

Lean project management

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Projects are temporary production systems. When those systems are structured to deliver the product while maximizing value and minimizing waste, they are said to be 'lean' projects. Lean project management differs from traditional project management not only in the goals it pursues, but also in the structure of its phases, the relationship between phases and the participants in each phase. This paper presents a model of lean project management and contrasts lean and traditional approaches. Four tools or interventions are presented as illustrations of lean concepts in action.

Keywords: construction management, Lean Project Delivery System (LPDS), lean project management, project management, value, waste

Les projets sont des systèmes de production temporaires. Lorsque ces systèmes sont organisés pour fournir le produit tout en optimisant la valeur et en minimisant les gaspillages, on dit qu'il s'agit de projets «au plus juste». La gestion de ce type de projet diffère de celle des projets classiques non seulement au niveau des objectifs visés mais aussi à celui de la structure des phases, des relations entre les phases et des participants à chaque phase. Cet article propose un modèle de gestion de projet au plus juste et oppose les deux approches. Quatre outils ou interventions sont présentés pour illustrer l'application des concepts «au plus juste».

Mots clés : gestion de la construction, système de fourniture de projet «au plus juste», gestion de projet au plus juste, gestion de projet, valeur, gaspillages

Introduction

Thinking about production has been shaped by the challenges of repetitive manufacturing. This has had two unfortunate consequences:

- 'making' has eclipsed 'designing' and
- project has been conceived as a peripheral, oddball form of production

Adherents of lean project management advance an alternative perspective. Production is defined as designing and making things. Designing and making something for the first time is done through a project, which is, for that reason, arguably the fundamental form of production system.

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Construction is one among many types of project-based production systems. Others include shipbuilding, movie-making, software engineering, product development and all forms of work-order systems such as plant and facilities maintenance. Theory, rules and tools must be developed for project-based production systems and their management. The Lean Project Delivery System¹ (LPDS) is a contribution to that objective.

The LPDS has emerged from a fusion of theoretical insights, methods from other industries and participative action research (see Ballard and Howell 1998 for a detailed explanation of the development of the production control component of the LPDS).

In the following, brief historical and theoretical backgrounds are provided, then the LPDS model is presented and explained, followed by four illustrations of its application and an invitation to join the effort to develop lean project management.

Historical background

The phrase ‘lean production’ was coined by a member of the research team studying the international automobile industry; the report of which was published in *The Machine That Changed the World* (Womack *et al.*, 1990). ‘Lean’ was used to name a third form of production system, one capable of producing more and better vehicles in less time, in less space and when using fewer labour hours than the mass or craft production systems that preceded it. New concepts and techniques were identified, including Just-in-Time (JIT) deliveries, Pull (versus Push) mechanisms for advancing work through a production system, making batch size reduction economical by reducing set-up times, and increasing transparency of the production system so everyone could help manage it.

Lauri Koskela first alerted the construction industry to the revolution in manufacturing, challenging it to explore and adopt these new concepts and techniques (Koskela, 1992). He hosted the first conference of the International Group for Lean Construction (www.vtt.fi/rte.lean) at VTT in Espoo, Finland, in August 1993. That small group of researchers decided to adopt the name ‘lean construction’.² The IGLC, now grown considerably since its founding, is dedicated to the development of a theory of production and production management, with the project as the most fundamental system for designing and making things.

But to conclude this brief history – the IGLC has grown each year, operating through annual conferences rotating through Europe, Asia, South America, North America, etc. The proceedings of the first three conferences have been published together in Alarcon (1997). The proceedings of the remaining conferences were published separately and are also available at the IGLC website.

National organizations, mostly oriented also to advancing practice as well as theory, have begun to emerge. The Lean Construction Institute (www.leanconstruction.org) was formed in the USA in 1997. Similar organizations exist in Chile and Denmark and others are in process of formation.

The UK’s most recent report on the construction industry. *Rethinking Construction* (Construction Task Force, 1997), promoted lean manufacturing as a model to be emulated. The researchers active in IGLC have brought lean concepts and techniques into the construction industries of the USA, UK, Finland, Denmark, Singapore, Korea, Australia, Brazil, Chile, Peru, Ecuador and Venezuela. University courses in construction and project management are beginning to incorporate lean construction material. To mention but a few, the University of California at Berkeley has been a leader in the USA, as has the Catholic University of Chile in Chile and the University of Rio Grande do Sul in Brazil.

Theoretical background

We understand projects to be temporary production systems linked to multiple, enduring production systems from which the project is supplied materials, information and resources. Every production system integrates designing and making a product. Production (and hence project) management is understood in terms of designing, operating and improving production systems (Koskela, 2001).

Production systems are designed to achieve three fundamental goals (Koskela, 2000):

- Deliver the product
- Maximize value
- Minimize waste

By way of example, principles for production system design include (Ballard *et al.*, 2001):

- Structure work for value generation
- Understand, critique and expand customer purposes
- Increase system control (ability to realize purposes)

Operating is conceived in terms of planning, controlling and correcting. In this context, to plan is to set specific goals for the system. To control is to advance towards those goals. To correct is to change the means being used or the goals being pursued.

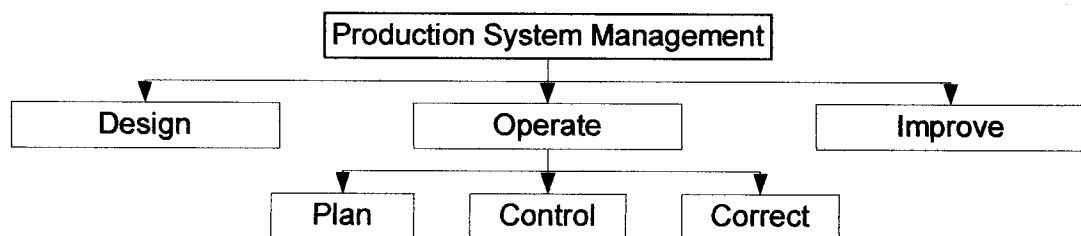


Figure 1 Production system management

Lean Project Delivery System (LPDS) Model

Projects have long been understood in terms of phases, e.g. pre-design, design, procurement and installation. Some of the key differences between traditional and lean project delivery concerns the definition of phases, the relationship between phases and the participants in each phase.

Project definition

The model in Figure 2 represents a series of phases in overlapping triangles, the first of which is 'Project Definition', which includes customer and stakeholder purposes and values, design concepts, and design criteria.

