MAKING PREFABRICATION LEAN

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ABSTRACT

Construction is not manufacturing. However, manufacturing provides the elements from which buildings, bridges, highways, houses and factories are constructed. Many of these elements are made-to-stock, but some key elements are made-to-order; e.g., HVAC ductwork, custom piping, pipe supports, precast concrete, electrical switchgear, reinforcing steel, structural steel and building envelope facades. These made-to-order products are produced by fabrication shops, which sit squarely at the intersection of manufacturing and construction.

Application of lean concepts and techniques to fabrication shops promises substantial benefits to the construction industry they serve. Perhaps chief among these benefits is reducing the lead time required for placing orders in advance of needed delivery. Long lead times can extend project durations, promote premature design decision making or otherwise avoidable design redundancy, and cause excess inventories and double handling of materials. A "long" lead time is determined relative to the ability of the customer (the construction site) to accurately forecast future states of the building process on site, and thus the ability to determine when a component will be required for installation. Lead times that exceed a site's window of reliability increase the probability of untimely delivery. On time-driven projects, such lead times also increase the risk of premature design decisions and/or building slack into designed capacities and strengths.

Switching perspectives, demand variability is arguably the biggest headache for fabricators. Late receipt of design information, frequent design changes and changes in installation timing and sequence disrupt production schedules and cause fabricators to risk the loss of capacity.

In this paper, we explore the interplay between demand variability and fabrication lead times and present a plan to study and understand their interdependencies.

KEY WORDS

Assembly, demand variability, fabrication, fabrication shop, lead time, made-to-order products, preassembly, prefabrication

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INTRODUCTION

Construction is not manufacturing. However, manufacturing provides the elements from which buildings, bridges, highways, houses and factories are constructed. Many of these elements are made-to-stock, but some key elements are made-to-order; e.g., HVAC ductwork, custom piping, pipe supports, precast concrete, electrical switchgear, reinforcing steel, structural steel and building envelope facades. These made-to-order products are produced by fabrication shops, which sit squarely at the intersection of manufacturing and construction.

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The ability to measure, understand and manage variability is critical to effective project management (a paraphrase of Hopp and Spearman, 2000). Variability comes in many forms and types, of which demand variability is one, and can be understood for our purposes as changes in requests after commitments have been made.[3] The specific application in which we are interested here is orders placed with fabricators that are subsequently changed either as regards the timing or sequence of deliveries or as regards the design of the product to be fabricated. Such changes are disruptive to the fabrication and delivery process. Fabricators attempt to protect themselves from these disruptions through a variety of means, including longer lead times and double booking of capacity.[4] Unfortunately, these preventive measures tend to deteriorate total production system performance.

Contracts are a contributor to the problem. Constructors rarely buy shop capacity, the use of shop resources, as opposed to buying products. Consequently the risk of capacity loss is borne by fabricators, who attempt to manage that risk by increasing lead times and double

3 Another type of demand variability is simply changes from forecasts or estimates.

4 "When the lead times exceed the site's window of reliability (which is most of the time) another result is that the fabricators not only design prematurely but also fabricate to build up stocks from which they can then supply 'just-in-time'. This is almost universal practice for US precast plants – they commonly produce up to 80% of a job before erection begins. The costs then include storage, cleaning, double-handling, and even repair." (Rafael Sacks, personal communication to the authors, April 2004.) See also Sacks, et al., 2003.

booking. Mass production thinking is frequently promoted by contractual terms of payment, which reward long production runs and early delivery.[5]

One key relationship between demand variability and lead time has previously been identified. According to Ballard et al. (2003), the lead time for acquiring specific products or services is long or short relative to the requestor's window of reliability. If a contractor can accurately predict one week in advance (...has a one week window of reliability) when a fabricated product will be installed, lead times greater than a week increase the risk that the product will be delivered earlier or later than needed. To further eliminate the waste involved in idle inventories, double handling of materials, and workers waiting on work, the industry must both increase work flow reliability and reduce supplier lead times, so that more products and services can be pulled to the site when needed.

