15

Lean construction tools and techniques

Glenn Ballard*, Iris Tommelein†, Lauri Koskela‡ and Greg Howell*

15.1 Introduction

Various tools and techniques have been developed to implement the Lean Project Delivery System (LPDS[1]) described in the preceding chapter. No list will be accurate for long, as innovation is very much underway and new tools and techniques emerge all the time.

15.2 Lean production management

Production management is at the heart of lean construction and runs from the very beginning of a project to handover of a facility to the client. Lean production management consists of Work Structuring and Production Control.

15.2.1 Lean work structuring

Lean work structuring is process design integrated with product design and extends in scope from an entire production system down to the operations performed on materials and information within that system. Lean work structuring differs from work breakdown structure (a technique of traditional, non-lean project management) in the functions it performs and the questions it answers, which include (also see Ballard, 1999):

- in what chunks will work be assigned to specialists?[2]
- how will work chunks be sequenced?
- when will different chunks of work be done?

* Lean Construction Institute
† University of California, Berkeley
‡ VTT Building and Transport, Finland

- how will work be released from one production unit to the next?
- will consecutive production units execute work in a continuous flow process or will their work be de-coupled?
- where will de-coupling buffers be needed and how should they be sized?
- how will tolerances be managed?

Lean work structuring produces a range of outputs including:

- project execution strategies
- project organizational structures, including configuration of supply chains
- operations designs (Howell and Ballard, 1999)
- master schedules
- phase schedules.

Collectively, these amount to a design of the 'temporary' production system (Figure 15.1, a partial ends–means hierarchy) and its links with the 'permanent' production systems

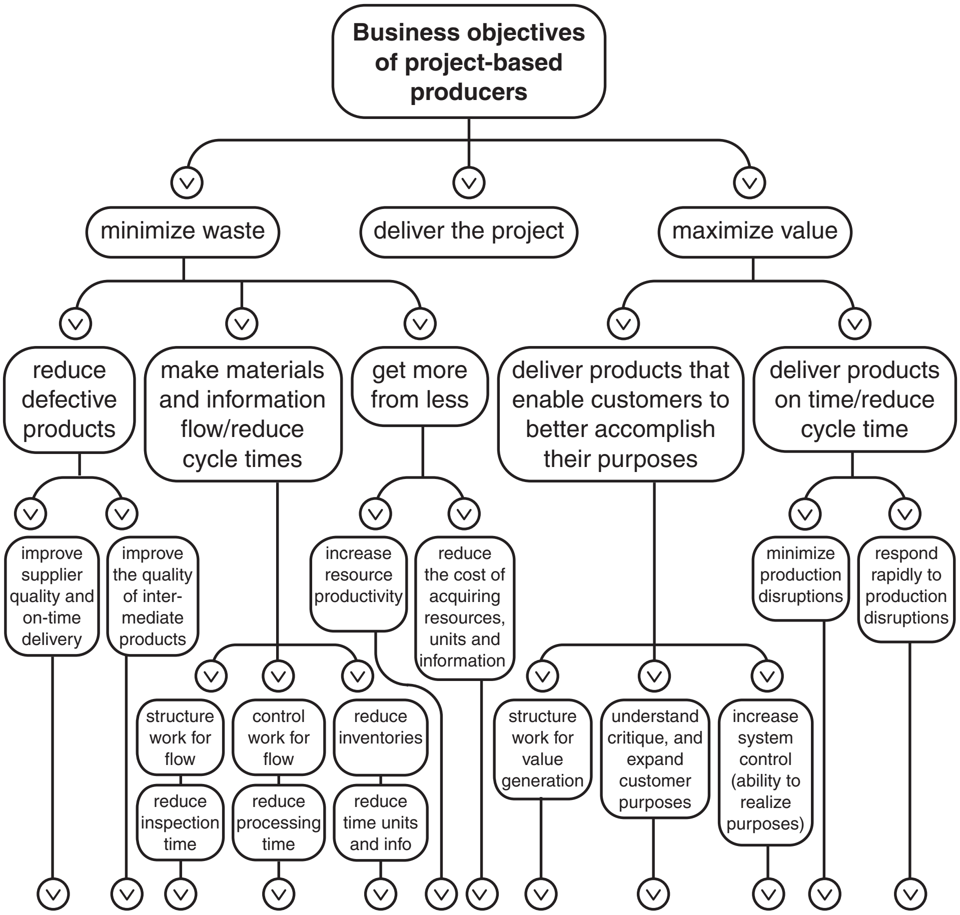

Figure 15.1 Production system design (Ballard et al., 2001).

that exist independently of the project. Production system design is said to be 'lean' when it is done in pursuit of the transformation/flow/value (TFV) goals.

15.2.2 Schedules

Schedules are those outputs of work structuring that link directly with production control. Schedules and budgets specify *should*, while production control translates *should* into *can*, by making scheduled activities ready for assignment, and eliciting a specific commitment to what *will* be done during the next week (or other near-term plan period). The lean construction principles applicable to schedules are:

- limit master schedules to phase milestones, special milestones, and long lead items
- produce phase schedules with the team that will do the work, using a backward pass, making float explicit, and deciding as a group how to use float to buffer uncertain activities.

Contrary to traditional construction management wisdom, detailed schedules produced at the beginning of a project do not assure project control. With few exceptions, the only thing known for certain at that time is that the project will *not* be executed in accordance with that schedule. What is needed, instead, is a hierarchical planning system that progressively develops detail as time for action approaches. Project control is to be achieved by continuously making adjustments in steering as we move through time, rather than by developing a network of detailed orders in advance, then monitoring and enforcing conformance to those (often unrealistic) orders.

The appropriate functions of master schedules are to:

- give us confidence that an end date and milestone dates are feasible
- develop and display execution strategies
- identify and schedule long lead items (defined as anything that cannot be 'pulled' to the project within the lookahead window)
- divide the project into phases, identifying any special milestones of importance to the client or other stakeholders.

Phase schedules, sometimes called 'pull schedules' in the lean construction community, are produced by those who will do the work in that phase, beginning with a backward pass from a target milestone. The best way yet discovered for producing phase schedules is to have a team of different specialists write down their tasks on cards and stick them to a wall, thus creating a logic network, which can be revisited by the team until sufficient float is generated to buffer uncertain activities (Ballard, 2000a). Phase scheduling through this collaborative approach assures the selection of value adding tasks that release other work.

15.2.3 Last Planner[1] system of production control

Planning is followed by control, i.e., by management processes governing execution so that project objectives are best achieved. The Last Planner refers to that individual or group that commits to near-term (often weekly) tasks, usually the front line supervisor,

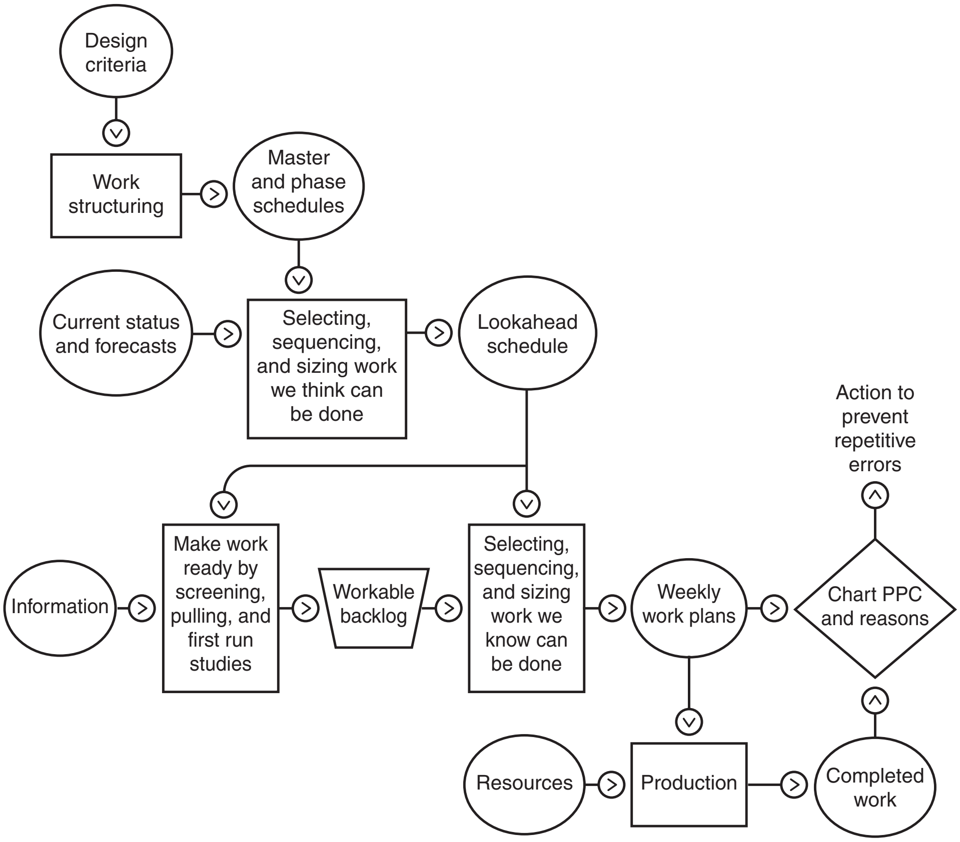

Figure 15.2 Last Planner System of production control.

such as a construction foreman, a shop foreman, or a design team boss. The Last Planner system of production control (Figure 15.2; Ballard and Howell, 1998; Ballard, 2000b) has three components:

- lookahead planning
- commitment planning
- learning

The primary rules or principles for production control are:

- drop activities from the phase 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 – require that defective assignments be rejected
- 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 to:

- 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).