Each of these elements may influence the other, so a conversation is necessary among the various stakeholders. Typically – like a good conversation – everyone leaves with a different and better understanding than they brought with them. Representatives of every stage in the life cycle of the facility are involved in this initial phase, including members of the production team which is to design and build the product.

Lean design

The gate between Project Definition and Lean Design is alignment of values, concepts and criteria. Lean Design also proceeds through conversation, this time dedicated to developing and aligning product and process design at the level of functional systems. The project may revert to Project Definition if the ongoing search for value reveals opportunities that are consistent with customer and stakeholder constraints, e.g. if there is time and money enough.

Lean Design differs from traditional practice in systematically deferring decisions until the last responsible moment in order

to allow more time for developing and exploring alternatives. The traditional practice of selecting options and execution of design tasks as soon as possible causes rework and disruption when a design decision made by one specialist conflicts with the decisions of another. The 'set-based' strategy employed in Lean Design allows interdependent specialists to move forward within the limits of the set of alternatives currently under consideration. Decisions must be made within the lead time for realizing alternatives, hence the importance in Lean Construction of redesigning supply networks to reduce their lead time.

Lean supply

Lean Supply consists of detailed engineering, fabrication, and delivery, which require as prerequisite product and process design so that the system knows what to detail and fabricate, and when to deliver those components. Lean Supply also includes such initiatives as reducing the lead time for information and materials, especially those involved in the supply of engineered-to-order products, which typically determine the pace and timing of project delivery.

Lean assembly

Lean assembly begins with the delivery of materials and the relevant information for their installation. Assembly completes when the client has beneficial use of the facility, which typically occurs after commissioning and start-up.

The management of production throughout the project is indicated by the horizontal bars labelled Production Control and Work Structuring. The systematic use of feedback loops between supplier and customer processes is symbolized by the inclusion of Post Occupancy Evaluations between projects.

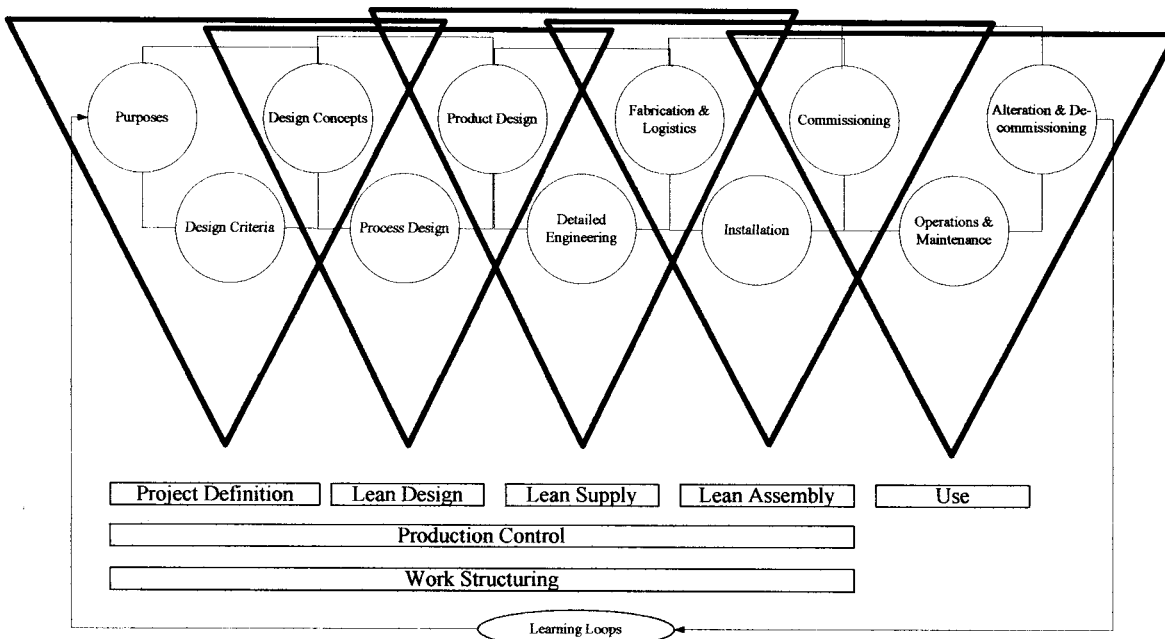


Figure 2 Triads of the Lean Project Delivery System (LPDS)

Comparison of lean and non-lean project delivery systems

Table 1 lists some of the differences between lean and non-lean project delivery.

To develop only one of these differences, consider buffers. Traditionally, each participating organization tends to build up large inventories³ in order to protect its own interests. These inventories may take the form of information, drawings, materials, work-in-progress, space or time. Lacking the ability to act at the level of the entire production system, an individual architectural firm, engineering firm, general contractor or specialty contractor may see no alternative than to build these inventories unilaterally as buffers against variability and risk. Within the lean approach, inventories are structured and sized to perform their functions within the system, primarily the function of buffering against variability.

Illustrations

Instances of concepts, techniques and applications are included here in order to illustrate the true nature of the LPDS and how it differs from non-lean project delivery. The four illustrations presented are:

- Last Planner System of Production Control
- Work Structuring through Pull Scheduling
- Negative versus Positive Iteration in Design
- Application of Lean Rules and Tools to Precast Concrete Fabrication

Illustration 1: the last planner system of production control

The last products of work structuring are specific project goals, typically presented in the form of schedules. Production control has the job of achieving those goals.

The Last Planner system of production control (Figure 3) has three components: (1) lookahead planning, (2) commitment planning and (3) learning. (For more detail, see Ballard and Howell, 1998; and Ballard, 2000b). The last planner is that individual or group that commits to near-term (often weekly) tasks, usually the front line supervisor, such as a construction foreman, a shop foreman or a design squad boss (extension of commitment planning and learning to direct workers is a likely future step in the evolution of lean construction). They issue directives that result in direct production rather than in more detailed plans.

