Strategic Positioning of Inventory to Match Demand in a Capital Projects Supply Chain

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Abstract: Industrial buyers of capital facilities have experienced and continue to experience pressure to reduce facility design and construction lead time. This pressure arises both internally (due to successes in manufacturing lead time reductions) and externally (due to competitive forces including narrowing product delivery windows). This paper presents a case study detailing one owner's efforts to reduce the length and variability of delivery time for long-lead construction materials in order to improve overall project lead time. The owner adopted a long-term multiproject perspective, procuring material in advance of specific projects and holding it at a position in the supply chain selected to allow flexibility for customization. Reduction in lead time of 75% from order to delivery of the material resulted for individual projects within the owner's capital plan. As a result, the material was available at the construction site well in advance of its need for erection. To study if holding material at alternative locations in the supply chain could provide a better match between delivery quantities and the demand for erection, the supply chain was simulated. In this case study, demand information was imprecise, allowing only the quantity of material delivered to be considered rather than matching specific items to specific locations. Nonetheless, the results demonstrate the utility of simulation in the capital projects supply chain and the value of improving demand forecasts.

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Introduction

This paper describes inventory management in the context of a case study of the capital projects supply chain (SC) of a large food-product manufacturing company. This company has requested anonymity and for simplicity will be referred to as Company X. Company X maintains a large number of manufacturing facilities around the world. It operates at very high capacity utilization at all facilities, generally in the mid- to high-90% range. As a consequence, new product rollouts or large promotions require an increase in production capacity that can be gained only by expanding an existing or adding a new facility, rather than by ramping up utilization.

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The motivation for change in Company X's traditional management of its capital projects SC was the difficulty experienced in completing projects on schedule. The cost of failure to meet expected project delivery times is enormous. Considerable advertising effort for new product rollout is coordinated with the opening of expanded or new facilities. Advertising commitments are capital intensive and often have long lead times; they allow little room for change once purchased. Finally, because of competitive pressures and seasonality in sales, it is impossible to extend a product delivery date once it is planned and scheduled.

The critical SC for Company X to complete an expansion or a new project is that for obtaining stainless-steel components. Prior to instituting this initiative, Company X experienced unpredictable availability of stainless steel. Shortages of stainless-steel pipe and pipe fittings were particularly problematic and resulted in the inability to support shorter project schedule objectives. Many other SCs feed a project, but for Company X this one has both the longest and the most variable lead time, and comprises components for an important system within the final facility. Before Company X's intervention in the SC, late project schedules were commonly avoided via expediting focused immediately upstream from the project. Further upstream in this multitier SC, at the mill for example, the owner was not able to expedite, because the owner's order of a specialized stainless steel was only a small fraction of the total business of the mill (Cox 1999)

In order to address the long and variable lead time for stainless steel, Company X entered the SC by acquiring inventory and holding it at a location upstream in the SC, independent of any specific project order. This paper presents Company X's solution, along with a simulation experiment to consider means of holding the material at alternative locations within the SC to provide a better match between the quantities delivered and those demanded for erection.

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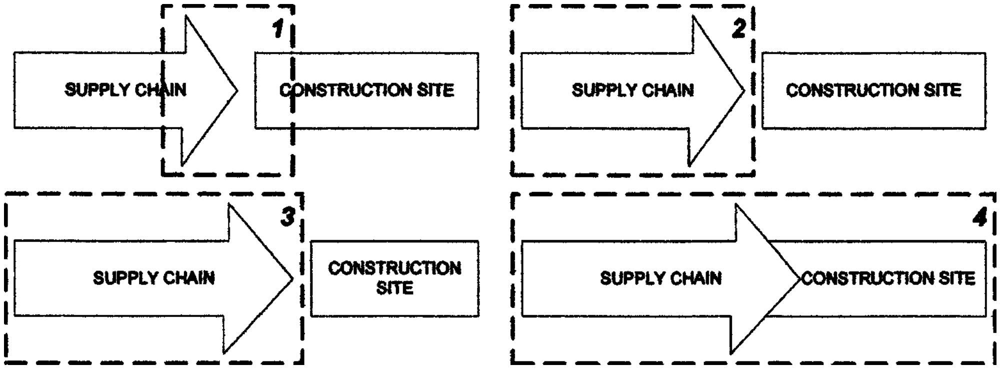

Fig. 1. Four roles of supply chain management in construction (Reprinted from *European Journal of Purchasing and Supply Chain Management*, Vol. 6, Vrijhoef and Koskela, "The Four Roles of Supply Chain Management in Construction," 169-178, Copyright 2000, with permission from Elsevier)

Supply Chain Management

SC Management (SCM) is the practice of a group of companies and individuals working collaboratively in a network of interrelated processes structured to best satisfy end-customer needs while rewarding all members of the chain. SCM is recognized as a leading process improvement, cost saving, and revenue-enhancing business strategy. All disciplines within a business can be, and most often are, involved in SCM initiatives within a company. While the idea has been embraced and deployed frequently in manufacturing, it is relatively new in construction (Tommelein et al. 2003).

