Lean Construction Papers

LCI White Papers

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A Guide to the Last Planner for Construction Foremen and Supervisor

Activity Definition Model
Implementing Pull Strategies in the AEC Industry
LCI White Paper-1
July 26, 1998
Glenn Ballard, LCI

The framework for this thought piece is the idea that there are three ways to coordinate work flow; i.e., schedule push, continuous flow, and (plan) pull.

To expand, the three techniques are:

- pushing different work activities toward future intersections in time through schedules
- flow through assembly chains in accordance with pre-agreed rules for spacing, handoffs, and pace,
- pulling elements together to be assembled.

Our current thinking is that a) we need to use schedules to initiate long-lead actions, b) we need to structure work on site as much as possible in assembly chains, through which work can flow continuously, without central control, and c) we can pull most materials and ultimately design information to the site to mate with actual or predicted subassemblies.

Scheduling is now the only well recognized technique for work flow coordination in construction. Structuring work packages around assembly chains will be the subject of a later white paper. The topic here is pull.

In order to pull materials into site assembly, we need to improve in two areas: 1) Improve work flow reliability in the site assembly process, and 2) Reduce the time required from order to delivery of materials to the site. The primary benefit of pulling is shorter projects, which will result from saving the time now spent filling inventory pipelines, and from more often being able to do the work that maximally advances the project. Secondary benefits include reduced working capital tied up in inventories of materials that are not being used, less labor time spent handling materials, and less loss, damage or misplacement of materials.

Improved work flow reliability allows material delivery orders to be placed earlier relative to their scheduled installation. (Note that we now infrequently distinguish between purchasing an item of material and ordering or releasing the item for delivery.) Reduced delivery times allow orders to be placed closer to the time the work will be done. Orders should be placed within the response time of those asked to deliver materials, but current low predictability of work completion and long response times makes it necessary to ‘order’ and accept deliveries of materials further in advance, so the accumulation of inventories and longer projects is inevitable.
Let’s make up some numbers. Let’s suppose that we are now able to accurately (90+% )
predict the completion of an item of work no more than 3 days ahead of its actual
completion. Let’s also suppose that it takes 5 days on average to get stuff to the site once
it is requested—e.g., fabricated items such as steel or pipe. If we wait until 3 days before
the work is scheduled to be done, we can’t get the stuff we need, so we order it earlier
and cause the waste of overproduction because of the mismatch between what’s delivered
and what can be immediately used in the assembly process. In fact, things are much
worse because our ability to accurately predict work completion is actually closer to 1
day and because the time now required to pull fabricated items to site is often 6+ weeks.
We need to get delivery time within our window of predictability and reliability. We need
to close the gap by increasing work flow predictability beyond 1 day and by reducing
delivery times below 6 + weeks.

That is a huge gap to be closed. How to do it? The Last Planner method (lookaheads,
screening, shielding) has been developed as a means of improving flow reliability.
General contractors/construction managers have the responsibility for coordinating and
managing assembly processes using these techniques. Action for improving plan
reliability: 1) Install Last Planner on sites, 2) Develop specialty contractor production
management systems so they can provide to assembly coordination accurate status and
forecast information regarding material flow.

In order to pull materials and information onto the site, we must also reduce the delivery
times of fabricators, suppliers, and designers. On subcontracted jobs, the primary burden
must be borne by the subcontractors. Let’s divide the world of materials into process
equipment, fabricated items, and commodities. Many items of process equipment are so
long-lead that they do not offer themselves as initial candidates for reducing delivery
times. They must for now continue to be coordinated by push schedules. Examples might
include chillers, fractionation towers, electrical panels, etc. (On the other hand, we’re
talking to Trane about joining LCI precisely so we can work on these longer lead items
such as chillers.) Some fabricated items may take 12 weeks or longer to fabricate and
deliver, sometimes because of capacity shortages and having to stand in line to get shop
space. However, there are medium-term fabricated items on which we might first
concentrate our efforts; e.g., structural steel, pipe supports, pipe spools, metal
components, etc. These are generally custom-designed, so require fabrication drawings or
instructions, often provided by the specialty contractor (SC) who is to install them. In any
case, let’s assume the SC is providing the fabricated item, so they can in some sense
‘control’ delivery, or at least find out when delivery is supposed to occur.

Is it possible to shift inventories from laydown yards on site upstream to a place between
design and fabrication, then pull fabricated items from that point onto the site? We would
need some agreements with design and with fabricators. We’ve done some early
exploration with fabricators. They say they would charge no more or a little more to
fabricate and deliver to site order rather than to schedule, assuming they have design
information that is correct and complete, and assuming they have that information in time
to themselves acquire the fabrication materials.
Actions for reducing delivery times: 1) Build slack into the schedule for production of fabrication drawings to allow a buffer of drawings and the associated materials to be built up at the fabricator or at some staging area ahead of fabrication, and 2) Get agreement on ordering/delivery procedures and payment with fabricators for responding to short-interval pull orders, perhaps once or more per week. 3) Explore the possibility of pulling fabrication drawings to the fabricator, then ultimately in future pulling model construction (assuming that’s the source of fabrication drawings or CAM instructions).

Even if early efforts do not significantly reduce duration, there are advantages to allowing design more time to make late changes and to get drawings right. However, our hypothesis is that a buffer between design and fabrication can be much smaller than the buffer between fabrication and construction now required for ‘good’ project performance.

We invite your questions and suggestions on this issue and seek LCI members willing to conduct experiments. Some members may already be using pull techniques. Please let us know what you are doing and how well it’s working. We are especially interested to hear from members who are or can pull from their own fabrication shops.

Related writings: This idea was first presented in the paper “Toward JIT in Construction”, presented at the 1995 IGLC meeting in Albuquerque. Real world need for buffer relocation and inventory reduction was demonstrated in Howell and Ballard’s research on piping for the CII. Iris Tommelein’s 1997 pipe spool simulation provided support for the hypothesis that pull techniques would reduce site inventories.
The hypothesis is that by allowing design time to complete drawings for a complete unit of work (activity area, floor, plant, total project), the site can pull whatever it needs from fabrication just when it’s needed for installation. Assuming that the fabrication rate stays the same, the installation rate will have to also stay the same or at least not intersect the fabrication line. Productivity improvement in installation can be captured in reduced cost from reduced labor. Duration will decrease because installation can work close to fabrication.

In this schematic, design is given about a 50% increase in duration. Fabrication starts after design is complete. Construction starts right after fabrication starts, allowing only perhaps a week’s worth of materials to be delivered to the site beforehand. Perhaps we can persuade Iris to model these possibilities.
A New Assignment Sizing Criterion  
LCI White Paper-2  
November 3, 1998  

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Questions and comments are not only welcome but eagerly awaited!

The quality criteria for assignments are definition, sequencing, soundness, sizing, and learning. Most efforts to improve PPC and the plan reliability it measures have focused on definition and soundness. One of LCI’s research goals for this year is to discover how to increase PPC to the 90% plus range, which we believe will increase productivity substantially. Four actions are key:

1) full empowerment of last planners to refuse assignments that do not conform to quality criteria,  
2) consistent analysis and action on reasons for failing to complete assignments,  
3) further improvement in definition by using First Run Studies in construction and Activity Definition Models in design, and  
4) adopting a sizing criterion for assignments that consistently demands less output from production units than their estimated capacity.

This White Paper is about the sizing criterion.

Definitions

I have changed my mind about one aspect of Last Planner. The issue is sizing assignments to the capacity of production units. First a few definitions.

♦ A production unit (PU) is an individual or a group performing some production tasks. PUs receive assignments. Most PUs are construction crews or design squads.

♦ Capacity means how much work a PU can do at any point in time with given tools and work methods in given conditions. A crew may be able to produce 50 units of output (linear feet of pipe, tons of steel, cubic yards of concrete, etc.) under current conditions. That is their capacity; the amount of work they are capable of accomplishing.