The primary rules or principles for production control are:

- Drop activities from the project schedule into a 6-week (typical) lookahead window, screen for constraints and advance only if constraints can be removed in time
- Try to make only quality assignments (see quality criteria below under Commitment Planning). Require that defective assignments be rejected. Note the analogy with Toyota’s requirement that workers stop the production line rather than allow defective products past their workstation. In directives-driven production systems like construction projects, it is possible to intervene in the planning process before direct production
- Track the percentage of assignments completed each plan period (PPC or ‘per cent plan complete’) and act on reasons for plan failure

Lookahead planning

The functions of lookahead planning are:

- Shape work flow sequence and rate
- Match work flow and capacity
- Maintain a backlog of ready work (workable backlog)
- Develop detailed plans for how work is to be done (operations’ designs)

Table 1 Lean versus non-lean project delivery

Lean	Non-lean
Focus is on the production system Transformation, flow and value goals Downstream players are involved in upstream decisions	Focus is on transactions and contracts Transformation goal Decisions are made sequentially by specialists and ‘thrown over the wall’
Product and process are designed together All product life cycle stages are considered in design Activities are performed at the last responsible moment Systematic efforts are made to reduce supply-chain lead times	Product design is completed, then process design begins Not all product life cycle stages are considered in design Activities are performed as soon as possible Separate organizations link together through the market and take what the market offers
Learning is incorporated into project, firm and supply-chain management Stakeholder interests are aligned Buffers are sized and located to perform their function of absorbing system variability	Learning occurs sporadically Stakeholder interests are not aligned Buffers are sized and located for local optimization

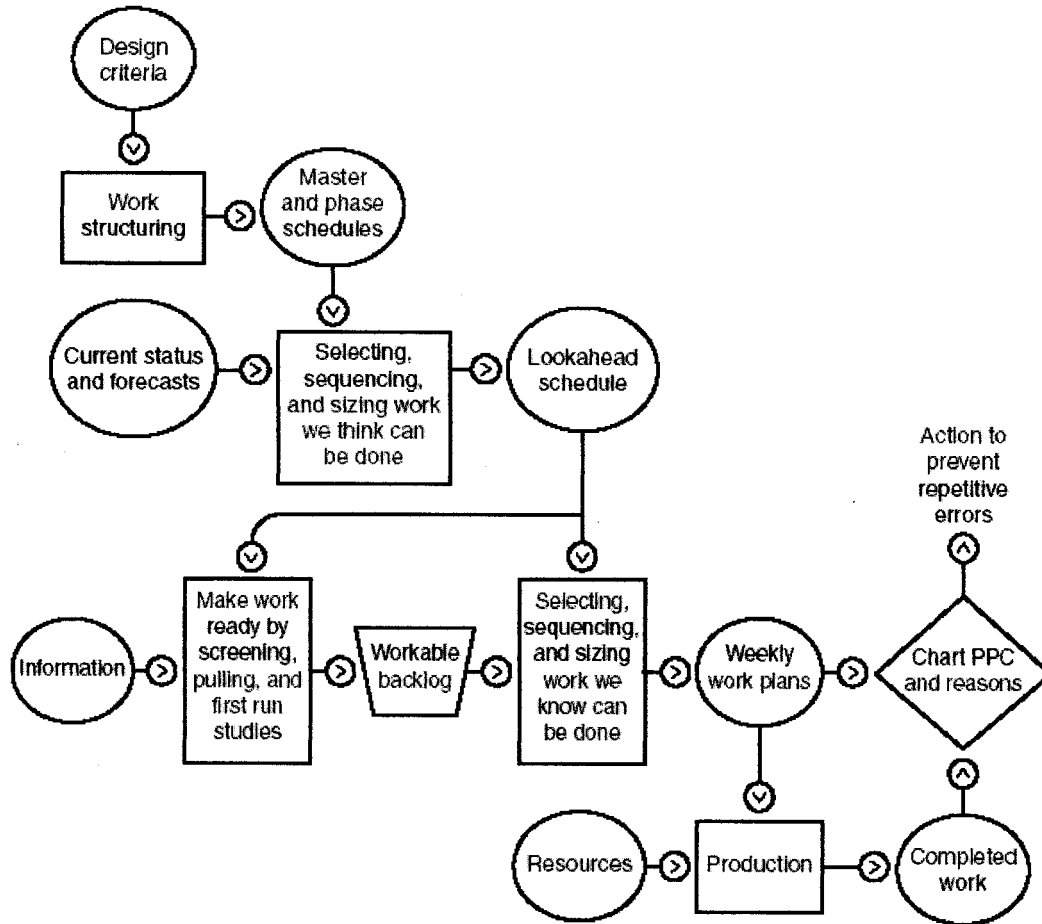


Figure 3 Last planner system of production control

Tools and techniques include constraints analysis, the activity definition model and prototyping of products or processes, also known as first-run studies. Constraints analysis is done by examining each activity that is scheduled to start within the period chosen as the project lookahead window.⁴ The constraints that prevent the activity from being a sound assignment are identified and actions are taken to remove those constraints. As shown in Table 2, the activity of designing a slab is constrained by lack of a soils report. Acquiring the soils report removes that constraint. Note that the addition of such 'make ready' tasks is one way in which the level of detail increases as scheduled activities enter the lookahead window.

The rule governing constraints analysis is that no activity is allowed to retain its scheduled date unless the planners are confident that constraints can be removed in time. Following this rule assures that problems will be surfaced earlier and that problems that cannot be resolved in the lookahead process will not be imposed on the production level of the project, whether that be design, fabrication or construction.

The Activity Definition Model (ADM: Figure 4) provides the primary categories of constraints: directives, prerequisite work and resources. Directives provide guidance according

to which output is to be produced or assessed. Examples are assignments, design criteria and specifications. Prerequisite work is the substrate on which work is done or to which work is added. Examples include materials, whether 'raw' or work-in-progress, information input to a calculation or decision, etc. Resources are either labour, instruments of labour or conditions in which labour is exercised. Resources can bear load and have finite capacities. Consequently, labour, tools, equipment and space are resources, but materials and information are not.

ADM is a tool for exploding phase schedule activities into greater detail. Explosion occurs through specification of constraints and through further detailing of processes.

Commitment planning

The Last Planner presents a methodology to define criteria for making quality assignments (Ballard and Howell, 1994). The quality criteria proposed are:

- Definition
- Soundness

Table 2 Illustration of constraints analysis

Project: Mega Building Report date: 3 November							
Constraints							
Activity	Responsible party	Scheduled duration	Directives	Prerequisites	Resources	Comments	Ready?
Design slab	Structural engineer	15–27 November	Code 98 Finish? Levelness? OK	soils report	10 h labour, 1 h plotter		no
<i>Get information from client about floor finish and level</i>	<i>Structural engineer's gofer</i>	3–9 November	OK	OK	OK		yes
<i>Get soils report from Civil</i>	<i>Structural engineer</i>	by 9 November	OK	OK	OK		yes
Layout for tool install	Mechanical engineer	15–27 November	OK	tool configurations from manufactures	OK	may need to coordinate with HVAC	no