Tools and techniques include constraints analysis, the activity definition model, and first run studies (first run studies are described in section 15.5 on Lean assembly).

Constraints analysis is done by examining each activity that is scheduled to start within the next 6 weeks or so. Six 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 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 affect one's ability to control work flow on site. Consequently, sizing of the lookahead window is a matter of local conditions and judgment.

The rule governing constraints analysis (Table 15.1) is that no activity is to be 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 identified earlier and that problems that cannot be resolved in the lookahead scheduling 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 15.3) 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

Table 15.1 Illustration of Constraints Analysis

Project: Mega Building
Report date: 3 Nov

			Constraints				
Activity	**Responsible party**	**Scheduled duration**	**Directives**	**Prerequisites**	**Resources**	**Comments**	Ready?
Design slab	Structural engineer	15 Nov to 27 Nov	Code 98 Finish? Levelness?	Soils report	10 hours labour, 1 hour plotter		No
Get information from client re floor finish and level	*Structural engineer's gofer*	*3 Nov to 9 Nov*	OK	OK	OK		Yes
Get soils report from Civil	*Structural engineer*	*By 9 Nov*	OK	OK	OK		Yes
Layout for tool install	Mechanical engineer	15 Nov to 27 Nov	OK	Tool Configurations from mfger	OK	May need to coordinate with HVAC	No

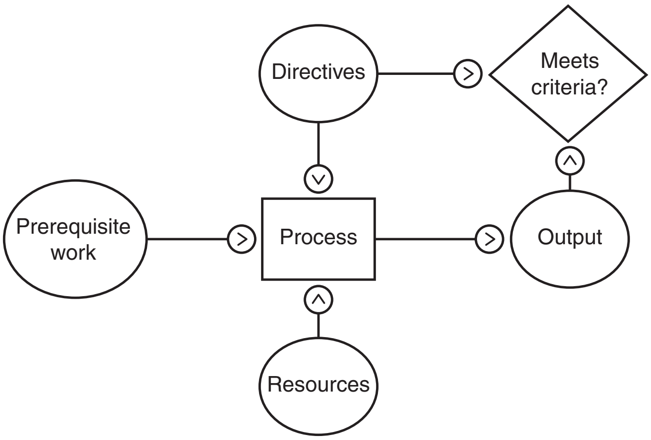

Figure 15.3 Activity Definition Model (ADM).

which work is added. Examples include materials, whether ‘raw’ or work-in-process, and information that is input to a calculation or decision. 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.

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
- 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 production units to doing work in order to shield these units 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 15.4). Root causes for plan failure are then identified and attacked, so that future problems may be avoided.

Increasing PPC leads to increased performance, not only of the production unit that executes the Weekly Work Plan (Table 15.2), but also of production units downstream as they can better plan 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. Implementation of the Last Planner therefore results in more reliable flow and higher throughput of the production system.

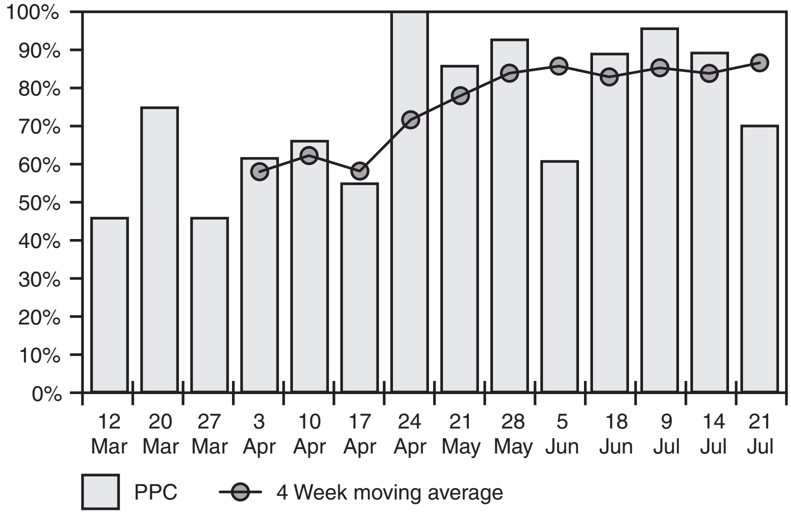

Figure 15.4 PPC chart – electrical contractor (1995 project in Venezuela).

Learning (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 15.5). 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 back to the lookahead process to seek improvements in our planning system. Some failures may result from the last planner not understanding the language and procedures of making commitments or from poor judgement 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 – such as those to do with management philosophy, policy, or conflicting signals.

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.

15.2.4 Benefits of lean production management

Lean production management is dedicated to reducing and managing variability and uncertainty in the execution of project plans. A starting point is the recognition that much uncertainty on construction projects is a consequence of the way projects are managed, rather than stemming from uncontrollable external sources. Making assignments ready by removing constraints within the lookahead process eliminates potential variability. Shielding production from work flow variability is often the place to start in implementation of the entire LPDS. Work structuring addresses the problem of managing

Table 15.2 Construction Weekly Work Plan

Project: Pilot **ACTIVITY**	**1 Week plan**										**FOREMAN: Phillip** **DATE: 20/9/96**
	Est	**Act**	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**	**Sat**	**Sun**	**PPC**	**Reason for variances**
Gas/F.O. hangers 0/14 'K' (48 hangers)			xxx	xxx Sylvano, Mario, Terry						No	Owner stopped work (changing elevations)
Gas/F.O. hangers 0/14 '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			xxx Charlie, Rick, Ben	xxx	xxx					Yes	
Chiller risers (2 chillers per week)						xxx Charlie, Rick, Ben	xxx	xxx		No	
Hang H/W O/H 'J' (240'-14")			xxx Mark M, Mike	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		Yes	
Weld out CHW pump headers 'J' mezz. (18)			xxx Luke	xxx	xxx	xxx	xxx	xxx		Yes	
Weld out cooling towers			xxx Jeff	xxx	xxx	xxx	xxx	xxx		No	Eye injury. Lost 2 days welding time
F.R.P. tie-in to E.T. (9 towers) 50%			xxx Pat, Jacky, Tom	xxx	xxx	xxx	xxx	xxx		Yes	
WORKABLE BACKLOG Boiler blowdown–bas vents–rupture disks											

remaining variability through thoughtful location and sizing of inventory and capacity buffers. Production management in its entirety assures as far as possible that each 'workstation' (specialist production unit) does work in the right sequence and rate for reliable release to its 'customer'.

Implementation of lean production management has been shown to substantially improve productivity. Figure 15.6 shows the change in PPC on a Chilean project after implementation of the Last Planner system. Figure 15.7 shows that project productivity improved by 86% in consequence of this improvement in work flow reliability.

This impact of PPC on productivity can be explained by reference to Figure 15.8, which is a somewhat peculiar presentation of the time/cost trade-off. From queuing theory, we know that the wait time of a work item accelerates as a processor approaches 100% utilization, assuming some variability in the system; the greater the variability, the steeper the acceleration. In traditional project management, it is assumed that variability is independent of management action and consequently that the trade-off between time and

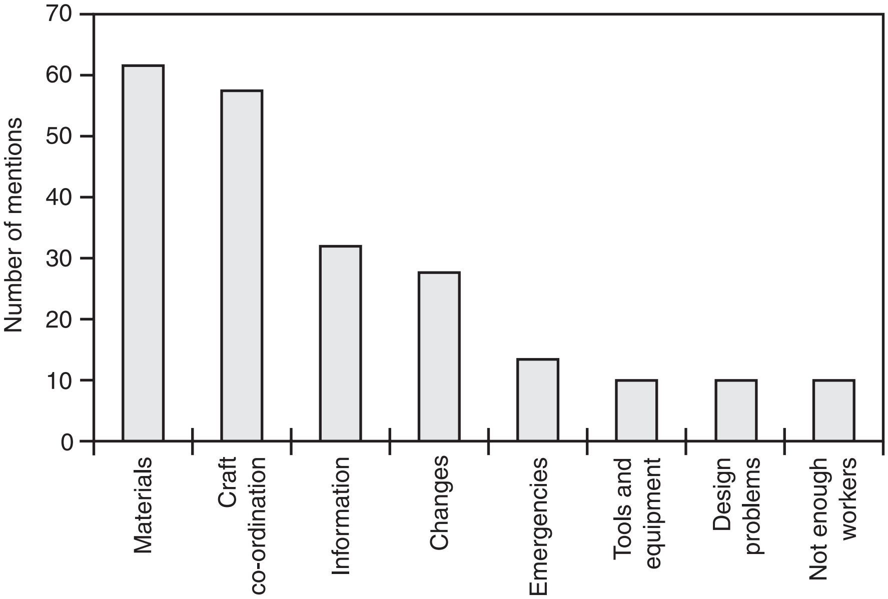

Figure 15.5 Reasons for plan failure.

