

MORE JUST-IN-TIME: LOCATION OF BUFFERS IN STRUCTURAL STEEL SUPPLY AND CONSTRUCTION PROCESSES

Iris D. Tommelein¹ and Markus Weissenberger²

ABSTRACT

The erection of a building's structural steel frame is a major construction phase on many a project. The main resource in this process, the steel erector's crane, defines not only the pace of erection of steel, but also the pace for handling and installing many other structural and non-structural materials. This production system cannot afford any delays. Some claim that structural steel therefore is managed as a just-in-time (JIT) process with materials being delivered to site as needed and installed promptly. This is the case only in appearance as is clear when one considers the JIT principles that were developed as part of Toyota's lean production philosophy. To illustrate the point, this paper draws on examples of typical structural steel supply chains from the industrial- and building construction sector. The use of symbols from manufacturing is investigated to map key production steps as well as buffers in-between them in order to elucidate where resources do and do not flow. Industry practices in these two construction sectors vary significantly. Neither one is lean. This paper reports on a preliminary investigation into the location of buffers in the structural steel supply and construction process. The reasons for having buffers at various locations are explored. A more in-depth investigation is recommended to gain a deeper understanding of the buffer sizing criteria and steel component sequencing rules that govern current practices. Insight into these will then help determine which buffers can be trimmed in order to reduce work in progress and cycle time. This will support the effort of achieving "more JIT" by making processes within individual companies as well as across the entire steel supply chain leaner.

KEY WORDS

Supply-chain mapping, integration, structural steel, fabrication, erection, pull-driven scheduling, just in time, JIT, kanban, buffer, lean construction.

¹ Associate Professor, Constr. Engrg. and Mgmt. Program, Civil and Envir. Engrg. Department, 215-A McLaughlin Hall, Univ. of California, Berkeley, CA 94720-1712 and Research Associate, Lean Construction Institute, phone: 510/643-8678, fax: 510/643-8919, tommelein@ce.berkeley.edu

² Exchange student in the Constr. Engrg. and Mgmt. Program at U.C. Berkeley in 1997-98, now Senior (5-year Civil Engineering Degree), Technical Univ. Hamburg-Harburg, Germany, weissenberger@tu-harburg.de

INTRODUCTION

The erection of a building's structural steel frame is a major construction phase on many a project. The main resource in this process, the steel erector's crane, defines not only the pace of erection of steel, but also the pace for handling and installing other structural and non-structural materials such as decking or grating, reinforcing bars, spray-on fireproofing, that is, work done by others in the "parade of trades" (Tommelein et al. 1998, 1999). This production system cannot afford any delays. Some claim that structural steel therefore is managed as a just-in-time (JIT) process, with materials being delivered to site as needed and installed promptly.

We set out to validate this claim by reviewing the literature on steel erection and interviewing steel fabricators, erectors, and contractors. In part, we were eager to find examples of JIT in current construction practice. A companion paper describes our findings regarding existing JIT systems for batching and delivering concrete (Tommelein and Li 1999). To make the present paper stand on its own, a few sections from that paper had to be repeated here.

JUST-IN-TIME SYSTEMS

The term 'Just-In-Time' (JIT), used for instance to describe the delivery of materials to a construction site, suggests that materials will be brought to their location for final installation and be installed immediately upon arrival without incurring any delay due to storage in a laydown or staging area. JIT is a concept developed by the Japanese who created the Toyota Production System, later translated into English as the lean production system. The ultimate objective of JIT production is to supply the right materials at the right time and in the right amount at every step in the process.

Toyota achieves JIT production by implementing a pull system using 'kanban,' loosely translated from Japanese as 'cards.' Kanban are designed to prevent overproduction and ensure that parts are drawn from process to process, in reverse order. They thus implement a replenishment system designed to control production quantities. Parts are taken and replenished only when needed and in the right amount.

The pull of product from upstream is illustrated by means of a **withdrawal kanban** as shown in Figure 1. The **customer process** withdraws parts from a **supermarket**, which is a place of limited capacity for storing product that is output by the **supplying process**. The supermarket gets replenished by issuing a **production kanban** when inventory is too low.

The production kanban thereby instructs the supplying process to produce more product. The supplying process produces only enough product to replace what was withdrawn. This method prevents overproduction but allows a tightly-bound inventory to build up between the supplying and the customer process (for more detail, see Hopp and Spearman 1996 and Rother and Shook 1998).

