3D MODELING AND REAL-TIME MONITORING IN SUPPORT OF LEAN PRODUCTION OF ENGINEERED-TO-ORDER PRECAST CONCRETE BUILDINGS

Rafael Sacks[1], Burcu Akinci[2] and Esin Ergen[3]

ABSTRACT

Previous research has highlighted the efficacy of the application of lean production principles in the precast concrete industry. The work also highlighted the dependence of engineered-to-order prefabrication in construction on both engineering and on process control information for production in construction. In current practice in most precast/prestressed plants in the US, producers typically fabricate pieces well in advance of their erection on site, resulting in relatively large buffers of product stored in extensive yards. This practice is generally attributed to the fact that precast production rates are significantly slower than erection rates, and to erratic demands for product from the erection process. The behavior is reinforced by the industry-wide willingness of building clients to pay up to 90% of the cost of precast products on production, rather than on delivery and erection. However, other factors prevent reduction of inventories: among them are the inability of current numbering methods and information systems to support long term erection sequence planning; the high cost and imprecision of real-time feedback (pull) information from the site and/or project management; and producers' unreliability in identifying and shipping pieces on time from yards that are difficult to manage due to their size. We propose that resolution of these problems requires concerted application of lean principles, of advanced information technology and of real-time monitoring (using Automated Project Performance Control technologies). The potential of information systems and interpreted monitoring data to support a lean production and delivery cycle for precast construction is explored in relation to each of the problems stated.

KEY WORDS

Lean production, precast concrete, 3D modeling, information technology, real-time monitoring.

[1] Lecturer, Faculty of Civil and Environmental Eng., 840 Rabin Building, Technion – Israel Institute of Technology, Haifa 32000, Israel, 972-4-829-3190 FAX 972-4-832-3433, cvsacks@technion.ac.il

[2] Assistant Professor, Department of Civil and Environmental Eng., Carnegie Mellon University, Pittsburgh, PA 15213-3890, 412-268-2959 FAX 412-268-7813, bakinci@andrew.cmu.edu

[3] Doctoral Student, Department of Civil and Environmental Eng., Carnegie Mellon University, Pittsburgh, PA 15213-3890, 412-268-2959 FAX 412-268-7813, eergen@andrew.cmu.edu

INTRODUCTION

A visitor to any typical precast/prestressed concrete construction plant in North America, who is familiar with the principles of lean construction, will be struck by the relatively large quantities of finished precast concrete pieces stored in extensive open-air storage yards, such as the double-tee yard shown in Figure 1. Deeper investigation of the precast supply-chains reveals additional large buffers in the engineering design phase and in the various branches that provide component parts for inclusion in the concrete pieces. This confirms the findings of (Vrijhoef and Koskela 1999) regarding construction supply chains in general.

Figure 1: Precast plant storage yard - double-tee section.

The upstream engineering and business processes common within the industry have been documented and analyzed in the course of ongoing research for the Precast Concrete Software Consortium (PCSC) (Sacks et al. 2003a; Sacks et al. 2003b). The most common process is outlined in Figure 2. The downstream production and erection processes are the focus of this paper. As is the case in structural steel construction (Tommelein and Weissenberger 1999), the primary resource employed for building erection, the mobile crane on site, generally drives the erection process. Given the large sizes of precast pieces, the need to avoid double handling, and the lack of storage space on site, precast concrete is generally considered to be a 'Just In Time' activity (JIT) from the erection perspective (Pheng and Chuan 2001). This reflects the point of view of the general contractor, in that pieces must be delivered to site 'just-in-time'; however, it hides the inefficiencies inherent in the supply-chains of embedded components and of the precast pieces themselves.