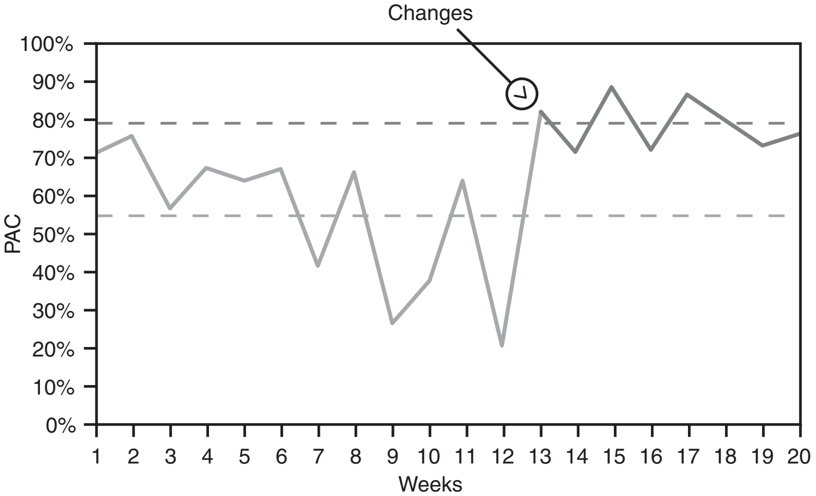

Figure 15.6 PPC improvement with Last Planner implementation (project in Chile, 1998).

cost is fixed, the only discretion for decision making is in finding the exact point where the trade-off can best be made.

The facts are quite otherwise. As demonstrated by applications of lean production management, variability in a production system (e.g., a project) can be reduced through management intervention, thereby changing the trade-off to be made between time and cost. In terms of Figure 15.8, a PPC of 50% might correspond to a utilization rate of 50%. To maintain the same pace of completion, increasing PPC to 70% might allow an increase

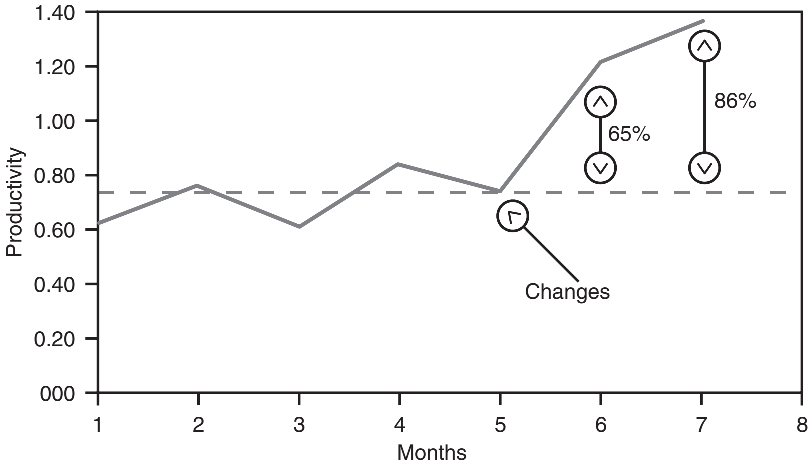

Figure 15.7 Productivity improvement with rising PPC.

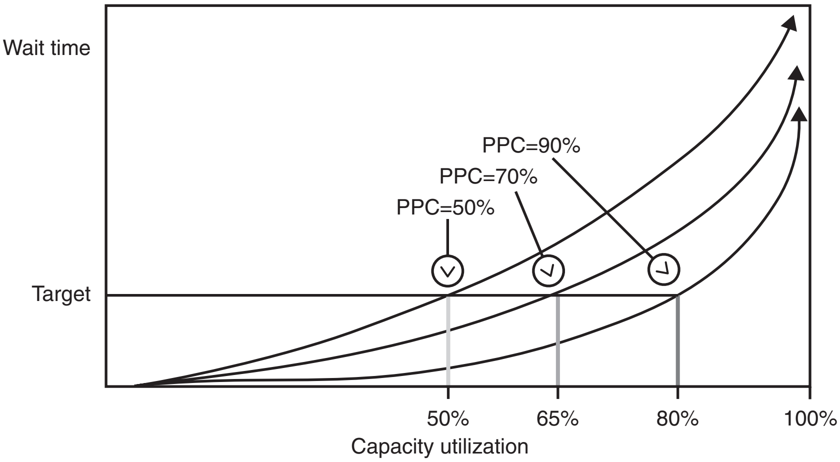

Figure 15.8 Improving the trade-off between time and cost by reducing work flow variability.

in capacity utilization to 65%, which amounts to productivity improvement of 30%. Alternatively, the pace of completion could be increased without increasing labour cost. Numerous instances of 30% or more improvement in productivity have been recorded in tandem with increases in PPC from roughly 50% to 70%.

15.2.5 Summary

Lean production management begins with work structuring and ends with production control, but these are related like the sides of a spinning coin. The coin keeps spinning throughout a project, so that production control takes on the job of executing schedules produced by work structuring, but work structuring has the job of buffering work flow against remaining variability, and continually adjusting plans as the future unfolds.

Structuring production systems, whether large or small, for the TFV goals increases value generation and reduces waste. Production control reduces variability in work flow and significantly elevates the level at which time/cost trade-offs are made. With less variability and uncertainty, inventory and capacity buffers can be reduced, further improving both time and cost performance. Even more important, project participants at every level become actively involved in the management of the project, achieving a transition from a centrally controlled, order-giving form of organization to a distributed control form of organization.

15.3 Lean design

Design is understood as encompassing not only product design, the traditional sphere of architects and engineers, but also process design. Product design determines what is to be produced and used, while process design determines how to produce it or use it. Process design includes structuring the project organization, deciding how to perform specific design and construction operations, deciding how to operate or maintain a facility, and deciding how to decommission and ‘un-assemble’ a facility. As previously discussed, design of both product and process are understood to be undertaken in pursuit of the TFV goals.

Designing can be likened to a good conversation, from which everyone leaves with a different and better understanding than anyone brought with them. How to promote that conversation (iteration), how to differentiate between positive (value generating) and negative (wasteful) iteration, and how to minimize negative iteration are all critical design management skills.

Some claim that purposes and design criteria can be defined prior to the design process, but iteration – a conversation – is necessary between purpose, concept and criteria. This necessitates exploration of alternative futures, which can often best be represented by sketches and models. Consequently, the project definition (Ballard and Zabelle, 2000a) triad of the LPDS (Figure 14.2) includes design concepts. The challenges of lean design (Ballard and Zabelle, 2000b) include:

- controlling project objectives of time and cost, and the goal of waste minimization without decreasing value
- generating, evaluating, and identifying alignment between purposes, concepts and criteria; the requirement for transitioning a project from project definition into design proper
- capturing and making accessible the design rationale of a facility, i.e., the decisions that were made, the alternatives that were considered, the criteria by which alternatives were evaluated and so on, throughout its life
- minimizing value loss as a project moves through its phases.

15.3.1 Practical methods

Figure 15.9 presents an overview of tools and techniques for lean design.