In a more general sense, a pull system may comprise a feedback mechanism for a station downstream to notify a station upstream that more product is needed. Product then is fabricated and shipped to meet this specific need. This mechanism purposefully constrains the amount of work in process in the system, which tends to reduce the product cycle time. The alternative is to produce product in anticipation of a need, i.e., based on a forecast need,

as is the case in push systems. Product pushed into the production process stands a greater chance of sitting idle, thereby not only tying up resources but also increasing its cycle time.

Tommelein (1998) compared and contrasted the delivery and installation of pipe spool at a construction site subject to various uncertainties using pull- and push-driven scheduling methods. Push systems tend to increase the amount of waste (e.g., long wait times, excessively large inventories) because they are estimate driven and include fudge factors to compensate for anticipated uncertainty. Uncertainty may or may not manifest itself during project execution. When it does, push systems have no means to quickly adapt to changing system requirements whereas pull systems do.

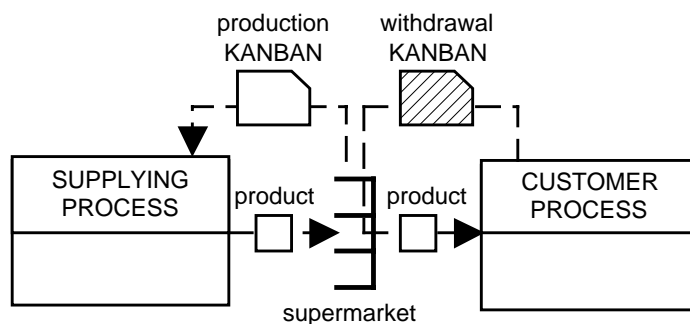


Figure 1: Kanban System (after Rother and Shook 1998 p. 42)






This notion of pull is an essential part of a JIT system. Associated questions of system design are “Where and when to pull?” and “What quantities of product to pull and allow into buffers at various stages in the process?” Our preliminary investigation of possible JIT practices in the steel supply chain thus led us to map key production steps as well as buffers in-between them in order to elucidate where resources are held up vs. where they are able to flow. Qualitative findings of this investigation are reported here. Further investigation will lead to a more quantitative analysis of industry practices.

VALUE STREAM MAPPING

Koskela (1992) pointed out that architects, engineers, and construction practitioners have for the longest time focused on conversion activities and overlooked issues of flow. Flow is important because work or materials that do not flow sit idle in inventory, tying up money (including the procurement cost of ingredients plus labor and machine time to bring them to the stage of completion they are in) as well as space. They stand the risk of being damaged or becoming obsolete due to design changes or market competition. Inventory means product waits: its cycle time increases, that is, it takes longer for the product to traverse all production steps it needs to go through before reaching its customer. As a result, project durations are larger than they would have been had flow not been inhibited.

Most tools used today by practitioners who manage construction, such as those for design, planning, scheduling, and costing, do not acknowledge flow: they do not explicitly capture changes of resource characteristics over time. Process modeling tools for discrete-

event simulation are an important exception and warrant more attention by the lean construction community. Such models can incorporate input regarding individually-characterized components, uncertainties of numerous kinds, and sequencing rules (e.g., Tommelein 1997) and then produce output data regarding buffer sizes, cycle times, idle times, production rates, etc. The symbols commonly used to depict process models for construction, however, have yet to distinguish how processes are being managed, for instance, whether or not a JIT system has been implemented. Practitioners in manufacturing, working for Toyota and then later for other companies ‘going lean’ developed their own pictorial language to help focus attention on what matters in their transition.

We borrowed such symbols from Rother and Shook (1998) and used them to map structural steel supply chains. Boxes  denote value-adding processes or tasks, such as ordering raw materials, fabricating steel, and transporting shipments to a site. A triangle \triangle denotes work in progress or inventory. It represents an accumulation of product (materials or information) possibly of unlimited amount and for an indeterminate duration. An inverted triangle ∇ is an order to batch. Kanban (introduced in Figure 1) denote orders to withdraw  or produce  product, in order to deplete or replenish a supermarket. A supermarket, represented by , refers to controlled inventory in terms of how much material is kept on hand and how replenishment takes place. The FIFO symbol $\frac{FIFO}{\square \triangle \square}$ denotes the first-in-first-out release of resources output by a task. The circular arrow  denotes a physical pull of materials from a supermarket. It differs from the withdrawal kanban in that it pertains to the amount of product needed at the time of the withdrawal and not necessarily a predetermined fixed quantity. A dashed line with an arrow $- - \blacktriangleright$ designates the flow of product. A solid white line \blacktriangleright is transportation of product to the customer site. A black-and-white dotted line $\dots \blacktriangleright$ shows that product is pushed into inventory.