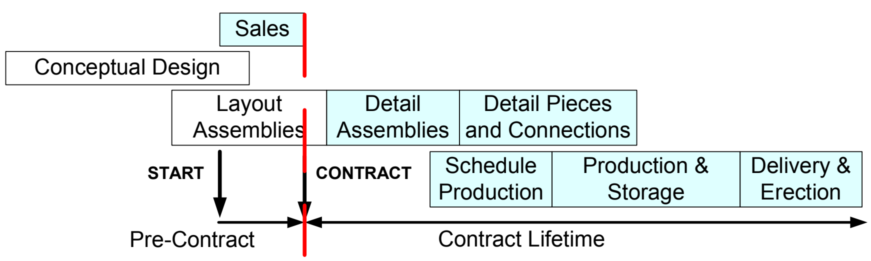

Figure 2: Precast construction process where precaster acts as a sub-contractor.

The following review presents the current state of affairs in US precast plants from a lean production/construction point of view. It is based on information gleaned from intensive information collection, interviews and observations made at three precast plants and on material provided by the PCI (Precast Concrete Institute):

- Finished pieces are often stored for as much as six months before shipping (Ergen et al. 2003). All three plants investigated have at various times worked below production capacity because storage areas have reached capacity. Maintenance of large buffers (product, work-in-progress or time) is common not only for finished pieces, but also within internal production departments (weld-shop, mold-shop, rebar-bending, purchasing) and for participants external to the precast producers (external engineering design firms, raw material suppliers, galvanizing plants, stone cutting shops, etc.).
- Lead-times from contract to start of erection for precast construction projects typically range from two to six months. Although lead-times are affected by the need to order custom parts for embedding in the concrete pieces, long lead times are mainly due to the time spent on intensive engineering design. The engineering design process includes two major stages – assembly level analysis and design, and piece level design and detailing (Figure 2). At each stage, the designs are typically submitted to the owner's architects and engineers for review.
- The rate of demand for delivery of pieces to construction sites is relatively unpredictable and erratic. Initial erection sequence planning is approximate. In all companies reviewed, accurate erection sequence planning was carried out at best two weeks before erection was scheduled to begin. Final schedules for the delivery of individual pieces are only confirmed within one to two days prior to the time that the pieces are required on site. For certain architectural pieces, trailers are loaded as much as a week in advance to allow cleaning and timely delivery of pieces.
- Since production precedes erection by more than two weeks, production planning is done mainly on the basis of the schedulers' experience[4], and includes significant inventory buffering (as explained below). Production planning is implemented at three levels of accuracy: (1) Long-term (months ahead) planning 'reserves' plant capacity for a project at the time a contract is signed; (2) Medium-term planning is performed with a two-week look ahead time frame, and is based on erection sequence plans submitted by the erection subcontractor; (3) Short-term production planning for each day's production is performed two days ahead of time.
- Production of individual pieces is technically feasible within two days prior to delivery, but is more commonly done one to six months before delivery. Owners (or general contractors) typically pay approximately 90% of the cost of a piece at the time it is produced, and the remainder is retained until project completion.

[4] Construction sequence for precast buildings is less predictable than for other construction types. Precast structures must be erected 'height-first', usually starting from a corner, and not 'floor-by-floor' (limited moment-capacity of erection cranes means that the crane must be positioned close to the final position of every piece, and then move back to build successive complete bays). In the absence of any explicit decision on the part of the general contractor and/or erector, the precast producer cannot reliably predict where erection will begin and in which direction it will progress.

Thus the cost of production is almost entirely financed by the client. This reflects a long-established lack of confidence on the part of erectors/contractors in precasters' ability to supply 'just-in-time' (Pheng and Chuan 2001). The contractors/erectors decouple their erection operation from the design and production operation by providing an incentive to the producer to generate a very large inventory buffer.

- Most plants operate on a basic 24-hour mold-preparation, casting, curing and stripping cycle. The capacity of any plant is lower than the number of bed positions per cycle, because cycles are missed when beds/molds require physical setup changes between different piece types (piece marks). Double tee beds, where the piece/piece-mark ratio averages 4-5, achieve 80-85% of nominal capacity. Architectural wall panel beds may achieve as little as 25% of nominal capacity, since the piece/piece-mark ratio is often close to 1.
- Beyond the technical limitations cited above, market demand fluctuations affect capacity utilization levels. For example, the median capacity utilization for the industry as a whole ranged between 64%-78% in 2001 (PCI 2001).