Vrijhoef and Koskela (2000) identified four levels of implementation of SCM in construction. The alternatives are numbered in Fig. 1 and the descriptions below paraphrase their text. One or several SC participants could lead each level of implementation. Levels of implementation are not mutually exclusive and, in fact, they are often pursued jointly.

1. SCM focuses on the impact of the SC on construction site activities and aims to reduce the cost and duration of those activities. The primary concern therefore is to establish a reliable flow of materials and labor to the site. Improvements may be achieved by focusing on the relationship between the site and direct suppliers. The contractor, whose main interest is in site activities, may be in the best position to adopt this role. For example, Crutcher et al. (2001) present a case in which an electrical contractor adopted this role.
2. SCM focuses on the SC itself and aims to reduce costs, especially those related to logistics, lead time, and inventory. The owner, the contractor, but also materials suppliers and manufacturers, may adopt this role. For example, Company X adopted this role by deciding to influence the SC leading up to the site, but not to change the management approach at the site.
3. SCM focuses on transferring activities from the site upstream in the SC and aims to reduce total installed cost and duration by avoiding inferior conditions on site, or achieving wider concurrency between activities barred by technical dependencies on site. Designers, suppliers, or contractors may adopt this role. Owners play a role here, by selecting SC partners and providing incentives to perform. For example, many modularization efforts achieve this objective.
4. SCM focuses on the integrated management and improvement of the SC and site production, that is, site production is subsumed by SCM. Owners, together with designers, suppliers, and contractors, may play this role. For example, Tsao and Tommelein (2001) present a case in which a light-fixture manufacturer adopted this role for one component's SC.

Cox and Ireland (2002) described many inefficiencies in the capital projects SC. They suggest that a failure to understand the entire SC results in individual decision making that is often contrary to the optimal function of the entire chain. Cox and Ireland go on to suggest strategies for the comprehensive analysis of an entire SC and the impact of policy decisions at different points in the chain.

Demand Forecasting in Construction

Demand forecasting is fundamental to managing SCs in manufacturing. By sharing demand information up and down the SC, all participants can stabilize production and reduce safety stock inventories, resulting in SC-wide cost savings. By contrast, forecasting demand in capital projects SCs is challenging. Owners need to adopt not only a long-term perspective when developing their capital plan, but they may also have to consider alternative contracting relationships. Traditional project-based contracting structures influence the degree to which demand information is shared, especially the demand for new or expanded capital facilities. In the present case, the owner moved to influence the SC directly because they had the best knowledge to forecast demand.

The owner is often in an excellent position to seek control of the SC upstream of the site for several reasons, including:

- The owner is most familiar with business strategies and results, and their need for new or expanded capital facilities.
- The owner often feels a need to have multiple contractors from whom to seek bids, in search of increased competition and lower prices. Getting too cozy with a contractor may be perceived as counterproductive, and maintaining a relationship with at least a few contractors will "keep them honest."
- Because owners work with more than one contractor, and these contractors in turn perform work for multiple owners, owners understandably are reluctant to broadcast sensitive business plan information about upcoming capital programs where it may become accessible to competitors.
- The owner can take a multiproject view across their capital plan that contractors who are selected on a project-by-project basis cannot.
- The owner controls the timing of new projects.
- The owner chooses the facility design and thereby controls project requirements. Especially in the case of industrial de-

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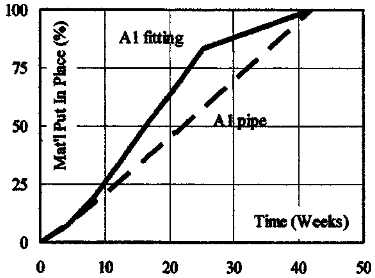

Fig. 2. Schematic earned value development for pipe installation per month at Company X project

sign where reference plant designs exist, as is the case here, the owner knows ahead of time what components will be needed at what point in the construction sequence.

In the present case, the owner seized control of the SC up to the point where materials arrived at the site. By considering the continuing and long-term expansion plans, Company X's procurement executives could determine an appropriate level of upstream inventory that would allow all possible expansion projects to proceed on schedule. It was not necessary to actually share any expansion plans. In fact, the manager of the facility holding the upstream inventory stated: "I have no idea why they want this much inventory." Once materials were at the construction site, the owner left them under the control of the project. Project managers working for the owner had incentives to make the project a success as compared to making their company a success overall.

The owner's procurement organization adopted a long-term view across projects, but realized that political factors internal to the company would make it difficult to influence the management of projects at the site. Thus, rather than seeking to modify the SC dramatically, for example, by adopting a just-in-time (JIT) delivery scheme, the owner's procurement organization attempted merely to achieve earlier delivery of all stainless steel. Their power to influence management extended only to the project fence. This supported the desire of the owner's project managers to have large quantities of material on site early, but also created the need to manage substantial inventories on site.