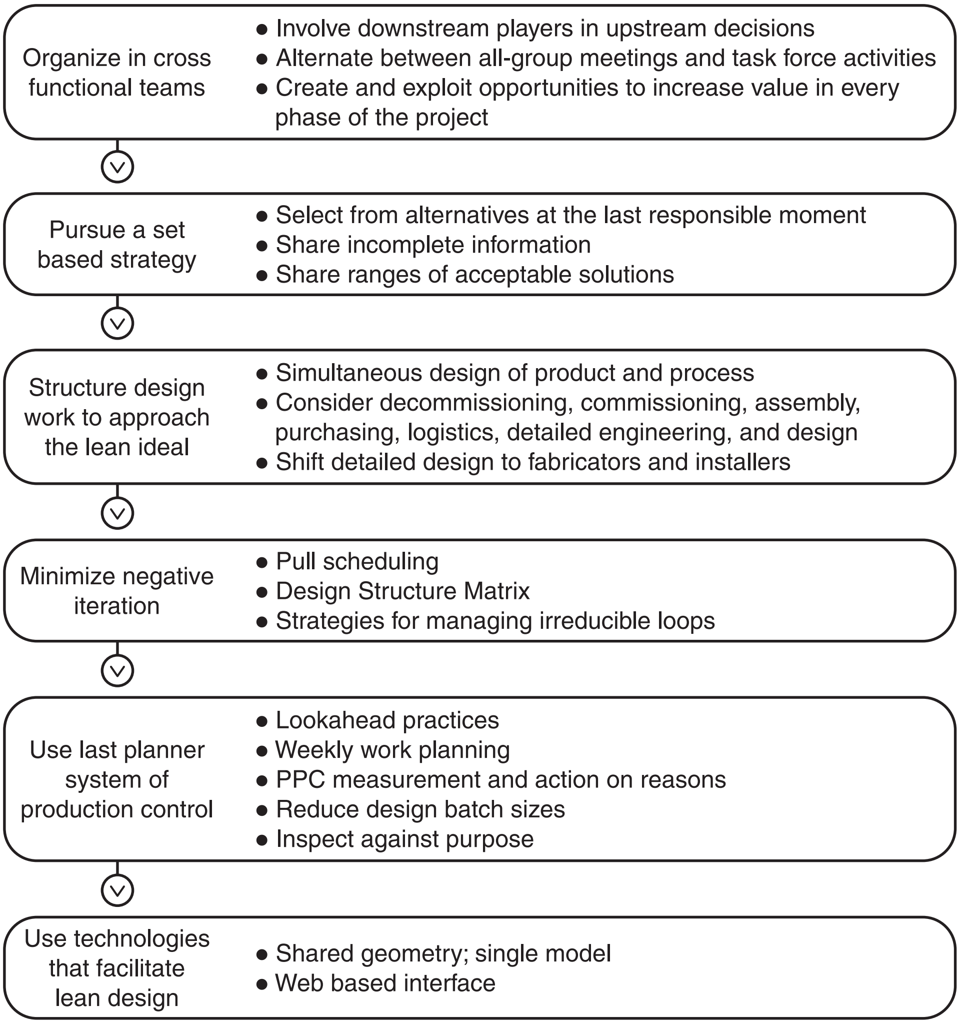

Figure 15.9 Overview of lean design (Ballard and Zabelle, 2000b).

Organize in cross-functional teams

Cross functional teams are the organizational unit for all phases of the LPDS. All stakeholders need to understand and participate in key decisions. It is not possible, however, for everyone to meet continuously and simultaneously; some division of labour is required. In general, the appropriate pattern to follow is alternation between bigger alignment meetings and work by individuals or by smaller teams on the tasks identified and agreed in those meetings.

Facility systems and sub-systems offer natural groupings for the formation of cross-functional teams. For example, a Foundation team might consist of the structural engineer, foundation contractor, key suppliers, etc. In addition, representatives from Superstructure, Mechanical/Electrical/Plumbing/Fire Protection, Interior Finishes, and other teams would participate.

In the design phase, the natural division is between product and process design, but the trick is to counteract the developed tradition of producing them separately and sequentially. Information technology can be helpful by making the state of both more visible, e.g., through shared, integrated models. Nevertheless, having representatives of each relevant specialty assigned to each team will always be essential.

Pursue a set-based design strategy

'Set-based engineering' has been used to describe Toyota's application of a least commitment strategy in its product development projects (Ward *et al*., 1995; Sobek *et al.,* 1999). That strategy could not be more at odds with current practice, which seeks to narrow alternatives to a single point solution rapidly, but at the risk of enormous rework and wasted effort. It is not far wrong to say that standard design practice currently requires each design discipline to start as soon as possible and co-ordinate only when collisions occur. This has become even more common with increasing time pressure on projects, which would be better handled by sharing incomplete information and working within understood sets of alternatives or values at each level of design decision making, e.g., design concepts, facility systems, facility sub-systems, components, and parts.

Toyota's product development process is structured and managed quite differently even compared to those of other Japanese automobile manufacturers. Toyota's product development develops multiple design alternatives, produces five or more times the number of physical prototypes than their competitors and puts new products on the market faster than their competitors and at less cost.

Toyota's superior performance is probably a result of reducing negative iteration, with that reduction being more than sufficient to offset time 'wasted' on unused alternatives. Negative iteration occurs as a result of each design discipline rushing to a point solution, then handing off that solution to downstream disciplines in a sequential processing mode.

Whether or not one has the time to carry alternatives forward, would seem to be a function of understanding when decisions must be made lest the opportunity to select a given alternative is lost. We need to know how long it takes to actually create or realize an alternative. If the variability of the delivery process is understood, safety-time can be added to that lead-time in order to determine the last responsible moment[4]. Choosing to carry forward multiple alternatives gives more time for analysis and thus can contribute to better design conditions.

Structure design work for value generation and flow

In the LPDS the intent is to structure work in pursuit of the lean ideals, i.e., to deliver what the customer needs, to deliver it instantly and to deliver it without waste. Such a work structure must anticipate every delivery phase, i.e., how the product is to be decommissioned at the end of its life, how it is to be altered to meet changing needs, how it is to be operated and maintained, how it is to be commissioned for operation and use, how the product is to be assembled, how the components are to be procured and fabricated, how the supply chains providing those components are to be configured, and how to structure commercial arrangements so that the relevant stakeholders and experts can be involved in making those decisions. All these 'process' considerations (and more) have to be determined in intimate conjunction with product design.

Integrating design of product and process means considering and deciding *how* to build and use something at the same time as we consider *what* to build. The challenge is to overcome the tradition of first designing the product, then throwing it over the wall to someone else to decide how or if it can be built, operated, altered, etc. Besides old habits, we have to overcome the centrifugal force of specialization and inadequate commercial models. Specialization is unavoidable, but we can do better at educating designers regarding process design criteria and at educating builders regarding product design criteria. As regards commercial models, even in projects executed under design–build forms of contract, it is now common to use design–bid–build with specialty contractors, which makes it impossible to involve them in the design process proper.

Minimize negative iteration

By definition, negative iteration does not add value. If conversation is the image for positive iteration, a bar-room brawl represents negative iteration. Several strategies have been identified for minimizing negative iteration. The first is the use of phase scheduling[5], plus re-organizing the design process as indicated below. Design naturally involves some irreducible loops, e.g., the mutual determination of structural and mechanical loads. Once identified, looped tasks are jointly assigned to the relevant teams of specialists. Those teams must then decide how to manage their interdependent tasks. General strategies that govern all design activities include use of the Last Planner system of production control and practicing set-based design. Specific strategies for managing iterative loops that have thus far been identified include:

- holding team meetings to accelerate iteration
- designing to the upper end of an interval estimate, e.g., design a structure so it will hold the maximum load that might be placed on it
- shifting early design decisions where they can best be made, perhaps outside the looped tasks
- sharing incomplete information.

Functional specialization, sequential processing and fear of liability drive designers and engineers to share work only when it is completed. Concurrent design requires just the opposite: frequent and open sharing of incomplete information so each player can make better judgements about what to do now. Information technology will go some way towards enabling such sharing, but the key obstacles will be old habits of thought and action. Education, frequent reminders, and ultimately successful experiences will be necessary in order to promote open sharing. Of course, it will remain necessary to properly qualify the status of information that is released. If you are considering a design concept, that is very different from releasing a model or sketch which is to be the basis of others' work. Until the new culture is developed, it seems prudent to attack that development within the optimum conditions provided by collocated teams dedicated to working together over multiple projects.

Design production control

In the LPDS, production control is applied in all phases, as soon as any type of plan is created. The Last Planner system of production control (Ballard, 2000b) is used throughout. Here we discuss only two techniques: reducing design batch sizes and a control technique that was developed in response to the demands of design processes, namely, evaluation against purpose.

All too often specialists transmit completed design information with little regard for the needs of other team members and downstream customers (Zabelle and Fischer, 1999). Design decisions and outputs are grouped (batched) in traditional ways that were developed when designing and building were not integrated, and when each discipline tended to practice throw-it-over-the-wall, sequential processing of project information. What is needed is to divide design outputs and communicate them more frequently to release other design work. Typically, this produces smaller batches and speeds up the design process. Since the set-up time[6] to review design information is short for engineers who are up-to-date with the status of a design, the penalty for batch size reductions is very small and does not negatively affect the design processing capacity of a team. Rather the opposite appears to be true: the set-up time and the work-in-process inventory become quite large if the batch size of design information is increased. In addition to dividing design decisions and outputs into smaller batches, it is also necessary for the various specialists to learn how to communicate incomplete information without misleading their co-workers. The mechanical engineer may be very happy to hear that heat loads may change, (s)he can decide to defer other decisions or perhaps arrange redundant capacity if there is no time for waiting. Currently, both tradition and fear of liability constrain the free flow of information among designers and engineers.

