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Improving Lean Supply Chain Management in the Construction Industry

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Abstract

Development of lean construction principles has for the most part centered on the field activities themselves. However, the ideology of lean focuses on the entire value stream of an operation from raw material to final product delivery. Waste and inefficiency is still evident throughout construction supply chains. This thesis investigates improvement opportunities in this industry, utilizing the practice of lean supply chain management. Key initiatives are identified through a literature review. Field study with a medium size building construction company addresses applicability in the field, showing: differences between lean and non-lean fabricators and effects on construction, where just-in-time material delivery may apply, effective staging of materials on site, and other observations from site. It is stressed that changes in supplier activity can improve field operations. Another improvement opportunity in lean supply is seen through communication technology, by utilization of new project management software. Finally, ties with Last Planner are discussed.
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1. INTRODUCTION

1.1 Background

It has been established that lean practice holds potential for improving construction. Since the early 1990s, lean principles and techniques adopted from the manufacturing industry have been examined for applicability in construction. The purpose behind this is to bring improvements to the construction process, similar to those seen in the manufacturing industry. Manufacturers have shown significant increases in productivity and quality, while reducing lead times. The construction industry has not shown these improvements and lags behind others in technology developments. Researchers and those practicing lean construction in the field have made significant progress up to this point. Many of these principles and techniques have been found to be effective in construction. Lean implementation has supported these views.

Lean is a common-sense approach that focuses on the elimination of waste in an operation. The types of waste that are referred to here are:

- Defects in products
- Overproduction
- Excess inventories
- Unnecessary processing
- Unnecessary movement of people
- Unnecessary transport of goods
- Waiting time

Lean requires an enterprise-level view of the value stream – from raw materials to finished goods delivered to the customer. This “value stream” includes all activities that directly or indirectly add to the final product being delivered. The proven methodology
of lean decreases lead times, reduces operating costs, improves quality, lowers inventory levels and increases flexibility in meeting customer demands. In addition, it is important to note that lean is a philosophy or way of thinking, not just a set of tools that can be cherry-picked.

For the purpose of this report the following definition will be used:

*Lean construction is the continuous process of eliminating waste, meeting or exceeding all customer requirements, focusing on the entire value stream and pursuing perfection in the execution of a constructed project* (Diekmann, 2004).

Again, much has been done in the area of lean construction. The Last Planner system of production control has become the most developed lean construction tool. This system was created by Glenn Ballard, co-founder of the Lean Construction Institute. It emphasizes the relationship between scheduling and production control, increasing plan reliability. This is accomplished by utilizing a “pull” system also known as reverse phase scheduling. Pulling here involves only doing work that releases work to someone else. By utilizing this approach various types of overproduction are avoided. Soloman (2004) discusses and tests the effectiveness of other various lean construction tools. These include increased visualization, daily huddle meetings, first run studies, visual workplace (5S) and fail safe for quality. Diekmann (2004) pushes this lean initiative a bit farther by developing an up-to-date summary of lean principles appropriate for construction. In addition, a six step process used to create a lean workplace is identified for contractors unfamiliar with lean thinking in construction. This work is further supported by a number of case studies and questionnaires.
However, much of the effort in developing and implementing lean construction has focused on field operations. As seen in the previous definition, lean focuses on the entire value stream of a construction operation. One area of this value stream where waste is still evident is with the supply chain. Members of this chain include manufacturers, suppliers, distributors and transporters. Often times these different business units work to satisfy their own objectives without considering effects of their actions downstream in the process. Dollars are wasted through ineffective supplier relations and transactions. These inefficient supply chains, along with incorrect design information, are bottlenecks that are inhibiting flow in the construction process, causing a “road block” for further value generation. The strategy involving the integration and coordination among these different members of the supply chain is called supply chain management. The term lean supply chain management then arises when fundamental concepts of lean are included. This is where more research is needed, in lean supply chain design and management.

The Lean Construction Institute (LCI) has identified supply management as a key research issue. The area covers standardization, modularization, prefabrication and preassembly initiatives, supply chain and supplier development, and discovering the appropriate methods for managing different types of materials. FIATECH is another organization that is concerned and heavily involved with this topic of lean supply in the construction industry. They are a non-profit consortium focused on fast-track development and deployment of technologies to substantially improve how capital projects and facilities are designed, engineered, built, and maintained. Their vision, strategy, and plan is presented through their Capital Projects Technology Roadmap. This
guiding plan consists of nine elements, the third working to provide a fully integrated, automated procurement and supply management system (i.e. tools and processes for planning, controlling, including financial controls for the procurement process). The four focus areas under this element are titled: Integration of Engineering and Project Controls with Procurement, Supply Chain Information Access and Standards, Integration of Procurement with Intelligent Job Site, and Evaluation of Supply Chain Structures. A FIATECH vision is to have a network that will securely deliver stock and custom materials as dictated by the master project schedule for respective steps in the construction process, reducing the need for on-site storage. Moreover, FIATECH supports the initiative of lean construction in their roadmap and believes strongly that improvements are needed in the supply aspect of the business. Two other academic leaders in the study of lean supply chain management in construction are Roberto Arbulu and Iris Tommelein.

1.2 Objective

This thesis aims to investigate improvement opportunities in the construction industry, utilizing the practice of lean supply chain management. Expected benefits from such improvements include reducing project lead times, decreasing costs, improving quality, and decreasing variability. Motivation behind this thesis comes from the desire to see construction companies achieve the success had by those in manufacturing and other service industries.
1.3 Methods

This thesis includes an extensive literature review on the topic and case study to investigate applicability in the field.

*Literature Review:*

- Review general topic of supply chain management
- Review construction supply chains and determine limitations and bottlenecks
- Review manufacturing supply chains and how they have applied lean thinking
- Review initiatives in the supply chain aspect of lean construction

*Case Study:*

- Evaluate current lean construction efforts of a local construction company
- Perform an assessment of a select job considering these supply chain initiatives
- Identify ties with current lean tools in use by the contractor
- Report observations, opportunities, and challenges
- Report recommendations
2. LITERATURE REVIEW

2.1 Defining Supply Chain Management

Before moving forward it is important to have a grasp on what a supply chain is, the members involved, and the role it plays in a successful business. With this established more can be said on managing these supply chains and on developing strategies for doing so effectively. A supply chain encompasses all the processes and phases a product goes through on its way to final customer delivery. It includes the flow of information, material, and services. Lee and Billington (1993) define supply chain as “a network of facilities that performs the functions of product development, procurement of material, transformation of material to intermediate and finished product, distribution of finished products to customers and after-market support for sustainment.” With this in mind, the members of the supply chain will include not only suppliers and manufacturers, but also warehouses, transporters, retailers and customers. Each is a stakeholder in the process.