♦ Load is the amount of work we demand or expect of a PU. Common practice in construction at present is to load to 100% of estimated capacity. In our example, that means we would assign 50 units of output to be produced by the crew each day.

Variability in productivity and in work flow (plan reliability)

Loading at 100% of capacity is acceptable when capacity is accurately predictable and when there is insignificant variation in the flow of work to the construction crew or design squad.
Unfortunately, actual production varies widely over time even for a single PU, and varies even more widely across different units. In addition, as we all are aware, work flow is not highly reliable. Indeed, even when we try to make good assignments, PPC is now often below 70%. In such circumstances, loading at 100% capacity decreases the probability that assignments will be completed as planned.

Coming from another angle, we can assume that there is a ‘natural’ variability of capacity even when methods, technology, and conditions are fixed. Further, there is the difficulty of accurately estimating even average capacity when there are changes in these variables or when the type of work changes or there is some change in crew or squad composition. Since we don’t make identical products in controlled conditions, capacity variation is a fact of construction life. Current production management techniques ignore this fact.

Besides the fact that capacity is variable, the second key fact is that capacity can be increased by reducing non-productive labor time. Further, non-productive labor time falls with increasing PPC.

Underloading can reduce the immediate productivity of a PU, assuming that no non-schedule-driven work (workable backlog) is available to absorb unused capacity. However, underloading assures that the PU’s plan reliability or PPC is higher, thus providing better advance notice to downstream PUs of work flowing toward them, and thus allowing them to increase their productivity. Since all but the very first in a chain of PUs receive work from others, potentially all benefit from adopting practices that improve PPC. Consequently, the next step in improvement of both plan reliability and productivity will most likely occur on projects where the various design and construction specialists practice some form of gainsharing, or at least collectively recognize their interdependence and potential gains. Otherwise, no one will be willing to sacrifice, even temporarily, for the sake of the whole.

We can say that initial, unilateral improvements in PPC and productivity need now to be superceded by collaborative improvements in PPC and productivity based on increasing the predictability of work flow across PUs.

**Don’t load to 100% of capacity**

In earlier writings, LCI advocated sizing assignments so they fully absorbed the productive capacity of those to whom the assignments were made. I now believe it would be better to underload production units in order to allow for variability in capacity, which is itself partially a function of variability in the flow of work to those production units. Underloading reduces the achievable output of a PU. They have more capacity than load. However, underloading also increases the capacity (potential productivity) of following PUs through its impact on work flow reliability.

**Impact of Sound Assignments**

It makes sense that the productivity of a production unit increases when we make more assignments to that unit that are sound; i.e., assignments from which all constraints have been
removed. Design information is current, materials are on hand, work space has been allocated, etc. More of total labor time is spent actually doing work instead of looking for materials, switching between tasks, and returning to finish work left incomplete.

BEFORE:

♦ initial average capacity is 50 units per day.
♦ 50% of the labor hours expended to produce that 50 units are actually wasted on rework and nonproductive waiting, looking, revisiting, etc.
♦ PPC of the PU is 50%.

AFTER:

♦ PPC increases to 70%, as a result of improving the soundness of assignments.
♦ nonproductive time (delays and rework) falls to 35% vs. the previous 50%.
♦ new capacity is 65 units per day.

This amounts to a 30% improvement in capacity of the production unit. Previously 50% of total labor hours were expended in the production of 50 units of output. Assuming no change in skills, effort, technology, or work methods, after the improvement in the soundness of assignments and consequent increase in PPC, the PU expends 65% of its total labor time on production and produces 65 units of output. Note that LCI has in fact found a 30% improvement in productivity of PUs on numerous occasions when PPC has been improved largely as a result of making sound assignments.

Potential impact of the new sizing criterion

With PPC at 70% throughout a chain of PUs, a PU still has considerable uncertainty about what work is actually going to be released to it by upstream PUs only one move away; usually as little as one week in advance. LCI suggests that the next wave of increases in PPC will come from a number of different initiatives, including sizing to the new criterion; namely, underloading sufficiently to allow for variability in PU productivity. In the absence of real data, I suggest that you try loading at 90% of the estimated capacity of PUs, then adjust as needed.

I expect this underloading to improve PU PPC, thus increasing the lead time downstream PUs have to make work ready. Speculative results:

♦ loading is at 90% of capacity; i.e., 59 (58.5) units are assigned to be produced each day.
♦ productive time increases to 80% from the previous 65%
♦ new capacity is 80 units per day.

What happens when sizing combines with soundness?
Underloading upstream production units increases the capacity of downstream production units, just as making only sound assignments increases the capacity of the production unit receiving those assignments. Assuming that we continue to load at 90% of capacity and that the new capacity is 80 units per day, load and productivity would be 72 units per day—an additional increase of 23% above the 58.5 units previously achievable—and a 44% improvement above the initial 50 units per day. However, as rising PPC reduces variation in capacity, we can increase load accordingly, thus further improving productivity. Supposing a 95% loading, output would be 76 units, an improvement of 52% above the initial 50 units per day.

This 52% improvement in productivity results only from increasing the percentage of paid labor time available for production. The other variable determining capacity is the fruitfulness of productive labor time, which is a function of operations (work methods) design, design constructability, skills training, and worker motivation. The 5-10% nonloaded time will be invested in precisely these areas. In fact, we may find it beneficial to keep loading at 90% or possibly even less in order to free labor time for investment in fruitfulness. Workers will be asked to spend time doing First Run Studies or defining design activities; providing feedback to upstream players on the adequacy and clarity of design criteria or design constructability; undergoing training in craft and managerial skills; etc. etc. We breakeven if we invest 10% of paid labor time and increase capacity enough to offset that cost; i.e., in our example, increase from 72 to 79 units per day.

If this analysis and these numbers are plausible, you can see the tremendous potential for improvement offered by lean construction concepts and techniques. Current productivity levels will be eclipsed and become irrelevant.

Overmanning

Those who have been in conversation with us for a long time might wonder if we have forgotten our own experiences on projects. We have seen consistent overmanning on large industrial projects; an attempt to have enough workers in place to do whatever work happens to become available. We have been very harsh in our judgment of this practice. Was this actually a type of underloading, a practice we are now advocating? Should we apologize to all those project managers we previously criticized?

We don’t think we owe any apologies. Just because we have workers doesn’t mean we have capacity. Capacity is a function also of what work there is to do and the quality of assignments which load that work onto the workers. We criticize managers who only manipulate job manning and neglect work flow. The overmanning we criticized in the past was not done to increase work flow reliability. In fact, it usually made it worse. Further, the actual capacity of an additional worker often was either insignificant or negative. Very low percentages of paid labor time was spent actually working. Additional workers added congestion and increased demands on scarce resources (tools, information), resulting in further degeneration of labor utilization, to the point that despite apparent overloading, real capacity wasn’t sufficient to do the work that did happen to be available.
The point here is that we must learn to manage work flow together with ‘manning’ to increase both plan reliability and productivity.

Moving forward

Underloading is better than overloading because it helps improve PPC, which ultimately helps improve productivity. We need to learn how to better estimate capacity and its variability in order to underload just enough to assure high plan reliability. Since variability reduces with increasing PPC, that makes our task easier.

I recommend that you initiate all the actions needed to improve PPC (see first paragraph). Also, before adopting this new sizing criterion, examine your current plan failures to determine what percentage result from overloading, and also what percentage result from poor definition, unsound assignments, etc. Causes may be hidden behind intermediate reasons, so look closely. Please let me know what you find.

If analysis reveals sufficient opportunity, try the 90% loading and observe its impact on your productivity, on PPC, and on the productivity of downstream PUs. If several member companies participate, we can set up some kind of information sharing mechanism, perhaps through the LCI web page, via email, and/or side meetings at LCI functions. Let me know if you’re interested or if you have questions.
Aiming for Continuous Flow
LCI White Paper-3
March 5, 1999
Glenn Ballard and Iris Tommelein, LCI

Previous white papers were devoted to pulling materials to the jobsite (WP-1) and to underloading workers and equipment in order to increase their actual capacity to produce work (WP-2). This white paper is about structuring work processes, specifically about continuous flow processes (CFPs)—construction's 'assembly lines'.

