores.

Table B-1 Comparison of Case Study Supply Chain to Validating Supply Chain

	Case Study Supply Chain	Other Supply Chain
Overall	Kitchen cabinet industry Employs 5000	Furniture industry Employs 2200
Raw Materials	Hardwood lumber and panel products	Hardwood & softwood lumber and panel products
Supply Chain	Three companies between raw material and final customer (four facilities)	Three companies between raw material and final customer (three facilities)
Raw Material Supplier	• One of a number of hardwood suppliers • Maintains company loggers • Multiple facilities (2)	• One of a number of hardwood suppliers • Maintains company loggers • Single facility
Focal Company	• Multiple facilities • Lumber drying on site • Pre-dryers • Build to order	• Multiple facilities • Lumber drying on site • Air drying • Build to inventory
Retailer	• Maintains own shipping with focal company • No delivery to customers	• Hires secondary shipping with focal company • Delivery to customers
Product Followed	• Red oak • Cabinet door • Case good	• Red oak • Cabinet door • Case good

The major differences between the two supply chains occur at the focal companies. First, the focal company of the case study has two separate facilities that make up the manufacturing process whereas the focal company of the other supply chain manufactures the finished product from lumber all under one roof. Second, the focal company of the case study manufactures the finished product to-order, which means they maintain component inventory but no finished product inventory, whereas the focal company of the other supply chain manufactures finished products to meet finished product inventory needs (the customers purchase from inventory), and does not maintain an inventory of components.

The furniture supply chain was analyzed similarly to the case study supply chain utilizing Value Stream Mapping as outlined by Womack (2006), specifically as outline for supply chains by Johns and Womack (2003). A product with a similar component as that of the case study supply chain and the material flow was followed from a raw material supplier, through the focal company, to a retailer of the final product. The resulting Value Stream Map is shown in Figure B-1.