This paper presents the framework and plan for research into the interdependencies between demand variability and fabricator lead time. An initial section is devoted to the definition of terms, followed by sections on drivers of fabricator lead time and drivers of demand variability. A case study is then presented in summary form to ground the definitions and concepts in reality, and is followed by a section stating conclusions and the plan for future research.

DEFINITION OF TERMS

This section is devoted to explaining how we are using the following key terms: assemble, fabricate, make, manufacture, preassemble, produce, prefabricate, prefabrication (premake).

Following the lean construction tradition (Ballard, et al., 2003), we understand "production" to encompass both designing and making. The focus of this paper and this discussion of terminology is on 'making' and its associated and component terms, with making always understood in its connection to designing.

In ordinary speech,"fabricate" suggests providing materials with desired properties such as shape, density, tensile strength, etc. "Assemble" signifies joining together. Consequently, it is natural to understand fabrication as providing the elements which are to be assembled together (recognizing, of course, that there may be an indefinite number of subassembly layers).

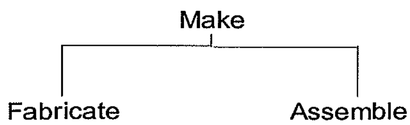

Figure 1: Types of 'making'

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5 "Again, this is the case in practice in precast concrete. Most clients demand early production so that they can confirm quality and supply before erection, and are willing to pay for it. The contracts usually include 75-80% payment on production (and the rest after erection)." (Rafael Sacks, personal communication to the authors, April 2004). See also Sacks, et al., 2003.

“Preassemble” and “prefabricate” place these activities before some reference point in time, which in construction is typically site installation. “Manufacturing” suggests factory production, which is usually, though not always[6], dedicated to making multiple copies of a design already existing, and includes both fabrication and assembly. “Making” also covers both fabrication and assembly, but is not restricted to factory production.

We use the terms largely in their ordinary meanings:

- Fabricate: to provide materials with desired properties such as dimensions, density, tensile strength, conductivity, etc., by means of molding, cutting, heating, mixing, separating, etc.
- Assemble: to join materials together by bolting, welding, glueing, nailing, etc.[7]
- Make: to bring a material object into being by fabricating and/or assembling.
- Prefabricate: to fabricate all or part of an object in some place other than its final position.
- Preassemble: to assemble all or part of an object in some place other than its final position.

Along with the above, a term is needed that encompasses prefabrication and preassembly. Given the previous definitions, the needed term would seem to be “premake” and its companion “premaking”, but these terms are not in common use and no unique term exists with this meaning. “Premanufacturing” suggests factory production, which is too narrow, given that effective prefabrication and preassembly can occur on site; for example, preassembly of structural steel frames on the ground rather than in situ, or prefabrication of concrete in mobile batchers. Gibbs’ term “off site fabrication” does not work for that same reason (Gibbs, 1999). The best existing term seems to be “prefabrication”, which is often used to indicate making something in advance of some temporal reference point. One example is the expression “prefabricated piping”, used to refer to the production of pipe spools prior to final assembly on site. Piping ‘prefabrication’ is a combination of fabrication (cutting straight run pipe to length, shaping a trunnion to fit to the curvature of the pipe) and assembly of previously fabricated components (pipe, fittings, flanges, valves, in-line instruments). Obviously, there is potential for ambiguity given the distinction between fabrication and assembly, but the difficulty of getting a new term accepted persuades us to run that risk and so add “prefabrication” to our list as follows:

- Prefabrication (premaking): making all or part of an object in some place other than its final position[8].

6 For a counter instance, see Wortmann, et al., 1997.

7 Note that ‘assembly’ is a mechanical concept, referring to the linking together of components structurally rather than chemically.

8 Note that in the case of all ‘pre’ terms, the ‘place’ can be either on site or off site.

DRIVERS OF PREFABRICATION LEAD TIME

Fabrication lead times are specified in the amount of time before initial delivery of product a customer order must be placed; in other words, the amount of time between acceptance of an order by the fabricator and the beginning of product deliveries to the customer.