TERMINOLOGY AND OBJECTIVES

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. The idea is to approximately balance 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 coordination burden on the 'central mind' and provides 'bubbles' of reliable work flow around which other work can be planned.

EXAMPLES OF CONTINUOUS FLOW PROCESSES

Consider the following examples of CFPs:

- interior wall rough-in
- finishing rooms of a hotel or hospital (painting, carpeting, etc. one unit after the other)
- excavating footings, placing formwork and rebar, then inspecting prior to placing concrete, and subsequently curing, stripping, and finishing
- excavation and shoring as in operations where lagging is placed in chunks of 6 feet or so in alternation with excavation
- setting, piping, wiring, and instrumenting process equipment

Key in these 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 tasks get repeated, and so on.

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: (1) data collection, (2) definition, (3) rough balancing, (4) team agreements, (5) fine balancing, and (6) change guidelines.
DATA COLLECTION

We need to know some things up front before we can design a CFP. We need information about the individual operations that are potentially involved in the CFP, and we need information on the relationships between those operations.

Individual operations are characterized by:

• work content
• method design (recognizing that this is precisely one thing that might be changed)
• setup time
• minimum resource unit (e.g., the minimum team for roughing in electrical overhead might be two workers with one scissor lift) (note that these may change with the redesign of operations)
• minimum process batch size (mostly determined by technical considerations such as having a room cleared for painting, but may vary with space needs)
• capacity (average installation rate) of the minimum resource unit with minimum process batches
• space and access need, protection requirements (e.g., spraying, noise, dust, etc.)
• variation in crew installation rate (note that variation can occur from processing error at the station, defective input from a supplier station or external supplier, differences in crew effort, differences in crew composition, or differences in the specific work to be done at a given time, the learning curve effect, and possibly other reasons)
• average and variation in installation rates for alternative process batches
• what materials are applied at the station? what are the batch sizes and space requirements for deliveries? what are the mean and standard deviation of on-time delivery rates for each type of materials?

While identifying the characteristics of individual operations, one needs to pay attention to available skill sets and equipment capabilities, yet not be misled by contractual or union boundaries, or other traditions that may constrain the view on operations.

Relationships between operations are characterized by:

• shared resources (e.g., crane or materials hoist, storage and work space, and access)
• buffer of WIP in-between them, prerequisite work in place

Figure 1 illustrates an operation with its crew, tools, and equipment needed to execute the method of choice. The production task also requires that prerequisite work be completed and that materials and directives be available. Figure 2 illustrates that there usually is a choice of pace at which the production task can be performed. This pace is set by the selection of a method and the associated resources.
Once descriptive data on individual production tasks and their alternatives is available, we can put different tasks together to form a system and see if it can be made into a CFP. Figure 3 illustrates a simple, linear sequence. This sequence is defined by output specifications (process dependencies), completion date, and possibly production rate (for coordination with downstream processes).

At first, production tasks will tend to be separated by buffers of inventory (Figure 3) and performed at different rates (Figure 4).
The team must decide which parts will be made into continuous flow 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 (e.g., in order to avoid creating an excessive number of joints, concrete is typically batched and placed at a rapid pace, relative to the time it takes to place formwork and rebar. It does make sense to build up an inventory of such formwork and rebar in place, prior to starting concrete work).

TEAM AGREEMENTS AND ROUGH BALANCING

The team must get together and define a strategy for moving through the building, recognizing that work content may vary from one location to the next. In the rough balancing stage, specific site constraints must be considered. For each production task:

- Create a project breakdown by area and component types.
- Select equipment and methods, identify those that will be shared.
- Define units of work (e.g., what will get done in a day) and identify work content per craft. Beware of craft jurisdictions!
- Size the crews to match the actual circumstances.
- Refine the methods design with actual crew in light of the site constraints.

These factors define the pace of the operations as work will progress to complete the project at hand. These decisions may yield a production schedule as illustrated in Figure 5.

Figure 5: Production Schedule Based on Strategy for Moving through the Building

Questions to be addressed are:

- To what extent can the operations be balanced, after exploration of redistribution of tasks?
- Which is the bottleneck operation(s)?

The decision to be made is:

- Which operations will or will not be part of a CFP?
FINE BALANCING

Once a CFP has been identified, the next step is to balance it, recognizing that each operation has two sets of drivers: (1) crew capacity and method (incl. resources, that is equipment and work space constraints) and (2) stuff coming from others, including prerequisite work, materials, and directives such as drawings and specs. (Figure 1).

To balance the system, compare throughput for each operation. The tricky part here is the conversion of units from one operation to the next, depending on the trade (e.g., hanging drywall is done by panel whereas painting is measured per unit area or per room). The best unit may be "one day of work" but this remains to be investigated. A critical consideration is the setup and cleanup times needed at the start and end of each day.

Adjust the crew sizes jointly with equipment and methods, to work faster or more slowly, provided the chosen method is a good one. Another way to expedite the process may be to redesign the operation (e.g., to reduce setup and cleanup time) or to restructure it so that the same amount of work gets done faster.

Balancing a system to achieve continuous flow preferably is done by assigning capacities, but is ultimately achieved by a combination of techniques including mutual adjustment, inventory buffers, and capacity buffers (Figure 6). Questions to be addressed are:

- Where to locate and how to size in-line inventory buffers? For example, a bottleneck process in the first position should be allowed to produce an output inventory prior to initiating remaining operations so the latter can operate without interruption.
- Where to locate and how to size inventory buffers of delivered materials.
- Where to locate and how to size capacity buffers? For example, differences or variations in processing rates may best be managed by sizing capacity at stations to accommodate the upper limit, thus 'wasting' capacity when work flow is not at that limit.

Balancing assumes a relatively stable load on each station and a relatively stable process batch. The entire line is governed as a single unit toward objectives of end date and delivery rate. Work gets passed from one production unit to the next in a first-in-first out manner. This will significantly reduce the scheduling effort if the variability of output is limited (also see the "Parade Game" paper).

![Figure 6: Aiming for Continuous Flow]
CHANGE GUIDELINES

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

RESEARCH TASKS

- Suggest other example CFPs.
- Document work methods, variability and ranges in their production rate as well as setup/cleanup times.
- Describe how site conditions may affect the execution of those methods.
- Collect data on capacity for various crew sizes and delimitation of work and required skills.
- Understand trade jurisdiction for those work methods.

REFERENCES

Construction operations, also called “work methods”, are the way the crew uses what they have to do work. Work methods appear simple enough as represented in the estimate: form, place, and strip. But within those cycles design is seldom detailed or explicit at the step or subcycle level. Under lean construction, the design of the product and the process occurs at the same time so factors affecting operations are considered from the first. Our aim is to make the design of the operation explicit and to assure the issues affecting the operation are considered at the most appropriate time.

Moving from the current state where the operation receives little attention to a full implementation of lean construction will require better understanding of how operations are designed today and then working to improve that process. For these purposes we can start by considering work method design in two phases. The first begins in product design and work structuring and continues until consideration by the last planner. The second phase carries forward from last planner consideration until the operation is completed.

In the first phase, which begins in design production and work structuring, decisions about the selection of materials, their joining, and configuration on site constrain the work method. For example, the choice of tilt up panels over masonry limits downstream choices about the work method. We have been tinkering with the idea that the first phase can be understood as a funnel where the surface of the funnel are the time, cost and quality boundaries. The
opening of the funnel is the range of solutions left. It decreases as time moves forward and decisions are made. In this image, downstream planners are progressively constrained while upstream managers hope that at least one acceptable solution remains within bounds.