Rother and Shook (1998) use these symbols for so-called “value stream mapping” where the term “value” pertains mainly to reducing work in process inventories and product cycle times. Our use of this notation stems as much from our desire to engage in mapping the structural steel supply chain as it does from our desire to test the adequacy of those symbols in representing architecture/engineering/construction processes and in capturing value.

STRUCTURAL STEEL SUPPLY CHAINS

In order to compare and contrast structural steel supply chains, different examples must be presented. In the examples that follow, we illustrate what we understand to be common industry practices though they are not practices applied on any one specific project. We take a birds-eye view of supply chains, showing ‘fabrication’ as a process but no specifics thereof, and including companies that may be involved for months if not years on a single project. Industry practices on industrial projects, including construction of power plants and petrochemical facilities, are described first.

EXAMPLE STRUCTURAL STEEL SUPPLY CHAIN FOR INDUSTRIAL CONSTRUCTION

Many industrial projects are delivered using engineer-procure-construct (EPC) contracts. This contract may be held by a single company or be divided up among several with design and procurement being done by one and construction by another company for instance. Figure 2 depicts a situation where the structural designer (line II) is different from the steel erector (line VII). Other parties involved with the project are the owner (I), the fabricator (III), the raw materials supplier (IV)(such as one or several steel mills and distributors), the shipping agent(s) (V), and the galvanizer (VI). The latter is to provide corrosion protection for steel that will remain exposed. Steel that needs fireproofing (not shown) is usually shipped to yet another facility prior to reaching the site.