Fabrication lead times (FLT) are the sum of shop drawing production and review time (SDT) + procurement time (PT) + fabrication time (FT) + preassembly time (AT) + delivery time (DT) + allowance for changes (AC)[9]. Delivery, cycle, procurement and shop drawing times typically include a safety margin intended to accomodate variability around the average durations of each of these process steps. Backlogs of work orders can extend this lead time.

$$FLT = SDT + PT + FT + AT + DT + AC^{10} \qquad \text{Equation 1}$$

The first phase of the research will be devoted to quantifying these components. Our hypothesis is that 'allowance for changes' is the largest component, or can be made the largest component by applying lean techniques to reduction of fabrication cycle time. Some support for that hypothesis was found during a Lean Construction Institute visit to Trane's modular air handling unit (AHU) factory in Lexington, Kentucky in 1998. Trane's factory managers explained that they had reduced the manufacturing cycle time for a modular AHU to 5 days, but still required 6 weeks order lead time because they expected, based on their experience, 3 changes to every order. We did not think at that time to inquire how those changes were divided between product design and process design (installation sequence or timing).

Production theory and the authors' experience suggest that fabrication lead times can be reduced in each of the above components by actions such as those shown in Table 1.

Table 1: Opportunities for reducing fabrication lead times

Lead time component	**Improvement opportunity**
Fabrication Lead Time	Reduce the batch size of releases (transfer batch) to the fabricator
	Make detailed engineering the first step in 'making'; i.e., pull from Installation
Delivery time	Avoid breakdowns by preventive maintenance of equipment
	Deliver to staging area in off-hours to avoid traffic congestion and assure availability at target delivery time
Assembly cycle time	Design and manage tolerances to avoid the necessity of physical joining of assemblies to assure fit
Fabrication cycle time	Reduce setup times and thence process batch sizes[11]
	Design for fabrication and assembly
Procurement time	Standardize parts; reduce part count
	Reduce matching problem[12] by restructuring supply chains

9 Allowance for changes should be recognized as a separate category in order to avoid concealing allowances in the other components.

10 With the addition of allowances for variability around averages:
$FLT = DT + DT_s + AT + AT_s + FT + FT_s + PT + PT_s + SDT + SDT_s + AC$ equation 2

11 The less time it takes to change from making one type of product to another, the less reason to increase the size of production runs to reduce the changeover (aka, setup) time as a percentage of total time.

Shop drawing time	Integrate detailing into design production, thus eliminating separate production and review of shop drawings[13]
Allowance for changes	Reduce the risk of changes in product design by reducing fabrication lead times
	Reduce the risk of changes in product design by making design decisions at the last responsible moment
	Reduce the risk of changes in installation timing or sequence through implementation of the Last Planner system by the installer
	Shift the risk of demand variability to the the party best able to control it; i.e., the installer. This can be done by having the installer purchase shop capacity rather than products from the fabricator

DRIVERS OF DEMAND VARIABILITY

But, the reader may be thinking, is demand variability really so great? And even if it is, aren't stores of completed products just the solution needed?

Lacking quantitative data at this early point in the research, we must rely on the testimony of industry practitioners, who report that changes in orders placed with fabricators are common and frequent. What are the drivers of these changes and what can be done to reduce the frequency and impact of changes? Those are questions to be answered more definitively in the future research, but we can perhaps usefully speculate here regarding these matters.

Work flow variability measurements from implementations of the Last Planner system of production control commonly reveal percent plan complete figures ranging from 30% to 70%, meaning that 70% to 30% of tasks committed to being completed in a plan period were not completed (Ballard and Howell, 1998). The authors have also frequently observed design squads and construction crews do work out of optimum sequence in an effort to avoid loss of capacity or in an effort to maintain scheduled progress—a practice known in the industry as 'chasing work'. It has been noted by Kim and Ballard (2000) that the use of earned value as a measure of progress invites working out of sequence (chasing work) because it does not attribute any value to the sequence in which work is completed.

Consequently, one type of change in orders placed with fabricators is expected to concern the timing and sequence of deliveries, and are hypothesized to be driven by changes in the timing and sequence of site installation activities.