The precast companies' priority is to improve their competitiveness compared with structural steel and cast-in-place construction. The problems they most commonly cite are the long engineering lead times, costly design and production errors, the cost of storage and other overheads, and their frequent inability to respond to change requests from owners and/or architects without increasing price (Sacks et al. 2003b). The PCSC (PCSC 2003) is in the process of procuring an advanced 3D modeling software package for precast engineering design and detailing, which is specifically intended to reduce engineering lead-times and error levels. The large, intangible buffer of design and engineering information currently maintained in every project will presumably be reduced. Specific provisions for functionality within the software as specified should lay the foundation for tighter integration of the engineering, production and erection sub-processes than that described above. However, no effort has yet been made to analyze the overall process as a project delivery process, with a view to proposing solutions for the production planning, storage, delivery and erection related problems. This, therefore, is the scope of this paper.

The paper continues with analysis and interpretation of the current state of affairs. Potential remedies for the underlying problems are proposed, and a research program is presented.

ANALYSIS AND INTERPRETATION

The nature of precast construction, the apparent discrepancy between 'slow' production rates and 'fast' erection rates, and the need to level plant production across numerous projects, were the three reasons most commonly cited by the company executives and engineers for the state of affairs described above.

On-site storage space is often limited and the cost of the crawler cranes employed for erection is very high, making it highly desirable that precast pieces be delivered just as they are needed. Off-site storage – usually in yards at the precast plant - provides a buffer that enables delivery of pieces to site in response to short-term calls with a high degree of confidence.

Precast erection is in general a continuous operation. Erectors typically set up to twenty pieces of structural precast in a day. However, a producer must supply numerous projects, which bear no scheduling relation to one another (other than, in certain cases, their reliance on common erection resources). The rate of demand for delivery of pieces to site for most plants varies from half the capacity production rate to five times that rate. Analytical solutions for minimizing inventory required for production of small and large series of precast pieces, produced on several molds, have been developed (Warszawski 1984), but these relate only to the situation where the required rate of delivery is fixed, and series are completed without interruption.

To assess the impact of delivery demand rate on production and inventory strategy, we consider each product type separately. Table 1 shows the relative quantity of various pieces in a sampling of 12 precast projects from different companies. Within each product type, there are a number of distinct piece designs (called piece-marks) for any project. The bottleneck in almost all structural projects is the production of double-tee pieces (from which floors are built), due to their quantity and to the fact that they can only be produced in special purpose prestressing beds. We compare three extreme situations for planning their production:

a) the erection sequence (i.e. the sequence of demand for delivery) is entirely known and will not vary, although the timing for delivery is not predictable, and all pieces are different;

b) the sequence of demand for delivery is *unknown* when production begins, and all pieces are different;

c) the sequence of demand is unknown, but all the pieces are identical.

Table 1: Quantities of pieces required for 12 typical precast buildings.

Piece Type	**Total number of pieces (12 projects)**	**Total number of piece designs (piece-marks)**	**Piece/Piece-mark Ratio**	**Proportion of total piece count**
Column / Lite-wall	560	520	1.1	8%
Wall	1558	1268	1.2	21%
Beam	31	20	1.6	0.4%
Double Tee	3372	854	3.9	46%
Girder	599	109	5.5	8%
Stairs	165	50	3.3	2%
Spandrel	584	314	1.9	8%
Other	497	200	2.5	7%

In situation (a), the production scheduler can sequence production to match erection. The resulting buffer required is shown in Figure 3a. This is similar to the case for fabrication and supply of rebar for cast-in-place construction, where the construction sequence is well known (Sakamoto et al. 2002). The buffer size for any given confidence-level for meeting demand need only reflect the variation in the timing of demand for delivery. Situation (c) has the same result.