The extent of choices on the design of operations

Confidence that a solution does exist increases through use of 3D CAD because it gives a clearer view of how the pieces might be assembled. The interdependence between product and process can be explored using computer models of the design so that work can be structured to best meet project objectives. Issues to be considered during this phase include:

- the design of the product itself,
- available technology and equipment,
- site layout and logistics,
- the size of work packages released to the crews,
- the size of work packages to be released to downstream crews,
- potential site environment factors (temperature winds etc),
- safety,
- the expected experience and skills of craft workers and supervisors,
- craft traditions or union work rules (to name but a few).

CAD cannot reveal factors such as the reliability of the planning system and the accuracy of early capacity allocation decisions that can affect the way work is done. For example, a pipe spool can be fabricated in a shop or on site. Site work may be required if inadequate shop capacity is available but may cost more. Marketing plans, proposals and cost estimates rest
on assumptions about the way capacity will be allocated and the work will finally be done, even though the determining details are far from resolved.

The funnel metaphor appears intuitively correct because all of the details are rarely resolved before the activity begins and most operations continue to evolve once underway. Process design, like product design, proceeds through examination and selection of options, moving from less to more detail. There is always some risk that progressive detailing will reveal impossible combinations of elements. The hope is that there will be some possible combination of elements that at least minimally satisfies design requirements. This image contradicts the view that there is one right or standard way to do work and suggests two strategies at the extreme. One is to leave as much flexibility as possible for the last planner. The opposite strategy would be to completely prescribe all details in advance and then assure that the planned for circumstance happens. (This may be another essential difference between the production phases of construction and manufacturing. In so far as construction is a prototyping process, the design of the operation will evolve. Once that stage is passed in manufacturing the details of the operation appear to be almost completely resolved. But of course Shingo teaches they are not – but the evolution takes years.)

There are obvious problems with designing construction operations under either strategy. Under the first, total flexibility makes planning and coordination with others difficult, and projections of cost or completion unreliable. In the second, early prescription ignores late developments. Although, following procedures established early and supported by intermediate planning might improve the reliability of workflow. We want to maintain as many acceptable options as possible within the constraints of facility type, location, stakeholder demands, applicable requirements, and customer needs. Just as with product design options, process design options progressively disappear as we move forward through time because we have overran the lead times of suppliers. For example, there are lead times for acquiring construction equipment, labor, permits, etc. A cost-superior alternative may not be feasible after a certain date because we can’t acquire what’s needed to implement that alternative and still meet the end date for the project. In addition to overrunning lead times of suppliers, we also may eliminate options by examination. We may not be able to use a certain forming technology because no local contractors have that skill or because it just doesn’t make sense for the type of walls we’re building. In fact, we may be able to specify the design for each operation in front end planning, but even so, there is more design work to be done within the detailed engineering phase (identification of steps, sequence, and resource requirements) and within the lookahead process (pace, batching, transfer requirements, buffer location and sizing, space management, etc.). And yet more design work to be done once the work package is released to the crew “Who’s getting the sand? Mike, you, and Ben do the prep work.”

This discussion raises related questions:

1. How should early decisions be made to maintain needed downstream flexibility or to assure planned circumstances occur?
2. In what circumstances and with what information should such consideration occur?
3. When should the details of the operation be considered?

LCI proposes that explicit consideration of the details of the operation occur in the lookahead process. Since method design is a reductive process the concept of last responsible moment should be employed so design issues requiring longer response times will be considered, and
that the timing for other issues be set so that essential factors driving the operation are still open. We suggest that First Run Studies be a routine part of planning prior to the start of new operations.

FRS conducted at this time may reveal that the last responsible moment has passed, or that all of the factors involved are not yet stable enough to support a complete plan. Both findings are important, the first for future planning, the second for completing the plan at hand.

Implementation of FRS moves forward the beginning of the 2nd design of operation phase, consideration by those directly involved. In the more typical circumstance, a foreman is assigned work and then confronts the circumstance on the ground. Most of the leverage is lost and planning for work can become coping with things missing or in the way.

The FRS planning meeting should occur 3-6 weeks before the start of a significant operation or class of work such as duct work, or stainless piping or plumbing trees. The meeting should include at least the lead worker, immediate supervisors and support. The meeting should produce a plan for how the work will be completed. The plan should be in sufficient detail to serve as a control document for the operation. The following check list can be used. The design process may be iterative so you can expect to revisit issues or take them in a different order. In any case, planning the way work will be done at the level of the steps or subcycle often results in a significant reconsideration of the way the operation will be completed and the effective capacity of the crew. In one example a crew placing 80 feet per day of 36” diameter reinforced concrete pipe improved their performance to 300 feet per day after 2 meetings. They removed the obstacles built into the way they were doing the work.

You may find much either has or should have been considered earlier or will or should be considered closer to the start of work. These findings should adjust your planning process. From a research perspective, these experiences will help us understand when is the best time to begin planning different aspects of the work.
Are we designing an operation at a workstation or a series of operations moving through multiple workstations? I.e., are we designing the installation of wall rebar or the process of building walls? Is the operation part of a continuous flow process, so that we must keep pace with others and are immediately dependent on an upstream station for prerequisite work; i.e., the key issue is balancing interdependent subcycles. Or, is the operation either independent or can be decoupled from providers of prerequisite work? The strategy for evolving operation designs presented later fits nicely here. Streamline each operation within a continuous flow process in order to ‘reveal’ latent capacity, then balance; as opposed to trying to balance flow across multiple workstations using historical data on capacity/productivity. In the process of streamlining, understand and minimize processing variability at each station, then incorporate either inventory or capacity buffers to accommodate remaining variability.

Turning from installation flow to supply flow: What variability exists in supply flows of materials and design information? To what extent can we act in the time available to reduce variability, and to what extent must we shield ourselves from remaining variability?

FRS/operations design is not limited to repetitive operations. Indeed, we recommend that all operations be subjected to FRS on each project. If selection is necessary for some reason, consider selecting critical, hazardous, and new operations for detailed planning and improvement in addition to repetitive operations. Repetitive operations obviously offer payback, but also most resist planning because everyone ‘knows’ how to do them already, unless they also fall under one of the other categories. Critical operations like heavy lifts have traditionally been planned to the gnat’s ass. Hazardous operations like enclosed space work have been planned somewhat, tho’ too little attention has been given to the actual steps to be performed as distinct from provision of pretest and safety gear. New operations obviously warrant planning because we can’t rely on what’s been done in the past.

**First Run Study Check List**

1) Requirements: What has to be done?
   a) Quantity & description
   b) Completion Date and Duration
   c) Budget
   d) Contract & specifications
      i) Inspection Criteria

2) Status of operation: What is the state of things?
   a) Plans to date - what is in place for the operation?
      i) Experiences from previous projects?
   b) Design Issues
      i) Is design clear and stable?
      ii) Reviewed for conflicts
      iii) Are there any questions or changes on the horizon?
      iv) Constructability - has the operation been considered for design changes to improve installation?
   c) Materials - available? familiar?
   d) Prerequisite work
   e) Space
      i) Access permits
ii) Storage
iii) Installation
iv) Environmental control
v) Other activities?
f) People
i) Skills
ii) Motivations
g) Tools & Equipment (You may find far fewer tools are needed as the plan becomes more considered and in detail.)
i) Energy sources

h) Safety - to be provided for by others or beyond installation crew?
i) Coordination with others - what is the status?

3) Sequence: How will the work proceed?
a) How many work fronts will be opened?
b) Where will the operation start?
c) Direction of progress?
d) Critical coordination issues or obstacles
   i) Decision hold/points
   ii) Alternates
e) Work release criteria for next step or operation?

4) Detail operation plan; Who stands where? Do we bolt pieces up and then lift, or lift then bolt?
a) Flow chart
b) Extent of prefabrication/pre-assembly
c) Safety concerns
d) Interactions (may be covered in other areas)
   i) Intermediate inventories
      (1) Size and purpose
   ii) Shared resources
e) Tools and equipment
f) Crew balance
g) Number of workers
   i) Special skills
h) Pacing and control tools
   i) Linear schedules or? {may want to distinguish a la Vorster between line of balance and linear}
i) Learning/evolution
j) Internal Flexibility
k) Hold points
l) Potential interferences/obstacles/impacts
m) Supervision plan concerns - what will they be looking for? monitoring progress?
n) Alternate work processes for special areas (how do we fit it in the corner?)