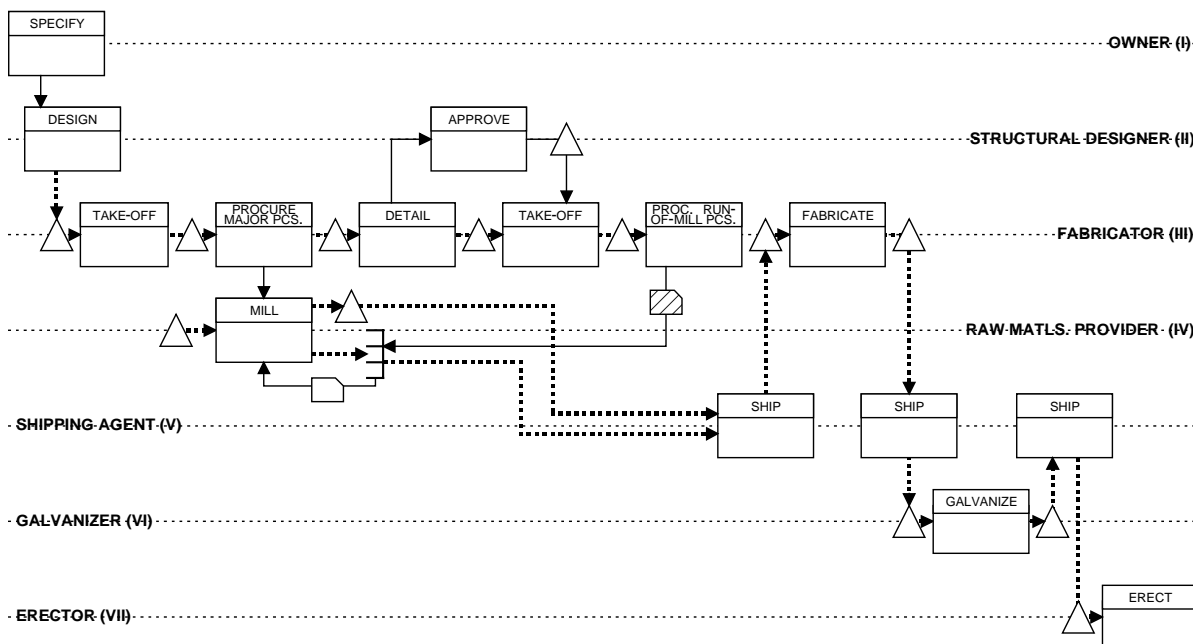


Figure 2: Example Structural Steel Supply Chain for Industrial Construction

The owner and designer go through a lengthy iterative process of articulating the project requirements and then translating them into design documents, including drawings and specifications. The final design needs approval not only from the owner but also from regulatory agencies (not shown). A fabricator is then selected and a batch of design documents released (line III). Especially on large projects this release of drawings will be phased. Doing so makes it possible to fast-track the process, provided permits can be secured in the same fashion.

Consideration must be given to the time it will take the fabricator to procure materials (procurement lead time). Large structural steel sections are not run-of-the-mill items. Their TAKE-OFF³ and PROCURE[ment] OF MAJOR PIECES is done early, possibly as soon as design concepts have been decided on, as they must be mill ordered. Steel mills typically

³ Items in CAPS denote process steps shown in the figure.

work on 6-week rolling schedules so there are windows of opportunity to hit, or steel delivery and thus fabrication will be delayed. When it comes to jumbo sections shipped from overseas mills, procurement lead time is an even bigger concern. In any case, major pieces are produced according to the mill's schedule and shipped soon thereafter to the fabricator.

Meanwhile, the fabricator proceeds with DETAIL[ing] connections and creating shop drawings for engineering APPROV[al]. Many steel components are custom designed and hundreds of different ones may be needed on any one project. The drawings await approval (unless the fabricator is willing to take a risk) prior to a second round of TAKE-OFF and PROCURE[ment of] RUN-OF-THE-MILL PIECES. Depending on how typical these pieces are, the fabricator may carry them in inventory or have to order a new load. These materials are called run-of-the-mill because mills produce them on a regular basis. They either keep them in their own supermarket-like inventory (as shown in figure 2) awaiting customers or sell them to distributors to store and resell at a higher price. Fabricators often buy them from the mill by the train load in order to keep procurement and shipping costs low even when not all materials in a load will be used on a given project.

Materials received by the fabricator are stored in a laydown yard, then retrieved one piece at a time for FABRICAT[ion] including cutting to size, drilling, welding, etc. Some materials may be partially fabricated then moved out of the way for some time to make room on the shop floor for other pieces to take priority. A significant amount of handling back and forth is the result of fabricator's objective of maximizing machine and labor utilization.

Finished pieces are loaded on flatbed trucks and shipped to the GALVANIZE[r] or fireproofer (not shown) if needed, and then to the site. The fabricator, who may already have been paid in part for materials procurement, gets paid in full for site delivery. The contractor, in turn, may also earn value for receiving materials in the laydown yard, which helps to offset their cost for materials management. Steel erection is done by the contractor's direct-hire labor. Cranes may be rented or provided by the owner if the owner has nearby facilities with equipment not needed on a full-time basis for plant maintenance.

As mentioned, design and construction may be handled by the same or different companies but fabrication is nearly always done by a third party. Because industrial projects tend to be complex and large, and numerous uncertainties remain unresolved at the start of the project—though more could be resolved if designers were made aware of contractors' sequencing decisions—a significant amount of real-time communication is needed between all parties to coordinate their production systems. Cooperative fabricators may provide transparency into their part of the supply chain by for instance revealing status data on a weekly basis including: (1) Release Number, (2) Drawing/Piece mark(s), (3) Date Received, (4) Tons of the Release, (5) Date Details Sent for Approval, (6) Date Details Approved, (7) Fabrication Start Date, (8) Fabrication Finish Date, (9) Date Shipped to Galvanizer, (10) Date Shipped to Fireproofer, and (11) Date Shipped to Site. This way, the contractor can 'see' work coming towards them and plan for steel erection accordingly. Note, however, that work is pushed onto the contractor, so it may not be sequenced optimally for construction.