From data obtained from two projects, the researchers developed generic curves representing the rate at which construction earned value for installed materials (Fig. 2). These curves show that installation of piping takes place over a period of several months, although typically delivery of nearly all piping was completed early in the process.

Origin and Evolution of Supply Chain Simulation

The origin of SC modeling is credited to Forrester (1958, 1961). Forrester describes a four-tiered SC architecture consisting of a factory, warehouse, distributor, and retailer, on which he based simulation studies to explain, for example, the "bullwhip" effect. He eschewed the isolationist focus characterizing operations research in the 1950's in favor of an intracompany approach, believing that management should focus on the interactions that occur at each of the interfaces within the SC.

Angerhofer and Angelides (2000) follow the evolution of SC simulation since Forrester's work. They provide an excellent synopsis of research and development performed through the 1980's and 1990's. Recent work in SC simulation focuses on the development of frameworks and their application to case studies. Most

Table 1. Classification of Simulation Case Studies

Simulation Type	Reference	Industry Group
Inventory management	Archibald et al. (1999)	Food Manufacturing
	Barnett and Miller (2000)	Retail Manufacturing
	King and Moon (1999)	Fabric Manufacturing
	Parsons and Siprelle (2000)	Food Manufacturing
	Schunk and Plott (2000)	Auto Manufacturing
	Swaminathan et al. (1998)	Food Manufacturing
	Trone et al. (2000)	Construction
Process improvement	AbouRizk et al. (1999)	Construction
	Halpin and Martinez (1999)	Construction
	Ingalls and Kasales (1999)	Computer Manufacturing
	Ioannou (1999)	Construction
	Law and McComas (1999)	Various Manufacturing
	Price and Harrell (1999)	Retail Manufacturing
	Sawhney et al. (1999)	Construction
	Tommelein (1997)	Construction
	Tommelein (1998)	Construction
Forecasting/demand management	Bhaskaran (1998)	Auto Manufacturing
	Mallya et al. (2001)	Retail Manufacturing
	Raghunathan (1999)	Retail Manufacturing

case studies rely on highly customized proprietary simulation environments (Bhaskaran 1998; Archibald et al. 1999; Trone et al. 2000). Such modeling efforts tend to originate from substantial players in the marketplace, due to the prohibitive cost of developing these frameworks. However, significant efforts are underway in developing general-purpose object-oriented simulation environments, typically featuring a drag-and-drop graphical user interface design and adequate flexibility for application in many industries. Such environments commonly use the event scheduling paradigm or block languages. By contrast, construction simulation has commonly been accomplished with general-purpose simulation environments based on the activity scanning paradigm, which seems to provide a more natural fit. The environments most commonly used to simulate construction are *SIMPHONY* (Hajjar and Abourizk 1999) and *STROBOSCOPE* (Martinez 1996).

As part of the literature review for this study, 19 articles were sampled from the proceedings of a recent simulation conference. Seven of these involve construction, the remainder involve manufacturing. Table 1 categorizes each case study, based on its primary focus of analysis, into one or more of the following problem types:

- Inventory management,
- Process improvement, and
- Forecasting/demand management.

Note that some references include more than one case study, and some case studies analyzed more than one problem type. The cases presented in Table 1 are indicative of the tone, if not the contents, of the relevant literature.

Inventory management case studies are common in manufacturing, and focus on optimizing service level and process time by varying either the location or quantity of inventory among several alternatives. Such studies usually involve multiple tiers in the SC. Inventory management is less frequently studied in construction. This may be because construction simulation has traditionally focused on on-site operations, where greater inventory (more mate-