Once the operation is underway, the first few cycles should be observed closely and considered against the plan. Still photos of each step and video of the process are useful for
analysis. Cycle times should be recorded and any interference or deviations from the original plan noted (although in early studies such deviations are almost as likely to be errors in the plan as in the work). The resulting document should accurately describe the operation in a way the workers and lead hand can understand while providing enough detail and data to support business decisions for improvement. Typical studies include process, crew balance and flow charts. {I always require also a ‘flow diagram’, meaning a diagram showing how things move through space. I think we should stress here the importance of measuring and understanding variability in processing durations and arrival rates of inputs.}

**Thoughts on the Evolution of Operations**

Construction operations usually begin with significant uncertainty but implementation of FRS will reduce it. The product may be well defined (but it isn’t always) and all resources may be on hand and well organized (but they rarely are). The crew, with some guidance from senior supervisors and inspectors, works out the details of each sub cycle or step. The flow of work through an operation is often jerky and hesitant because people are learning as they go, the supply of resources is erratic, and the duration of sub cycles varies. On some sites, problems with resources so disrupt the operation that the crew simply works as each piece of work comes available. In this case there is little reason to improve or strive for any particular level of performance. Instead the operation unfolds in response to changing circumstances and developing skills instead of being actively designed.

Work methods appear to evolve in two dimensions along a predictable path. The human dimension is how well the crew understands the operation. The interaction between sub cycles is the primary technical issue. For example, interaction is high if the second step must wait on the first. Or interaction may be high if sub cycles share a common resource such as a ladder. Reducing interaction is one key to improving performance.¹

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Evolution of Construction Operations

This might be accomplished by inserting a surge pile or intermediate inventories between the steps or by providing two ladders so sub cycles can proceed independently. Low interaction means both sub cycles can continue without interruption from the other. (In a sense the Last Planner system of drawing assignments from workable backlog is built on the same principle. Here the workable backlog buffers installing work from variations in organizing the resources to do the work.)

The operation begins at point 1 because the crew does not completely understand all of the details of the work, and interactions between sub cycles are usually high, and throughput low. This does not mean the crew is untrained, rather that immediate circumstances such as the location of materials, the number and condition of tools, the skills and strengths of the crew must be considered as the method develops. The extent of interaction is related to the lack of familiarity of the crew with the operation and the fact that the inventory of work in progress has not accumulated at intermediate points. So the crew does one step at a time. While this may be slow, it is a prudent strategy which minimizes rework as the crew is less likely to embed errors if they move one item through all steps in the operation before breaking the crew into sub units. For example consider the impact of a crew unpacking and incorrectly assembling several hundred light fixtures. Errors are usually discovered when the product of one sub cycle or operation must be joined to another. It may be wise to assure the crew really is aware of potential errors before rushing into high production.

At the end of a few repetitions, point 2, the crew is much more familiar with operation and has sorted out most of the technical details. They may have installed a few intermediate inventories to reduce the need to transport materials. Thus the movement from point 1 to 2 is based primarily on learning.

But the sub cycles still interact to limit performance. The operation can be dramatically improved at this point if someone provides needed resources (ladders or s) and the permission to change the operation. Unfortunately this is rare as the pressure to produce the next unit locks the crew into the method at hand. This is an important factor in the development of operations. If the crew is under constant pressure to produce the next unit, they will never be
able to reorganize the operation and develop the intermediate inventories needed to reduce interaction. In many cases the pressure to complete arises from efforts to show progress for the control system or to release some small amount of work to the next crew.

Point 2 is the time to reorganize the operation to efficiently produce the last unit by breaking the operation into concurrent steps that do not interact. (This point may be reached far more quickly if the design and learning process follows the FRS pattern.) This causes the movement from point 2 to 3. At point 3 intermediate inventories have been installed but are only roughly sized to allow variations in sub cycle completion.

Movement to from point 3 to 4 is rare. Runs do tend to be short and often most of the repetitions are complete before point 3. Engineering information is the key to moving from 3 to 4 because it is only possible to optimize the operation when the unimpeded cycle times that determine the real capacity are known. It is then possible to reduce the intermediate inventories and move back to a tightly coupled state while still maintaining low interactions. Tight coupling and low levels of interaction mean rapid completion as throughput is high.

First Run Studies run studies speed the evolution of an operation as the movement between stages is not left to chance. The crew and entire production team comes to grips with the details of the operation in planning before mobilizing in the field. Areas of uncertainty can be identified in advance and decisions made on the coping and learning process to be employed. Often the crew can reduce the time spent in the initial learning phase of the operation by thinking through the details in an open discussion aided by simple graphics. The idea of interaction can be added to the study by drawing a process chart showing sub cycles and then exploring where intermediate inventories might be placed at the outset without risking quality. Raising the issue of intermediate inventories often changes how lead workers conceive work methods and increases their foresight. In most First Run Studies, the crew asks “How many of these cycles do we have to do?” This question is rarely asked when the operation is designed in the field as the apparent problem is completing the next sub cycle.

Planning helps the crew move from point 1 to point 2 and opens the possibility that the operation can be continuously modified to improve performance by moving from 2 to 3 and so on. In part this improvement occurs because the planning meeting allows people inside the crew and out a chance to offer their experience and insight. The response from the crews is usually enthusiastic. Their brains are engaged and they learn general principles that can be applied in future operations. As one worker said, “Before, no one ever asked us how we would do it right.” An additional benefit of First Run Studies comes with involving safety and quality control in the design of the operation instead of trying to inspect it in later. The documentation prepared in the course of completing a First Run Study provides a way to capture best practices and “remember” them for future projects.
DEFINITIONS

Production Unit (PU): an individual or group performing production tasks; the recipients of assignments.

Decoupling buffers: inventory between processes that reduces their interdependence, or excess capacity in one of two interdependent processes that allows work to flow reliably through both.

PRINCIPLES

§ Minimize and manage variability.
§ Integrate product and process design.
§ Structure for work flow through batching and buffers, with a preference for capacity buffers over inventory buffers.

TECHNIQUES

§ Team scheduling
§ Process/supply chain mapping
§ Locating and sizing buffers

WORK FLOW VS OPERATIONS

According to Shingo, process is the flow of materials between work stations (“production units” in the AEC industry), while operations are performed on materials at work stations. Operations actually shape or otherwise physically alter the materials being worked on, while they are only aggregated, disaggregated, or moved during process. This use of these English terms does not align very well with other accepted uses, but the distinction is clear nonetheless. We suggest using the term “work flow” to indicate what Shingo (or his translator) meant by “process”, mindful of his advice to first structure work flow, and only then turn to operations.

Work structuring is the most fundamental level of process design, answering the questions:

§ In what chunks\(^1\) will work be assigned to specialist production units (PUs)?
§ How will work chunks be sequenced through various PUs?
§ In what chunks will work be released from one PU to the next?
§ Where will decoupling buffers be needed and how should they be sized?

\(^1\)“Chunk” is preferred to “batch” because the latter is commonly used to indicate multiples of an identical unit. “Batch” will also be used on occasion when there is no ambiguity regarding composition.
When will the different chunks of work be done?

The objective is to structure for flow, not only task accomplishment and control, as with conventional work breakdown structures, use of which has encouraged suboptimization.