Project production can be abbreviated to the steps:

- determine customer (and other stakeholder) purposes and needs
- translate those purposes and needs into design criteria
- apply those criteria to the design of product and process
- purchase, fabricate, deliver and install materials and components in accordance with that design.

Value is maximized when needs are accurately determined and when those needs are maximally satisfied by the product produced and the process employed to produce it. The industry habit, however, is to inspect outputs in that sequence of steps against standards, assuming that those standards themselves have been properly established. For example, fabricated items are inspected against the detailed fabrication drawings and relevant specifications; what is missing is re-evaluation of the drawings and specifications against stakeholder needs, on the chance that conditions or knowledge have changed, or that a better idea has emerged.

Any opportunity to improve understanding of purposes and needs, design criteria, or design should be taken whenever doing so adds value. The operating assumption in current practice is that the process only flows one way, so it is almost impossible to make an improvement downstream once a ‘standard’ has previously been established.

15.3.2 Technologies facilitating lean design

A key support tool for simultaneous product and process design (and for work structuring in general) will be integrated product and process models, i.e., complex databases capable of representing product design in 3D and also capable of modelling the manufacturing, logistics, assembly, commissioning (start-up), operations, maintenance, alteration, and decommissioning of that product or its components.

Designing within a single model has obvious advantages, e.g., minimizing interferences, visualization and exploration of alternatives, and the creation of a tool for use during post-construction operations, maintenance, and future adaptations. Even better, and certainly more practical, is accessing the data generated on different platforms and using that data to produce models, do trade-off analyses, and so on. Three-dimensional modelling can be useful in project definition, design production, and detailed engineering. In project definition, models can be used like sketches to display alternative concepts. In design proper, models can be used to ensure that the design of systems, sub-systems and components are adhering to interface specifications. In detailed engineering, the product can be built in the computer before being built in physical space and time.

> Once specialists are involved early and organized into cross-functional teams by facility systems, they can use the computer model as a tool to integrate and test components within their systems and to verify the compatibility of various system architectures. The computer model then becomes a value generation tool that supports the real-time consideration of multiple concepts for each system and component. Rather than a more sophisticated form of drafting, the model becomes a tool for simulating the product (and increasingly the process as well), so that better decisions can be made. Ultimately, and perhaps not in the far distant future, we will learn how to design and build the project, process, and team in the course of modelling. (Zabelle and Fischer, 1999)

15.3.3 Benefits of lean design

Adopting a lean approach to design improves both value generation and waste reduction. Value is generated through more methodical and thorough processes for identifying, challenging and clarifying customer and stakeholder purposes, through pursuit of a set-based strategy and the additional time provided for exploration of alternatives and analysis of trade-offs, and through practices such as evaluating outputs against purposes rather than only against immediate requirements. Waste is reduced through the superior product/process design that results from the lean approach. Product designs that are more easily, safely and rapidly built, product designs that are more economically and efficiently operated and maintained, product designs that are more easily altered to changed needs and that cause less environmental damage during realization and on demolition – all these are the result of integrated product and process design, the hallmark of lean design.

15.4 Lean supply

15.4.1 What is lean supply and who is involved in it?

Generally speaking, supply refers to the hand-off between a supplier and a customer. To stress the F in the TFV perspective, supply comprises three flows:

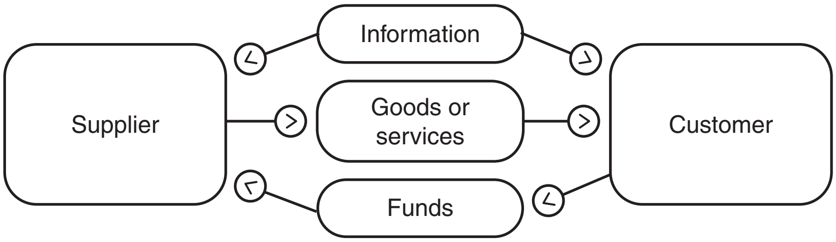

Figure 15.10 Supply flows of information, physical goods or services and funds.

- a two-way exchange of information
- a one-way flow of goods (temporary or permanent materials) or services (people and equipment) from the supplier to the customer
- a one-way flow of funds from the customer to the supplier.

Figure 15.10 illustrates these flows as going directly from a supplier to a customer and back, however, flows may also occur in an indirect fashion. More specifically, supply refers to the processes that result in delivery of goods and services to the site, which is the ultimate location of assembly of construction components. Accordingly, Lean Supply is the third triad in the LPDS (Figure 14.2).

Lean supply is achieved by implementing lean production principles and techniques (such as transparency, pull, load levelling, and just-in-time delivery) to supplier–customer relationships, across organizational boundaries. In the process of implementing Lean Supply, companies may find that impediments to effective implementation exist not only due to organizational boundaries, but also due to the formation of functional silos within their own organization.

Suppliers and customers linked by various flows are also referred to as a ‘supply chain’. The lean production techniques so appropriate for streamlining production processes within a single shop, a department, or an organization equally apply to supplier–customer relationships across organizational boundaries. The field of supply-chain management (SCM) is, in fact, an outgrowth of efforts to integrate the functions, goals and objectives of logistics (by nature a flow-oriented task), procurement and production. These developed as independent fields of study after World War II. Many of today’s best practices in SCM mirror the goals, objectives and techniques of lean production.

15.4.2 Supply chain challenges

Today’s supply chains in construction are long and complex. They include not only owners, designers, engineering specialists, contractors and sub-contractors, but also manufacturers, shipping agents, and other suppliers of goods and services, ranging from commodities to highly specialized made-to-order products. On any specific project, hundreds if not thousands of such companies may constitute the supply chain. A holistic approach towards project delivery as proposed by the LPDS therefore includes the configuration of an extremely complex system.

Many relationships in project supply chains are forged on a one-on-one basis in order to meet the business objectives of the companies involved; they are rarely established with overall supply chain performance in mind. In fact, metrics to gauge overall supply chain performance are sorely lacking in the construction industry. Relationships may or may not pre-date any one project, but irrespective of this, specific agreements are typically invoked opportunistically, based on capabilities and estimated capacity at the time a project's needs arise. Construction supply chains require rapid configuration when those demands become known. Regrettably, forecasting such demand accurately any considerable period ahead of time is nearly impossible in many sectors of our industry.

Construction supply chains also are fraught with inefficiencies. Buyers, like sellers, make unclear and unreliable commitments, unintentionally or intentionally, in terms of specifying exactly when and what goods or services will be needed, and how and when deliveries or hand-offs will take place. They do so in part because it is easier to be vague than to be precise (Vrijhoef *et al*., 2001), and few management systems are designed to promote reliability (the Last Planner is an exception). Moreover, supply agreements rarely spell out penalties for unreliable performance; if they do, such penalties are seldom enforced or end up being unenforceable. Increasing unreliability leads to deteriorating performance (e.g., Tommelein *et al.,* 1999), but today's contracts and legal practice do not provide incentives for supply chain participants to behave differently. Complex and unreliable systems tend to be wasteful and this is all too true of construction supply chains.

15.4.3 Improving lean supply

Lean supply (Figure 14.2) spans Product Design, Detailed Engineering, and Fabrication and Logistics.

Product design for lean supply

Lean supply in the architecture–engineering–construction industry deliberately includes lean product design, which is the counterpart of product development for manufacturing. Accordingly, lean supply can leverage the tight interface with lean design upstream, in addition to taking advantage of lean assembly downstream.

Organize in cross functional teams. The value of organizing in cross-functional teams was already pointed out in Lean Design, however, it is worth stressing the involvement of non-traditional players in these teams. Apart from the traditional players – architects, engineers and contractors – the construction supply chain comprises materials suppliers and fabricators, as well as procurement, materials management and logistics providers. The latter contribute significantly to supply-chain performance by linking design to execution and should therefore be included early on as integral players in a lean team. (Note that our educational systems separate architecture from engineering and construction students, and that few such students are apprised of functions performed and value provided by this 'missing' link.) Specialty contractors and key component suppliers must sit at the table and engage in conceptual design discussions so that they can be informed early of emerging requirements and reveal their production constraints.

Lean design means design for procurability, design for constructability, design for maintainability, in short, Design for X (DFX) where X stands for an ability downstream in the supply chain. Similarly, lean supply recognizes that the design and design detailing functions must be fulfilled with procurement (and other downstream processes) in mind. Detailing commits to a specific product, and when combined with procurement, it also commits to a specific vendor and the associated production process (e.g., information required by that vendor and that vendor's production lead times and quality) (Sadonio *et al*., 1998).