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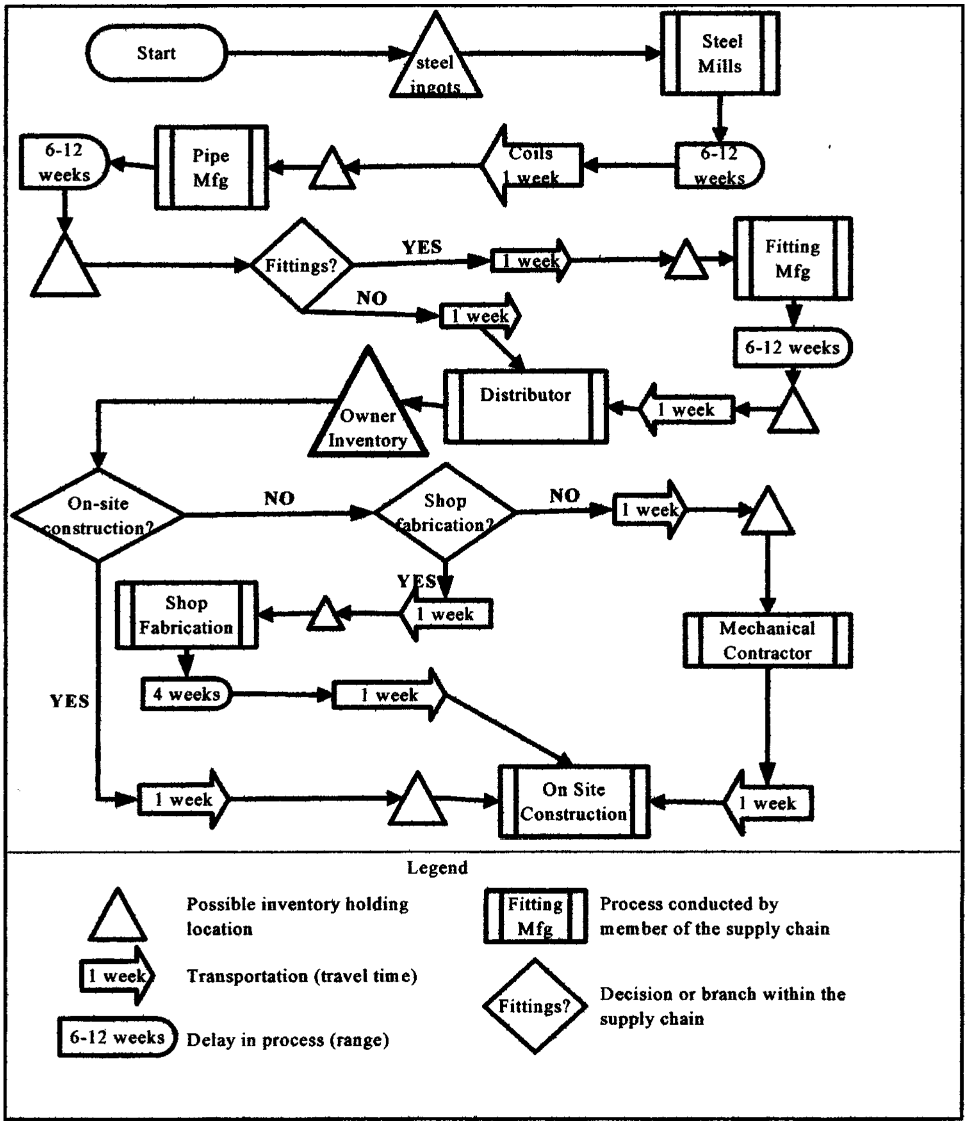

Fig. 3. Value stream map for stainless-steel pipe and fittings

rials on site) is generally—though erroneously in our opinion—perceived to be better. The physical constraints encountered on construction sites relative to the dimensions of materials handled also make a layout problem formulation more natural than a location problem formulation (Francis et al. 1992).

Process improvement case studies are prevalent in the construction industry, and often have a site focus, with little or no emphasis on management of the SC interfaces that Forrester espoused. For example, alternatives may include additions/deletions of capacity by increasing/decreasing crew or machine size at various locations within the system. They may also include alternative methods that achieve the same objective.

Forecasting and demand management simulation is done to either anticipate or mitigate risk due to consumer behavior. The authors are not aware of construction case studies that considered this problem type. By contrast, this problem is addressed as either a primary or secondary focus of simulation in a significant number of manufacturing case studies. This type of simulation is done to analyze the transmission of instability up the SC (bullwhip effect), determine the impact of new channels on the marketplace, stabilize forecasts to suppliers, etc. It may lead to improvements in scheduling, inventory management, or workflow.

Applicability of Supply Chain Simulation in the Construction Industry

SCM is more mature in manufacturing than in construction, as indicated by many differences in the modeling and analysis approaches between these industry sectors, including the widespread use of simulation tools to optimize SC relationships in manufacturing. Few cases in the construction literature involve simulation of multiple tiers in the SC. Consideration is typically given to the transfer and inventory of goods within one tier, rather than to optimizing the handoff or inventory levels between tiers.

Some exceptions are notable, however. Tommelein (1998) addresses the difficulty in applying SC concepts due to the unique "matching" problem faced in construction: A significant fraction of the materials delivered to the construction site must be precisely matched to their installation location. Contractors are held liable for completion dates, but they usually become involved in the delivery process too late to be able to control the SC upstream of the site other than via expediting. Accordingly, contractors seek the earliest possible delivery of materials at the site rather than seek delivery designed to correspond to planned installation. In