Therefore the coordination of these various business units is denoted by the term supply chain management (SCM). This term became widely used in the 1990s and now receives much attention in study as well as practice. Mentzer (2001) defines supply chain management as “the systematic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole.” So SCM is
an integration strategy, focusing on benefit for all players in the supply chain and value for the final customer.

With the competition in today’s marketplace, having effective SCM is critical for business success. Technology advancements in particular have allowed companies to make significant improvements. Communication via the internet has opened up a number of opportunities for faster business transactions and real-time information exchange. Global sourcing has also given companies more options for deflation.

Every supply chain has different challenges. Each has different customer requirements, product types, organizational structures, schedules, etc. Business strategies vary. However, there are still similarities in how supply chain leaders must approach their given situation. Hugos (2003) identifies three steps to aligning supply chain and business strategy: understanding customer requirements, defining core competencies and the roles the company will play to serve customers, and develop supply chain capabilities to support the roles the company has chosen. These are three basic but critical steps that must be taken to stay afloat in competitive markets. Hugos (2003) goes further to explain how companies must “make decisions individually and collectively regarding their actions in five areas: Production, Inventory, Location, Transformation, and Information.” When evaluating these five business drivers, the goal is to find the best mix of responsiveness and efficiency for the market being served. Each supply chain will achieve this in its own unique way.

Another commonly heard term in this realm of operations is logistics. It is important to note, as experts support, that there is a difference between the concept of SCM and the traditional concept of logistics. Hugos (2003) also touches on this quoting,
“logistics typically refers to activities that occur within the boundaries of a single organization and supply chains refer to networks of companies that work together and coordinate their actions to deliver a product to market.” SCM basically includes all traditional logistics, along with other activities. It takes a systems approach to coordinating all the entities within the business. Logistics will focus on optimization within a certain area of an organization, such as distribution.

2.2 Construction Supply Chains

Construction supply chains, as expected, end with the customer. Upstream sits any involved engineering, construction, or professional services firms. These organizations fill all the planning, engineering, and project management functions of the project. From here, the respective material, labor, and equipment supply is sourced. Cox and Ireland (2002) illustrate this construction supply chain in figure 1.

![Figure 1 The myriad of construction supply chains](image)

Supplier and contractor selection is achieved through bidding and typically based on lowest cost, given adequate capability and experience. Procurement options vary
depending on the project. This “purchasing” of construction is achieved through construction contracts. The most widely used formats of contracts is the competitively bid contract and the negotiated contract. Competitively bid contracts, which yield low and competitive prices, are utilized the most. Two main types of these are (1) lump sum contract and (2) unit-price contract.

The process of materials management is another important aspect of the construction supply chain. Halpin (1998) shows that the four main phases of the material life cycle is order, approval process, fabrication and delivery process, and installation process. Contractors begin the cycle by placing purchase orders or awarding subcontracts. Materials are subject to review by the architect or design professional. An approval process must be in place before moving onward. Along with the contract drawings, subcontractors and suppliers must also provide details through shop drawings, product data, and samples. Submittals are then returned after review and delivery requirements and dates are established. The third phase of fabrication and delivery is the most critical of the four phases (Halpin 1998). Lead time for items here is critical and must be monitored carefully. Deliveries are brought to the job site and staged, usually in bulk amounts. Finally, the materials are incorporated into the project during the installation process.

One primary limitation of effective SCM in construction is the fragmentation of supply chain members. There are a number of sourcing options along with complicated structures of power within the different markets. Construction also runs on a project by project basis. Each is unique in scope and design. Suppliers and customers are quite frequently changing and relationships with the constructor need to be re-developed. Cox
and Ireland (2002) quote, “construction supply chains have remained contested, fragmented and highly adversarial because of the conflicting nature of demand and supply.”

From this also comes a very important problem affecting further improvement in the industry, which is the myopic control of the supply chain. By this it is meant that upstream members of the supply chain are not able or interested in seeing the effects and impacts of their behavior downstream. Problems are caused in certain phases of the supply process, left unattended, and then compounded as they move or are passed on down the line. Efficiency over the entire project life cycle suffers from this. The value stream is not controlled.

A second key limitation or problem in construction SCM is evident through ineffective material management. Buffers of inventory are created on job sites when excessive amounts of material from suppliers are delivered and staged. Excessive movement of materials becomes necessary. Many times extra materials around job sites stop others from doing productive work. Also, they may not even be easily accessible for the installers. Thomas (2005) illustrates these material problems in figures 2-3, and supports that efficient management of these materials is essential in managing a productive and cost efficient site.
Lastly, the effective use of information technology (IT) is another limitation in the construction industry. These technologies are not readily available for relaying real-time information to members of the construction supply chain. Project managers do not always have integrated software available in helping them with strategic planning. The development of IT solutions is also important in financial transactions on a project.

2.3 Manufacturing Supply Chains and Lean Practice

Supply chains in manufacturing are also quite complicated, for example in the auto industry, but are generally more steady and consistent in its members. Due to the nature of the business, manufacturers typically keep a steady stream of work going with
their primary suppliers. They develop multi-year agreements and establish relationships. Supplier quality is also monitored. Most manufacturing operations are continuous and not solely run on a project by project basis, as is its construction counterpart. Manufacturing involves a production system where construction projects are more temporary productions systems. Manufacturing also involves shipping and distributing the product to the end customer. This is another significant difference verses that of construction, where the final product is in place at project completion and ready to handover. Manufacturing operations usually center on a single production facility and the supply chain includes first-tier suppliers, sub-tier suppliers, vendors, transporters, warehouses, retailers, and customers.

Lean thinking has transformed every aspect of the manufacturing industry. What started as an initiative of lean manufacturing has developed into the vision of lean enterprise. Companies have applied lean improvement efforts to nearly every aspect of their business, especially in managing the entire supply chain. They have come to realize how taking a structured view in assessing the performance of their respective supply chains can reveal improvement opportunities. Wincel (2004) quotes, “SCM and lean manufacturing intersect most significantly in profitability objectives, customer satisfaction objectives, and quality objectives.” These are three drivers behind the pursuit of a lean supply chain in the industry.

The technique of value stream mapping (VSM) is responsible for kicking off many lean efforts. This term “value stream” includes all activities that add value to the final product or service. For example, installing a door on an automobile adds value while double or triple handling materials from one place in the shop to another does not.
VSM involves mapping all the processes in a business operation and sorting value added steps or activities from waste. This exposes the waste and allows the organization to begin finding ways of removing or at least reducing this waste. In other words, consideration is given to how the process can be arranged to improve efficiency. The mapping from the original process is named the current state map and then after some suggestions and changes, a future map is created. Examples of these are seen in Appendix A.