Nevertheless, because of uncertainties in the release and sequencing of drawings early in the supply chain, followed by uncertainties in the release and sequencing of fabricated and shipped materials, contractors consider it good practice to make sure they have enough materials on hand to keep their crews busy for a few weeks if not months. Howell and

Ballard (1996) and Tommelein (1998) describe similar practices in the piping function. The contractor's strategy is to try to de-couple their field operations to the largest extent possible from the flow of materials upstream in the supply chain (Howell et al. 1993) in order to provide their work force with the greatest flexibility in choosing which work to do next and thereby enable them presumably to be optimally productive. Large laydown areas are thus commonplace especially on greenfield sites where space appears to be free and abundant. Off-site laydown space is rented for brownfield projects where space is tight. Extra handling of course costs extra money and can be avoided when the flow of materials off- and on-site is more thoughtfully routed and pieces orderly sequenced.

EXAMPLE STRUCTURAL STEEL SUPPLY CHAIN FOR BUILDING CONSTRUCTION

The structural steel supply chain for building construction differs in several regards from the one for industrial construction. The building's frame may in fact be more complex, especially when it supports a very tall structure, so the major steel sections require extra procurement effort.

The industry is also organized differently. On design-bid-build projects, a common delivery method for buildings, the owner typically hires an architectural engineering (AE) firm, which in turn hires a structural designer. When the AE has prepared all bid documents, the project is put out for bid. A general contractor (GC) is then selected. The GC subcontracts the steel work to the fabricator, who in turn subcontracts field installation work to a structural steel erector. The latter essentially provides the crane and skilled labor, whereas the former is responsible for acquiring, fabricating, and shipping the materials to site in the sequence needed for erection. The fabricator may also subcontract the structural steel detailing work.

Fabricator and erector work as a tightly knit team. The GC will meet with them during bid preparation. They must assess the project site constraints to position the erector's crane, as it determines not only the steel erection sequence but also the layout of other temporary facilities and thus the flow of many construction resources. This sequencing in turn drives the fabrication schedule. It must of course meet the GC's master schedule but must also be efficient⁴. The fabricator who subcontracts the erection work has an incentive to minimize that work and does so by thoroughly planning the sequencing and site delivery of steel pieces in the order they will be needed.

As for logistics, a big difference between the industrial and the building sector is that more often than not building space is very tight, especially on projects located in an urban environment. Industrial projects tend to be more remotely sited. Materials deliveries to building projects accordingly are constrained by traffic patterns and transportation permit requirements. Trucks parked in the street along the edge of a site ready to off-load steel may not remain there for any extended time. When deliveries take place, the crane gets dedicated to off-loading and moving pieces to a staging area, namely the highest floor with decking,

⁴ The measure of efficiency would include not just a single resource's utilization (e.g., crane or fabrication facility), but possibly a combination of resource utilization rates and their variability, augmented with factors accounting for the rate at which the project progresses and cost. The measure will be different, depending on what one considers of "value."

buffering rather than a supermarket. The owner pays the fabricator for finishing work even if the site is not yet ready to receive it. If project delays are incurred, the owner may even award an extra fee for longer-term storage, so the fabricator has an incentive to complete as much work as early as possible. Large buffers of ready-to-ship materials create a feel-good situation, but at a cost!

DISCUSSION

The creation of large buffers either at the contractor's or fabricator's site is contrary to JIT production system design. As the word JIT suggests, materials must be fabricated or delivered on time, which means not too late but not too early either. This implies that variability regarding timing, actual pieces released, as well as quality must be limited and controlled.

In a true JIT system, this timeliness pertains not only to a single hand-off between two production steps, but rather, one aims at achieving JIT flow between all production steps. In the idealistic extreme, this means having no buffers at all! In practice, this means buffers must be determined strategically. Admittedly, doing so is not an easy task, especially in a production system of complex products that involve several organizations as is the case for structural steel. But this is what lean production systems design is all about: achieving flow where possible and thoughtfully locating buffers and sizing them to achieve cost-effective decoupling with minimal impact on cycle time.

A significantly amount of additional data is needed to describe the structural steel supply chain at a level of detail that makes it possible to strategically locate and size buffers. The difficulty is doing so stems in part from the fact that structural steel is custom designed and every project requires a variety of components that change as construction progresses. Because of construction's one-of-a-kind project nature, the structural steel supply chain differs from manufacturing systems for more standardized products, which can be likened to the Toyota Production System. The manufacturing symbols used here for mapping the steel supply chain provide no room for defining individually-characterized resources or detailed sequencing rules. While their ability to show processing durations and delay times has not been used in this paper (we expect to do so in future work), we doubt that using only deterministic values will suffice. Some representation of uncertainty will have to be incorporated in the maps.