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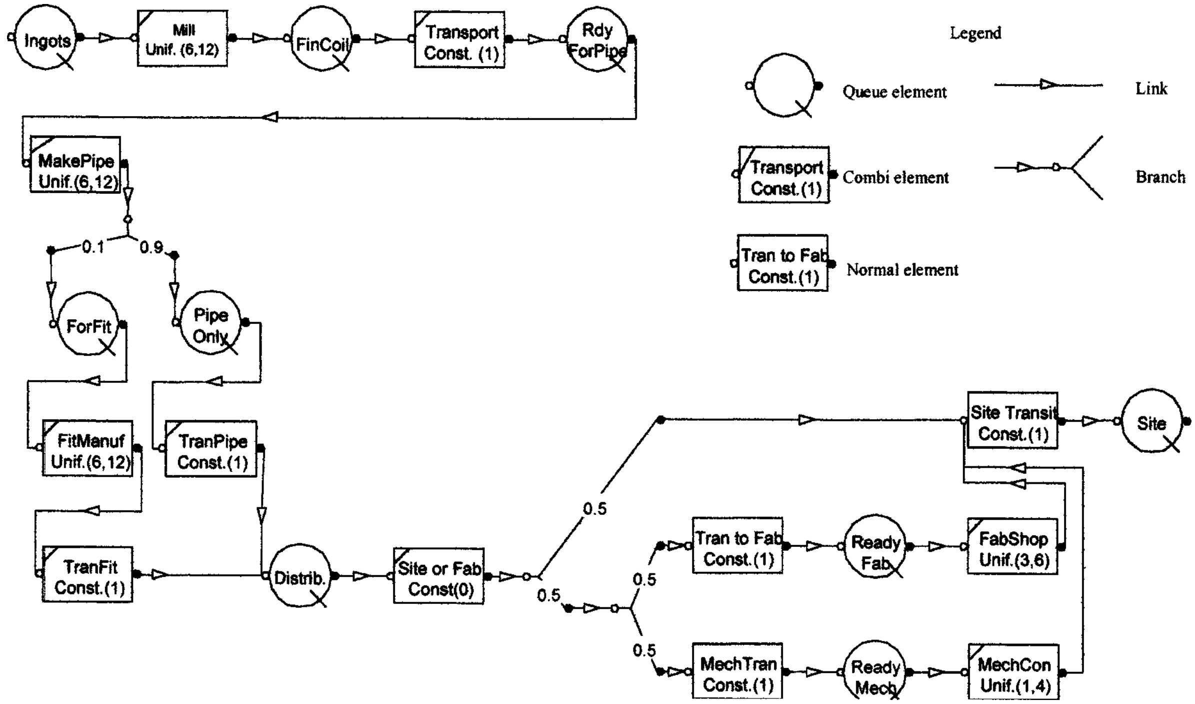

Fig. 4. CYCLONE simulation model of the stainless-steel pipe and fittings supply chain

other words, they want to get the material into a position in the SC within their reach, literally and figuratively, and for the most part their reach extends only to the site. Inventory of material may build up on the site as a consequence of this approach, but because owners have been told it leads to more reliable project delivery, they appear willing to pay the associated costs. Large inventories are one (costly) means to decouple site work from the upstream SC (Howell et al. 1993).

Tommelein et al. (1999) showed that variability in production levels for closely coupled subcontractors results in decreased overall throughput. Bashford et al. (2003) described the implications of different production management strategies in the residential SC, in particular for subcontracted workload variability. Arbulu et al. (2002) demonstrated the impact of batch sizing and multitasking on process throughput in a pipe support design and fabrication context. Each of these examples included key results measures related to production levels over time for different alternatives.

Many manufacturing cases consider production levels over time, but also emphasize financial performance. They evaluate costs of inventory and production management, often both before and after tax (Table 2). Construction simulations may well include cost considerations, but usually with less sophistication. Furthermore, they frequently ignore inventory management costs or treat them only conceptually, even if inventory levels are presented. This may be because the complexity of the capital projects SC often hides inventory holding expenses, or because incentive and penalty structures often focus on time. Given that costs associated with inventory management on site are not tracked very precisely, it should not be surprising that quantification of holding costs upstream in the SC is rare as well. In any event, we do not present explicit inventory holding cost calculations either. More research is needed to substantiate such costs; we speculate that lower inventory levels at the construction site or points upstream in the SC would result in lower inventory management costs and improved SC performance overall.

That construction simulation tends to focus on process improvement is an indication of the infancy of the application of SC concepts to the industry. The enormous challenges in construction inventory management have only recently been recognized, and leave vast opportunities for research and development into the application of SC simulation. For example, in an extensive study of piping projects, Howell and Ballard (1996) observed that project success appeared to correlate to having 60% of the pipe spools on hand by the time 20% of the pipe has been installed. This correlation is in keeping with Company X's mindset and actions to achieve early delivery. Current practice notwithstanding, Howell and Ballard promoted more reliable planning and

Table 2. Typical Simulation Performance Measures by Problem Type

Inventory management	Process improvement	Forecasting/demand management
Gross margin	Service level	Absolute forecast error
Gross margin return on investment	Total inventory	Service level
Service level	Time in process	Total inventory
Total inventory	Queue size (wait time)	
Time in process	Utilization	
Utilization	Costs (total, product, entity, inventory, processing, and transportation)	
Costs (total, product, entity, inventory, processing, and transportation)	Net profit after tax	
Sales		
Inventory turns		
Profit margin		
Return on assets		
Stockout delay		

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judicious inventory reduction as means to achieving better performance.

Mapping the Supply Chain

Simulation of any SC begins by identifying the processing tasks, delays, transportation requirements, and holding positions of resources in buffers through interview and observation of managers, subject-matter experts, and stakeholders within the SC, as was done for Company X. The SC map for stainless-steel pipe and pipe fittings depicted in Fig. 3 uses symbols based on Damelio (1996).