In situation (b), a piece of any piece-mark could be required at any time. If every piece were different, therefore, when erection begins, the probability that the precaster can supply the pieces required is equal to the proportion of the pieces that have been produced. The buffer size must therefore be set according to the required confidence level, as shown in Figure 3b.

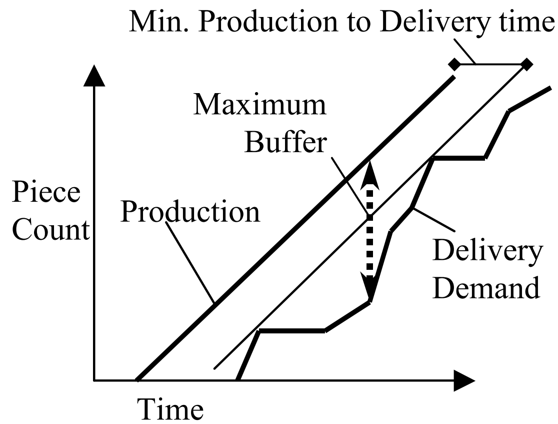

Figure 3(a): Erection sequence is known and unvarying - situation (a), OR all pieces are identical – situation (c).

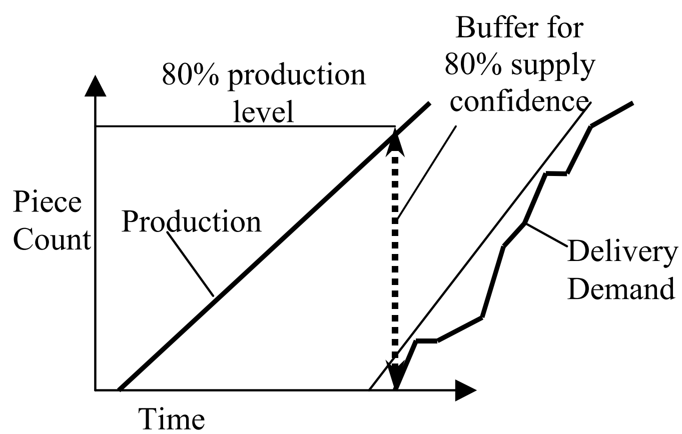

Figure 3(b): Erection sequence unknown, all pieces different.

In reality, current practice in precast concrete is much closer to situation (b) than to situations (a) or (c). Firstly, there are numerous pieces of each piece-mark (the average piece/piece mark ratio was found to be 1.4 for architectural projects and 2.5 for structural projects). Pieces are also different across projects. Secondly, erection sequencing is not made available to producers until approximately two weeks prior to delivery. As a result, most precast production schedulers adopt the rule of thumb, by which 80% of the double-tees in a project should be produced before erection begins.

When considering production for multiple projects, we make three additional observations:

1) Over any extended period, the average rate of production must be greater than or equal to the average rate of delivery (i.e. the number of pieces produced, less those discarded due to error, is equal to the number of pieces delivered), and
2) Situation (a) above expresses fluctuations in the rate of demand across multiple projects as well as it expresses it for a single project.
3) Very few plants actually operate at full capacity.

The reasons cited by precast producers (the unpredictable nature of construction, the apparent discrepancy between 'slow' production rates and 'fast' erection rates, and the need to level plant production across numerous projects) do not adequately account for the inventories maintained. In fact, lack of knowledge of the erection sequence greatly exacerbates the impact of the variability in demand. To better understand the real reasons, one must consider the following additional features of current precast practice:

- Precast designers do not uniquely identify each piece in a structure. Erection drawings are annotated with 'piece-marks', which are the same for identical pieces. However, piece-marks frequently change through the design-life of a project. As a result, erectors are unwilling to prepare erection sequences in terms of piece-marks. If companies assigned unique and constant 'assembly control numbers', erectors could set erection sequence in terms of these codes, without regard for the piece-mark that will ultimately be used in each location. This could then be done as soon as the conceptual design was complete and approved, early in the project.
- Precast production schedulers receive only 'best-case' delivery dates from general contractors. Until erection actually begins, they essentially have no feedback when site schedules are changed. Once erection begins, they receive requests to supply pieces to site (pull instructions) approximately 48 hours before the pieces are required for erection. They receive little or no feedback from erectors concerning the actual progress of erection on site (even where the erectors are employed directly by the precast production company). Production schedulers therefore often place priority on pieces for particular projects that are in fact unneeded due to delays at those sites. Under such conditions, short-term planning cannot be agile enough to cope with local deviations from plan. Protective buffering is a common response.
- Production policies place priority on maximizing the utility of double tee and other beds. As an overall policy, this precludes the agility necessary to cope with last-minute variations in demand.

- Numerous cases were reported in which the ability to supply pieces on time was reduced by the size of inventory. The lack of effective tools for management of large capacity storage yards resulted in the inability to locate existing pieces, which then had to be produced from scratch. This in itself has previously been perceived as a problem worthy of research (Dawood and Marasini 2001), although it could be said that its solution may in fact obscure the underlying problems.
- Long engineering lead-time, with piece detailing occurring at the end of the process, means that quantity take-off for made-to-order components that must be cast into precast pieces can delay production. This is particularly true when the components themselves have long lead times.
- Existing information systems do not facilitate delivery planning and scheduling from the point of view of the erector in any way. Erectors on site rely on paper drawings and reports, and call in deliveries by phone. Coordination of delivery typically consumes up to 15% of an erection foreman's time.
- When design changes are requested or needed, the long response times required for engineering mean that no agility is available for quick production turn-around. Contractors/erectors protect themselves by ordering well in advance.

The costs of maintaining large inventories are threefold. While they are accrued by different parties in the supply chain, they ultimately increase the price (and reduce the competitiveness) of precast construction. Firstly, the direct costs of storage (handling, management, financing of real-estate, etc.) are incorporated in the price paid by the client to the precaster. Architectural pieces are routinely cleaned and/or sand-blasted immediately before shipping, as a result of having been stored outdoors for extended periods – in all, between stripping from the mold to loading onto the trailer for delivery, a piece is handled four times. Secondly, the client must finance the cost of the precast pieces from the time they are produced (and paid for), rather than from the time they are erected. Thirdly, the cost of making changes to a piece is much higher when it has already been produced than if the change were made on paper only.

PROPOSED REMEDIES

Previous research concerning application of lean principles to precast piece production (Ballard et al. 2003) resulted in a number of recommendations, which focused in particular on restructuring the production plant in cells rather than distinct departments. The success of restructuring in increasing production throughput, as implemented in a plant in the UK, has been striking. Additional recommendations included the use of 3D computer modeling for engineering, implementing information systems for production control, and rationalizing product designs to reduce the number of product types. The driving consideration is the need to reduce lead-time to less than the 'window of reliability' of the erection work on site.

Sophisticated 3D modeling systems for precast concrete construction are currently being developed by two software consortia, both resulting from a research project led by Eastman at Georgia Tech (Eastman et al. 2003). The software will replace drafting with parametric 3D modeling for precast engineering design and detailing, and much of the human effort currently required for detailing will be automated. Its impact for production is expected to be in terms of a) reducing engineering lead times from months to days, b) reducing errors (Sacks et al. 2003a), c) providing reliable data for procurement of components, and d) enabling accurate assembly control numbering. These systems are planned for wide adoption by late 2004. The systems should enhance the ability of plants to respond to design changes with agility, which suggests more variety in piece designs (effective parametric systems will correctly implement a design change and immediately produce corrected production drawings). Thus from a lean point of view, while both lead times and production variability associated with engineering errors are likely to be significantly reduced, increased rationalization of piece types is highly unlikely.