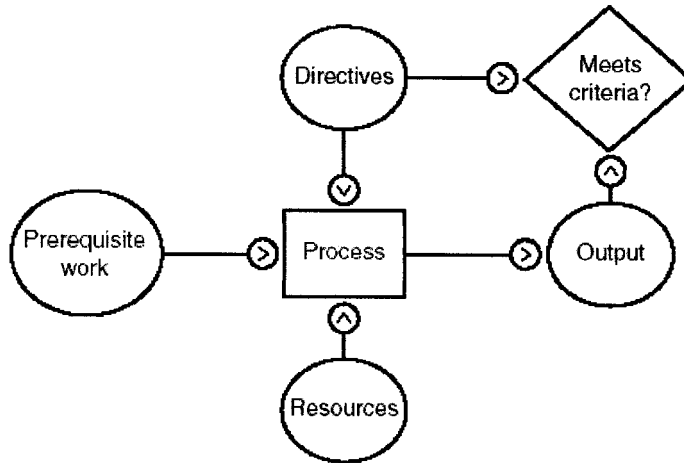


Figure 4 Activity Definition Model (ADM)

- Sequence
- Size
- Learning (not strictly speaking a criterion for assignments, but rather for the design and functioning of the entire system)

The Last Planner considers those quality criteria in advance of committing workers to doing work in order to shield them from uncertainty. The plan’s success at reliably forecasting what work will get accomplished by the end of the week is measured in terms of PPC (Figure 5).

Increasing PPC leads to increased performance, not only of the production unit that executes the Weekly Work Plan (Table 3), but also of production units downstream as they can plan better when work is reliably released to them. Moreover, when a production unit gets better at determining

its upcoming resource needs, it can pull those resources from its upstream supply so they will be available when needed. Consequently, it is not surprising that implementation of the Last Planner system has produced more reliable flow and higher throughput of the production system (Ballard and Howell, 1998; Ballard, 2000b; Koskela, 2000; Ballard *et al.*, 2002a,b).

Learning (also known as reasons analysis and action)

Each week, last week’s weekly work plan is reviewed to determine what assignments (commitments) were completed. If a commitment has not been kept, then a reason is provided (Figure 6). Reasons are periodically analysed to root causes and action taken to prevent repetition. Obviously, failure to remove constraints can result in lack of materials or prerequisite work or clear directives. Such causes of failure direct us

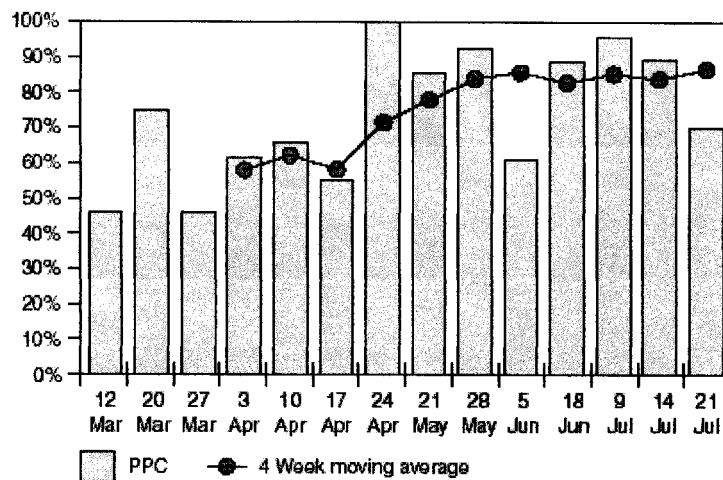


Figure 5 PPC chart electrical contractor (Ballard *et al.*, 1996)

Table 3 Construction weekly work plan

Project: Pilot ACTIVITY	1 Week plan							FOREMAN: Phillip DATE: 20/9/96	Reason for variances		
	Estimated	Actual	Monday	Tuesday	Wednesday	Thursday	Friday			Saturday	Sunday
Gas/PO hangers O/H 'K' (48 hangers)		XXX	XXX Sylvano, Mario, Terry							No	owner stopped work (changing elevations)
Gas/PO hangers O/H 'K' (3 risers)				XXX Sylvano, Mario, Terry	XXX	XXX	XXX			No	same as above – worked on backlog and boiler breakdown
36" cond water 'K' 42' 2–45 deg 1–90 deg Chiller risers (2 chillers per week)		XXX Charlie, Rick, Ben	XXX		XXX	XXX Charlie, Rick, Ben	XXX			Yes	
Hang H/W O/H 'J' (240'–14")		XXX Mark M, Mike	XXX	XXX	XXX	XXX	XXX	XXX		Yes	
Cooling tower 10" tie-ins (steel) (2 towers per day)		XXX Steve, Chris, Mark W,	XXX	XXX	XXX	XXX	XXX	XXX		Yes	
Weld out CHW pump headers 'J' mezz. (18)		XXX Lake	XXX	XXX	XXX	XXX	XXX	XXX		Yes	
Weld out cooling towers		XXX Jeff	XXX	XXX	XXX	XXX	XXX	XXX		No	eye injury, lost 2 days welding time
FR.P tie-in to E.T. (9 towers) 50%		XXX Pal, Jacky, Tom	XXX	XXX	XXX	XXX	XXX	XXX		Yes	
WORKABLE BACKLOG Boiler blowdown– basements–rupture disks											

back to the lookahead process to seek improvements in our control system.

Some failures may result from the last planner not understanding the language and procedures of making commitments or from poor judgment in assessment of capacity or risk. In these cases, the individual planner is the focus of improvement. Plan failures may also result from more fundamental problems – in management philosophy, policy, conflicting signals, etc.

Whatever the cause, continued monitoring of reasons for plan failure will measure the effectiveness of remedial actions. If action has been taken to eradicate the root causes of materials-related failures, yet materials continue to be identified as the reason for failing to complete assignments on Weekly Work Plans, then different action is required.

Illustration 2: work structuring through pull scheduling

Work Structuring is a term developed by the Lean Construction Institute (Ballard, 1999a) to indicate process design. The last products of work structuring are schedules. Pull techniques and team planning are used to develop schedules for each phase of work, from design through handover (Ballard, 2000a). The phase schedules thus produced are based on targets and milestones from the master project schedule and are the source of scheduled activities that enter the project's lookahead window.

A Pull technique is based on working from a target completion date backwards, which causes tasks to be defined and sequenced so that their completion releases work. A rule of

'pulling' is only to do work that releases work to someone else. Following that rule eliminates the waste of overproduction, one of Ohno's seven types of waste (Ohno, 1988; also Shingo, 1992). Working backwards from a target completion date eliminates work that has customarily been done but does not add value.