In 1995, Company X recognized the pernicious effects of the length and variability of its stainless-steel SC, and decided to intervene in order to reduce the lead time. Company X considered the locations shown as triangles in Fig. 3 as holding places, and ultimately chose the one labeled "Owner Inventory." This selection was made based on intuition and convenience rather than based on any detailed analysis. Locations further upstream were considered too far away to control. However, by the time pipe reached tiers further downstream, it had been customized sufficiently to reduce flexibility. Company X contracted with a single independent distributor to store, handle, and control material. The owner placed an amount of pipe roughly equivalent to the amount used for one new manufacturing facility into the inventory.

The distributor provided tracking information on pipe, fittings, and flanges to Company X. This information had not previously been available from any member of the SC, and has allowed improved planning and scheduling and the data to evaluate the owner's capital program. Costs incurred by Company X for carrying this inventory have been more than offset by price savings achieved through bulk purchases and through commodity savings owing to inflation and market volatility in stainless-steel prices.

The map depicted in Figure 3 was developed via interviews with Company X personnel within the purchasing and capital facilities development departments. In addition, upstream SC member input was sought via interviews with personnel from the distributor and the pipe manufacturer. Faculty researchers conducted the interviews and an intern on a ten-week assignment within Company X assisted in obtaining more detailed information, including the data needed to estimate the delay times shown in Fig. 3 [see Walsh et al. (2002) for additional anecdotal details].

Simulation of the Supply Chain

The SC map (Fig. 3) was used to develop a simulation model (Fig. 4) in order to consider the implications of alternative holding points for inventory on the arrival of stainless-steel pipe and fittings at the construction site. The simulation experiments were conducted using the *CYCLONE* template in *SIMPHONY*. The pipe and fittings were broken into 100 packets, each representing 1% of the total to be used. The primary output of interest was the arrival of material at the site versus time.

Table 3. Summary of Simulation Experiments with Multiple Inventory Holding Locations

Starting locations	Company X's implementation	Simulation experiment code M1	M2	M3
Mill	0%	20%	30%	40%
Pipe manufacturer	0%	50%	50%	40%
Distributor	100%	30%	20%	20%

Since most of the time from order to delivery is scheduling wait time, process time and wait time were combined into a single delay time. This simplification should not indicate the lack of possible supplier scheduling or process improvements within these individual steps, but rather that it is currently difficult for Company X to exert influence over those processes.

All simulation runs are based on the model presented in Fig. 4, with the following alternatives varying the location of inventory:

- All inventory held ahead of the Mill,
- Inventory prepositioned at a Distributor, and
- Multiple holding locations (Table 3).

Calibration and validation of the model used individual process durations established based on interviews and invoice data taken from the files of Company X and its Distributor, against the known overall arrival times. The case in which the stainless steel was ordered, processed from ingots queued before the steel mill, was considered first. Based on a review of order data in Company X's files and interviews with SC participants, the processing times for each stage in the SC were allowed to vary within a uniform distribution. The extent to which results might be affected by the selection of alternative distributions was not studied. This model was evaluated for a range of iterations from 10 to 1,000. No significant change in the average and standard deviation of the completion of delivery to the site was noted after 100 iterations. The second case assumed that all of the stainless steel needed was in storage at the Distributor when ordered for the project. This alternative models the 1995 SC intervention by Company X.

The simulated arrival times at the site for these two cases are shown in Fig. 5. The figure shows the average result for 100 iterations of the model (solid line) along with the three-standard-deviation range (gray line). Shipping and receiving records were available for a small number of projects conducted under both approaches, allowing the writers to develop fairly general information about the actual arrival times which result from each. The results of the simulation show reasonable agreement with these

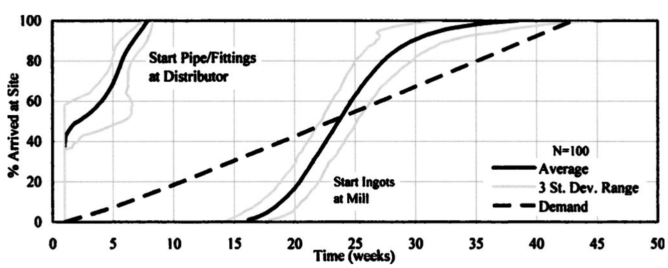

Fig. 5. Arrival time at site for cases with all material starting at the mill and distributor

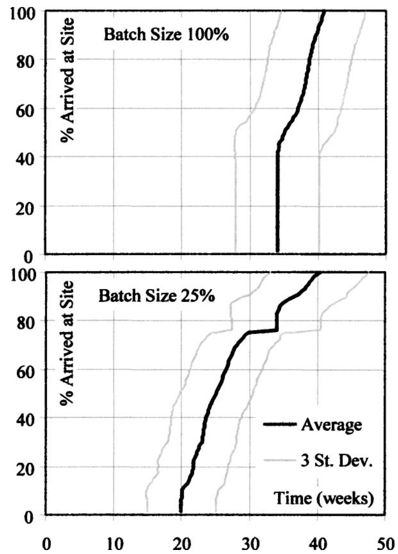

Fig. 6. Impact of distributor batch size on arrival time profile

actual arrival times. Furthermore, the results were discussed with personnel at Company X, who indicated that these results matched their expectations. More comprehensive validation/calibration would be desirable in the general case, but the lack of extensive record keeping made such activities impractical. Also shown for reference is the schematic demand curve (Fig. 2, dashed line), adjusted to the week of first delivery.