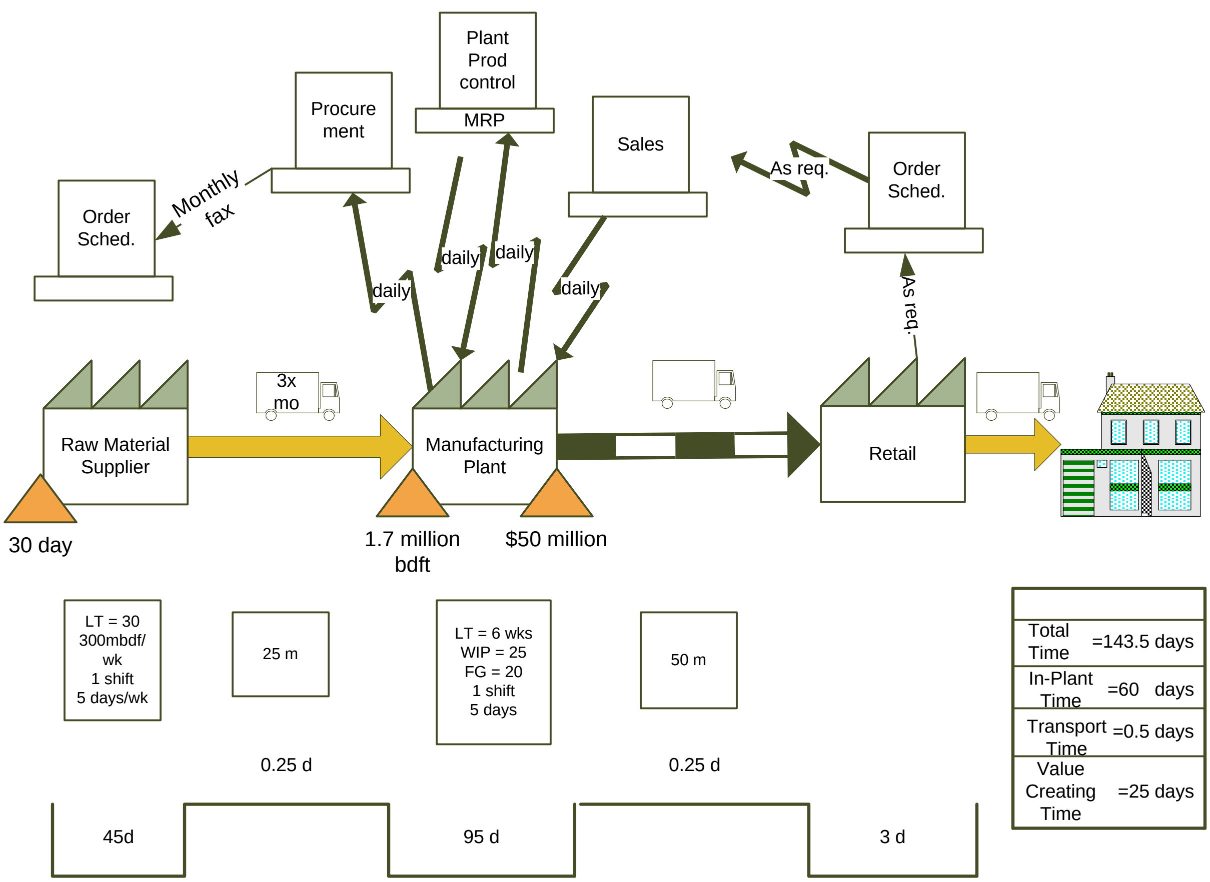

Figure B-1 Value Stream Map of Hardwood Furniture Supply Chain

Table B-2 Analysis of Case Study Supply Chain to Validating Supply Chain

	Case Study Supply Chain	Other Supply Chain
Total Lead Time	95 days	143.5 days
Inventory Locations	• Focal Company – Dry lumber storage (Component Plant) • Focal Company – Component storage (Component Plant) • Focal Company – Component storage (Assembly Plant) • Raw Material Supplier – log decks	• Focal Company – Dry lumber storage • Focal Company – Finished goods • Raw Material Supplier – log decks
Retailer	• Demonstration inventory only • Orders delayed	• Demonstration inventory only • Orders immediately sent
Focal Company -production lead time Supplier orders Information from customers	 11 days (Comp + Asm Plants) 30 day to delivery No final customer contact	 6 weeks 60 day to delivery No final customer contact
Raw Material Supplier	30 day delivery	30 day delivery

A comparison of the two supply chains (Table B-2) show that the difference in lead times between the two supply chains are primarily due to three factors. First, the Raw Material Supplier for the validating supply chain maintains a larger safety stock of logs at the sawmill than the Raw Material Supplier for the case study supply chain (30 versus 18 days). Second, the

Focal Company for the validating supply chain utilizes air-drying (drying in the elements) before the drying process unlike the Component Plant for the case study supply chain which utilizes a pre-dryer (control chamber). The air drying method can take longer than when utilizing a pre-dryer thus adding time to the total lead time of the supply chain. Finally, the Focal Company for the validating supply chain has a much larger lead time through the manufacturing process than the case study supply chain.

In regards to inventory, the Focal Companies from both supply chains maintain a majority of the inventory of their respective supply chains with the Raw Material Suppliers of both supply chains holding similar inventories to each other in their incoming inventories at their sawmills. The difference in inventories between the Focal Companies from each supply chain is based on the differences in production strategies for each company. The case study Focal Company manufactures to order (at the Assembly Plant) and holds no finished goods inventory. The validating Focal Company makes to finished goods inventory (and sold from there) and holds no component inventory. However, the component inventory strategy of the Component Plant in the case study supply chain is identical to that of the finished goods strategy of the Focal Company of the validating supply chain. They both manually balance inventory levels against production capacity, product usage rate, and work in progress.

The flow of information through the two supply chains is quite similar. The Retailer shares with the Focal Company only information directly related to the product. In both cases, the Focal Companies do not maintain any contact with the Final Customer, relying mostly on the Retailer for customer service. Also in both cases, the product orders are not shared with the procurement officers, who must base all decisions on current inventory levels and past usage causing a delay from actual demand both through the lead times within the Focal Companies and whatever was created due to delays between Retailers and production.