Team planning involves representatives of all organizations that do work within the phase. Typically, team members write on sheets of paper brief descriptions of tasks they must perform in order to release work to others or tasks that must be completed by others to release work to them. They tape or stick those sheets on a wall in their expected sequence of performance. Planning usually breaks out in the room as people begin developing new methods and negotiating sequence and batch size when they see the results of their activities on others.

The first step of formalizing the planning and the phase schedule is to develop a logic network by moving and adjusting the sheets. The next step is to determine durations and see if there is any time left between the calculated start date and the possible start date. It is critical that durations not be padded to allow for variability in performing the work. We first want to produce an 'ideal' schedule.

It is standard practice to try to build as much float as possible into the duration of tasks for which you are responsible. This results from lacking a mechanism for coordination. The Last Planner system will eventually create confidence both that interests will be protected and that work flow will be managed. Consequently, designer and builder specialists can provide unpadded durations for their assigned tasks, confident that uncertainties will be buffered and that unfair burdens will be rectified.

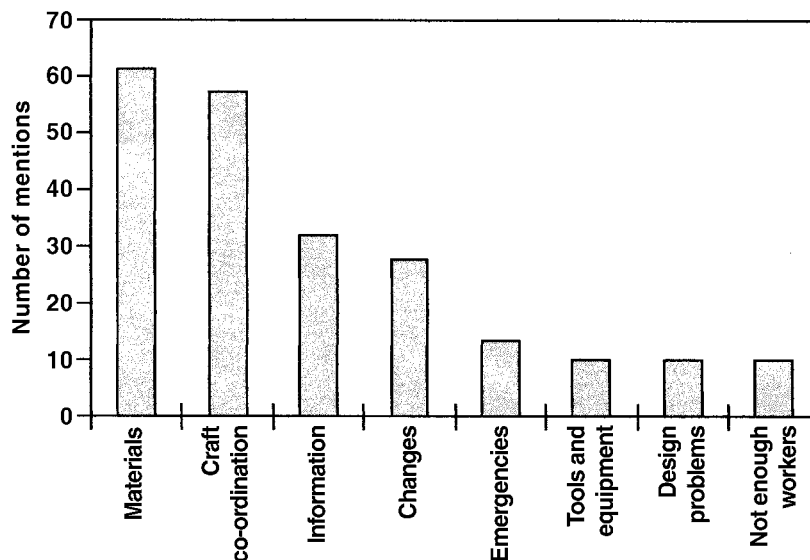


Figure 6 Reasons for plan failure

The team is next invited to re-examine the schedule for logic and intensity (application of resources and methods) in order to generate a bigger gap and more float. Then they decide how to spend that time:

- Assign to the most uncertain and potentially variable task durations
- Delay start in order to invest more time in prior work or to allow the latest information to emerge or
- Accelerate the phase completion date

If the gap cannot be made sufficiently positive to absorb variability, the phase completion date must slip out, and attention turns to making up that time in later phases. The key point is deliberately and publicly to generate, quantify and allocate schedule contingency.

Once the team has agreed on the phase schedule, the schedule and the activities represented on it can only be changed under three conditions:

- Prime contract changes
- Activities on the schedule cannot be performed without violation of Last Planner rules (allow scheduled tasks to advance in the lookahead window only if you are confident they can be made ready when scheduled. Allow assignments into weekly work plans only if you are confident they will be completed as scheduled) or
- Someone comes up with a better idea and all team members can be persuaded to agree

This may involve a transfer of money or at least promises of future money transfers across organizational boundaries as changes in the phase schedule will not likely benefit all parties equally.

Purpose/participants/process

The purpose of Pull scheduling is to produce a plan for completing a phase of work that maximizes value generation and one that everyone involved understands and supports; to produce a plan from which scheduled activities are drawn into the lookahead process to be exploded into operational detail and made ready for assignment in weekly work plans.

Representatives of those with work to do in the phase participate in the production of phase schedules. For example, a team working to schedule a construction phase typically involves the general contractor and subcontractors, and perhaps stakeholders such as designers, client and regulatory agencies. Participants should bring relevant schedules and drawings including the master schedule and perhaps even the contract. The process involves the following steps:

- Define the work to be included in the phase, e.g. foundations, building skin, etc., and the phase deliverables
- Determine the completion date for the phase plus any major interim releases from prior phases or to subsequent phases
- Using team scheduling and stickies on a wall, develop the network of activities required to complete the phase, working backwards from the completion date, and incorporating any interim milestones
- Apply durations to each activity, with no contingency or float in the duration estimates
- Re-examine logic, resource intensities and work methods to try to shorten the duration
- Determine the earliest practical start date for the phase
- If there is time left over after comparing the time between start and completion with the duration of the activities on the wall, decide what activities to buffer or pad with additional time:
- Which activity durations are most fragile?
- Rank order the fragile activities by degree of uncertainty
- Allocate available time to the fragile activities in rank order

Illustration 3: negative versus positive iteration in design

Assuming that design is by its nature an iterative and generative process (Ballard, 1998), how should we understand waste in design? Waste reduction has been characterized by Koskela (2000) in terms of minimizing what is unnecessary for task completion and value generation. Consequently, that iteration is wasteful, which can be eliminated without loss of value or causing failure to complete the project. Precisely what iteration can be thus eliminated is a matter for empirical research. Informal surveys of design teams have revealed estimates as high as 50% of design time spent on needless (negative) iteration. An additional research goal is to learn how to identify negative iteration before suffering its consequences.

There are certainly other types of waste in design than negative iteration. One example is design errors. Reinertsen (1997, p. 78) characterizes design outputs as defective when they fail because something previously known was forgotten or neglected. By contrast, design outputs can be failures but not errors if they fail because of lack of knowledge not previously possessed.

Beam penetration case

Lottaz *et al.* (1999) tell a story illustrating negative (needless) iteration. Holes for a refrigeration conduit were required in a

beam (Figure 7). Primary dimensions were: d (the diameter of a hole), e (the distance between holes), x (the distance from the first hole to the column) and h (the depth of the beam).

The architect first specified values for the four dimensions then sent an annotated drawing to the steel fabricator, who changed the values for e and x and sent it on to the engineer. The engineer reduced the diameter of the hole (d) and sent the document back to the architect. Perhaps in a fit of pique, the architect reduced the value of x from 1100 to 1000 mm and finally involved the HVAC subcontractor, who made further changes and the cycle of changes and transmissions continued. The erection contractor was running out of time, so the contractor fixed values for the dimensions and had the beam fabricated. Unfortunately, he was then unable to persuade the team to accept his solution. The result was considerable time and money lost on the project.