As expected, the use of prepositioned inventory located at the Distributor buffers the project from the long and variable SC upstream of the site. The average time to complete delivery (arrival of 100% of the pipe) is reduced by about 78%, from 38 weeks to 8 weeks. Variability in complete delivery time is reduced as well, judging by the three standard deviation range.

Batching policies in the upper portions of the SC have not been modeled directly. Rather, the process times for elements upstream of the Distributor include batching effects and scheduling delays. Even pre-1995, a distributor was present to act as a consolidator of nearly finished goods. In some cases, the distributor would collect all of the pipe and fittings before releasing them downstream. Or, the distributor might serve as a routing agent, handling material with only minimal storage time; intermediate conditions are also possible. Given the importance of batching policies on SC performance (e.g., Arbulu et al. 2002), the impact of these decisions was further evaluated. Fig. 5 depicted the simulation results using a batch size of 1%. Fig. 6 depicts the simulation results with batch sizes of 25% and 100%. These results illustrate that in this system (though it may not generally be the case) large batches affect the first arrival more than the completion of delivery. Variability also is higher when larger batches are used.

This comparison brings out the import of the slope of the site arrival curves (Figs. 5 and 6). This slope represents the arrival rate of material at the site per week, or the arrival rate. The construction management philosophy for Company X relies upon early delivery of pipe and fittings to the site (the left-most curve in Fig. 5). While there is some variation over time in demand for pipe during construction (Fig. 2), the demand pattern is relatively steady over the construction process and extends over a longer duration than that of any scenario considered thus far. Fig. 5 shows that the dashed line representing actual installation of pipe is well below the simulated delivery pattern throughout the project, even to the three-standard-deviation range. As a consequence, the project will require on-site laydown space for nearly all of the pipe delivered. The advantages of this early delivery to craft assignment flexibility may be offset by a lack of flexibility to revise the actual pipe material in response to changes after arrival, costs associated with storage and rehandling, and damage/loss of pipe while stored on site.

Tommelein (1998) presented a number of potential advantages of coordination in a pull-driven system in which pipe was delivered a short time before it was required by the construction activity. In the present case, one mechanism for extending the delivery window to better match the construction demand is presented by prepositioning inventory at multiple locations upstream of the site. Three scenarios of this type were considered, with the pipe inventory divided among three locations (Table 3). These locations were selected based on trial and error to develop a more gradual arrival pattern.

Fig. 7 shows the resulting site arrival time histories. To provide a sense of the range in the simulation results without unduly cluttering the graph, only the M1 minus-three-standard-deviations and the M3 plus-three-standard-deviations curves are included. The average curves from Fig. 5 and the actual usage data from Fig. 2 are shown for reference. These models demonstrate that a delivery pattern, much more in keeping with the demand patterns, can be created by the choice of holding locations for prepositioned inventory. In doing so, risk is not significantly increased, as even the three-standard-deviation range of the arrival curve is still ahead of demand, but laydown space and inventory management requirements are significantly reduced.

Pipe deliveries were assumed to be interchangeable, but this understates the communication and coordination efforts required to make the inventory prepositioning and the affiliated customization match the construction schedule. With no intention to minimize the difficulty of these efforts, the objective here is merely to demonstrate a method by which the delivery pattern can be approximately matched to the construction demand pattern.

Discussion

The results presented in Fig. 7 demonstrate that locating and sizing buffers in the SC serve as a means of matching demand and supply levels at the construction site. JIT philosophies have been effectively used in manufacturing settings to match supply and demand, thereby reducing the need for onsite inventories. Propagated up the SC, a JIT management system can reduce inventory levels, and the related costs, systemically. Company X's approach obviously increases inventory, at least at one tier. However, the objective was to size and locate the required inventories for the system while considering project risk, and to place them in the hands of the party best able to manage them.

Company X's approach should be compared to the early project procurement approach known as PEpC (Vorster et al. 1998) as the difference is subtle but important. PEpC espouses supplier involvement in project design, and procurement of long-lead items at the start of engineering to reduce total project lead time. In contrast, Company X ordered, and even took delivery via their distributor, of critical long-lead materials even in advance of a specific project on which to use those materials.