Appendix C - Retailer/Assembly Plant Simulation Model

Simulation program designed in Arena, shown in Siman code.

```
;     Model statements for module:  Create 2


35$          CREATE,        1,HoursToBaseTime(0),Entity 1:HoursToBaseTime(0),1:NEXT(36$);


36$          ASSIGN:        Begin.NumberOut=Begin.NumberOut + 1:NEXT(2$);
;
;     Model statements for module:  Assign 10
;
2$           ASSIGN:        Final stock=0:
                            Total Production=0:
                            failedreplenishment=0:
                            stockouttemp=0:
                            extrastock=0:
                            Replenishments=0:
                            stockout=0:NEXT(10$);
;
;     Model statements for module:  Assign 16
;
10$          ASSIGN:        EOQ=20:
                            Avgdemand=1:
                            AvgLeadTime=40:
                            StdevLeadTime=3.11:
                            StdevUsage=0.329:
                            daysofknowledge=2:NEXT(11$);
;
;     Model statements for module:  Assign 17
;
11$          ASSIGN:        Stock1=EOQ:
                            futurestock1=EOQ:
                            avgusage=8/avgdemand:NEXT(7$);
;
;     Model statements for module:  Assign 14
;
```

```
7$          ASSIGN:       Minimum=5:NEXT(Create working stock);

Create working stock DUPLICATE: 50,16$:NEXT(16$);
;
;     Model statements for module:  Assign 20
;
16$          ASSIGN:       futuredelay=norm(avgusage,stdevusage):NEXT(20$);
;
;     Model statements for module:  Decide 11
;
20$          BRANCH,       1:
                  If,daysofknowledge>0,39$,Yes:
                  Else,40$,Yes;
39$          ASSIGN:       Is there advanced knowledge.NumberOut True=Is there advanced knowledge.NumberOut
          True + 1:NEXT(1$);

40$          ASSIGN:       Is there advanced knowledge.NumberOut False=Is there advanced knowledge.NumberOut
          False + 1
                  :NEXT(19$);
;
;     Model statements for module:  Process 1
;
1$          ASSIGN:       Actual Delay between order arrivals.NumberIn=Actual Delay between order
          arrivals.NumberIn + 1:
                  Actual Delay between order arrivals.WIP=Actual Delay between order arrivals.WIP+1;
44$          QUEUE,        Actual Delay between order arrivals.Queue;
43$          SEIZE,        2,NVA:
                  manufacturing,1:NEXT(42$);

42$          DELAY:        futuredelay,,NVA;
41$          RELEASE:      manufacturing,1;
89$          ASSIGN:       Actual Delay between order arrivals.NumberOut=Actual Delay between order
          arrivals.NumberOut + 1:
                  Actual Delay between order arrivals.WIP=Actual Delay between order arrivals.WIP-
          1:NEXT(27$);
;
;     Model statements for module:  Assign 27
```

```
;
27$          ASSIGN:       Total Production=Total Production+1:NEXT(22$);


22$          DUPLICATE:    1,17$:NEXT(18$);
;
;     Model statements for module:  Process 3
;
18$          ASSIGN:       knowledgeleadtime.NumberIn=knowledgeleadtime.NumberIn + 1:
                    knowledgeleadtime.WIP=knowledgeleadtime.WIP+1;
93$          DELAY:        daysofknowledge*8,,VA;
140$         ASSIGN:       knowledgeleadtime.NumberOut=knowledgeleadtime.NumberOut + 1:
                    knowledgeleadtime.WIP=knowledgeleadtime.WIP-1:NEXT(23$);
;
;     Model statements for module:  Assign 24
;
23$          ASSIGN:       Stock1=Stock1-1:NEXT(24$);
;
;     Model statements for module:  Decide 13
;
24$          BRANCH,       1:
                    If,Stock1<=0,143$,Yes:
                    Else,144$,Yes;
143$         ASSIGN:       stockout1?.NumberOut True=stockout1?.NumberOut True + 1:NEXT(25$);


144$         ASSIGN:       stockout1?.NumberOut False=stockout1?.NumberOut False + 1:NEXT(15$);
;
;     Model statements for module:  Assign 25
;
25$          ASSIGN:       stockout=stockout+1:
                    stockouttemp=stockouttemp+1:NEXT(15$);
;
;     Model statements for module:  Dispose 2
;
15$          ASSIGN:       Dispose 2.NumberOut=Dispose 2.NumberOut + 1;
145$         DISPOSE:      Yes;
;
;     Model statements for module:  Assign 21
```

```
;
17$          ASSIGN:       futurestock1=futurestock1-1:NEXT(8$);
;
;    Model statements for module:  Decide 5
;
8$           BRANCH,       1:
                           If,futurestock1==minimum,146$,Yes:
                           Else,147$,Yes;
146$         ASSIGN:       Minimum?.NumberOut True=Minimum?.NumberOut True + 1:NEXT(3$);

147$         ASSIGN:       Minimum?.NumberOut False=Minimum?.NumberOut False + 1:NEXT(16$);
;
;    Model statements for module:  Process 2
;
3$           ASSIGN:       Replenishment Delay.NumberIn=Replenishment Delay.NumberIn + 1:
                           Replenishment Delay.WIP=Replenishment Delay.WIP+1;
149$         DELAY:        Normal(AvgLeadTime,StdevLeadTime),,VA;
196$         ASSIGN:       Replenishment Delay.NumberOut=Replenishment Delay.NumberOut + 1:
                           Replenishment Delay.WIP=Replenishment Delay.WIP-1:NEXT(9$);
;
;    Model statements for module:  Assign 15
;
9$           ASSIGN:       extrastock=extrastock+stock1:NEXT(4$);
;
;    Model statements for module:  Assign 11
;
4$           ASSIGN:       futurestock1=futurestock1+EOQ:
                           Stock1=Stock1+EOQ:
                           Replenishments=Replenishments+1:NEXT(12$);
;
;    Model statements for module:  Decide 7
;
12$          BRANCH,       1:
                           If,stockouttemp>=1,199$,Yes:
                           Else,200$,Yes;
199$         ASSIGN:       Was there a stockout?.NumberOut True=Was there a stockout?.NumberOut True +
       1:NEXT(13$);
```

```
200$        ASSIGN:     Was there a stockout?.NumberOut False=Was there a stockout?.NumberOut False +
        1:NEXT(16$);
;
;    Model statements for module:  Assign 18
;
13$         ASSIGN:     failedreplenishment=failedreplenishment+1:NEXT(14$);
;
;    Model statements for module:  Assign 19
;
14$         ASSIGN:     stockouttemp=0:NEXT(16$);
;
;    Model statements for module:  Process 4
;
19$         ASSIGN:     actual delay.NumberIn=actual delay.NumberIn + 1:
                    actual delay.WIP=actual delay.WIP+1;
204$        QUEUE,      actual delay.Queue;
203$        SEIZE,      2,VA:
                    manufacturing,1:NEXT(202$);

202$        DELAY:      futuredelay,,VA;
201$        RELEASE:    manufacturing,1;
249$        ASSIGN:     actual delay.NumberOut=actual delay.NumberOut + 1:
                    actual delay.WIP=actual delay.WIP-1:NEXT(26$);
;
;    Model statements for module:  Assign 26
;
26$         ASSIGN:     Total Production=Total Production+1:NEXT(0$);
;
;    Model statements for module:  Assign 9
;
0$          ASSIGN:     Stock1=Stock1-1:NEXT(5$);
;
;    Model statements for module:  Decide 4
;
5$          BRANCH,     1:
                    If,Stock1<=0,252$,Yes:
```

```
                    Else,253$,Yes;
252$        ASSIGN:       stockout?.NumberOut True=stockout?.NumberOut True + 1:NEXT(6$);

253$        ASSIGN:       stockout?.NumberOut False=stockout?.NumberOut False + 1:NEXT(21$);
;
;    Model statements for module:  Assign 13
;
6$          ASSIGN:       stockout=stockout+1:
                    stockouttemp=stockouttemp+1:NEXT(21$);
;
;    Model statements for module:  Decide 12
;
21$         BRANCH,       1:
                    If,Stock1==minimum,254$,Yes:
                    Else,255$,Yes;
254$        ASSIGN:       Minimumcurrent.NumberOut True=Minimumcurrent.NumberOut True + 1:NEXT(3$);

255$        ASSIGN:       Minimumcurrent.NumberOut False=Minimumcurrent.NumberOut False + 1:NEXT(16$);
;
;    Model statements for module:  Create 3
;

256$        CREATE,       1,HoursToBaseTime(20799),Entity 1:HoursToBaseTime(20800),1:NEXT(257$);

257$        ASSIGN:       Replications.NumberOut=Replications.NumberOut + 1:NEXT(28$);
;
;    Model statements for module:  Assign 28
;
28$         ASSIGN:       Final stock=extrastock:NEXT(31$);
;
;    Model statements for module:  Record 5
;
31$         COUNT:        afailedreplenishment1,failedreplenishment:NEXT(32$);
;
;    Model statements for module:  Record 6
;
32$         COUNT:        bstockout1,stockout:NEXT(33$);
```

```
;
;    Model statements for module:  Record 7
;
33$         COUNT:        cReplenishments1,Replenishments:NEXT(30$);
;
;    Model statements for module:  Record 2
;
30$         COUNT:        dextrastock1,extrastock:NEXT(34$);
;
;    Model statements for module:  Record 8
;
34$         COUNT:        eTotal Production1,Total Production:NEXT(29$);
;
;    Model statements for module:  Dispose 3
;
29$         ASSIGN:       Dispose 3.NumberOut=Dispose 3.NumberOut + 1;
260$         DISPOSE:      Yes;
```