Another type of change in orders placed with fabricators is expected to concern the product itself, and is hypothesized to be driven by design changes; i.e., changes in the geometry or composition of the fabricated products. The authors also expect to find that design changes themselves are driven in part by the time pressure on designers, which tends to increase as installers demand ever earlier delivery of fabricated products. The

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12 The probability of on-time delivery of n parts to a station in a supply chain is the product of the probability of on-time delivery for each of the parts. For example, if there are three parts, with A's probability at 99%, B's at 95% and C's at 97%, the probability of on-time delivery of ABC = .99 * .95 * .97 = 91%.

13 See PCSC (2003) for an initiative led by Chuck Eastman at Georgia Tech to develop a bespoke 3D modeling program for a consortium of precast concrete fabricators in response to finding that engineering (shop drawing production) was the largest contributor to lead time (they did not isolate an Allowance for Changes).

interdependence between these drivers is apparently quite complex. See Figure 2 for time our attempt to display that interdependence.

Starting at the top, we suppose that the contractor's production control practices are characterized by low PPC and chasing work. This drives changes in the installation rate or sequence, which drives changes in the required delivery date for fabricated products and also increases the amount of fabricated products in the contractor's inventory buffer because some products will have to wait to be installed after they are delivered. If delivery dates are changed, that will cause the fabricator to increase his lead time in an effort to protect himself. That increased lead time will cut into the time available for design, which will tend to increase the probability of later design changes, which in turn will further drive changes in installation rate or sequence. Design changes will also have a greater negative impact, the greater the amount of fabricated products already made. Fear of this consequence tends to cause contractors to order even earlier, which further increases the frequency of changes in installation rate or sequence and directly increases the amount of fabricated products in the contractor's inventory buffer. This can also occur as a consequence of payment terms, when fabricators are paid upon delivery.

Supposing for the moment that the causal relationships illustrated in the diagram are real, we see that contractors tend to cause the opposite of what they intend. They chase work in an attempt to stay on schedule or accelerate, but the consequences are slower,

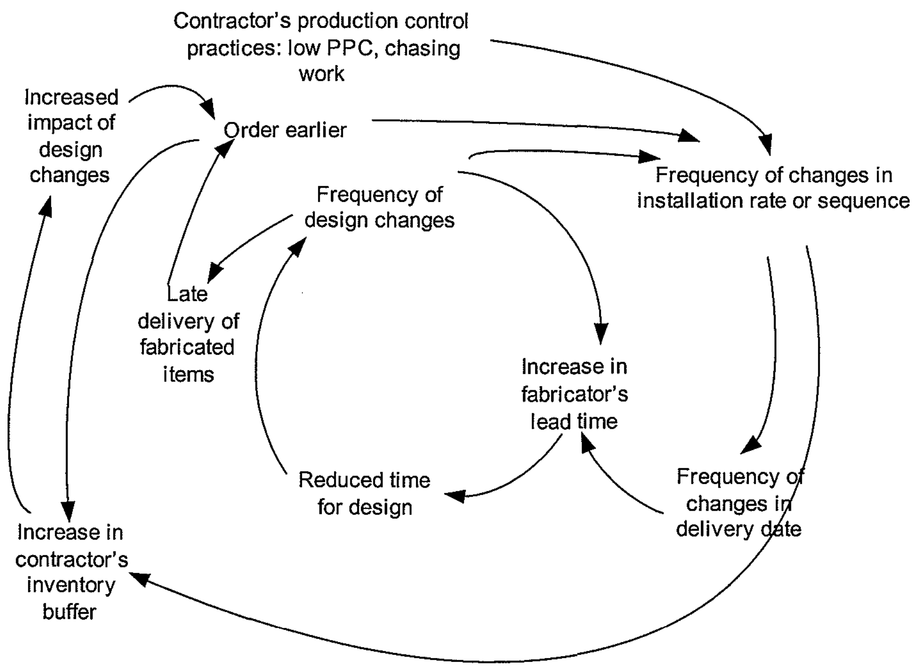

Figure 2: Interdependence of demand variability and fabrication lead

more costly projects. It does not seem likely that contractors would deliberately reduce the amount of time available for design if they understood that doing so increases the frequency of design changes. The problem is that the interdependencies are not understood; in part because they are complicated, involve multiple parties, and result from actions across multiple projects. For example, frequent changes by contractors in fabrication orders cause fabricators to increase their lead time, which in turn robs designers of time to do their job properly, which increases the frequency of changes in fabrication orders.