Prepositioning the long-lead materials in the SC has the added advantage of delaying irreversible customization as compared to holding the material on site. For simplicity, assume that the degree of irreversible customization grows more or less steadily as

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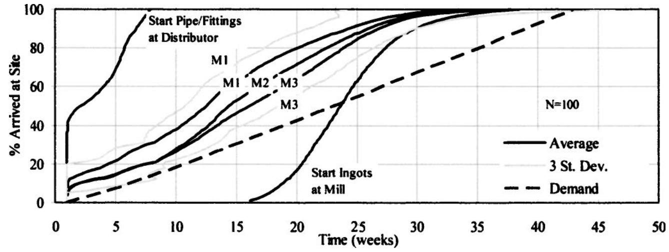

Fig. 7. Arrival time at site versus time for multiple holding location models M1–M3 (Table 3)

the material moves along the SC, while the delivery time decreases steadily (Fig. 8). For this case, since the delivery time from the mill was unacceptably long, the owner moved material downstream in the SC (in the direction shown under the horizontal axis). The owner thereby lost the ability to influence the processes conducted upstream of the distributor (such as the specification of the steel chemistry or pipe diameters), but accepted this loss in favor of reduced delivery time. In the scenarios presented in Fig. 7, with material deployed at multiple locations in the SC, the owner can customize, and the resulting delivery pattern is not unduly different from the demand pattern.

Another approach, not used in this case, is so-called postponement. In a postponement strategy, the SC is reconfigured so that irreversible customization is delayed by changes to the product and/or the process (the labeled arrow in Fig. 8). The advantage of postponement is that delivery times can be reduced more for a given level of irreversible customization. To date, Company X has not attempted to change their processes or products to support postponement. Evaluation of the degree of irreversible customization at different points in the SC is an interesting field for potential new research, in particular for the assessment of the cost/benefit relationships for the lost flexibility of early delivery.

Summary and Conclusions

Inventory management in construction requires striking the balance between the contractor's desire to have materials on site early in a project, and the SC benefits from inventory reduction. At one extreme, 100% inventory prior to project commencement maximizes crew assignment flexibility and eliminates the possibility of construction delays due to shipment delays. However, this is costly due to the up-front capital requirement, inventory-holding costs, damage/loss of materials, inflexibility in response to design changes, and lack of planning that may result from perceived flexibility. At the other extreme, reliance on a JIT philosophy places the contractor at the mercy of their suppliers and

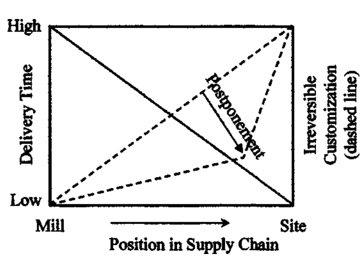

Fig. 8. Relationship between irreversible customization, delivery time, and position in the supply chain

at risk of incurring construction delay. However, JIT is beneficial in terms of savings in up-front capital, minimization of inventory-holding costs, reduction in damage/loss of materials, increased flexibility in response to design changes, and improved performance thanks to the enforced planning reliability.

Prepositioning inventory in order to match the supply with the contractor's demand is one solution to minimizing risk to both owner and contractor. While in this case, the owner exerted control over the SC by obtaining and holding inventory in the SC, in the general case other members of the SC, including the contractor and key suppliers, could likewise adopt such a role. The reasons why the owner is well positioned for the kind of control mechanism adopted in this case were described, and include the owner's detailed knowledge of their upcoming demand for facilities and their interest in maintaining the secrecy of product promotion plans.

A supplier might wish to gain control of the SC in order to increase market share and stabilize their demand through development of a larger risk pool. Further, a supplier may take over more parts of the SC in order to acquire technologies or block competitors' access to those technologies. The primary motivation for the contractor to seek control of a SC is to control lead time and improve their ability to successfully navigate the matching problem. Because they are mainly service providers, however, it is harder for general contractors to exert control over the SC than it is for subcontractors, who are more likely to also have a product stream.

The owner in this case used inventories of physical goods to reduce lead times. Inventory was held at a location in the SC until needed for a project. Simulation demonstrated that variation in the level and location of inventory is one strategy for modifying the material delivery rate. SC reconfiguration to support postponement is another strategy. Perhaps, another strategy would be to acquire virtual inventory, in the form of guaranteed manufacturing capacity at the mill. However, this strategy can be problematic to deploy in a long SC, because the power of one buyer generally diminishes as one moves up the SC. The writers hasten to point out that the success of this strategy seems tightly coupled to the ability of the owner to accurately forecast demand for new facilities. However, additional research is needed to quantify this relationship.

The results of these simulations were presented to Company X, leading to several policy changes. Recent conversations with Company X reveal that their approach has, in fact, been modified in favor of the multiple holding place strategy. Specifically, while the same distributor location has been maintained, some owner inventory is now kept in front of the pipe manufacturer, providing increased flexibility to produce different pipe sizes. Discussions are being held to reserve some mill capacity. These actions confirm the practicability of multiple points of inventory as shown in the simulation.

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data collection required for the development of the maps presented in this work.

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