Appendix D - Assembly Plant/Component Plant Simulation Model

Simulation program designed in Arena, shown in Siman code.

```
;     Model statements for module:  Create 1
;
53$           CREATE,        1,HoursToBaseTime(0.0),Entity 1:HoursToBaseTime(1),1:NEXT(54$);


54$           ASSIGN:        Create 1.NumberOut=Create 1.NumberOut + 1:NEXT(4$);
;
;     Model statements for module:  Assign 7
;
4$            ASSIGN:        CPOrders to Schedule=0:
                             CPOrders=0:
                             APOrders=0:
                             Stockout=0:
                             CPStockout=0:
                             MTDOrders=0:
                             MTDProd=0:
                             DailyProductionAvg=0:
                             TotalCPProduction=0:
                             TotalAPDemand=0:
                             TotalRetailDemand=0:
                             Stockout=0:NEXT(0$);
;
;     Model statements for module:  Assign 1
;
0$            ASSIGN:        Daysaveraged=30:
                             AP4Inventory=30:
                             AvgDemand=10.5:
                             Stdevusage=0.439:
                             DaysofKnowledge=0:
                             Batchsize=120:
                             AP1Inventory=0:
                             AP2Inventory=10:
                             AP3Inventory=20:NEXT(32$);
```

```
;
;
;     Model statements for module:  Assign 25
;
32$          ASSIGN:        AvgUsage=8/AvgDemand:
                    DesiredCPInventory=11*4*AvgDemand:
                    InitialCPInventory=DesiredCPInventory+400:
                    CPInventory=InitialCPInventory:NEXT(9$);

9$           DUPLICATE:     1,16$:
                    1,10$:
                    1,1$:NEXT(22$);
;
;     Model statements for module:  Assign 20
;
22$          ASSIGN:        AP1delay=norm(Avgusage,Stdevusage):NEXT(23$);
;
;     Model statements for module:  Process 9
;
23$          ASSIGN:        Process 9.NumberIn=Process 9.NumberIn + 1:
                    Process 9.WIP=Process 9.WIP+1;
58$          DELAY:         AP1delay,,VA;
105$         ASSIGN:        Process 9.NumberOut=Process 9.NumberOut + 1:
                    Process 9.WIP=Process 9.WIP-1:NEXT(24$);
;
;     Model statements for module:  Assign 21
;
24$          ASSIGN:        AP1Inventory=AP1Inventory+1:
                    TotalRetailDemand=TotalRetailDemand+1:NEXT(25$);

25$          DUPLICATE:     1,22$:NEXT(26$);
;
;     Model statements for module:  Decide 10
;
26$          BRANCH,        1:
                    If,AP1Inventory==Batchsize,108$,Yes:
                    Else,109$,Yes;
```

```
108$          ASSIGN:       Decide 10.NumberOut True=Decide 10.NumberOut True + 1:NEXT(30$);


109$          ASSIGN:       Decide 10.NumberOut False=Decide 10.NumberOut False + 1:NEXT(27$);
;
;     Model statements for module:  Assign 24
;
30$           ASSIGN:       AP1Inventory=0:
                       APOrders=APOrders+1:NEXT(35$);
;
;     Model statements for module:  Assign 32
;
35$           ASSIGN:       TotalAPDemand=TotalAPDemand+Batchsize:NEXT(31$);
;
;     Model statements for module:  Dispose 11
;
31$           ASSIGN:       Dispose 11.NumberOut=Dispose 11.NumberOut + 1;
110$          DISPOSE:      Yes;
;
;     Model statements for module:  Dispose 8
;
27$           ASSIGN:       Dispose 8.NumberOut=Dispose 8.NumberOut + 1;
111$          DISPOSE:      Yes;
;
;     Model statements for module:  Assign 18
;
16$           ASSIGN:       AP2delay=norm(Avgusage,Stdevusage):NEXT(17$);
;
;     Model statements for module:  Process 8
;
17$           ASSIGN:       Process 8.NumberIn=Process 8.NumberIn + 1:
                       Process 8.WIP=Process 8.WIP+1;
113$          DELAY:        AP2delay,,VA;
160$          ASSIGN:       Process 8.NumberOut=Process 8.NumberOut + 1:
                       Process 8.WIP=Process 8.WIP-1:NEXT(18$);



;
```

```
;
;     Model statements for module:  Assign 19
;
18$          ASSIGN:       TotalRetailDemand=TotalRetailDemand+1:
                       AP2Inventory=AP2Inventory+1:NEXT(19$);


19$          DUPLICATE:     1,16$:NEXT(20$);
;
;     Model statements for module:  Decide 9
;
20$          BRANCH,       1:
                       If,AP2Inventory==Batchsize,163$,Yes:
                       Else,164$,Yes;
163$         ASSIGN:       Decide 9.NumberOut True=Decide 9.NumberOut True + 1:NEXT(29$);


164$         ASSIGN:       Decide 9.NumberOut False=Decide 9.NumberOut False + 1:NEXT(21$);
;
;     Model statements for module:  Assign 23
;
29$          ASSIGN:       AP2Inventory=0:
                       APOrders=APOrders+1:NEXT(35$);
;
;     Model statements for module:  Dispose 7
;
21$          ASSIGN:       Dispose 7.NumberOut=Dispose 7.NumberOut + 1;
165$         DISPOSE:      Yes;
;
;     Model statements for module:  Assign 16
;
10$          ASSIGN:       AP3delay=norm(Avgusage,Stdevusage):NEXT(11$);
;
;     Model statements for module:  Process 7
;
11$          ASSIGN:       Process 7.NumberIn=Process 7.NumberIn + 1:
                       Process 7.WIP=Process 7.WIP+1;
167$         DELAY:        AP3delay,,VA;
214$         ASSIGN:       Process 7.NumberOut=Process 7.NumberOut + 1:
```

```
                    Process 7.WIP=Process 7.WIP-1:NEXT(12$);
;
;     Model statements for module:  Assign 17
;
12$          ASSIGN:       AP3Inventory=AP3Inventory+1:
                    TotalRetailDemand=TotalRetailDemand+1:NEXT(13$);

13$          DUPLICATE:    1,10$:NEXT(14$);
;
;     Model statements for module:  Decide 8
;
14$          BRANCH,       1:
                    If,AP3Inventory==Batchsize,217$,Yes:
                    Else,218$,Yes;
217$         ASSIGN:       Decide 8.NumberOut True=Decide 8.NumberOut True + 1:NEXT(28$);

218$         ASSIGN:       Decide 8.NumberOut False=Decide 8.NumberOut False + 1:NEXT(15$);
;
;     Model statements for module:  Assign 22
;
28$          ASSIGN:       AP3Inventory=0:
                    APOrders=APOrders+1:NEXT(35$);
;
;     Model statements for module:  Dispose 6
;
15$          ASSIGN:       Dispose 6.NumberOut=Dispose 6.NumberOut + 1;