There are many contributors to the negative iteration in the beam penetration case. We might first question the sequence of design tasks. Was the architect the best person to establish initial values, then the fabricator, then the engineer, etc? The Design Structure Matrix (DSM) is a device for eliminating or reducing iterative loops by resequencing design tasks (Austin *et al.*, 1998). DSM is appropriate when a specific design direction has been established or for the exploration of alternative design sequences. Once iterative loops have been minimized, we propose that selection be made from among the strategies presented below in order to manage each of those loops.

Table 4 Techniques for reducing negative iteration

Design structure matrix
Team problem-solving
Cross-functional teams
Shared range of acceptable solutions (values)
Share incomplete information
Reduced batch sizes
Team pull scheduling
Concurrent design
Deferred commitment
Least commitment
Set-based versus point-based design
Overdesign

Another major contributor to negative iteration in the Lottaz *et al.* case is sequential processing, which not only adds to the time expended on the problem, but also actively hinders resolution. The architect (or anyone else) could have called a meeting to decide as a group on the values for the relevant dimensions. If the various contributors to the decision had been together in one place, at minimum there could have been an acceleration of the iterative looping. At best, there could have been genuine team problem-solving. Using cross-functional teams and team problem-solving to produce design is a staple of contemporary product development processes.

Many other concepts and techniques of advanced design management are relevant to the reduction of negative iteration. Suppose the participants had been willing to *share the*

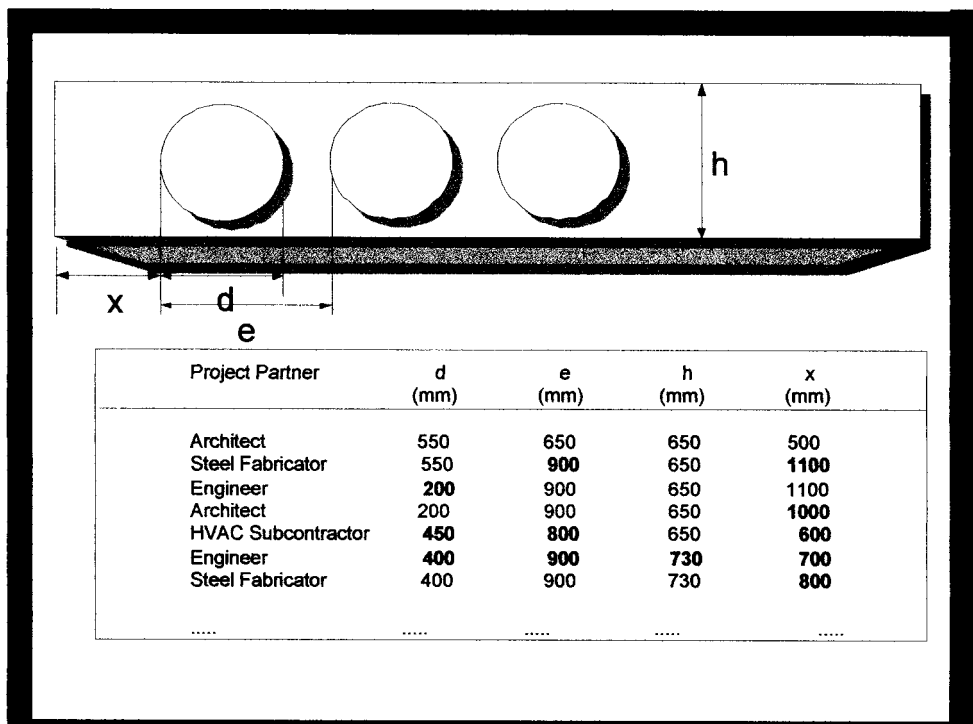


Figure 7 Beam penetration case. Source: Lottaz *et al.* (1999)

range of values acceptable to each. In that case, it would have been a simple matter to determine first if the problem as stated was solvable, i.e. if there were values for each dimension acceptable to all. They might have been unwilling to share that knowledge even if they were brought together face-to-face in hopes that the final solution better favoured themselves as opposed to others. Indeed, it appears to this author to be a routine of current design practice that supposedly collaborating specialists effectively compete for the priority of the values or criteria associated with their specialties (Ballard, 1999b). Willingness to share incomplete information has long been identified as a necessity for concurrency in design (Clark and Fujimoto, 1991). This can perhaps be best understood in terms of the lean production practice of *reducing batch sizes*, which belongs with DSM as a technique for restructuring the design process. Sequential processing results in part from the implicit rule that only completed design work is advanced to others. In terms of the beam penetration case, suppose the design team members agreed up front on work sequence, which would start by Team Member A providing just that information needed for Team Member B to perform his calculation. B would in turn release that information to C, allowing C to do work, etc.

Deferred commitment is a strategy for avoiding premature decisions and for generating greater value in design. It can reduce negative iteration by simply not initiating the iterative loop. A related but more extreme strategy is that of *least commitment*, i.e. to defer decisions systematically until the point at which failing to make the decision eliminates an alternative. Knowledge of the lead times required for realizing design alternatives is necessary in order to determine last responsible moments. Such knowledge now tends to be partial or lacking.

When task sequence cannot be structured to avoid iterative looping, and when it is necessary to make a decision quickly, and when team problem-solving is not feasible as a means of accelerating iteration, *design redundancy* may be the best strategy. An example: structural loads are not known precisely, but an interval estimate can be reliably produced. In that case, it might be decided to design for maximum load rather than to wait for more precise quantification.

Posing alternative design solutions as sets rather than as point solutions is the strategy at the heart of the method of Set-Based Design (SBD). The beam penetration case is described by Lottaz *et al.* (1999) in order to present a technique and software for specifying ranges of values for continuous variables and modelling the solution space resulting from the intersection of alternative ranges. This approach has two roots, one theoretical and one from practice. The Lottaz *et al.* paper emerged from the domain of artificial intelligence and the attempt to develop concepts and techniques for solving problems involving multiple constraints, exploration of which is beyond the scope of this paper. The other root is Toyota's method of managing product development processes (Sobek and Ward, 1996; Sobek *et al.*, 1999; Ward *et al.*, 1995).