Breaking out of this vicious cycle will require joint action by the major players, since no one party controls the entire system.

CASE STUDY IN MODULE FABRICATION

In December, 2003 the authors did a study, unpublished, of the off site fabrication and assembly of mechanical-electrical modules. The study was done just prior to the start of fabrication. An example of the type of modules studied is shown in Figure 2. The material and information flow diagram of the module production system is shown in Figure 3.

The modules were designed and installed by a contractor responsible for engineering, procurement and installation, referred to here as the EPC Contractor. The Fabricator was awarded a contract to do detailed engineering, to fabricate and to deliver modules to the installation site. Coordination of fabrication and installation was to be achieved by means of a periodically updated schedule and by means of module releases. Modules were to be released by building zone and module type two months ahead of scheduled start of module installation. Each module was sized to what could be hauled by truck and trailer across public roads without special permit. Modules were of different types, all mounting mechanical and electrical equipment, wiring and piping on light steel frames, with the mounted items designed to be coupled together in final position.

Figure 3: Mechanical-Electrical modules (Pasquire and Connolly, 2002)

Engineering and detailing were expected to take 5 weeks. The EPC Contractor held contracts with the suppliers of all components and materials with the exception of the steel components used to build the module frame, the contract for which was held by the Fabricator. The Fabricator ordered made-to-stock components (from the steel component supplier directly and otherwise through the EPC Contractor) weekly, and ordered made-to-order components by zone release, the first of which was to contain 13 modules. Lead times for materials and components were not determined, but made-to-order products often take 2-6 weeks or more, which would add considerably to procurement time and would make matching more difficult, and hence increase the probability of longer fabrication durations. Lacking actual data, we assume 1 week Procurement Time for all materials and components.

The Fabricator planned to fabricate all items in a zone release prior to starting module assembly. Fabrication was expected to take approximately 6 weeks, plus 1 week for galvanizing the steel members, then two weeks for module assembly. All of these durations appear to have included contingency, but that was not specified quantitatively. Module assembly was increased in duration by the need to physically build two modules together to assure fit, after which one was to be shipped and the other remain behind for the next fit. Consequently, two modules rather than one were in assembly at any point in time, increasing assembly duration from one week to two.

Delivery was to be made in two stages: first to a staging area near the site, where the plan was to maintain 3 modules 'just in case', then another 2 modules on site, including the module in process of being installed. Deliveries of specified modules to the staging area were to be done only when requested by the EPC Contractor. Similarly, deliveries from staging area to Site were to be done only when requested by the EPC Contractor. The transit time from Fabricator to Site was one day, so Delivery Time amounted to 5 days[14]. No explicit provision was made either for variability around average durations or for Allowance for Changes, although the specified process durations very likely include such allowances.

Substituting values in Equation 1 yields a value for Fabrication Lead Time of 16 weeks[15]:

$$FLT_{MEP\ Modules} = 5\text{ weeks (SDT)} + 1\text{ week (PT)} + 7\text{ weeks (FT)} + 2\text{ weeks (AT)} + 1\text{ week(DT)} + 0\text{(AC)}$$
$$= 16\text{ weeks.}$$

Given this production system design, how will the system behave? From the causal relationships shown in Figure 2 and he system design shown in Figure 4, we can predict with a very high level of confidence that the buffer of finished goods (completed modules) will fill all available storage space, increasing WIP and reducing flexibility to changes in sequence and timing, with the consequences shown in Figure 2; namely, increased risk of design changes (more completed modules to be impacted by design changes); increased cost for warehousing, handling and maintenance; accelerated owner payments[16] as the Fabricator will

14 These durations, inventories and rules were agreed during the course of the study. The original durations and inventories were larger and rules for pulling modules forward were not explicit.

15 If lead times for made-to-order components were greater than one week, the lead time would be increased by that difference. For example, if the component with the longest lead time was 6 weeks, the total lead time for the system would be 21 weeks, further increasing risk and vulnerability.