219$         DISPOSE:      Yes;
;
;     Model statements for module:  Assign 2
;
1$           ASSIGN:       AP4delay=norm(Avgusage,Stdevusage):NEXT(2$);
;
;     Model statements for module:  Process 2
;
2$           ASSIGN:       Process 2.NumberIn=Process 2.NumberIn + 1:
                    Process 2.WIP=Process 2.WIP+1;
221$         DELAY:        AP4delay,,VA;
```

```
268$          ASSIGN:       Process 2.NumberOut=Process 2.NumberOut + 1:
                     Process 2.WIP=Process 2.WIP-1:NEXT(3$);
;
;     Model statements for module:  Assign 3
;
3$            ASSIGN:       AP4Inventory=AP4Inventory+1:
                     TotalRetailDemand=TotalRetailDemand+1:NEXT(5$);

5$            DUPLICATE:    1,1$:NEXT(6$);
;
;     Model statements for module:  Decide 4
;
6$            BRANCH,       1:
                     If,AP4Inventory==Batchsize,271$,Yes:
                     Else,272$,Yes;
271$          ASSIGN:       Decide 4.NumberOut True=Decide 4.NumberOut True + 1:NEXT(8$);

272$          ASSIGN:       Decide 4.NumberOut False=Decide 4.NumberOut False + 1:NEXT(7$);
;
;     Model statements for module:  Assign 8
;
8$            ASSIGN:       AP4Inventory=0:
                     APOrders=APOrders+1:NEXT(35$);
;
;     Model statements for module:  Dispose 2
;
7$            ASSIGN:       Dispose 2.NumberOut=Dispose 2.NumberOut + 1;
273$          DISPOSE:      Yes;
;
;     Model statements for module:  Create 4
;

274$          CREATE,       1,HoursToBaseTime(8),Entity 1:HoursToBaseTime(8):NEXT(275$);

275$          ASSIGN:       Create 4.NumberOut=Create 4.NumberOut + 1:NEXT(34$);
;
;     Model statements for module:  Record 1
```

```
;
34$        TALLY:      CoPInventory,CPInventory,1:NEXT(33$);
;
;    Model statements for module:  Dispose 16
;
33$        ASSIGN:     Dispose 16.NumberOut=Dispose 16.NumberOut + 1;
278$       DISPOSE:    Yes;
;
;    Model statements for module:  Create 5
;
279$       CREATE,     1,HoursToBaseTime(8),Entity 1:HoursToBaseTime(8):NEXT(280$);

280$       ASSIGN:     Create 5.NumberOut=Create 5.NumberOut + 1:NEXT(36$);
;
;    Model statements for module:  Assign 33
;
36$        ASSIGN:     Dailydemand=APOrders:
                 APOrders=0:NEXT(38$);

38$        DUPLICATE:  1,42$:NEXT(37$);
;
;    Model statements for module:  Process 11
;
37$        ASSIGN:     T0.NumberIn=T0.NumberIn + 1:
                 T0.WIP=T0.WIP+1;
284$       DELAY:      160,,VA;
331$       ASSIGN:     T0.NumberOut=T0.NumberOut + 1:
                 T0.WIP=T0.WIP-1:NEXT(39$);
;
;    Model statements for module:  Process 12
;
39$        ASSIGN:     Shipping Delay.NumberIn=Shipping Delay.NumberIn + 1:
                 Shipping Delay.WIP=Shipping Delay.WIP+1;
335$       DELAY:      8,,VA;
382$       ASSIGN:     Shipping Delay.NumberOut=Shipping Delay.NumberOut + 1:
                 Shipping Delay.WIP=Shipping Delay.WIP-1:NEXT(40$);
;
```

```
;     Model statements for module:  Assign 34
;
40$          ASSIGN:        CPInventory=CPInventory-(DailyDemand*Batchsize):NEXT(51$);
;
;     Model statements for module:  Decide 15
;
51$          BRANCH,        1:
                        If,CPInventory<0,385$,Yes:
                        Else,386$,Yes;
385$         ASSIGN:        Stockout1.NumberOut True=Stockout1.NumberOut True + 1:NEXT(52$);

386$         ASSIGN:        Stockout1.NumberOut False=Stockout1.NumberOut False + 1:NEXT(41$);

;     Model statements for module:  Assign 38
;
52$          ASSIGN:        Stockout=Stockout+1:NEXT(41$);
;
;     Model statements for module:  Dispose 17
;
41$          ASSIGN:        Dispose 17.NumberOut=Dispose 17.NumberOut + 1;
387$         DISPOSE:       Yes;
;
;     Model statements for module:  Process 13
;
42$          ASSIGN:        T0 duplicate.NumberIn=T0 duplicate.NumberIn + 1:
                        T0 duplicate.WIP=T0 duplicate.WIP+1;
389$         DELAY:         160-(DaysofKnowledge*8),,VA;
436$         ASSIGN:        T0 duplicate.NumberOut=T0 duplicate.NumberOut + 1:
                        T0 duplicate.WIP=T0 duplicate.WIP-1:NEXT(44$);
;
;     Model statements for module:  Process 15
;
44$          ASSIGN:        Shipping Delay duplicate.NumberIn=Shipping Delay duplicate.NumberIn + 1:
                        Shipping Delay duplicate.WIP=Shipping Delay duplicate.WIP+1;
440$         DELAY:         8,,VA;
487$         ASSIGN:        Shipping Delay duplicate.NumberOut=Shipping Delay duplicate.NumberOut + 1:
                        Shipping Delay duplicate.WIP=Shipping Delay duplicate.WIP-1:NEXT(43$);
```

```
;
;     Model statements for module:  Process 14
;
43$          ASSIGN:       Scheduling Delay.NumberIn=Scheduling Delay.NumberIn + 1:
                           Scheduling Delay.WIP=Scheduling Delay.WIP+1;
491$         DELAY:        8,,VA;
538$         ASSIGN:       Scheduling Delay.NumberOut=Scheduling Delay.NumberOut + 1:
                           Scheduling Delay.WIP=Scheduling Delay.WIP-1:NEXT(45$);
;
;     Model statements for module:  Assign 35
;
45$          ASSIGN:       CPOrders to Schedule=CPOrders to Schedule +DailyDemand:NEXT(46$);
;
;     Model statements for module:  Batch 3
;
46$          QUEUE,        Batch 3.Queue;
541$         GROUP,        ,Permanent:5,Last:NEXT(542$);

542$         ASSIGN:       Batch 3.NumberOut=Batch 3.NumberOut + 1:NEXT(47$);
;
;     Model statements for module:  Assign 36
;
47$          ASSIGN:       Productionorder=CPOrders to Schedule:
                           CPOrders to Schedule=0:NEXT(48$);
;
;     Model statements for module:  Process 16
;
48$          ASSIGN:       Production.NumberIn=Production.NumberIn + 1:
                           Production.WIP=Production.WIP+1;
544$         DELAY:        16,,VA;
591$         ASSIGN:       Production.NumberOut=Production.NumberOut + 1:
                           Production.WIP=Production.WIP-1:NEXT(49$);
;
;     Model statements for module:  Assign 37
;
49$          ASSIGN:       CPInventory=CPInventory+(ProductionOrder*Batchsize):NEXT(50$);
```

```
;     Model statements for module:  Dispose 18
;
50$           ASSIGN:        Dispose 18.NumberOut=Dispose 18.NumberOut + 1;
594$          DISPOSE:       Yes;
```