The current practice of buffering stems from the desire to optimize labor and machine utilization and from admitting that uncertainties exist in the supply chain. Many uncertainties are the result of variability, which could be understood better if at least it were measured and explicitly accounted for. This is not the current practice in construction. Uncertainties and variability should not be taken for granted. They should be acknowledged, managed, and minimized to a reasonable degree. In fact, one technique to identify them is to reduce buffer sizes in-between various production steps in order to see and learn the extent to which they are needed. Process improvement efforts can then focus on those steps where the impact on throughput of the system as a whole will be most significant. Example improvements in construction are those that aim at reducing uncertainty, as is done for instance through reliable planning by the Last Planner (Ballard and Howell 1998), work methods design, and work structuring (Ballard et al. 1999).

Existing construction industry practices and contractual incentives counter the objective of achieving flow. A few examples were given in this paper. Nevertheless, a number of fabricators as well as parts and components suppliers to the construction industry have successfully implemented lean practices in their own shops (e.g., WireMold, Trane, Square-D). But this success is constrained by their upstream suppliers and downstream customers. JIT and other lean principles are aimed at streamlining the entire process across all organizational boundaries and allowing product to flow from conception to installation.

Opportunities for change in the lean direction exist, especially with the construction industry actively seeking alternative delivery methods. Frank exchange of production plans and performance data are a step in the right direction. Although a fabricator providing production transparency is useful, it is only a small step towards trimming the supply chain. As it is often done now in the situation described, work gets pushed onto the contractor. However, to minimize work in process, product must be made to order, upon customer demand. This means that the contractor should be able to pull materials through all upstream processes, including not only fabrication but also permitting and design. Pulling goes beyond mere coordination of phasing of permits and releasing of design documents with construction. Whereas coordination may be limited to revealing sequences and timing to others, pull implies that there is agreement to mutually adjust to each other's needs and to synchronize production steps in order to improve system performance. Pull will be easier to implement when needs are well defined and can be revealed ahead of time, that is, when all supply chain partners work according to reliable plans. This is where the real opportunity lies for fast-tracking a project and cutting cycle time as well as cost.

EPC projects hold the greatest potential for implementing incentives that promote improvements to the overall production process spanning across organizational and, within organizations, across departmental boundaries. Construction schedules of reliable quality and created early can drive design and pull the release of drawings through the fabricator. Fabricator capacity can then be committed to (including payment for the reservation) accordingly.

Design-build (DB) projects, like EPC projects, also provide opportunities in this regard that remain unrecognized and thus unexploited. Team members on these projects have a vested interest in making their joint effort succeed. They therefore may be more willing and able to cross their traditional organizational boundaries and try to meet production objectives that stress supply chain performance. For example, a design-build developer (responsible for design, construction, as well as complete financing during construction) engaged in building design, then realized they could not meet the owner's schedule because they could not get the needed steel rolled in a timely fashion. To cut cycle time, steel mills and steel resellers were visited around the country and procured sections that were readily available and more-or-less matched the design. The design then was adapted and further developed to suit the dimensions of the procured steel.

Note that while EPC and DB projects provide great opportunities for the implementation of lean construction practices, lean construction practices can apply to any project.

SUMMARY

This paper has given examples of structural steel supply chains in two sectors of the construction industry, namely industrial construction and building construction. Value stream symbols from manufacturing were tried as a means to map them. The resulting maps show a very simplified view of the structural steel supply chain. They highlight that buffers are used at nearly all stages in the process and that steel therefore cannot possibly flow. Flow is advocated in JIT production. Only a minimal amount of it is achieved in building construction regarding site deliveries of structural steel, though one can barely call this the implementation of JIT practices.

Buffering is done to allow processes to achieve high equipment and labor utilization and to shield downstream processes from upstream uncertainties. Individual process performance may therefore look good but it results in increased product cycle time and thus extended project duration as well as increased costs for maintaining work in process. When not judiciously located and sized, buffers may grow to be disproportionately large or anxiety-provoking small.

We suggest that further study be conducted into the intricacies of the structural steel as well as other supply chains, so that the rationales for buffering and the associated risks and rewards can be elucidated. Whether they are contract- or production driven will guide further analysis. Insight into these will then help determine which construction principles best apply so the production system can be shaped in order to obtain more benefits of JIT practices.