16 Assuming that fabricators are paid on completion of a module.

naturally want to be paid regardless if the modules can be installed; lower on-time delivery rates and/or increased cost from the Fabricator starting and stopping work in attempting to keep step with site changes. What could be done to avoid these problems?

RECOMMENDATIONS

The following recommendations were rejected by the EPC Contractor, perhaps influenced by the fact that the risks associated with the production system design were borne entirely by the client and not by the contractor.

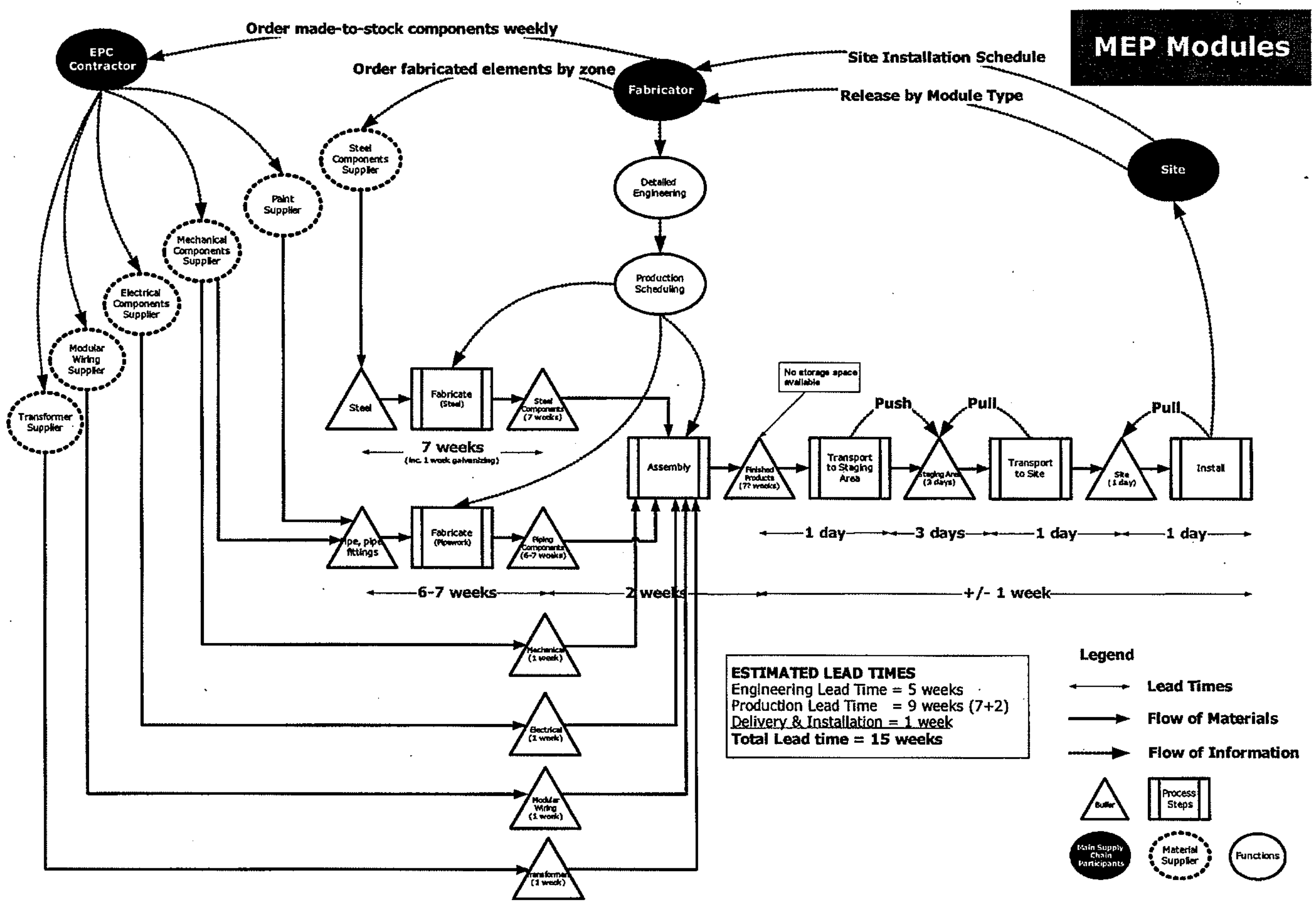

Figure 4: Material and information flow diagram for module production system

- Explore means for reducing variability in site installation rate or sequence, including implementation of the Last Planner system of production control (Ballard & Howell, 1998).
- Reduce supplier lead times.
- Improve fabricator processes
  - Evaluate the alternative of purchasing fabricator capacity in order to remove the incentive to continue production despite an interruption in site installation
  - Evaluate & recommend plan to use pull mechanisms to coordinate work flow between feeder stations and primary workstations
  - Explore, evaluate & develop means for assuring alignment of modules that does not require physical 'batch' assembly.
  - Explore, evaluate & develop the pushing of some subassembly and kitting upstream in the supply chain to reduce the matching problem.
  - Reduce batch sizes of manufacturing releases.
  - Evaluate in more detail the estimated durations for fabrication and assembly.
  - Explore the possibility to fabricate the components and sub-assemblies for one module at a time, (allow batching in fabrication as long as it doesn't interfere with the pace of one piece flow). This could cut fabrication time in half.
- Improve Design/detail Process
  - Expedite design completion to allow sufficient lead time for supply (being mindful of the need to truly complete design).
  - Explore, evaluate & develop means for reducing the probability of design changes and for accommodating design changes.
  - Evaluate practicality of completing detailed engineering as the first step in the manufacturing work stream.
- Improve Commercial Clarity
  - Design and implement a plan to measure the holistic value stream and compare to current commercial model.
  - Generate a risk/opportunity commercial model for implementing some/all of the above.

CONCLUSION AND FUTURE RESEARCH

As illustrated in the case study, fabricator lead times tend to be inflated, in part in an attempt to protect the fabricator from demand variability. This inflation amounts to a type of buffer or contingency insuring against the risk of demand variability. We suggest consolidating the 'contingency' provided for demand variability in a separate category from the other components of fabrication lead time so that it can be better managed. This is the strategy advocated by Goldratt regarding schedule contingency (Goldratt, 1997).