Illustration 4: application of lean rules and tools to precast concrete fabrication

Application of the Last Planner system of production control on projects has been demonstrated to increase plan reliability (Ballard, 2000), which is measured by PPC: the percentage of weekly or daily releases of work from 'supplier' to 'customer' compared with what was planned. How far in advance releases (work flow) can be accurately predicted from plans establishes a window of reliability within which the supplier's production can function effectively. With regard to engineered-to-order products such as precast concrete, it is important that lead times, the advance notice of need for delivery provided by a construction site, fall within that window of reliability. For example, suppose a construction site achieves 80% PPC looking 1 week ahead, but the precast supplier's lead time is 2 weeks. PPC 2 weeks in advance might only be 60%, assuring that perhaps 40% of requested precast elements will not be able to be installed, thus building up unneeded inventory at site. If lead times do not fall within the window of reliability of the 'customer' process, then pulling materials from suppliers will inevitably build up unneeded inventory. On the other hand, if Pull mechanisms can be used effectively, site inventories can be reduced and the production system's robustness vastly increased. A shorter lead time increases system robustness because it allows less wasteful and more rapid recovery from upsets. In other words, if something goes wrong, it can be fixed quickly with minimal disruption to factory operations and to other orders.

In February 2001 experiments were performed in two production cells at Malling Precast Products Ltd,⁵ Shear Walls and Nap T's, to demonstrate the feasibility and benefits of lean production concepts, including one piece flow and pull, with the objective of improving throughput or production rate (which amounts to an improvement in productivity if resources are not increased) and of reducing manufacturing lead time (Ballard *et al.*, 2002a,b) Production had previously been organized around functional departments: supply, welding, reinforcement steel cutting and bending, concrete, etc. Schedules were used to 'push' work through the various process steps required to manufacture and deliver a precast element. In deterministic systems with no variation in duration, quality or sequence, scheduling can be effective. However, no production system is without variation. Consequently, Push mechanisms tend to build up inventories between process steps as synchronization fails. Work-in-progress inventories were very evident at Malling before its lean transformation.

A process flow chart⁶ for the Shear Walls production cell (Figure 8) reveals the new flow-oriented design of that production system, which then served as a model for other cells. Redesign began by structuring for that output rate demanded by the client project, which needed to have nine shear walls delivered each day for an extended period. Three two-person teams placed rebar mats in moulds. Steelfixers (reinforcing ironworkers) kept three mats tied and ready for placement. When a mat was taken, they tied another. This pull mechanism (for more on pull; Hopp and Spearman, 2000) prevented

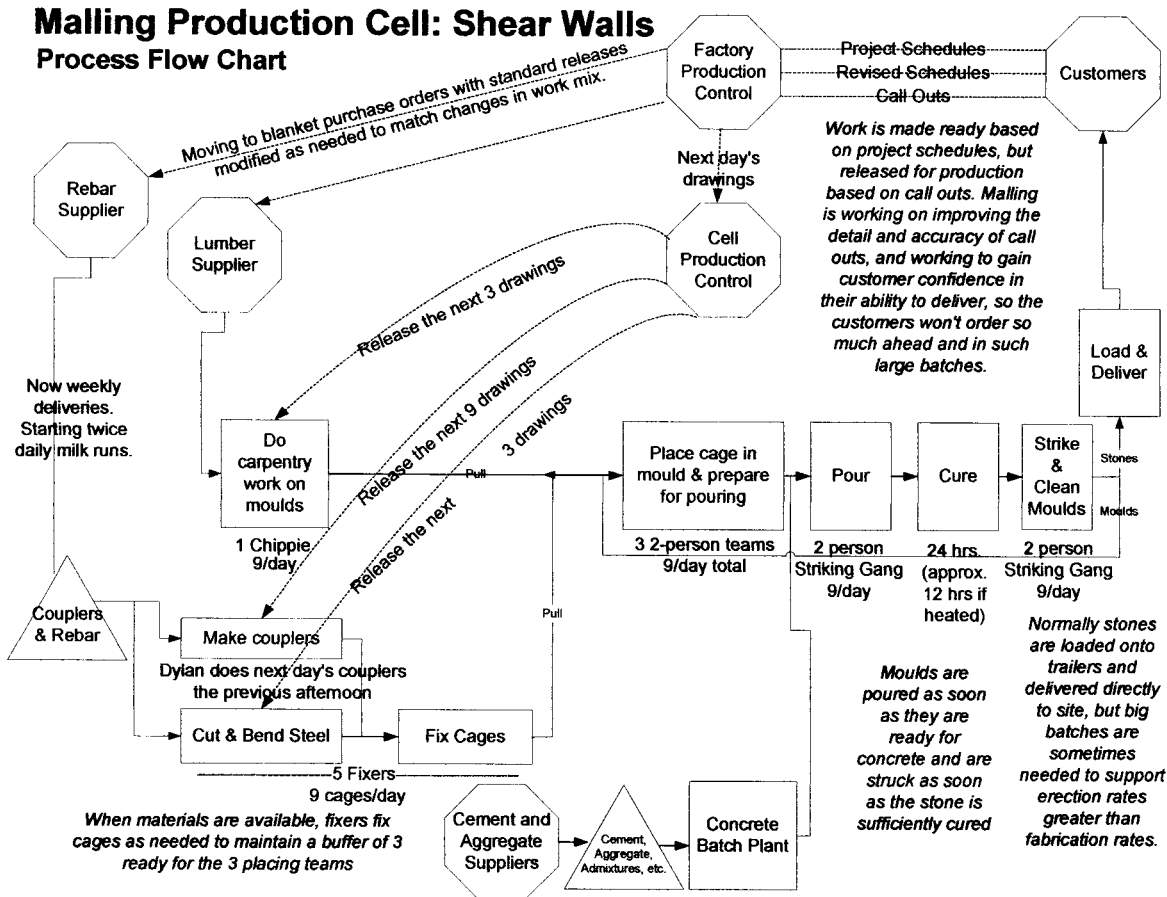


Figure 8 Shear walls production cell

build up of work-in-progress inventory, keeping cycle times low and increasing cell robustness and flexibility. Once ready for concrete, moulds were filled immediately, as opposed to the previous practice of batching pours late in the day. The new system produced three shear walls in every 3 hours because three individual walls proceeded through each of the process steps in each of those 3-hour periods. Further, work flow was controlled locally by the workers in the cell, each of whom learned to 'see' how the entire system was performing.