A secondary benefit is expected from integration of the 3D modeling systems with production management information systems. Specifically, adoption of assembly control numbering as standard practice should enable erectors to plan and commit to erection sequences earlier in the process than is common without such systems in current practice.

Given the remaining drawbacks listed in the previous section, we propose that work restructuring and IT systems implementation can be made more effective by tighter coupling of the information flows between plant production management, the storage and shipping functions, and on-site erection/construction management. This has two aspects: automated *data collection and interpretation* of information describing the status of each function, and electronic *communication* of that information to each of the functions. Figure 4 illustrates the concept. The production planning IT system is configured with a data-base which receives real-time updates of information gathered by fully automated equipment mounted on the precast handling equipment – gantry cranes, straddle lifts, trucks, and erection cranes.

The key <u>feedback</u> information is that provided from the construction site to the production system. The concept of crane mounted construction progress monitoring was proposed in the framework of Automated Project Performance Control (APPC) research (Sacks et al. 2002). In that work, a knowledge-based module was required to identify building elements being built in conventional cast-in-place construction. In this case, RFID tags carrying unique production control IDs are attached to the precast pieces, so that their identity is read directly by the crane mounted RFID reader. Location data from a GPS monitor mounted on the crane can be manipulated with monitoring data defining the crane rotation, boom angle and hook height to determine the location in the building into which the piece was placed. The erector uses a display based on the 3D engineering model – which might include color coding of the pieces installed and those already in production – to set medium-range and short-range look-ahead erection schedules in terms of assembly control numbers. The scheduler at the production plant shares the same view of this visual 'Last Planner' image: in this way, both short-term 'pull' signals and medium-term demand variation information is relayed to the plant as soon as the decisions are made on the site.

On the other hand, providing the contractor with accurate information describing the status of the pieces for the project may contribute to increased confidence in the precaster's ability to maintain reliable supply, thus reducing the pressure to accumulate stocks (predicated of course on reliable performance by the precaster).

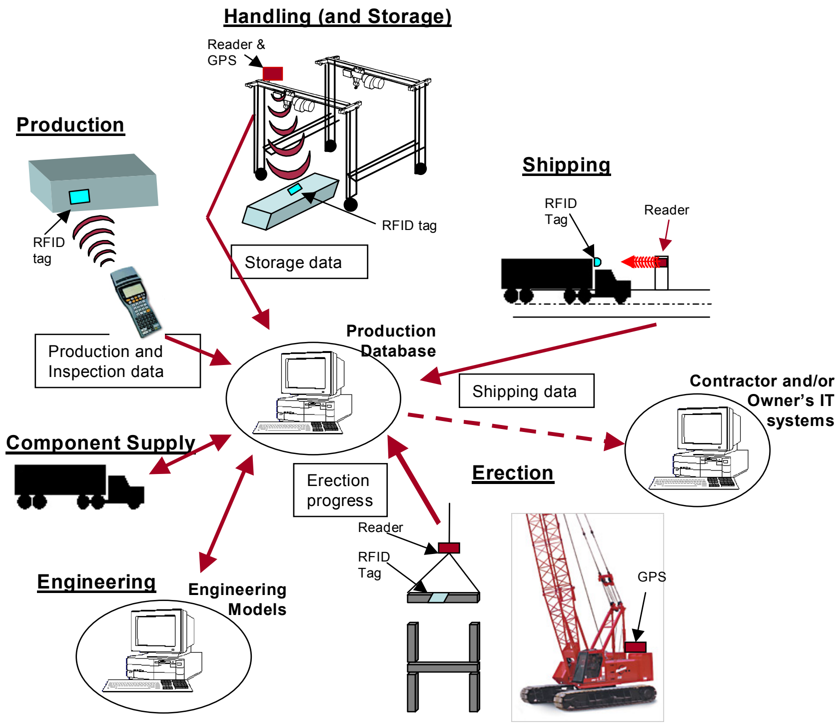

Figure 4: Data collection during production, storage, shipping and erection.