Reducing demand variability and fabricator lead times must occur together, and will require collaboration at minimum between installer and fabricator, and for more fundamental improvement, will require collaboration with architects and engineers as well. Owners may play a vital role in demanding performance improvement and requiring the application of lean concepts and techniques.

Research is needed to support this critical industry initiative. Key research questions include:

1. Have competent users of the Last Planner system of production control reduced their demand variability? If so, have their fabricators reduced their lead times accordingly, or, if not, could fabricators safely reduce their lead times? Has increasing the contractor's window of reliability enabled them to pull more products to installation dates? What can be done to further reduce work flow variability, and hence demand variability?
2. What are the lead times for various fabricated products; e.g., switchgear, HVAC ductwork, rebar preassemblies, precast concrete, pipe spools, pipe supports, cladding, air handling units, chillers, pumps? What can be done to reduce those lead times without reducing demand variability?[17]
3. What allowance for change should fabricators include in their lead times for a given level of demand variability on the part of their customers?
4. What competitive advantage is provided to client, contractor and fabricator by the combined effect of reducing demand variability and reducing fabricator lead times?

A study of work flow reliability is dedicated to question 1 above. Descriptive research is underway to determine the extent to which work flow variability has been reduced through applications of current best practice in production control. Experimental research will follow to develop methods and tools for going beyond best practice. The researchers hypothesize that further improvement will require a combination of learning from plan failures and better lookahead planning; specifically more detailed planning of operations in order to anticipate tasks that need to be made ready.

A second research project on fabricator lead times is now in the planning stage. The authors propose to collect data on question 2 through a survey, followed by value stream mapping of the fabrication processes for key products that have not yet been mapped, and experimental restructuring of value stream maps to reduce lead times.

A third research project will be devoted to answering question 3—providing a method for quantifying allowance for change in fabricator lead times. This project will bring together the

[17] A number of researchers have been active in this area. See Arbulu 2002 and Elfving 2003 for two of the most comprehensive studies of lead time for fabricated products.

results from the previous two projects, and will try to answer question 4, working with supplier-contractor alliances in which both parties are dedicated to lean construction concepts and techniques.

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