A central principle of today’s project management is: If every bit of work is done as quickly as possible, the project will be completed as soon as possible. This would be true only under the assumptions of the task or conversion view previously discussed in Chapter One. Adherents to the conversion view disregard work flow, the repetitive cycling that makes one production unit reciprocally interdependent with others, and the actuality of which makes their principle incorrect. When work flows through multiple production units iteratively, increasing the speed with which one PU processes work does not reduce total cycle time unless the other PUs can adjust accordingly. The conversion view conceives projects to be like relay races, in which the baton is exchanged only once. However, that is rather the exception than the rule. Production units move from phase to phase, from floor to floor, from unit to unit, from room to room, etc. In each phase, floor, unit, and even room, there commonly are multiple cycles of processing in which material or information flow from one PU to the next.²

DESIGN FLOW, SUPPLY FLOW, ASSEMBLY FLOW

Designing and making capital facilities involves three work flows. Schematically represented in the figure below are:

- two assembly flows, [Construction A-1, Construction A-2, and Construction A-3] and [Construction B-1, Construction B-2, and Construction B-3], intersecting in Construction C-1.
- flows of materials and design information to assembly PUs [Engineering A-1 and Procurement A-1 feeding into Construction A-1], [Engineering A-2 and Procurement A-2 feeding into Construction A-2], etc.
- flow of design/engineering information among the various specialists PUs involved in producing the design: [Engineering A-1, Engineering A-2, Engineering A-3] and [Engineering B-1, Engineering B-2, and Engineering B-3].

Note that design flow is circular, indicating its iterative nature, while supply flow is represented as a horizontal flow, and assembly flow is represented as a vertical flow.

² For an illustration of these concepts, see Tommelein et al.’s 1998 “Parade of Trades Game.”
Supply chains or networks are established production systems. Construction projects create temporary factories dedicated to assembly and testing. These temporary factories get their materials and components from these preexisting supply chains. Understanding how work flows through these chains is essential in order to structure work for flow.

Some materials and components are produced to stock because the demand for them is sufficiently predictable and because they have standard designs. Others are produced to order and are custom designed. Wallboard is produced in transportable pieces and can be easily cut into whatever shapes are needed. Some curtain wall systems are predesigned and can be acquired with relatively small lead times. However, curtain wall systems requiring custom design, the manufacturing of selected stone cladding, and the design and manufacture of dyes for extruding aluminum frames have long lead times and are vulnerable to changes in design and to precision of structural installation. Many construction materials are custom designed and fabricated; e.g., structural steel, precast concrete structures, industrial piping, rebar, concrete, some windows, and even some types of process equipment such as air handling units and chillers.

Project by project, work structuring applies to the temporary assembly factory and to the project design process. Another work structuring task, not necessarily linked to a specific project, is to understand and streamline those production networks supplying fabricated items to projects. We have found that fabrication chains tend not to have undergone the lean revolution, but rather remain batch and queue processes. As such, it is not surprising to find that materials spend much more time waiting in queues rather than being fabricated. Structuring fabrication shops for flow is perhaps the most immediate application of lean principles precisely because they are types of manufacturing.
ORGANIZING FOR WORK STRUCTURING

It is preferable to jointly assign iterative processes to that team of specialists among whom the work flow cycles. Given its design and consequently iterative nature, work structuring should also be jointly assigned to the entire production team, including design, supply, and installation specialists. Otherwise, vital knowledge will be missing about skills, capacities, component availability, fabrication or assembly technologies, etc. In addition, the iterative work structuring process will be stretched out over time.

This is not to say that all work structuring/process design decisions must be completed before designing or making can proceed. If the team is confident that constituent processes can be internally structured to fit technically and temporally with upstream and downstream processes, that internal structure can be designed later by those directly involved. This is similar to contracting a work scope to be completed within a given schedule window, except, in this case, scope is specified in terms of process, with specified inputs and outputs, in addition to time constraints.

Traditional roles and relationships are changing as the industry moves toward a lean delivery process. We suggest the following basic roles:

- client
- planner/controller
- design specialist
- specialty contractor
- supplier

The production management role of planner/controller may not align with control of project finances. Indeed, some consortia of specialty contractors have hired their own planner/controller, reversing the traditional relationship. In the memorable words of an attendee at a Lean Construction Institute seminar, “You mean the fleas are gonna hire th’ dawg?”

In the lean delivery system, specialty contractors move upstream into the design team. Integrating specialty contractors and design specialists into a team effectively producing a design is a key challenge facing the industry as it turns towards the lean model.

TYPES OF WORK FLOW COORDINATION

Production systems are made up of production processes, which in turn consist of operations. An operation transforms information or materials from an original state into a desired state. One process is separated from another process by a buffer, usually an inventory of information or materials. Within processes, there are either no or small inventories between operations. Work flow in production systems may be coordinated in a number of different ways, including:

- schedule push-long lead items plus work scopes only loosely integrated with the bulk of the facility
- plan pull-materials and design from offsite to onsite
- continuous flow-installation and testing
To this list might be added a fourth type of work flow coordination: team design, in which team members engage in a type of negotiating process and coordinate their actions by mutual adjustment (see Mintzberg’s *Structure in Fives*).

Continuous flow processes (CFPs) are production networks through which work is advanced from PU to PU on a first-in/first-out basis. Decoupling buffers indicate the boundaries of CFPs. CFPs need not be designed in detail at the beginning of a project unless needed to assure the feasibility of commitments to achieving milestones.

In continuous flow processes, ready work exists ahead of a PU in the work released to it by the preceding PU. For example, a crew of electricians could be released that amount of rooms (perhaps 8) they are able to rough-in each day. Eight rooms is the batch size for that PU in that assembly process. In addition, a materials buffer should be maintained, sized to accommodate variability in material deliveries to the PU. In the example given, the materials buffer would contain switch boxes, conduit, wire, fittings, etc. The size of material buffers can be reduced through more frequent deliveries; i.e., through smaller delivery batches. Obviously, it is preferable to reduce the size of material buffers by reducing the flow variability they are designed to accommodate.

Assembly processes that are loosely coupled with downstream assembly operations typically use much larger batch sizes of released prerequisite work. A pipefitting crew may have released to it a piping activity area containing a reactor, three pumps, and a compressor. The electrician crew that follows them may not be allowed to work in the area until all piping is completed. Obviously, reducing batch sizes is desirable because it allows what amounts to an overlap of the two crafts, but depends on the reliability of future releases to the pipefitter PU.

WORK STRUCTURING (PROCESS DESIGN) AND PRODUCT DESIGN

- Design criteria for both are generated from customer needs
- Simultaneous evaluation of what and how to build against design criteria

Interdependence of product and process design decisions; e.g., glass curtain wall system may be technically incompatible with stick-build site fabrication; multiplanar auditorium design may not be constructable by available contractors; Italian marble fits customer needs perfectly as regards facility appearance, but cannot be procured in time to meet the desired end date.

WORK STRUCTURING PROCESS

Work structuring is a complex process. It includes the following sub-processes, which generally occur in the order listed:

- chunking
- sequencing
- releasing
- decoupling
- scheduling
The objective is to anticipate and prepare for design, procurement, fabrication, logistics, installation, testing, start-up, operations, maintenance, modification, decommissioning, and disposal. What principles or objectives should govern the structuring of work? Objectives might include:

- group work together that is to be done by the same resources either at the same time or sequentially,
- assign iterative design tasks collectively to the team having the needed resources,
- avoid throw-it-over-the-wall behavior, and generally,
- pursue the lean ideal of providing a custom product in zero time with nothing in stores.

Relevant principles include those stated at the beginning of this chapter, and also: Simplify the coordination task by assigning related work to single production units.³

**CHUNKING**

Chunking is decomposition of wholes into parts. Both product and process are decomposed into chunks. The artefact to be designed and built is divided into the systems, sub-systems, and components which provide desired or required functionalities and properties. The processes of design, supply, and assembly are divided into temporal phases, the completion of which deliver the product. Typical work structure levels for assembly work flow are⁴:

- Facility/Project
- Phase
- Module
- Work Package/Operation
- Assignment

Wortmann et al. (1997) propose the following engineering (design) work flow control points:
1. the customer’s functional requirements specification
2. functionalities and design criteria for artefact systems
3. general specification of the geometry and composition of artefact systems
4. detailed specification of the geometry and composition of artefact systems
5. fabrication and assembly instructions for non-standard components and sub-assemblies.