Manufacturers have found their supplier relations to be very important. They form close interweaving relationships with their suppliers. Resulting from this, efficiency of the transaction increases and the product or service is being produced at the lowest possible cost. In addition, major suppliers to manufacturers who practice lean also begin to incorporate lean and continuous improvement into their organizations. For example, lean efforts in the shops of these suppliers may result in a reduced lead time for products. The manufacturer or customer of this supplier will then benefit from the responsiveness. Another example is seen when suppliers improve their quality. This keeps much burden off of manufacturers who would otherwise have to deal with any quality problems downstream during their part of the process.

Materials management also has become a science with manufacturers. Just-in-time delivery and visual control have shown great improvements by lowering inventory in the shop, eliminating multiple handlings of materials, decreasing search time for materials and tools, and improving safety, just to name a few. This term “just-in-time” means making and delivering only what is needed, only when it is needed, and only in the amount needed. This falls back on the previous discussion of working closely with
suppliers. Visual control includes the practice of organizing any materials in the shop and utilizing the lean 5S process, which includes sorting, setting in order, shining, standardizing, and sustaining.

The implementation of the kanban tool has supported the central lean philosophy of having a “pull” production system. A pull system basically means that all work being done is to fulfill actual customer orders. Work is not being done or “pushed” just to create product with hope of selling it downstream. The kanban tool is basically a way of signaling for more raw materials to be drawn into the production process or for more raw materials to be made available. The two kinds of kanbans used in the Toyota Production System to serve these functions are production instruction kanbans (production kanbans) and withdrawal kanbans (transport kanbans). The term kanban means ‘card’ or ‘sign’ and are usually some type of printed cards on each item or signal. When items have been used or transported, kanbans come off of the items and go back to the preceding processes as orders for more of the item. This helps maintain a minimum and maximum inventory level. It also allows quick response to changing customer demand.

Finally, the use of information technology, the internet, and various software systems have allowed traditional manufacturers to stretch their capabilities and greatly improve their efficiencies. Various ERP (Enterprise Resource Planning) software packages, such as Oracle, have allowed for efficient procurement and accurate production control. On-line capabilities have extended to include various ways of exchanging information and showing product information. Overall, the manufacturing industry has found a number of ways to optimize work processes throughout the supply chains utilizing various developments in IT.
2.4 Lean SCM and Construction

Research into the supply chain aspect of lean construction has become of great interest to many in the industry. Ballard (2000) discusses the mission of the Lean Construction Institute and displays their vision through a model they call the Lean Project Delivery System (figure 4).

Figure 4 Lean Project Delivery System

On page 121 of the Diekmann report, the authors conclude that “there is clearly a coupled opportunity to apply lean thinking to the supply chain and design and contracting processes to create what the Lean Construction Institute calls the Lean Project Delivery Process” (Diekmann, 2004). The Lean Supply phase of this model is of interest here, and consists of detailed engineering of the product design produced in Lean Design, then fabrication or purchasing of components and materials, and the logistics management of deliveries and inventories. The remainder of this section will be grouped into discussion under these three areas.
2.4a Detailed Engineering

This first topic under the Lean Supply phase concerns the transition from design to supply management. This occurs when product and process designs are developed. It aims at streamlining this transition through the use of new technologies, untraditional collaboration between involved parties and standardization.

3D Modeling. This concept challenges the industry to investigate the uses of 3D modeling for detailed engineering. The software is available and other industries have already taken advantage of this. Where applicable, fabrication will be driven from these models. They give a more realistic view of the product before fabrication and offer more proof of proper fits and tolerances.

Engineering and supply collaboration. During this transition of the project from design to supply, there is much time used in detailing, getting approvals, redesigning, etc. The engineers are working with designs before suppliers have even been chosen, and in many instances these designs are then changed after someone has been awarded the work. The lean initiative here is to get suppliers involved earlier in the design phase. This will alter contracting and change the way agreements are made, but in the long run work flow could be improved. Arbulu (2003) lists a number of advantages of this: engineers can identify product catalogues early on, joint optimization of the design process, suppliers can tailor catalogue designs to best meet design requirements, suppliers can gain insight into the project sooner and can manage their own supply chains better, engineers can expedite approval processes, and both can quickly resolve requests for information. This collaboration also falls under Srinivasan’s (2004) seventh principle for building and
managing the lean supply chain, which urges industry to “build partnerships and alliances with members of the supply chain strategically, with the goal of reducing the total cost of providing goods and services.” This brings an element of systems thinking to the construction industry. It is this type of thinking that is needed to improve performance of the whole construction supply chain. As many experts will quote, optimizing the separate links of the supply chain independently does not optimize the supply chain. Making improvements only within your organization and settling with arm’s length relationships is not sufficient. Those in the construction industry need to explore how partnering and developing strategic alliances can add benefit to projects. Moreover, these relationship barriers that exist in the construction industry must be breached before true lean supply chain management can exist and thrive.

*Standardizing products.* An additional concept following from collaboration is the use of standardized products and reduction in part counts. By reducing the number of different product models, engineering time is reduced and fabrication becomes much smoother due to fewer changeovers. In addition, a lot of time and energy can be saved in the field from these minor changes, by reducing changeovers, sorting time, etc. Diekmann (2004) shows this to be an applicable principle of lean and product optimization in construction. An example of a simple frame steel building is used. Design called for more than 40 different sizes of bar joists. The report moves to say that if this number had been reduced to say 20, significant savings would be seen along the value stream. This idea of standardization is important to implement where applicable in a lean production system. Finally, Arbulu (2003) states that, “industry leaders, early adopters of supply chain management practices, have been able to save about 6-7 weeks
off the lead time traditionally required to deliver pipe supports.” The tactics just
mentioned have been the major causes of these improvements.

2.4b Purchasing and fabrication

The important initiatives within this area of Lean Supply appear to be with
strategic procurement and with the application of lean manufacturing techniques to
fabrication shops.

Supplier and cost management. Strategic procurement involves evaluating how
you acquire goods and services and viewing this as an extension of other company
strategies. Procurement and supply chain costs make up a large portion of the cost in a
construction project so the importance is clearly seen. Wincel (2004) shows six major
areas of initiative within SCM being: supply base management, supplier quality, cost
management, cost improvement, distribution/transportation/logistics, and organization.
These first four are relevant here. Without going into detail on each of these, the general
strategy here is to develop management practices that focus on cost reduction and quality
improvement throughout the supply base. It emphasizes again cultivating relationships
with suppliers, basing supplier selection on quality as well as price, and looking at
financial improvements in the supply chain.