ACKNOWLEDGMENTS

The authors would like to acknowledge the contributions made by several industry practitioners in the course of this research. They gave generous amounts of their time and knowledge about the structural steel supply chain. Markus Weissenberger also wishes to thank all faculty and staff in the Construction Engineering and Management Program at U.C. Berkeley for their warmth, support, and dedication to education he experienced during his stay. This work was funded in part by a seed grant from U.C. Berkeley's Committee on Research and by grant CMS-9622308 from the National Science Foundation (NSF) whose support is gratefully acknowledged. Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of NSF.

REFERENCES

- Alarcon, L. (ed.)(1997). *Lean Construction*. A.A. Balkema, Rotterdam, The Netherlands, 497 pp.
- Ballard, G. and Howell, G. (1998). "Shielding Production: Essential Step in Production Control." *J. Constr. Engrg. and Mgmt.*, ASCE, 124 (1) 11-17.
- Ballard, G., Howell, G.A., Tommelein, I.D., and Zabelle, T.R. (1999). *Lean Construction: A Revolution in the Design and Building of Capital Facilities*. Lean Construction Institute, Ketchum, ID, www.leanconstruction.org.
- Bernold, L.E. and Salim, Md. (1993). "Placement-oriented design and delivery of concrete reinforcement." *J. Constr. Engrg. and Mgmt.*, ASCE, 119 (2) 323-335.

- Hopp, W. and Spearman, M. (1996). *Factory Physics*. McGraw Hill, Boston.
- Howell, G.A. and Ballard, H.G. (1996). *Managing Uncertainty in the Piping Process*. RR 47-13, Constr. Industry Institute, Univ. of Texas, Austin, TX, Sept., 103 pp.
- Howell, G., Laufer, A., and Ballard, G. (1993). "Interaction between Sub-cycles: One Key to Improved Methods." *J. Constr. Engrg. and Mgmt.*, ASCE, 119 (4) 714-728.
- Koskela, L. (1992). "Application of the New Production Philosophy to Construction." *Tech. Report 72*, CIFE, Stanford Univ., CA, September, 75 pp.
- O'Brien, W.J. (1995). "Construction Supply Chains: Case Study and Integrated Cost and Performance Analysis." *Proc. IGLC-3*, Albuquerque, NM, 187-222 in Alarcon (1997).
- Rother, M. and Shook, J. (1998). *Learning to See: Value Stream Mapping to Create Value and Eliminate Muda*. v.1.1, Oct., The Lean Enterprise Institute, Brookline, Mass.
- Thomas, H.R., Sanvido, V.E., and Sanders, S.R. (1989). "Impact of Material Management on Productivity—a Case Study." *J. Constr. Engrg. and Mgmt.*, ASCE, 115 (3) 370-384.
- Tommelein, I.D. (1997). "Discrete-event Simulation of Lean Construction Processes." *Proc. Fifth Ann. Conf. Intl. Group for Lean Constr.*, IGLC-5, 16-17 July at Griffith Univ.-Gold Coast Campus, Queensland, Australia, 121-135.
- Tommelein, I.D. (1998). "Pull-driven Scheduling for Pipe-Spool Installation: Simulation of Lean Construction Technique." ASCE, *J. Constr. Engrg. and Mgmt.*, 124 (4) 279-288.
- Tommelein, I.D. and Li, A.E.Y. (1999). "Just-in-Time Concrete Delivery: Mapping Alternatives for Vertical Supply Chain Integration." *Proc. 7th Ann. Conf. Intl. Group for Lean Constr.* IGLC-7, 26-28 July, held at U.C. Berkeley, CA.
- Tommelein, I.D., Riley, D., and Howell, G.A. (1998). "Parade Game: Impact of Work Flow Variability on Succeeding Trade Performance." *Proc. 6th Ann. Conf. Intl. Group for Lean Constr.*, IGLC-6, 13-15 August held in Guarujá, Brazil, 14 pp.
- Tommelein, I.D., Riley, D., and Howell, G.A. (1999). "Parade Game: Impact of Work Flow Variability on Trade Performance." ASCE, *J. Constr. Engrg. and Mgmt.*, Sept./Oct. Issue.