Long-term supplier relationships. Relationships between buyers and sellers have traditionally been transactional and established on a one-on-one basis to meet the requirements of a single project. In contrast, lean production advocates longer-term, multi-project, relational agreements. In order to leverage the benefits to all involved, those agreements are best established with a select few suppliers, where the actual number in 'few' must reflect the nature of the product or service that is supplied. Longer-term agreements provide an incentive for the parties involved to streamline their various flow processes (e.g., by setting up standard work processes and unambiguously defining deliverables) and they provide greater opportunity for feedback and learning.

Early identification of suppliers and their involvement in design can prevent the design–bid–*redesign*–build work that is all too common today – the consequence of designers not understanding the possibilities, requirements, criteria and constraints faced by those detailing and then executing a design. Lean suppliers will further avoid waste by, for example, providing quality products and making reliable deliveries, thereby obviating the need for customers to inspect, expedite or reschedule activities. The LPDS treats suppliers as undiminished participants in the project delivery system and structures rewards commensurately.

Detailed engineering for lean supply

The detailed engineering, fabrication and logistics tasks interact closely with product design, since the ease of making and transporting goods, and ultimately the ease of installation, are but some lean design criteria. The benefits of shifting detailed design to fabricators and installers (including specialty contractors) have been stressed already.

Detailed engineering of engineered and made-to-order products combined with the approval process frequently has a lead time that is significantly greater than that of fabrication itself and is therefore a prime target for efforts to reduce cycle time. Batching as well as multi-tasking practices in detailing and fabrication, like those in design, are detrimental to throughput performance. In contrast, standardization of products and processes would improve performance. Note that such standardization does not need to stifle innovation; in the computer industry, for example, new standard interfaces between components are regularly created to keep up with the lightning-fast evolution of technologies (e.g., parallel connections, SCSI, USB, firewire, USB2).

Fabrication and logistics for lean supply

The ideal one-piece flow of 'lean' translates into small and frequent hand-offs in a continuous-flow system driven by customer pull. Pull means that goods and services are delivered only upon demand in response to a real need, as opposed to being delivered to stock so as to meet a forecast need. Forecast construction needs are typically captured in master schedules, which are cost per mile (CPM)-based push schedules. Systems fraught with uncertainty perform significantly better when such schedules are augmented by real-time pull (Tommelein, 1998). Today's construction supply practices face major opportunities in this regard. All too often, uncertain forecasts and long lead times, combined with poorly-chosen financial incentives, lead to the build-up of large on-site inventories of materials not needed immediately for installation. More accurate short-term planning (e.g., the Last Planner) combined with closer-to-real-time communication from customer to supplier (e.g., web-based systems that provide information transparency) and the ability of suppliers to deliver quickly to real demand (short lead times), are all needed to implement pull in lean supply.

Admittedly, lead times in supply will continue to be significant especially when transactions are conducted in a global marketplace. Few manufacturers that serve the construction industry already have become lean. Others are making the transition but do not yet know how (or prefer not) to let supply chain partners take advantage of their ‘leaning’ and leverage the lessons learned by applying them across organizational boundaries. The move towards lean is especially notable in companies that span multiple echelons in the supply chain, such as specialty contractors that have their own off-site fabrication shops and field-install their fabricated materials. The benefits of lean increase with the scope of application of lean.

Transportation. Transportation of construction goods is largely done on a supplier-by-supplier and material-by-material basis. The construction industry has not taken advantage of opportunities offered by other supply arrangements, such as earlier consolidation of various materials that will be needed later at the same time (examples are kitting of parts and prefabrication of modules). Like traditional designers, manufacturers, fabricators and other suppliers batch their deliverables in order to minimize set-up costs and take advantage of transportation costs. Even though faster and more economical means of transportation are being developed, transportation will remain a source of lead time with uncertainty. The supply chain can be made leaner by procuring from suppliers that are located in closer geographic proximity.

Purchasing vs. releasing for delivery. The distinction between design and execution equally applies to purchasing and release for delivery. For example, Tommelein and Li (1999) describe the process for ordering ready-mix concrete as two-fold; first, placing an order with the ready-mix batch plant one or several weeks prior to site need in order to reserve production capacity and allow time for the plant to order and receive concrete ingredients; second, calling in a few hours or a day in advance of the placement to confirm the time at which the site will be ready to receive the truck, with concrete mixed at most half an hour or so prior to delivery. Purchasing and releasing are often thought of in combination. By recognizing that they are separate (Ballard, 1998), one gains an additional degree of freedom in configuring and managing the supply chain, which serves the implementation of lean supply.

15.4.4 Supply chain design and control

Lean supply chains must be designed with the following value-adding tasks in mind:

- physical movement of products
- change in unit of hand-off

- temporary storage or velocity adjustment to allow for synchronization
- providing timely information.

The focus of lean supply is on the physical movement of products or delivery of services to the customer. While 'transportation' is often regarded as a wasteful activity, particularly when it involves re-handling of materials, at least some part of it is value adding because construction sites are located some distance away from raw material quarries.

Lean supply takes advantage of the opportunity to change the unit of hand-off, when batch sizes of outputs released in upstream processes do not match batch sizes of inputs required in downstream processes. Changes in units of hand-off are needed only because one-piece flow was not possible.

Lean supply purposefully seeks out opportunities for early assembly, modularization, use of standard materials and components, kitting or 'bagging and tagging,' and other kinds of (re)packaging in order to avoid matching problems and the effect of merge bias downstream. Matching problems occur when several items are needed at the same time for final assembly, but one or several are missing (e.g., Tommelein, 1998) so that no work can be completed. Merge bias means that any one matching item being late will delay final assembly. Synchronization of the supply chains that merge at final assembly, and tight control on their duration are therefore key factors in achieving lean supply.

Lean supply also aims to synchronize supplier and customer production, adjusting transportation speeds or providing for intermediate staging (buffering) because supply and demand could not otherwise be balanced. Fabricators aim to level job-shop schedules whereas installers face surging demands to meet project schedules. The two are therefore often in tension with each other (Akel *et al.*, 2001).

Information transparency

Finally, lean supply requires the judicious creation of information transparency to alleviate demand uncertainties in the various supply organizations and to enable the pulling of resources through those parts of the supply chain where it can be achieved.

15.4.5 Roles of SCM in construction

Vrijhoef and Koskela (2000) identified four roles of supply SCM in construction. The alternatives are numbered in Figure 15.11 and the descriptions below paraphrase their text.

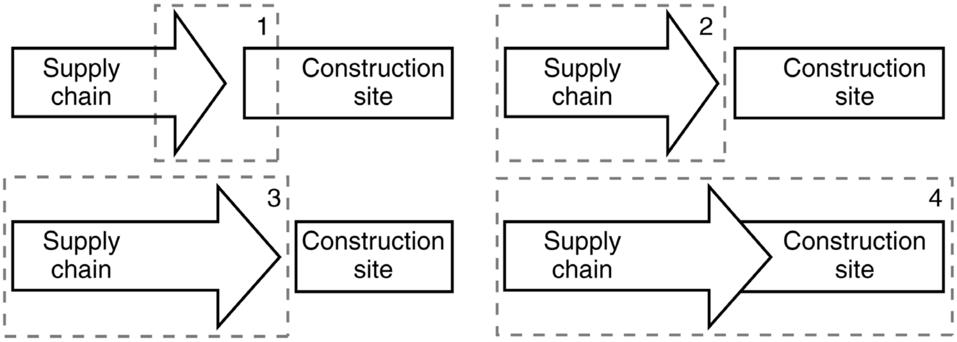

Figure 15.11 Four roles of supply chain management in construction (Vrijhoef and Koskela, 2000).

Each role could be played by one or several supply chain participants. Roles are not mutually exclusive and in fact are often pursued jointly.

- SCM focuses on the impact of the SC on construction site activities and aims to reduce the cost and duration of those activities. The primary concern therefore is to establish a reliable flow of materials and labour to the site. Improvements may be achieved by focusing on the relationship between the site and direct suppliers. The contractor, whose main interest is in site activities, is in the best position to adopt this role.
- SCM focuses on the SC itself and aims to reduce costs, especially those related to logistics, lead time and inventory. The contractor, but also materials suppliers and component manufacturers, may adopt this role.
- SCM focuses on transferring activities from the site to earlier stages in the SC and aims to reduce total installed cost and duration by avoiding inferior conditions on site or achieving wider concurrency between activities, which is not possible due to technical dependencies on site. Designers, suppliers or contractors may adopt this role. Owners play a key role in this regard, by selecting SC participants and providing them with incentives to perform.
- SCM focuses on the integrated management and improvement of the SC and site production, that is, site production is subsumed by SCM. Owners, together with designers, suppliers, and contractors, may play this role. For example, a light-fixture manufacturer adopted this role (Tsao and Tommelein, 2001) for one part of the construction supply chain.