Lean manufacturing in fabrication shops. Another key factor in successfully
practicing lean supply chain management in the construction industry is by ensuring that
fabrication shops delivering to job sites are utilizing lean thinking in their shops. The
construction group benefits from this in a number of ways. One is seen in the speed with
which a lean shop can react to changes. These shops have lower inventory and reduced
batch sizes from utilizing a production pull system, have better visibility of their process, and are familiar with quick product changeover. These aspects of lean allow for quicker changes in production when the need arrives. Other benefits from using shops that practice lean include quality improvements and more effective delivery methods. These will be discussed more in following sections.

**Quality control.** An extension from lean manufacturing concepts is the theory of ‘quality at the source’ or in-process inspections. It is a lot easier dealing with and fixing quality problems where they originate (in the fabrication shop, etc.) than encountering them in the field. Shops that practice lean manufacturing usually have a systematic and effective approach to quality control. First, defects are caught earlier in the process and taken care of by whoever notices the problem. Then these incidents are documented and continuous improvement plans are utilized to analyze causes and prevent future problems. The construction group in the field benefits by not having to discover these defects out in the field. Any quality inspections on site prior to installation (a non-value added task) may also be eliminated.

**Pre-assembly and moving work upstream.** This is another lean concept and a topic of interest in the research community. This initiative involves pre-assembling components off site whenever appropriate and in theory, moving work upstream in the process. Shop environments are more controlled (weather, space, etc.) than field environments and this is one benefit of doing pre-assembly work early in the process. Another benefit could be seen if labor rates are cheaper in the shop than in the field. Following from the previous section, moving quality control upstream has its benefits. Also, it is common knowledge now that lean focuses on the minimization of inventories.
However, when small inventories do exist it may be beneficial to hold these materials upstream until needed, like in a fabrication shop versus on site. More will be said on material delivery and coordination next.

2.4c Logistics Management of Deliveries and Inventories

Effectively managing deliveries and site material inventories is the concern in this third area of Lean Supply. It also acts as the transition into the Lean Assembly phase of the Lean Project Delivery System.

*Pulling to site demand and JIT.* The idea of creating “pull” systems in a production environment is central in implementing lean. In the context here with material deliveries, the popular term used is just-in-time (JIT). Davis (2004) explains that “JIT takes its name from the idea of replenishing inventory only in the quantity needed, as close to the time of actual need as possible, with material being “pulled” through the production system by end-item demand.” This aspect of lean construction involves delivering only what materials are ready for installation, in the amounts needed, and at the time it is needed. The production system here would be the actual construction. The end-item demand is what is needed on site at that point in time. Ideally, the materials are brought straight to the point of use for installation without incurring delays due to storage in a laydown or staging area.

This concept of pull system is contradictory to the traditional push system, where materials that are needed on the job are delivered in bulk and sit around the site for weeks until used. This creates inventory, extra handling, and other waste, that does not add value to the project. A great example of JIT delivery that many lean construction
researchers use is that of concrete. The initiative now is utilizing this concept with other materials introduced to the jobsite. By reducing the sizes of material batches and making deliveries in sequence with job phases, work flow can be improved. Of course, there are other issues that arise from this such as increasing the number of supplier shipments, adjusting contracts, etc. However, most organizations are finding the benefits to outweigh the work put into any changes that need to be made.

Several papers have been released on the topic of pull systems and JIT in construction. Tommelein (1998) shows through simulation that a lean-production pull technique can theoretically improve performance of pipe-spool installation in process-plant construction. She discusses the so-called “matching problem” in this type of industry, where everything must come together at the right time for the installation crew to begin work. First the location is chosen, then the type of pipe, then the pipe supports and other accessories. On large jobs with hundreds of piping details, this becomes a complicated task. The pull technique is utilized by using real-time feedback from construction to drive sequencing of off-site work. Matching parts are brought in at appropriate times and the construction process is more efficient.

Ballard (2003) also explores pull techniques and JIT in construction by presenting a materials management strategy for selected made-to-stock products – consumables, PPE, hand tools, power tools, etc. The project it is applied to is the construction of a major transportation hub. The strategy is called Kanban and involves replenishing the items when inventory drops to a pre-determined level. A “marketplace” on site manages these items and when items are needed a “milk run” vehicle is sent to a preferred supplier. These milk runs occur on a daily basis and for this project, a supply depot was
established between 2 and 5 miles from the project to reduce collection cycle time. Overall, the research showed this type of strategy having a positive impact on labor productivity. It was noted however that this was a very large project which justified the use of such a system. There is still concern as to whether or not it makes sense on smaller projects.

**Communication and IT.** This is a topic in supply chain management which really falls under all three focus areas in this paper; however, is of most interest here with interactions at the site level. Effective communication is essential in any operation but even more so in a lean one. Information must move smoothly within and between organizations to optimize flow and generate value for the final customer, two objectives of lean. Finding ways to communicate more effectively with everyone involved in a construction project is an important aspect of having a lean culture. What IT does is provide visibility throughout the supply chain. New developments in technology, software systems, and online capability provide a number of ways for organizations to link information in real time. Raw material suppliers, fabricators, construction managers, subcontractors, owners, and others can collaborate through the effective use of IT to check the status of each other. Field managers can access information on material inventory levels and release times from their suppliers through access-controlled extranets. RFI’s and submittals can be transferred and approved online. Owners can update themselves on construction job completion through the internet. These various uses of IT streamline business. Lead times are reduced. The number of paper transactions is reduced. And most importantly, visibility of job status is improved.
Materials and site management. Having a material management plan and promoting good housekeeping is the idea here. The field lean construction tool of 5S provides a systematic procedure for housekeeping. Thomas (2005) defines site material management as “the allocation of delivery, storage, and handling, spaces and resources for the purposes of supporting the labor force and minimizing inefficiencies due to congestion and excess material movement.” Thomas goes on to mention that through a number of studies, it has been noted that material management deficiencies create negative impacts on labor productivity. The authors present several principles of site material management. The location of staging areas should be one concern on projects. The number of staging areas, the quantities within these areas, and the marking of different material types should be strategically determined. It may be possible to take materials straight from the truck to the workface. As mentioned with JIT, deliveries should also match the sequence of the weekly work plan. Finally, the movement of materials onto the workface is another concern. The most optimal way of moving materials to the different floors without slowing work flow needs to be determined.
3. CASE STUDY

3.1 Project Description

In support of this thesis, a lean study was conducted with an established Cincinnati contractor, a regional medium size company focused on building construction. The group had been incorporating lean tools into their field operations and has successfully implemented Last Planner. The other tools they had been working to implement were Visual Workplace, Increased Visualization, Daily Huddle Meetings, Fail Safe for Quality, and First Run Studies/System Improvement Events. The company organized what they called an advanced lean team to facilitate the use of these tools. Along with continued development of these tools, their goal was in becoming a “lean enterprise” by incorporating improvement efforts into all other areas of their business. This research in lean SCM supported these efforts. The time frame for involvement with this group was approximately five months.