Perhaps it can be agreed that the design process includes: 1) determining design criteria for product and process, 2) conceptual design of the product, 3) detailed design of the product; i.e., engineering and production processes consist of a set of production steps (operations) to be completed in a given sequence. Group sequential production steps into a single process when the same resource capacity is used and there are little or no intermediate waiting times. (from Wortmann et al. 1997).

³ Halpin and Riggs (1992) propose the hierarchical levels of project, activity, operation, process, and work task. Project schedules are made up of activities, each of which may consist of multiple operations, such as form-rebar-pour for placing concrete walls. Operations in turn are made up of multiple tasks. For example, forming involves measuring and layout, collecting or fabricating materials, building the formwork, and bracing the formwork.
integration of the product systems, and 4) process design. Work structuring of design flow specifies the interface between and the work flow within these mega-chunks.

**Determining Design Criteria for Product and Process** is referred to with different terms, including “design brief”, “project definition”, “programming”, and “front end loading”. Most agree on the importance of understanding the customer’s business case or the user’s intended use. There may, however, be multiple customers within a single organization. Consider an industrial plant. Often corporate engineering oversees design and construction of capital facilities projects. Marketing has sold the project. Financial managers are concerned with ROI. Facilities management is concerned with operating costs and maintainability. Operating groups that are to use the facilities come closest to a classic definition of ‘customer’ because they are concerned with functionalities and capacities of the facility.

Beyond customers, there are other stakeholders. It is critical to understand the demands of regulatory bodies, zoning and permitting commissions, property managers, leasing agents, environmental advocates, etc. It is also important to understand which of the stakeholder demands are negotiable and which are not.

What are the applicable requirements? Codes, standards, and laws are the prime candidates, but even here alternatives often exist. For example, codes specify structural requirements for wind loading, but necessarily are conservative, lacking exact load information for a specific location and facility configuration. Wind tunnel testing of models can often be used to relax the requirements by producing more exact load information.

Stakeholders and requirements are often linked to the location of the facility. Once location is known, the governing bodies and codes, soil conditions, wind loads, seismic zone, etc. can be determined. These data on local conditions, added to knowledge of requirements, stakeholder demands, and customer values constitute a requirements set for the design. The next step is to translate those requirements into engineering specifications; i.e., to translate from the voice of the customer into the voice of the engineer. Quality function deployment and related tools and techniques are available for this purpose and will be further developed through experience and research in the near future.

The primary chunks in this phase are: 1) determining requirements, and 2) determining design criteria. However, as shown in the figure below, this phase cannot normally be completed without some examination of alternative product and process designs at the conceptual level. Customers may not fully understand either the consequences of their desires or the alternatives available to them.

Consequently, this first design phase is above all a combination of investigative work and ends-means negotiation.

In the delivery process, work flows generally from left to right through linked triads, within which the flow is iterative through multiple loops. For example, Requirements (customer needs, stakeholder demands, etc), Design Criteria, and design Concepts/Technologies are tightly interlinked. Although there is a general movement from Requirements to Design Criteria to Concepts/Technologies, it is not feasible to define Requirements without confronting stakeholders with alternative products or product characteristics. Further, it typically requires several such travels through the trio in order to be assured that inapplicable concepts have been eliminated.
Once design concepts and technologies are selected to be carried forward, Concepts becomes part of the second triad along with Work Structure and Components, which also requires several iterations to complete. The idea of carrying forward multiple design concepts and technologies comes from Set Based Design. The potential benefit of Set Based Design is to increase customer value by doing a more thorough examination of alternatives, as opposed to the traditional practice of selecting as quickly as possible a single alternative to be further detailed. Too often, that single alternative has been promoted by designers for reasons other than increasing customer value.

Alternatives can be maintained as long as there is sufficient lead time for acting on them. One reason for understanding supplier lead times is so that design decisions can be made before the alternatives die.

Once Components are selected, that initiates the third triad: Components, Detailed Engineering, Purchasing/Fabrication/Delivery. Components may be items of equipment, prefabricated items, or materials. For example, the decision may have been made to use a central chiller, but the selection of the specific chiller has yet to be made. Again, a certain visual appearance of the building may have been decided, but specific materials have to be selected to provide that appearance.
Component selection is contingent upon the ability to integrate those components into facility systems and to integrate facility systems into the facility. Consequently, a component preferred for its visual impact may be rejected because of the difficulty it poses for facility operating costs or buildability. Components and materials are procured from supply chains, most of which exist independently of the project. The price, lead time, or logistics of those supply chains may not fit with project needs.

The fourth triad is initiated when the Components are delivered to the site and concludes with Post Occupancy Evaluation and Feedback to the beginning of the process.
No model is perfect. This one conceals the fact that learning and feedback does not wait for the facility to be occupied. Other properties not made explicit include the concurrent design of product and process in the second triad and also the fact that control of work flow through this entire process is initiated as soon as a rudimentary plan is developed.

**SEQUENCING**

Sequencing determines the order in which chunks at the various work structure levels are processed. The big idea is to work backwards from desired result to beginning, attempting to flush out unnecessary and untimely activities, and attempting to structure the flow of design and materials to the site to best support installation. The relevant guideline is to only do work that allows someone else to do work.

Work structuring produces:

- Work elements at various structural levels
- Process flow diagrams
- Execution strategies
- Master milestone schedule
- Initial lookahead schedule

Execution strategies may be directed at a number of different objectives:

- Procurement-forming the team; early involvement of downstream players in upstream decisions.
  A constraint on team formation may be selection of specific facility system technologies such as steel versus concrete structure. Consider involving either a single supplier that can deliver either alternative, or getting proposals from suppliers of each.
Process flow diagrams are useful tools for sequencing chunks because they visually display possible sequences that can be examined and redesigned. Process flow diagrams may differentiate between various types of inputs. For example, in the Fire Sprinkler diagram below, the intent was to show criteria governing the process or its outputs in circles entering the process rectangle from the top. Inputs to be processed or converted into outputs were to be shown in circles entering from the left side of the process rectangle. The bucket shape was used to indicate a decoupling buffer; in this case, the materials stockpiled at the site.

Process flow diagrams and schedules are best created by a team drawn from those who are to do the work being diagrammed. Diagramming involves deciding how to decompose the work into parts and also decisions about execution strategies/sequencing, release criteria, and decoupling buffer location and sizing. Goals include 1) grouping iterative tasks for joint assignment to the PUs involved, and 2) structuring operations in continuous flow processes (CFPs) to distribute and simplify control. Iterative or looped design tasks can be identified by use of the design structure matrix (DSM).

5 See Chapter 4 for a discussion of the various types of process models and techniques available.
RELEASING

Release rules and criteria specify the conditions in which chunks of work move between PUs. Release rules and criteria can be shown as annotations on the diagrams. Schedules result from the application of available capacities and desired milestones to process flow diagrams.

The fundamental release rule is: Release A only if A meets applicable criteria. Typically criteria include the quality characteristics of A. In pull systems, criteria also include the readiness of downstream PUs to receive A.

Releasing work to PUs:
- In continuous flow processes: releasing is equivalent to assigning. Example: 8 rooms released today are the assignment for the electricians to rough-in tomorrow.
- In noncontinuous processes, work is released into workable backlog from which the PU may select assignments. Example: pipefitter crew selects piping isometrics to install within released activity areas.

DECOUPLING

Decoupling buffers are necessary when work flows cannot be synchronized. This occurs when there is variation in processing or delivery rates, when there are differences in rates, or when the way in which work is batched for moving or processing changes from one PU to the next.