The challenge of lean supply therefore is not on any one supply chain participant, but on all participants.

15.5 Lean assembly

Lean Assembly is the fourth triad in the LPDS (Figure 14.2). It includes Fabrication and Logistics, Installation, and Commissioning. In construction, the final installation of components (modular or not) takes place *in situ*. 'Lean' aims to minimize this effort while also expediting the entire delivery process.

15.5.1 Practical methods

In addition to using the Last Planner to control the planning system, lean assembly takes advantage of several other tools and techniques.

Lean assembly for commissioning

Commissioning is the last step in the production process prior to turn-over of a facility to the owner. Turn-over defines the pull of the customer, so it is with turn-over in mind that all tasks in the delivery system must be sequenced and executed. To reflect this pull, commissioning and the other elements of lean assembly are discussed in reverse order of their appearance in the triad. The work of different trades must thus be co-ordinated and completed at set times in order to allow for entire systems to be turned on, calibrated and tested. In traditional scheduling practice other network logic may prevail over this, thereby jeopardizing the turn-over date.

Lean installation

First-run studies for operations design (Howell and Ballards, 1999). Construction operations are the way crews use what they have to do work. Work methods appear simple enough when represented in the estimate, but that design is seldom detailed or explicit at the step or sub-cycle level. Under lean construction, the design of the product and the process occur at the same time so factors affecting operations are considered from the first. Ultimately, operations design reaches all the way through the delivery system, as it is part of work structuring.

In product design, decisions about the selection of materials, their joining and configuration on site, constrain the work method. Designers thus constrain the range of solutions left. That range will narrow further as time advances and downstream planners make additional assumptions; downstream planners are thereby progressively constrained while hopefully being able to find at least one acceptable method.

All details are rarely resolved before an activity begins and most operations continue to evolve once underway. This image contradicts the view that there is one right or standard way to work. It suggests two strategies in the extreme: one is to leave as much flexibility as possible for the last planner, while the opposite is to completely prescribe all details in advance and then assure that the planned circumstance happens.

Designing operations under either strategy has obvious problems. In the first, total flexibility makes planning and co-ordination with others difficult, and projections of cost or completion unreliable. In the second, early prescription ignores late developments. Insofar as construction is a prototyping process, expecting to prescribe all details is unrealistic, nevertheless, establishing procedures early and supporting them by intermediate planning might improve the reliability of work flow. Just as with product design options, process design options progressively disappear as time passes because we have hit the lead time of suppliers (last responsible moments). Certain options may also be eliminated by examination.

The design of an operation may be specified in front-end-planning, but more design work will remain to be done in the engineering phase and within the lookahead process when the work package is released to the crew. First-run studies must be a routine part of planning, conducted preferably 3 to 6 weeks prior to the start of a new operation (Howell and Ballard, 1999). They include actually performing the operation in as realistic a manner as possible, in order to try out and learn how to best perform the work involved, identify skills and tools available or needed, interaction of the operation with other processes (e.g., Howell *et al.* 1993), and so on.

The interdependence between product and process design can be explored using computer models of the design (such as discrete-event simulation and 3D computer-assisted design; CAD) so that work can be structured to best meet project objectives. Issues to be considered include:

- design of the product itself
- available technology and equipment
- site layout and logistics
- size of work packages released to the crews
- size of work packages released to downstream crews
- potential site environment (temperature, precipitation, wind, etc.)

- safety
- expected experience and skills of craft workers and supervisors
- craft traditions or union work rules.

First-run studies and operations design are not limited to repetitive operations. Indeed, all operations should be subjected to a design study on each project. Typical studies include process, crew balance and flow charts, as well as space schedules that show how resources move through space and work progresses. It is of utmost importance to measure and understand variability in arrival rates of inputs and processing durations. Construction operations usually begin with a significant uncertainty but first-run studies will reduce it.

First-run studies result in identifying a good (not the best, although this is the lean ideal) way to do work, thereby setting a standard against which all those conducting the work can gauge performance. Standardized work is a hallmark of lean production, but such standards should not be viewed as rigid in any way. They are subject to examination and improvement (e.g., ‘kaizen’, a Japanese term used in the Toyota production system to refer to the search for continuous improvement) to result in a new and better standard when appropriate. Standards are very important, however, in that they make it easy to delegate responsibility for execution and control to those conducting the work, and they facilitate learning by clearly defining a process that can be mutually agreed upon and critiqued.

Aiming for continuous flow (Ballard and Tommelein, 1999). A continuous flow process (CFP) is a type of production line through which work is advanced from station to station on a first-in–first-out basis (Ballard and Tommelein, 1999). The idea is to balance, approximately, the processing rates of the different stations so that all crews and equipment can perform productive work nearly uninterruptedly while only a modest amount of work-in-process (WIP) builds up in between stations.

The objective of achieving continuous flow is maximizing the throughput of that part of the system while minimizing resource idle time and WIP. Just as pull techniques are limited by the relative size of supplier lead times and windows of reliability, not all work can be structured in CFPs. However, doing so where possible reduces the co-ordination burden on the ‘central mind’ and provides ‘bubbles’ of reliable work flow around which other work can be planned.

Examples of work that can be executed as a CFP include excavating footings, placing formwork and rebar, then inspecting prior to placing concrete, and subsequently curing, stripping and finishing; or finishing rooms of a hotel or hospital (painting, carpeting, etc.) one after the other. The key to CFPs is that work gets done in small chunks, each chunk is involved in one production task (or operation) and, once processed, is worked on in subsequent production tasks. In the mean time, the first task gets repeated, and so the process continues.

In order to assess whether or not continuous flow is appropriate, and then to achieve it, a number of steps must be taken. The steps in CFP design are:

- data collection
- definition
- rough balancing
- team agreements
- fine balancing
- change guidelines.

While identifying the characteristics of individual operations, e.g., in terms of work content, method design (though this may change), set-up time, minimum resource unit, minimum process batch size, capacity, space and access needs, and more, one also needs to pay attention to available skill sets and equipment capabilities. One should not be misled, however, by contractual or union boundaries that may constrain the view on operations.

Once descriptive data on individual production tasks and their alternatives is available, different tasks can be put together into a system and the potential for it to be made into a CFP identified. The team must decide which parts will be made into CFPs and which parts will be decoupled by means of buffers. This decision is driven in part by the amount of flexibility that exists in the operation's design and the required resources; technology might also be a driving factor.

In the rough balancing stage, specific site constraints must be considered as they define the pace of the operations as work progresses to complete the project at hand. Balancing a system to achieve continuous flow is done by a combination of techniques, including assigning capacities, mutual adjustment, inventory buffers and capacity buffers.

For self-governance, the specialists operating at different stations in the line must agree on a division of operation, pacing or production rate, the size and quality characteristics of transfer batches, balancing techniques such as multi-skilling or rate adjustment, and strategies for adjusting to differences in load over time and other variability if unforeseen needs arise.

Multi-skilling. Lean production promotes multi-skilling of teams of workers so they will be able to perform more than just a few specialist tasks and assemble a multitude of systems, thereby avoiding process fragmentation otherwise imposed by tradition or trade boundaries. Multi-skilled workers can better support and maintain CFPs by being able to do a broader range of work, which is especially important when work flows are variable.

Fabrication and logistics for lean assembly

Preassembly. The greater number of components that are pre-assembled prior to their final installation, the more straightforward the final assembly process becomes, provided, of course, that assemblies can be managed logistically.

Standardized and interchangeable parts. The repeated use of standardized parts greatly eases assembly; not only will crews be familiar with the parts, they will also be able to learn from their repeated use. In addition, the use of a limited number of parts keeps matching problems at a minimum.

Just-in-time deliveries. Lean assembly must, of course, be closely co-ordinated with lean supply. Ideally, materials will be received just-in-time (JIT) and strategically located on site. JIT does not mean that everything is delivered at the last minute – a better translation from the corresponding Japanese concept is ‘at the appropriate time’. Materials must be buffered as needed to match work flow requirements both upstream and downstream in the process. In a CFP, WIP will thus be minimal.

One-touch handling. One-touch handling is a lean ideal that provides a good metric for otherwise numerous re-handling steps from receipt on site to laydown, and from issuing to staging of materials prior to their final installation. Some materials can be directly installed, whereas others are parts or components for sub-assemblies yet to be produced. Of those items that are ready for installation, some can be directly installed from the delivery vehicle. Three rules-of-thumb for one-touch material handling are:

- off-load directly from delivery vehicle into final position when possible (e.g., pipe spools, most equipment)
- if direct off-loading is not possible off-load within 'crane reach' of final position (e.g., structural steel requiring pre-assembly at the site)
- deliver consumables (e.g., grinding disks, gloves) and commodity materials (e.g., fittings, gaskets, bolts) directly into the hands of users, as opposed to warehousing and issuing them based on requisitions.