3.2 Research Questions and Methodology

Research Questions:

What could be pursued within the supply aspect of lean construction?
How may these initiatives tie in with other tools currently in use?

Methodology/Strategy:

Gain insight into and evaluate current efforts with lean construction
Perform an assessment considering the 2nd and 3rd SCM initiatives discussed in the literature review
Fabrication
Logistics management of deliveries and inventories
Identify ties with current tools used
Report observations, opportunities, and challenges
Field study was conducted on the construction site of a 12 story 410,000 sq. feet hospital research building (Figure 5). Two phases of the project were observed during the five months. One was the erection of the cast-in-place reinforced concrete frame. The other was installation of the building skin – exterior framing, masonry walls, brick, etc. The general contractor (ContA) averaged about 10 staff and 25 laborers on the project. Some of the other participating trades were the formwork subcontractor, rebar subcontractor, masonry subcontractor, miscellaneous metals fabricator and installer, exterior framing subcontractor, and exterior specialty/window/curtainwall fabricator and installer.

3.4 Overview of Lean Construction Tools in Use

Last Planner – ContA has successfully implemented this system of production control. They follow the formal sequence of implementation – Master Schedule, Reverse Phase Schedule (RPS), Six-Week Lookahead, Weekly Work Plan (WWP), Percent Plan Complete (PPC), and Variance Analysis. Reverse Phase Schedules, stretching 12 weeks, were created for both the concrete frame and the skin. These two phases were headed under different project managers. Each manager maintained a lookahead a bit larger than
six weeks due to the repetitive nature of their work, and each had separate weekly work plan meetings. Meetings were held jointly with regards to safety and coordination. Each weekly work plan reviewed work for the current week, went over work for the next week, set to address any item on the RPS that was left out, and gave a small list of workable backlog items. Finally, PPC and variance was recorded for each week. Examples of PPC charts and variance analysis for both phases of the project are found in Appendix B. For the building enclosure, an average PPC value for this date in the project was 81.5% and top reasons for plan variance were pre-requisite work and materials. For the concrete frame, an average PPC value for this date in the project was 82.4% and top reasons for plan variance were weather and labor. When compared to the previous lean study that ContA was involved in where the PPC average was 75%, these values over 80% show some improvement. Reasons for variance have been quite common.

ContA explains that the Last Planner process has definitely improved their operation. It has given them more forward visibility, they are more aware of dates and commitments they need to meet and it has reduced project variability. As the tool is suppose to provide, it has replaced optimistic planning with realistic planning. This is accomplished by evaluating worker performance based on their ability to reliably achieve their commitments. In addition, it appears that project managers over jobs using this tool do not appear as stressed out.

Increased Visualization – The use of this tool is noticed from signs and other postings around the jobsite. Figures 6-9 show some examples. These include concrete pour schedules, weekly work plans, safety signs, and floor number postings.
Figure 6 On-site Concrete Pour Schedule

Figure 7 On-site Weekly Work Plan

Figure 8 On-site Safety Sign
This tool of increasing visualization has helped ContA by ensuring everyone on site is aware of key information. Seeing these things allows the construction team to remember them much easier. Brief questionnaires have been filled out by the workforce and have supported these views.

Visual Control (5Ss) – This lean tool simply emphasizes good housekeeping. The formalized process of achieving this is the 5S process (Sort, Straighten, Shine, Standardize, and Sustain). ContA enforces this on jobsites with their subcontractors and assigns cleanup crews from their own workforce. Figures 10-12 show the job following this emphasis on good housekeeping.
This mindset of creating a visual workplace has helped ContA reduce clutter, create usable space, achieve cleaner and more organized jobsites, and make the construction process more transparent. Time spent looking for material or a defect is minimized. Safety is improved from this lack of clutter.

Daily Huddle Meetings – These meetings or “tool box talks” are held daily by the jobsite foremen as well as by the craft workers. The foremen may meet at the end of the day reviewing the work completed and the work to be completed the next day, while the craft workers may meet in the morning to discuss work to be accomplished, safety concerns, material needs, etc. These meetings have shown to be a great means of communication and encourage employee involvement. This involvement creates employee empowerment and allows quicker response to problems.
Fail Safe for Quality – This tool involves finding ways to ensure quality (or safety) during construction, verses after the fact quality control. ContA does occasionally find ways to do this and reaps the benefit. Lighting may be increased for slab pours. Quality control can be enforced before concrete is poured. The construction group could also mandate that workers leave the trailers with harnesses and other PPE already on and on properly. Formalizing this process and naming it has made more people aware of the thought process. Work is accomplished with fewer defects, safety is improved, and the overall flow of the job is improved.

First Run Studies / System Improvement Events – These include productivity studies and any other improvement events held. These are similar to Kaizen events that are held in the manufacturing industry. Kaizen is the Japanese word for improvement. This lean construction tool involves looking at some task in the field and finding out how to do it better, more efficiently, safer, and quicker. For example, this task could be in erecting formwork for a column or framing a section of wall. This is still new to many but ContA does believe in utilizing this mindset and has achieved some success with it.

3.5 Assessment

Fabrication – The central focus of this part of the assessment was the application of lean manufacturing techniques in fabrication shops. Two off-site fabrication shops supplying the job were chosen for the study, call them SubA and SubB. SubA utilized lean principles and SubB did not. SubA supplied the exterior cladding systems (windows, curtainwall, etc.) and SubB supplied all miscellaneous metals (ledge angle, beams, etc.). Both fabricators also handled field erection. Walkthroughs were taken of each
fabrication shop. Business processes were discussed. Process maps or flow charts of both operations were later created. For each operation a general map was created and then a map of just the physical fabrication. These are found in Appendix C. More formal value stream maps were not created here. That level of detail into each operation was not desired. Improving one chain in particular was not the focus, but rather to get information necessary to make a comparison between lean and non-lean suppliers in the construction industry. Activities on site were then monitored to investigate material flow into the field and to see how lean and non-lean supply chains can have differing effects on field activity.

Logistics management of deliveries and inventories – The central focus of this part of the assessment was JIT delivery and materials management on site. Materials for the building enclosure were looked at in detail. Quantities being delivered were determined. Times, schedules, and methods for these deliveries were monitored. The idea here was to find where JIT delivery of materials applies and where it does not. Other aspects of materials management that had to be looked at were the use of staging areas and the amounts of excess inventory around site. The idea here was to find out if and how staging areas were being used, and to identify any materials sitting around in excessive amounts.