Appendix E - Component Plant/Raw Material Supplier Simulation Model

Simulation program designed in Arena, shown in Siman code.

```
;     Model statements for module:  Create 2
;
35$          CREATE,        1,HoursToBaseTime(0.0),Entity 1:HoursToBaseTime(1),1:NEXT(36$);
36$          ASSIGN:        Create 2.NumberOut=Create 2.NumberOut + 1:NEXT(2$);
;
;     Model statements for module:  Assign 3
;
2$           ASSIGN:        Stockouts=0:
                    Monthlydemand1=0:NEXT(1$);
;
;     Model statements for module:  Assign 2
;
1$           ASSIGN:        LumberUsageAverage=15684:
                    LumberUsageStdDev=3163:
                    KilnDrying=40:
                    KilnCapacity=92000:
                    StartKilnCapacity=184000:
                    Inkilns=184000:
                    DryLumber=200000:
                    Predryingtime=344:
                    InPredryerdrying=0:
                    InPredryernotdrying=1536000:
                    Delivery=8000:NEXT(18$);
;
;     Model statements for module:  Assign 16
;
18$          ASSIGN:        FutureDryLumber=DryLumber-(10*LumberUsageAverage):NEXT(4$);
;
;     Model statements for module:  Dispose 2
;
4$           ASSIGN:        Dispose 2.NumberOut=Dispose 2.NumberOut + 1;
39$          DISPOSE:       Yes;
```

```
;
;     Model statements for module:  Create 3
;
40$           CREATE,        1,HoursToBaseTime(8),Entity 1:HoursToBaseTime(8):NEXT(41$);
41$           ASSIGN:        Create 3.NumberOut=Create 3.NumberOut + 1:NEXT(3$);
;
;     Model statements for module:  Assign 5
;
3$            ASSIGN:        LumberUsage=norm(LumberUsageAverage,LumberUsageStdDev):NEXT(5$);
;
;     Model statements for module:  Assign 6
;
5$            ASSIGN:        DryLumber=DryLumber-LumberUsage:NEXT(22$);
;
;     Model statements for module:  Assign 21
;
22$           ASSIGN:        Monthlydemand1=Monthlydemand1+lumberusage:NEXT(16$);
;
;     Model statements for module:  Dispose 7
;
16$           ASSIGN:        Dispose 7.NumberOut=Dispose 7.NumberOut + 1;
44$           DISPOSE:       Yes;
;
;     Model statements for module:  Create 6
;
45$           CREATE,        1,HoursToBaseTime(0),Entity 1:HoursToBaseTime(8):NEXT(46$);
46$           ASSIGN:        Create 6.NumberOut=Create 6.NumberOut + 1:NEXT(17$);
;
;     Model statements for module:  Assign 14
;
17$           ASSIGN:        FutureDryLumber=DryLumber-
((kilndrying/8)*LumberUsageAverage)+inkiln:NEXT(15$);
;
;     Model statements for module:  Decide 2
;
15$           BRANCH,        1:
                         If,FutureDryLumber<=110000,49$,Yes:
```

```
                    Else,50$,Yes;
49$        ASSIGN:      check.NumberOut True=check.NumberOut True + 1:NEXT(7$);
50$        ASSIGN:      check.NumberOut False=check.NumberOut False + 1:NEXT(10$);
;
;    Model statements for module:  Assign 7
;
7$         ASSIGN:      InPredryernotdrying=InPredryernotdrying-KilnCapacity:
                    InKiln=InKiln+KilnCapacity:NEXT(6$);
;
;    Model statements for module:  Process 1
;
6$         ASSIGN:      Kiln Drying Loading Unloading.NumberIn=Kiln Drying Loading Unloading.NumberIn +
1:
                    Kiln Drying Loading Unloading.WIP=Kiln Drying Loading Unloading.WIP+1;
52$        DELAY:       KilnDrying,,VA;
99$        ASSIGN:      Kiln Drying Loading Unloading.NumberOut=Kiln Drying Loading Unloading.NumberOut
+ 1:
                    Kiln Drying Loading Unloading.WIP=Kiln Drying Loading Unloading.WIP-1:NEXT(8$);
;
;    Model statements for module:  Assign 8
;
8$         ASSIGN:      InKiln=InKiln-KilnCapacity:
                    DryLumber=DryLumber+KilnCapacity:NEXT(9$);
;
;    Model statements for module:  Dispose 4
;
9$         ASSIGN:      Dispose 4.NumberOut=Dispose 4.NumberOut + 1;
102$       DISPOSE:     Yes;
;
;    Model statements for module:  Dispose 5
;
10$        ASSIGN:      Dispose 5.NumberOut=Dispose 5.NumberOut + 1;
103$       DISPOSE:     Yes;
;
;    Model statements for module:  Create 7
;
104$       CREATE,      1,HoursToBaseTime(169),Entity 1:HoursToBaseTime(168):NEXT(105$);
```

```
105$          ASSIGN:       Create 7.NumberOut=Create 7.NumberOut + 1:NEXT(19$);