- Lead times were reduced for structural precast elements to 1 week (call offs 1 calendar week ahead of needed delivery), corresponding to a reduction in manufacturing cycle time⁷ to 1–1/3 days
- The Shear Wall production cell had previously averaged 3.2 walls per day, with 12 workers. After application of lean 'rules and tools' to restructure work flow, 12 workers produced nine walls per day, an increase in the productivity rate of 181%
- The T's production cell was restructured in a very similar way, resulting in an improvement from a baseline of nine T/s per day to 18 T's per day, an increase in the productivity rate of 100%

- One-piece flow and Pull concepts were rapidly extended to other production cells. In consequence, factory throughput as measured by revenue (Figure 9) changed from an average weekly rate of £130 000 before February 2001 to approximately £260 000 afterwards, with an increase in the workforce from 115 to 122. Reports from the second quarter of 2002 indicate that revenue has stabilized at approximately £300 000 per week
- A number of actions and changes signalled a shift in management philosophy toward employee involvement and empowerment; specifically: (1) formation of a Quality of Work Life Council and immediate action on its first recommendations, (2) involvement of factory personnel in design and implementation of process improvements and (3) making direct workers responsible for controlling work flow within their production cells
- Production system robustness was increased in direct consequence of reducing cycle time.⁸

Conclusion

It is now hopefully apparent how the lean project management system differs from non-lean project management. The illustra-

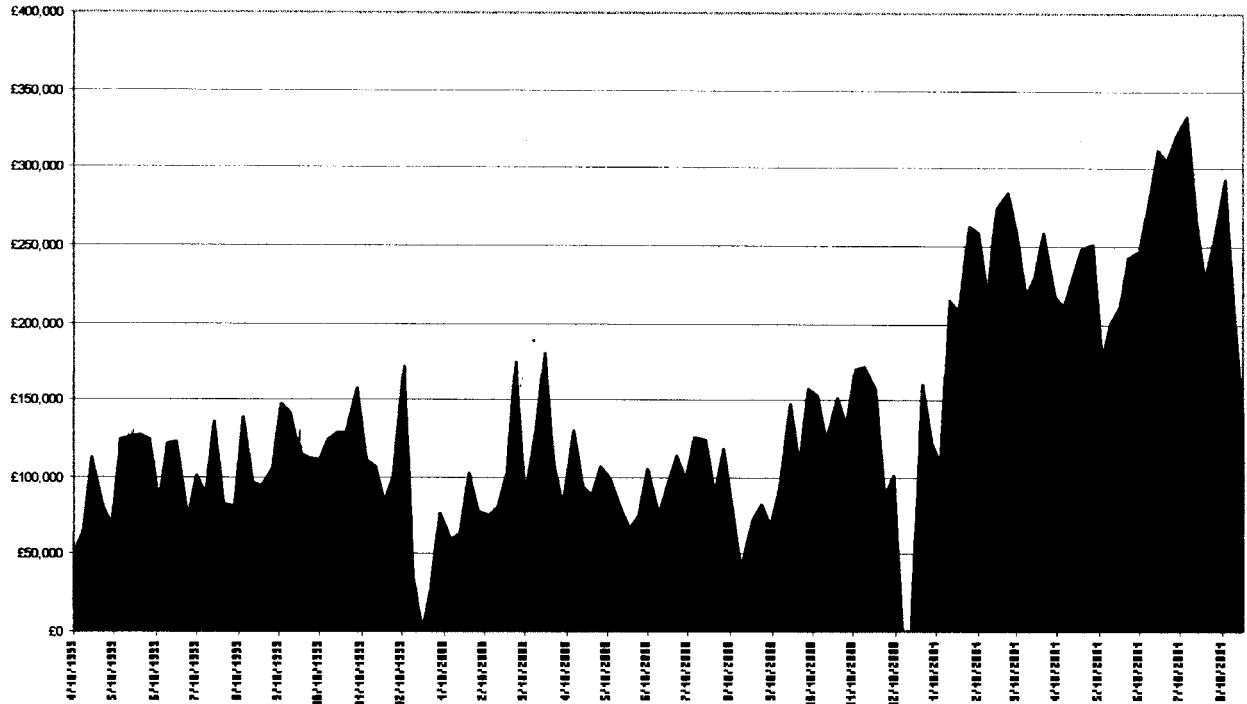


Figure 9 Change in mailing revenue for 17 April 1999 to 26 August 2001

tions and reports of implementation suggest that the LPDS is also a superior management system. Even partial implementations have yielded substantial improvements in the value generated for clients, users and producers, and also a reduction in waste, including waiting time for resources, process cycle times, inventories, defects and errors, and accidents.⁹

The LPDS is far from a completed work. Much remains to be done in the development of lean principles and techniques for the design, operation and improvement of project-based production systems. Further, implementation issues have only begun to be examined systematically. Structuring organizations for value generation and waste reduction offer many challenges for future research and practice.

The Toyota Production System was fundamentally a conceptual innovation, a new way of thinking about production and production management. Applying that new way of thinking to project management appears to offer opportunity for performance improvement comparable with those achieved with the change from mass to lean forms of manufacturing. Researchers and practitioners are invited to join the Lean community and its efforts to improve construction industry performance.

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Endnotes

¹The expression 'Lean Project Delivery System' has been previously used (Best and De Valence, Ch. 15) to name the lean project management approach, with the intention of denoting how a product is produced and delivered, from customer order to handover. No connection is suggested to a particular contractual structure or method of procurement such as design–construct or design–bid–build. While some contractual structures facilitate specific aspects of lean project management, none guarantee them, and many lean techniques can be applied in all delivery systems.

²Some have interpreted lean construction as an imitation of manufacturing, an error that might have been avoided if a different name had been chosen.

³Note the difference between 'inventory' as an accounting concept and as a production concept. In accounting, inventory is an asset to be increased. In production, inventory is waste to be reduced to a minimum.

⁴Six weeks is typical, but lookahead windows may be shorter or longer, depending on the rapidity of the project and the lead times for information, materials and services. On the one hand, since long lead items are items that cannot be pulled to a project within the lookahead window, extending that window offers the possibility of greater control over work flow. On the other hand, attempting to pull too far in advance can run foul of one's ability to control work flow on site. Consequently, sizing of the lookahead window is a matter of local conditions and judgment.

⁵Malling is a subsidiary of the O'Rourke Group, located in Grays, Essex, UK.

⁶The flow chart is modelled after Toyota's materials and information flow diagrams. For details, see Rother and Shook (1998), who use the term 'value stream maps'.

⁷Manufacturing cycle time is the time it takes for a product to be transformed from raw material to finished product. In this case, the starting point is release of an element to the factory for production. Lead time is that amount of time in advance of delivery that 'orders' must be sent to the supplier.

⁸A production system is said to be more robust if it can function effectively under a wider range of conditions and is less vulnerable to upset or disruption (Taguchi *et al.*, 2000).

⁹See LCI's Congress papers [[at www.leanconstruction.org](http://www.leanconstruction.org)] for reports by industry practitioners of lean implementations.