3.6 Observations

Fabrication – After visiting the shops, many differences were noticed between the two. SubA was very far along incorporating lean into their business and SubB really had not implemented anything along these lines. The first difference noted with SubB was
the larger amount of product sitting in queues between processes. One idea with lean is to reduce batch sizes moving through the plant and to minimize inventory. By reducing batch sizes work flow is improved and space is more effectively utilized. Lead times for items are reduced. Inventory hides defects and by minimizing it quality can also be improved. Quality control procedures were the next difference noticed. SubA implemented a quality control program which not only empowered employees to identify defects at their stations but also consisted of a formal procedure for improving quality through a measuring system. A quality tracking form for each job is kept with scoring and employee sign offs. A quality report with impact score is given if a defect occurs. Higher impact scores are given if defects are found later in the process. The goal is to keep scores low and identify defects as early in the process as possible. The worst case scenario is finding a defect in the field and the program acts to prevent that. The only means of quality control seen with SubB was through daily inspection by the shop foreman.

Pulling work versus pushing work is another concept of lean manufacturing. The question here is what and how much of a product do you produce. This also follows from the idea of reducing batch sizes. SubA produced only to site demand in the quantity needed and at the time they needed it. For example, a production run would consist of all the punched opening windows for level one of the building. The next week, these windows would all be installed on the job site. On the contrary, SubB would produce in mass quantities. For example, a production run would consist of all brick ledge angle for the whole building, when all that is really needed for that next week is that for the first floor. Plant management did agree with the site installers that only portions would be
brought to the site at a time, which was appropriate. However, all the rest of the ready angle has to be staged in the plant and sits until needed. This takes up space and results in carrying costs. In addition, SubA used lean thinking to utilize downtime. Any extra time was filled with assigned side work, such as hardware or mounts needed for installation. This work was not critical and could be done at anytime. Traditional means would show jumping ahead of schedule and moving ahead to the next job. This goes against lean principle.

More clutter was seen in the SubB shop as compared to that of SubA. SubA uses the lean philosophy of 5S, which focuses on organizing shops, eliminating unneeded items, dedicating a place for everything, and sustaining any improvements made. It was evident in the walkthrough. You could find things easier, it was safer, and the process was more visual. This visual management is another initiative with lean. SubA showed production boards of what was happening in the shop, had clear floor layouts, and had kanbans which helped with replenishing tool consumables and materials. Lighting was even better in the facility of SubA. Finally, standardization of shop drawings was noted in the shops. SubA used computer printouts while SubB still used a mix of computer generated and hand generated. Standardization is another element needed in creating a lean shop.

The number of raw material suppliers used also brought up discussion. One aspect of supplier and cost management is to try to reduce your number of suppliers if possible. The fabricator can find cost savings and establish better business relationships with a smaller preferred group. SubA and SubB were quite different in their type of work which made this a difficult comparison, but some observations were noted. SubA did
have a relatively small number of suppliers and had one primary for metal, glass, and rubber. With these few, they also had pull systems in place for how much and when they received materials. Inventory tracking forms were then maintained to compare ordered versus received. SubB had a very large number of suppliers, whom delivered in bulk amounts.

Quick changeover is another term heard with lean manufacturing that is evident here. This involves being able to switch over machines and manpower to a different job relatively quickly. With SubA producing in phases, they seem to be able to do this quite easier than SubB. This helps with workflow and with changes in orders or deadlines. Srinivasan (2005) states, through his 5th principle for building and managing the lean supply chain, to “buffer variation in demand with capacity, not inventory.” SubA shows the capacity here to effectively handle variation in demand. SubB may handle it through inventory. As opposed to a lean shop, SubB may also have problems with sudden changeovers, resulting in shipping delays.

Table 1 summarizes these observations between lean and non-lean fabrication shops.

<table>
<thead>
<tr>
<th></th>
<th>SubA</th>
<th>SubB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead Times</td>
<td>Shorter</td>
<td>Longer</td>
</tr>
<tr>
<td>Queues</td>
<td>Small if any between processes</td>
<td>Larger between processes</td>
</tr>
<tr>
<td>Quality Control</td>
<td>Formal program, Improvement</td>
<td>Final inspection by shop foreman</td>
</tr>
<tr>
<td># Suppliers</td>
<td>Few</td>
<td>Many</td>
</tr>
<tr>
<td>Batch Sizes</td>
<td>Small, In job phases</td>
<td>Large, Whole job quantities</td>
</tr>
<tr>
<td>Inventory Control</td>
<td>Regularly, Tracking Forms</td>
<td>None noted</td>
</tr>
<tr>
<td>Visual Management</td>
<td>Obvious</td>
<td>None noted</td>
</tr>
<tr>
<td>5S/Workplace Organization</td>
<td>Effective</td>
<td>Lacking</td>
</tr>
<tr>
<td>Standardization</td>
<td>Computer shop drawings</td>
<td>Computer and hand shop drawings</td>
</tr>
<tr>
<td>Quick Changeover</td>
<td>Available</td>
<td>Lacking</td>
</tr>
<tr>
<td>Capacity</td>
<td>More flexible with demand</td>
<td>Less flexible with demand</td>
</tr>
</tbody>
</table>

Table 1 Fabrication shop lean comparison
Site activities with regards to these suppliers were also monitored and observations were made. During the study one problem that arose was delays from SubB in supplying the brick ledge angle. The hold up seemed to be at the galvanizer, which was the final step before shipment to the site. This lack of control in the supply chain is a common problem in the construction industry. On the other hand, lean can offer improvements. SubA was just starting field installation at the conclusion of the study. No delays were seen with them and they seemed to be able to react relatively quickly to changes.

SubA’s field crew had a number of comments on how lean initiatives have positively affected their work. For starters, they said there is less material sitting around the job sites. They have what they need but don’t have all the other clutter. The idea of delivering material just-in-time has worked for them. The biggest improvement they have seen since rolling out lean initiatives is having commitment of material being there. With more effective planning, lean methods throughout the shop, weekly communication between site and shop, and pulling of materials based on site need, field crews have fewer problems and are able to be more productive. Pre-assembling more in the shop has also helped the ease of installation on site. Lean thinking has also affected how they handle fasteners on site. Instead of dropping bulk quantities of fasteners they make kits of what they need with procedures for replenishment. In certain circumstances, the vendor will come out and replenish these items if counts get down to a certain level.