;
;     Model statements for module:  Assign 17
;
19$          ASSIGN:       rmorder=0.25*(1200000-
(Inkilns+inpredryerdrying+inpredryernotdrying+drylumber))+Monthlydemand1:
                           Monthlydemand1=0:
                           tobedelivered=rmorder:NEXT(27$);
;
;     Model statements for module:  Record 6
;
27$          TALLY:        RMOrderstock,rmorder,1:NEXT(20$);
;
;     Model statements for module:  Process 3
;
20$          ASSIGN:       Process 3.NumberIn=Process 3.NumberIn + 1:
                           Process 3.WIP=Process 3.WIP+1;
109$         DELAY:        48,,VA;
156$         ASSIGN:       Process 3.NumberOut=Process 3.NumberOut + 1:
                           Process 3.WIP=Process 3.WIP-1:NEXT(30$);
;
;     Model statements for module:  Assign 23
;
30$          ASSIGN:       PreDryingLumber=Normal(8540,870):NEXT(31$);
;
;     Model statements for module:  Decide 3
;
31$          BRANCH,       1:
                           If,tobedelivered<predryinglumber,159$,Yes:
                           Else,160$,Yes;
159$         ASSIGN:       Decide 3.NumberOut True=Decide 3.NumberOut True + 1:NEXT(32$);
160$         ASSIGN:       Decide 3.NumberOut False=Decide 3.NumberOut False + 1:NEXT(33$);
;
;     Model statements for module:  Assign 25
;
32$          ASSIGN:       PreDryingLumber=tobedelivered:NEXT(21$);
;
```

```
;     Model statements for module:  Process 4
;
21$          ASSIGN:       Process 4.NumberIn=Process 4.NumberIn + 1:
                           Process 4.WIP=Process 4.WIP+1;
162$         DELAY:        Uniform(16,168),,NVA;
209$         ASSIGN:       Process 4.NumberOut=Process 4.NumberOut + 1:
                           Process 4.WIP=Process 4.WIP-1:NEXT(28$);
;
;     Model statements for module:  Process 7
;
28$          ASSIGN:       Process 7.NumberIn=Process 7.NumberIn + 1:
                           Process 7.WIP=Process 7.WIP+1;
213$         DELAY:        8,,VA;
260$         ASSIGN:       Process 7.NumberOut=Process 7.NumberOut + 1:
                           Process 7.WIP=Process 7.WIP-1:NEXT(12$);
;
;     Model statements for module:  Assign 9
;
12$          ASSIGN:       InPredryerdrying=InPredryerdrying+PredryingLumber:NEXT(11$);
;
;     Model statements for module:  Process 2
;
11$          ASSIGN:       Process 2.NumberIn=Process 2.NumberIn + 1:
                           Process 2.WIP=Process 2.WIP+1;
264$         DELAY:        Predryingtime,,VA;
311$         ASSIGN:       Process 2.NumberOut=Process 2.NumberOut + 1:
                           Process 2.WIP=Process 2.WIP-1:NEXT(13$);
;
;     Model statements for module:  Assign 10
;
13$          ASSIGN:       InPredryerdrying=InPredryerdrying-PredryingLumber:
                           InPredryernotdrying=InPredryernotdrying+PredryingLumber:NEXT(14$);
;
;     Model statements for module:  Dispose 6
;
14$          ASSIGN:       Dispose 6.NumberOut=Dispose 6.NumberOut + 1;
314$         DISPOSE:      Yes;
```

```
33$          DUPLICATE:     1,34$:NEXT(21$);
;
;     Model statements for module:  Assign 26
;
34$          ASSIGN:        tobedelivered=tobedelivered-predryinglumber:NEXT(30$);
;
;     Model statements for module:  Create 8
;
315$         CREATE,        1,HoursToBaseTime(640),Entity 1:HoursToBaseTime(8):NEXT(316$);
316$         ASSIGN:        Create 8.NumberOut=Create 8.NumberOut + 1:NEXT(0$);
;
;     Model statements for module:  Record 1
;
0$           TALLY:         DryLumberStock,DryLumber,1:NEXT(23$);
;
;     Model statements for module:  Record 2
;
23$          TALLY:         InKilnStock,Inkiln,1:NEXT(24$);
;
;     Model statements for module:  Record 3
;
24$          TALLY:         Predryerdrying,inpredryerdrying,1:NEXT(25$);
;
;     Model statements for module:  Record 4
;
25$          TALLY:         Predryernotdrying,inpredryernotdrying,1:NEXT(26$);
;
;     Model statements for module:  Record 5
;
26$          TALLY:         TotalOnSiteStock,drylumber+inkiln+inpredryerdrying+inpredryernotdrying,1:NEXT(29$);
;
;     Model statements for module:  Dispose 9
;
29$          ASSIGN:        Dispose 9.NumberOut=Dispose 9.NumberOut + 1;
319$         DISPOSE:       Yes;
```