RESEARCH REQUIRED

Numerous thrusts of research and development are necessary to achieve the level of integration described above:

- Proposal and implementation planning of lean process changes in an environment in which both 3D modeling and integrated real-time information is available. Re-organizing a production facility around product-specific cells rather than 'service-providing departments' (e.g. weld shop, rebar fabrication, form building, etc.) relieves the dependence of the final production activity on the departments. However, it is still reliant on the engineering department for the most important resource – information. Automation of piece detailing and bill of material generation could enable each cell in a production facility to 'pull' its own information on demand, including dealing directly with low level detailing changes.
- Development of a mathematical or algorithmic model of precast production that would take into account varying rates of demand from numerous sites, and include both the timing and the reliability of erection scheduling information as input variables. Were such a model available, it could not only aid in testing proposed process improvements, but also form the basis of computer-aided production planning systems of the future.

- Preparation and testing of a computer simulated process for predicting and testing the potential impacts of the various remedies on plant production and inventory levels. This could serve as an alternative to a procedural model (as described in the previous item), and fulfill the same goals. Given the arbitrarily varying nature of the rates of demand, and the need to incorporate probabilistic modeling, this may prove to be a more computationally efficient approach than the procedural one.
- In-situ testing of real-time monitoring equipment in the different physical conditions and development of associated information modules and their user interfaces.
- Development of a precast concrete product (data) model, which is essential for integration of the various and diverse proprietary information systems that must share information through the life-cycle of precast products. Pilot work in this direction is already underway at Georgia Tech (Eastman et al. 2003), as a natural progression of the current 3D modeling effort.
- Measurement of current practice performance indicators, with the goal of monitoring the real impact of each aspect of the proposed systems as they are implemented.

CONCLUSIONS

Investigation of three precast plants has revealed large product and time buffers of finished engineered-to-order precast concrete pieces and in the supply chains of the components embedded in them. Engineering information is delivered in large batches and with long lead-times. The findings are almost identical across all the companies visited.

The lack of predictability in the timing of demand for precast pieces to be delivered to different construction sites does not account for the sizes of inventory accumulated. The lack of knowledge of the erection sequence for each project – resulting from inadequate information generation and reporting systems – exacerbates the problem at all levels of forward planning.

Previous research has highlighted the benefits to be gained by restructuring the engineering and production processes in the plants in two ways: a) adoption of advanced 3D modeling systems for engineering analysis and design, and integration with management information systems, and b) re-aligning production lines and supply chains according to lean production principles. Neither of these tackles the information gap that exists between production in the plant and construction in the field. At a basic level, the new modeling and information systems must provide appropriate unique identifiers for piece-locations in building designs to facilitate early definition of erection sequence. At a more fundamental level, we propose real-time integration of the feedback information loops from finishing, yard storage, shipping and erection with the plant production scheduling function. This is to be achieved by automatically monitoring the flow of pieces through the chain, interpreting the monitored data in the context of a digital building model, and reporting it to all the actors involved.

The expected benefits include effective communication of pull signals from the construction site to the production plant, improved control of inventory and better management of storage yards. The main contribution, however, is in increasing the duration and reliability of the look-ahead window from the point of view of the production controller. An improvement of one or two days in advance notice of the need for pieces for erection is significant if the result is that the look-ahead window becomes longer than the lead-time required for production. Automatic data collection ensures that all of the information is gathered; information that is unavailable in current practice because it must be collected by personnel whose priorities lie elsewhere. As such, an automated feedback information system may be a primary enabler of leaner precast supply chains.

Precast concrete construction is typical of other high-value engineered-to-order prefabricated components of buildings, such as elevators, HVAC and other mechanical systems, window and door assemblies, etc. As such, progress in research toward tighter integration of the production and erection activities in the precast domain is likely to be applicable to a range of construction industry supply chains.

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