In general, they said that lean initiatives have given them a better way of managing. Better commitments and visual management in the field has been key. From the literature review and case study, it seems obvious that operations run the smoothest
when all players in the supply chain (raw material suppliers, fabricators, and construction installers) incorporate lean thinking into their individual work. From this, opportunities present themselves to reduce lead time for engineered-to-order products.

Logistics management of deliveries and inventories – The site used in this study was very organized and staging areas were very efficient.

Figure 13 Site plan

Three gates to the site were accessible. These are labeled G1, G2, and G3 on the site plan (Figure 13). Deliveries were scheduled and routed to the tower crane, buckhoist (elevator near the tower crane), north staging area, or loading dock. A delivery board in the office was used to schedule deliveries (Figure 14). This gave everyone a visual of what areas and times were open for deliveries. Most material was brought into the north staging area (Figure 15).
In many instances, materials being delivered were taken straight to the area of use versus just dropping them in the yard and letting them sit. This was accomplished by effectively coordinating delivery times, ensuring that pre-requisite work was completed, creating any space needed, and making needed lifts or machines available for moving materials. For example, a steel truck would arrive and immediately the tower crane would begin unloading to the upper floors. A brick truck would arrive and forklifts
would be available with the use of the buckhoist to move material to the appropriate floor. These observations showed that material control around the site was quite a lean process. Excess inventory and delivery quantities were investigated. With regards to the building frame, reinforcing steel and formwork were of interest. Steel movement was effective and quantities delivered were appropriate. Formwork did cause some concern but was given an assigned staging area. Some excess formwork was staged in the upper corner of the north staging lot (Figure 15). With winter coming slower concrete curing times would result, and some excess forms were also needed because those in use may not be torn down as fast. With regards to the building enclosure, materials of interest were sheathing, metal studs, and brick.

Sheathing and metal studs were obtained easily when needed and in appropriate quantities from a local supply house. However brick, which is a long lead time item, was seen in excess amounts around the building. On one particular day during construction an inventory count was taken of the first 9 floors. 210 skids of brick were spotted sitting in the building. It was noted that 10-12 skids were being set daily, so there was enough brick being staged for approximately 20 days or 4 weeks. Block was also seen in some excess amounts. The material count from this day is seen in Table 2.
<table>
<thead>
<tr>
<th>Floor</th>
<th>Brick</th>
<th>Block</th>
<th>Structural Sheathing</th>
<th>Insulation Board</th>
<th>Ledge Angle</th>
<th>Mason Mix</th>
<th>Core Fill</th>
<th>Grout</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>56</td>
<td></td>
<td></td>
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<td>7</td>
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<td></td>
<td>1</td>
<td>4</td>
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<td></td>
</tr>
<tr>
<td>8</td>
<td>76*</td>
<td>26*</td>
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<td>9</td>
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<td>29</td>
<td>4.5*</td>
<td>4*</td>
<td>1</td>
<td>17</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Totals (# units/skids)</td>
<td>210</td>
<td>58.5</td>
<td>6.75</td>
<td>9</td>
<td>5</td>
<td>1</td>
<td>17</td>
<td>15</td>
</tr>
</tbody>
</table>

* indicates a current working level for that material

Table 2 Material count 11/28/05

This brick appeared to be a target for reduction in delivery quantities. Reasons were noted from the brick team on why these amounts of brick were brought on-site. The first issue came from the fact that brick needs to come from the same lot to ensure a successful match. So to get the ready brick out of the shop and reduce the number of delivery days, high volumes were delivered. Ensuring that the brick was dry was another concern for the bricklayers, so having it sit in the building for days alleviated this concern. Then a large block of time was scheduled for use of the lifts to bring material into the building all at once. Another worry for bricklayers was running out of brick so the team wanted to ensure they had plenty available. These challenges had by the brick team were understood but thoughts still surfaced on converting this brick supply process to a more JIT process. These thoughts are noted in the recommendations section of this paper.

In Diekmann (2004) the authors give the lean concept of JIT in construction an applicability rating of 75%. This seemed to be the case in this study as well. Two
challenges they present are – establishing close working relationships with suppliers, incompatibility of construction needs and cost-effective manufacturing sequences. Large inventories go against the flow concept inherent in lean and JIT addresses this. On the other side, challenges are inherent in a construction environment and some of these were noted here. Lifts must be available to get materials to the point of use. More shipment days are needed from suppliers. Constructors run risks of running out of material. There also becomes large numbers of other trades to coordinate with and to work around.

Last Planner – One goal of the study was to see how these initiatives of lean SCM could tie into the existing lean tools, technologies, or current practices utilized by ContA. The first tie noticed was through the Last Planner process. Material issues need to be drawn out more during the lookahead. Lead times and procurement dates must go into the phase schedules. ContA was seen pushing subs to do this during the scheduling meetings. Just as the Last Planner process utilizes the theory of a pull system, materials need to be pulled from the suppliers (not pushed) to meet site demand. Material control must go hand in hand with the Last Planner meetings. This includes weekly communication between suppliers or fabricators and the site regarding material status.

It is common knowledge that one of the biggest causes of construction delays is lack of material. These reasons for variance from plan are tracked through the Last Planner weekly foreman meetings (Appendix 2). Material is a common problem that shows here, but it is usually left at that. This problem is significant enough that it deserves more attention. By focusing more on inventory control and material lookaheads, and by trying to incorporate lean thinking into supply, improvements could be made and monitored through these variance charts.
CMiC – The second tie to current company practice was through their implementation of the project management software, CMiC (http://www.cmic.ca). This software is a key breakthrough for the communication and IT aspect of lean supply chain management. ContA has been using the software for project management but also utilizes it throughout other departments in the company, like estimating, accounting, and payroll. In the field it has been used, for example, to manage RFIs and submittals. It provides daily reports useful to field personnel. It also gives ContA a centralized location for various communications. Figure 16 shows the CMiC product line. The project management package available contains the following categories of tools: cost and budget management, bid and procurement management, document management, site management, and collaboration manager.

![CMiC Product Line](image)

The last two were of interest in this study.

The site management tool shows potential for improving materials management around the jobsite. ContA had not yet used this module to its fullest. The software claims to help by supplying a place to document what is happening on site, tracking material deliveries, and reporting on equipment used and materials received. The application is also said to generate productivity trends during the course of the project.
The collaboration manager tool was the other, of even greater interest. It is said to “provide a full featured turnkey collaborative environment for all project stakeholders to interactively communicate in real time” (http://www.cmic.ca/collabman.htm). This is a web-based tool that allows everyone involved in the project certain access to important job information. It provides a centralized location for communications and document transfers.