Minimum–maximum inventory rules can be followed to conform to this rule while matching work place characteristics.

Distributed planning. Finally, recognizing that there are numerous Last Planners on any one project – planning is inherently a distributed task – lean assembly relies on information flows that support distributed co-ordination of shared resources including space (Choo and Tommelein, 2000). A key to effective distributed planning is to recognize that each planner needs to plan with significant detail but not all that detail is to be revealed to everyone else with whom work must be co-ordinated. Some others will want certain details, whereas others do not. Detail must be selectively revealed as and when needed, depending on the circumstances. This thinking, like so many other concepts in the LPDS, requires a paradigm shift from current practice, which is dominated by the central control paradigm.

15.5.2 Summary

Many of the tools and techniques described under lean assembly are equally applicable in and across other triads of the LPDS. We have described them here because many of our experiences with lean production were gained in construction, before we considered lean project delivery with a broader scope. Practitioners may find quick rewards by applying our lean construction tools and techniques at the site level, prior to covering more scope.

15.6 Conclusion

Many powerful tools and techniques have been developed to manage the LPDS. Some of these are conceptual, some are procedural, some are embedded in software. Whereas several tools are simple, others are more complex, for example, the Last Planner system is a complex tool, itself including multiple rules and techniques, namely the Activity

Definition Model, constraints analysis, and PPC. One-touch material handling is a conceptual and simpler tool, an ideal to be pursued with rules to be followed in its pursuit.

This varied tool set is very powerful in the hands of managers inspired by the lean conceptualization of projects and of project management. Bertelsen *et al.* (2001) reported at the Third Annual Lean Construction Congress that Danish contractors had reduced project durations by 10%, increased productivity by 20%, and improved profitability 20–40% on projects where they applied lean principles. Like everyone else, they are still in the early stages of their lean revolution, and have not yet applied all elements of the lean system nor yet applied all of its tools and techniques.

A true revolution in construction management is underway and it is as yet far from achieving its full potential. Indeed, the lean ideal suggests that 'full potential' will never be reached, as pursuit of the ideal eclipses all previous performance benchmarks. New tools and techniques will undoubtedly be developed in the never-ending pursuit of perfection.

Endnotes

1 Lean Project Delivery System (LPDS) and Last Planner are both Trademarks.

2 For an excellent example of chunking strategies, see Tsao *et al.,* 2000.

3 Extension of commitment planning and learning to direct workers is a likely future step in the evolution of lean construction).

4 There appears to be an opportunity for alternatives such as concrete and steel superstructures to compete on lead time. Shorter, less variable lead times would allow delaying design decisions to accommodate customer needs for late-breaking information, or could be used to shorten overall project durations.

5 Other tools can also be useful; e.g., the design structure matrix, which is used to sequence design tasks to eliminate avoidable looping – see www.mit.dsm.

6 Set-up time is a term from manufacturing indicating the time required to switch from producing one product to producing another product or to producing to a different set of specifications. An example from construction is changing crane booms. An example from fabrication is changing heads on the machine that produces different sizes of round sheet metal duct. An example from design is the time required to collect and focus one's thoughts when interrupted from a complex intellectual task.

References and bibliography

Akel, N.G., Boyers, J.C., Tommelein, I.D., Walsh, K.D. and Hershauer, J.C. (2001) Considerations for streamlining a vertically integrated company: a case study. In: *Proceedings 9th Annual Conference of the International Group for Lean Construction* (IGLC-9), 6–8 August, National University of Singapore.

Alarcon, L. (ed.) (1997) *Lean Construction* (Rotterdam: A.A. Balkema).

Ballard, G. (1998) Implementing pull strategies in the AEC industry. *Lean Construction Institute White Paper No. 1.* www.leanconstruction.org

Ballard, G. (1999) Work structuring. *Lean Construction Institute White Paper No. 5.* www.leanconstruction.org

Ballard, G. (2000a) Phase scheduling. *Lean Construction Institute White Paper No. 7*. www.leanconstruction.org

Ballard, G. (2000b) *Last Planner System of Production Control*. PhD Dissertation, Dept. of Civil Engineering, University of Birmingham, U.K. www.leanconstruction.org

Ballard, G. and Howell, G. (1994) Implementing lean construction: stabilizing work flow. In: *Proceedings 2nd Annual Conference on Lean Construction*. Pontificia University Catolica de Chile, Santiago, September. www.vtt.fi/rte/lean/santiago.htm

Ballard, G. and Howell, G. (1998) Shielding production: essential step in production control. *Journal of Construction Engineering and Management,* ASCE, **124** (1), 11–17.

Ballard, G., Koskela, L., Howell, G. and Zabelle, T. (2001) Production system design in construction. In: *Proceedings 9th Annual Conference of the International Group for Lean Construction*, 6–8 August, National University of Singapore. www.leanconstruction.org

Ballard, G. and Tommelein, I.D. (1999) Aiming for continuous flow. *Lean Construction Institute White Paper No. 3*. www.leanconstruction.org

Ballard, G. and Zabelle, T. (2000a) Project definition. *Lean Construction Institute White Paper No. 9*. www.leanconstruction.org

Ballard, G. and Zabelle, T. (2000b) Lean design: process, tools & techniques. *Lean Construction Institute White Paper No. 10*. www.leanconstruction.org

Bertelsen, S., Christoffersen, A.K., Jensen, L.B. and Sander, D. (2001) Studies, standards and strategies in the Danish construction industry implementation of the lean principles. In: *Getting it Started Keeping it Going*, *Proceedings of the 3rd Annual Lean Construction Congress*, Lean Construction Institute, August, Berkeley, CA.

Choo, H.J. and Tommelein, I.D. (2000) WorkMovePlan: database for distributed planning and coordination. In: *Proceedings 8th Annual Conference of the International Group for Lean Construction* (IGLC-8), 17–19 July, Brighton, UK. www.sussex.ac.uk/spru/imichair/iglc8/08.pdf

Howell, G. and Ballard, G. (1999) Design of construction operations. *Lean Construction Institute White Paper No. 4*. www.leanconstruction.org

Howell, G., Laufer, A. and Ballard, G. (1993) Interaction between subcycles: one key to improved methods. *Journal of Construction Engineering and Management*, ASCE, **119** (4), 714–28.

Sadonio, M., Tommelein, I.D. and Zabelle, T.R. (1998) The LAST DESIGNER'S Database-CAD for sourcing, procurement and planning. In: *Proceedings of Computing Congress '98*, ASCE, pp. 364–75.

Sobek, D.K., Ward, A.C. and Liker, J.K. (1999) Toyota's principles of set-based concurrent engineering. *Sloan Management Review*, Winter, **40** (2), 67–83.

Tommelein, I.D. (1998) Pull-driven scheduling for pipe-spool installation: simulation of lean construction technique. *Journal of Construction Engineering and Management*, ASCE, **124** (4), 279–88.

Tommelein, I.D. and Li, A.E.Y. (1999) Just-in-time concrete delivery: mapping alternatives for vertical supply chain integration. *Proceedings 7th Annual Conference of the International Group for Lean Construction* (IGLC-7), 26–8 July, Berkeley, CA, pp. 97–108.

Tommelein, I.D., Riley, D. and Howell, G.A. (1999) Parade game: impact of work flow variability on trade performance. *Journal of Construction Engineering and Management*, ASCE, **125** (5), 304–10.

Tsao, C.C.Y. and Tommelein, I.D. (2001) Integrated product/process design by a light fixture manufacturer. In: *Proceedings 9th Annual Conference of the International Group for Lean Construction* (IGLC-9), 6–8 August, National University Singapore.

Tsao, C.C.Y., Tommelein, I.D. and Howell, G. (2000) Case study for work structuring: installation of metal door frames. In: *Proceedings 8th Annual Conference of the International Group for Lean Construction*, University of Sussex, Brighton, UK.

Vrijhoef, R. and Koskela, L. (2000) The four roles of supply chain management in construction. *European Journal of Purchasing and Supply Management,* **6**, 169–78.

Vrijhoef, R., Koskela, L. and Howell, G. (2001) Understanding construction supply chains: an alternative interpretation. In: *Proceedings 9th Annual Conference of the International Group for Lean Construction* (IGLC-9), 6–8 August, National University of Singapore.

Ward, A., Liker, J.K., Cristiano, J.J. and Sobek, D.K. II (1995). The second Toyota paradox: how delaying decisions can make better cars faster. *Sloan Management Review,* Spring, **36** (3), 43–61.

Zabelle, T.R. and Fischer, M.A. (1999) Delivering value through the use of three dimensional computer modeling. In: *Procedings 2nd Conference on Concurrent Engineering in Construction*, Espoo, Finland.