First, it provides for real time communication updates for team members, from meeting minutes and job progress to bid information to project contracts. Everyone has one site to go to for constantly up-to-date information. Second, it allows for quicker and more efficient document transfers. Drawings can be uploaded then attached to an RFI or communication, before sending to another party. Responses can then be sent back with updated drawings. The process is paperless, online, and utilizes email. Stakeholders can become more updated on where materials are so they can take appropriate action. Overall, this tool provides better visibility for those in the supply chain, which is needed right now in the construction industry. It allows improved ways of managing information and gives construction teams a competitive advantage through effective usage of IT.

3.7 Recommendations

One goal of the company at this stage in their development was moving toward becoming a lean enterprise by instilling the philosophy of continuous improvement throughout their organization. Resulting from this lean study came many ideas and insights on how ContA may improve their operations through lean thinking in the area of supply chain management. These are listed below in appropriate groupings.
Fabricators and suppliers:

- For each job, perform a brief value stream assessment of each supply chain. This will help identify value added from non-value added activities. Collectively work to make improvements in these supply processes prior to project execution.
- Give higher consideration during job bidding to fabricators that practice lean manufacturing in their shops. The Last Planner process, being a pull system and lean construction technique, will be more effective with lean upstream processes feeding into it. Timeliness, flexibility and quality should be better overall with the use of these lean suppliers.
- Develop strategies incorporating lean principles with preferred and common fabricators, suppliers, or subcontractors in each market.
- Discuss with suppliers and fabricators new options for pre-assembly or pre-fabrication.

Site activity:

- In general, incorporate lean supply concepts and inventory control into site planning.
- Provide more real time feedback regarding status of the project on site to fabricators off site.
- Make the organized and efficient use of staging areas, as seen on the case study job, standard practice across other jobs.
- Keep inventory levels and delivery quantities to an acceptable minimum. Practice just in time (JIT) material delivery, synchronized with the project schedule.
• Setup and negotiate a job utilizing the JIT mentality with brick. Brick was a target for reduction on the case study job site. Discuss vendor managed inventory, more frequent shipments with small quantities to site, effective scheduling of lifts on site to allow for more frequent picks, and the covering of brick during shipment to ensure that it is installation ready upon arrival.

_Last Planner and Production Control:_

• Involve subcontractors more with identifying material constraints and issues ahead of time during the lookahead process

• Aim to decrease material variance tracked in Last Planner. This is a commonly seen reason for plan variance and deserves special attention.

• Include items regarding procurement and material lead times into the Last Planner reverse phase schedule (RPS).

_Technology:_

• Roll out the use of the CMiC Collaboration Manager. Once gaining buy in from all major players in the project, performance of the supply chain should be improved. This is accomplished by streamlining work processes, providing a real time updated online document center, improving communication and tracking, reducing paperwork, and decreasing lead times for important transactions.

• Continue development of CMiC site management functions

• Integrate the project schedule into usage of CMiC

_General business:_

• Push the success had with lean on this case study job to other jobs

• Have another similar lean supply study during the interior package of a project
4. CONCLUSIONS

This thesis was focused on investigating improvement opportunities in the construction industry, utilizing the practice of lean supply chain management. This topic is an extension of lean construction theory and techniques. A literature review was conducted and some of the current initiatives in the supply chain aspect of lean construction were identified. These initiatives span from design to construction and decisions involve anyone from upper management to site labor. Many of these concepts, like collaboration and cost management need to be factored in during the higher level planning that occurs early in the life of a project. They require involvement, discussion, and agreement by many active participants in the project. On the other hand, some of these initiatives, like effective materials management and staging on site, are created and implemented right at construction.

Application of this research was completed through field case study with a local contractor. An assessment was done with these lean supply initiatives in mind; specifically two of the initiatives from the literature review were given primary attention, these being fabrication and logistics management of deliveries and inventories. Observations were collected from informational interviews, supplier shop visits, and construction site activity. A listing of recommendations, challenges, and thoughts was then made for review by the local contractor who hosted the project. These recommendations consisted of improvement ideas in this arena and discussed how supply chain management concepts tie in with lean methods and other technology applications currently practiced and used by the contractor.
An important thought coming out of this work is how suppliers and their shop activity can hurt or improve the performance of the construction site. For example, material amounts delivered can have differing effects on the site. Installers need what they are installing for that week. Extra material around the job can cause extra handling, get in the way of other trades, and even get damaged when staged somewhere long enough. Quality is another topic here. The worst case situation is finding defective material in the field. Shops having developed and improving quality control procedures will ensure that what is in the field is ready to install, without problems. Effective, consistent, and real time communication between those involved in the project off-site and those on-site is also critical to project performance. The use of IT can be of great help here.

There is need for future research. One interest is to create incentives to get suppliers more involved with this lean thinking. Finding ways to get buy-in from all project stakeholders and incorporating these needs into the contract is a challenge. Integrating suppliers more into the Last Planner process is of interest. Material problems are common causes to variances in the schedule. A goal here, again as shared by FIATECH, is to create an integrated, automated procurement and supply network that is dictated by the project schedule. Moreover, additional research is needed finding construction materials that, delivered on a just-in-time basis, allow better performance of operations at the install site. In this study, brick showed to be a great candidate.
REFERENCES


APPENDICES

Appendix A Example manufacturing value stream maps
Appendix B Last Planner files from case study
Appendix C Fabricator process maps
Appendix A Example manufacturing value stream maps

Example Current State Map from Manufacturing VSM

Example Future State Map from Manufacturing VSM
Appendix B Last Planner files from case study

PPC Chart – Building Enclosure

Variance Analysis – Building Enclosure
Appendix B Last Planner files from case study

PPC Chart – Concrete Frame

Variance Analysis – Concrete Frame

Variance

<table>
<thead>
<tr>
<th>Cause of Variance</th>
<th>Target missed</th>
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<tbody>
<tr>
<td>ContA Labor</td>
<td>0</td>
</tr>
<tr>
<td>Steel Labor</td>
<td>4</td>
</tr>
<tr>
<td>Formwork Labor</td>
<td>13</td>
</tr>
<tr>
<td>Steel Manuf.</td>
<td>1</td>
</tr>
<tr>
<td>Steel Delivery</td>
<td>1</td>
</tr>
<tr>
<td>Weather</td>
<td>8</td>
</tr>
<tr>
<td>Crane Time</td>
<td>1</td>
</tr>
<tr>
<td>Design</td>
<td>1</td>
</tr>
<tr>
<td>Layout</td>
<td>1</td>
</tr>
</tbody>
</table>
Appendix C Fabrication process maps

SubA General_Punched Opening Windows

SubA Fabrication_Punched Opening Windows

Cut → Fabricate → Sub-Assy

Assembly → Glaze → Package