Wollmann et al. (1997) propose the following criteria for determining release points and decoupling buffers:
- Reducing uncertainty: Monitor work flow at points where variability is expected. Place buffers at these points to isolate subsequent phases or process from uncertainties in the previous phase or process.
- Presence of a resource capacity bottleneck: It is important to maximize utilization of bottleneck resources because they control the rate of flow (throughput) through the production system. Decoupling buffers should be established both before and after bottlenecks.
- The product structure: Some design, supply, or assembly outputs may be needed before others. Requiring an explicit release at these points assures that the actual timing and sequence of work is known.

Decoupling buffers, along with chunks and their sequences, may be located and sized on process flow diagrams. For example, see Rother and Shook’s Learning to See.

Deliberately maintaining excess capacity is part of a strategy for increasing capacity (see LCI White Paper-2). In addition, excess capacity may be necessary simply in order to maintain a desired production rate or sequence. This is the case when delivery (of materials) or release (of prerequisite work) rates are so variable that they cannot be effectively buffered with inventories. In such cases, it may be necessary to simply maintain sufficient labor and tools to absorb a varying work flow.

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6 See Chapter 5 for a discussion of pull and push systems of work flow control.
Obviously, it is preferable to reduce variability, but in certain instances, that may not be possible within the time available.

Capacity buffers are also preferable to inventory buffers when time is at a premium. While true that unused productive capacity can never be recovered, it does not add to project durations. Indeed, use of capacity buffers to speed work flow can reduce project durations. AEC industry players have thus far tended to use capacity buffers only when the cost of unused capacity was to someone else’s account.

The issue of buffer location, type, and sizing is of enormous importance for our industry. Prior to the advent of lean thinking, it has not been unusual to see buffers located suboptimally as a result of a single PU attempting to protect itself against unreliable work flow. For example, Howell and Ballard (199QQ) found that contractors doing plant work routinely demanded earlier and earlier delivery of fabricated pipe spools relative to installation dates, resulting in huge piles of stuff at job sites and substantially lengthening project durations—not to mention increasing the frequency of late and costly design changes by robbing engineering of time to get their work completed properly.

**SCHEDULING**

The norm in current project management is to produce a detailed schedule early in a project, then use that schedule to coerce behavior into conformance by appeal to contractual obligation. Various levels of detail can be shown, but these are all views of the one schedule. Further, the customary focus on enforcing what SHOULD happen is not often paired with equal attention to causing or determining what work CAN be done. As a consequence, commitments regarding what work will be completed and released to other production units often cannot be relied upon. Indeed, the very concept of commitment is conflated with the signing of the contract or acceptance of the assignment. We see the need to enrich the language of project planning and control. A production management system surely should identify what work SHOULD be done, what work CAN be done, what work WILL be done, and the work we actually DID.

It has been our experience that a single schedule produced at the beginning of the work to be done is insufficient for all but the simplest and shortest projects. A hierarchy of schedules is needed because of uncertainty. In dynamic conditions, detailed scheduling must be done near in time to the activities being scheduled. Consequently, as shown in the figure below, we differentiate between three types of schedules, each having their own specific purposes and functions:

- A Master Schedule specifies SHOULD at a milestone level.
- A Lookahead Process creates CAN by making activities ready and matching load and capacity.
- A Weekly Work Plan expresses commitment to what WILL be done.
Planning System

Items are allowed to enter, advance, or remain in each level of the hierarchy in accordance with different rules, which reflect their different functions.

Entry Rules

- Rule 1: Allow activities to remain in the master schedule unless positive knowledge exists that it should not or cannot be executed when scheduled.
- Rule 2: Allow activities to remain in the lookahead window only if the planner is confident that it can be made ready for execution when scheduled.
- Rule 3: Allow activities into weekly work plans only if all constraints have been removed.

Producing the master schedule, and initial phase and lookahead schedules

Scheduling consists of organizing the process flow diagram on a timeline. In the lean construction model, the master schedule is not a detailed control document, but rather has the following purposes:

- Demonstrate the feasibility of completing the work within the available time.
- Develop and display execution strategies.
- Determine when long lead items will be needed.
Identify milestones important to client or stakeholders.

The typical level of detail recommended for the master schedule is modules within phases. Further detailing of work packages and operations within modules is usually best done in the lookahead process, within approximately six weeks of the start of the operation. This should again be done by the team involved directly in the work being planned. This merges into operations design with the inclusion of First Run Studies in the lookahead window (see Chapter 5).

As with all design, process design tends to be iterative. Chunking, sequencing, releasing, decoupling, and scheduling may be completed only after multiple cycles. An initial decomposition into chunks may need to be changed to allow a preferred sequencing. In the same way, a given sequencing of chunks may be changed in response to limited capacities or unacceptable task durations.
Flow Driver - A System For Reducing Fabricator Lead Time

LCI White Paper - 6
31 July 1999

by Todd R. Zabelle and Glenn Ballard
Lean Construction Institute

Introduction

The superiority of pull-based production systems over traditional batch and queue (mass) is evident and resulting in the transformation of several industries. In White Paper-1 we presented the benefits of pull-based production for AEC projects. In that paper we proposed that in order to use pull-based systems on AEC projects, a window of reliability greater than supplier lead-time must be obtained. The Last Planner system of production control was created to increase the window of reliability, which subsequently will exceed the lead time for acquiring most commodity materials; i.e., those available off-the-shelf. However, a large number of components are fabricated to order and typically have lead times of 4-12 weeks; far exceeding current reliability windows. Consequently, it will be necessary to reduce those lead times. This paper presents the conceptual framework for Flow Driver, a process for reducing fabricator lead time.

Background

Over the past year, members of LCI’s staff have visited several fabrication facilities (fabricators) to better understand current production practice amongst those supplying finished goods (materials) to the AEC industry. All but one, Trane Manufacturing, are using some form of traditional batch and queue (mass) production. During these visits Glenn Ballard is often heard stating “We only have seen one type of fabricator regardless of the goods being produced.” Almost always the obligatory presentation of the firm’s history indicates that their present production process has evolved over the years with little or no attention paid to systems development. When asked if they have considered the application of lean production, each of them has proven to be unfamiliar with the topic. It seems at this point safe to say that many, if not most, of those producing materials for the AEC industry have had little if any exposure to contemporary production theory.

Initial performance metrics derived from these visits are as follows:

- Queue time far exceeds processing time
- Batches are processed in the largest size possible
- An effort is made to locally suboptimizing process or work station

Hypothesized reductions in lead time are:

- Fabricated steel reduced from ten weeks to two weeks
Air-Handler units from sixteen weeks to five
Industrial piping from six weeks to two

Discussion - Why are we where we are?

If such performance improvement is obtainable one must inquire as to why lead times are so long and what keeps us from reducing them. It seems that several issues are at hand. The most apparent are the “throw it over the wall” work flow mentality, purchasing on low price without considering supplier performance, and poor plan reliability at the assembly site. These issues, coupled with evolution of distribution channels, form what Jim Womack termed “The lack of a social basis for collective analysis of the overall industry value stream.”

Prior to addressing business models and distribution channel evolution we must first however develop the necessary processes to improve performance. Once the processes are developed and tested we will be better able to identify the business model issues that need to be addressed.

Improving Performance Through Flow Driver

Based on our observations to date we are of the opinion that opportunity for improvement abounds at the majority of fabricators serving the AEC industry. Through the application of four simple tools; work mapping, analysis, compression and prototyping we can begin to move closer to our goal of a window of reliability greater than material lead time. The following is a step by step guide for the improvement of a fabrication process.

Step One - Work Mapping

Describe the current state of the fabricator’s process through the application of LCI’s Work Mapping language. Draft the overall facility layout, routing of information and materials and location of suppliers providing raw materials to the facility. Include the fabricator’s order acquisition and order forecasting processes. Confirm the accuracy of your map with fabricator personnel. {ADD A SCHEMATIC WORKMAP AS AN EXAMPLE}

Step Two - Analysis

Enter performance metrics. Determine the dominant products or product families. Record processing times, queue times, work-in-process (WIP), defect rates, rework durations, set-up times, transfer batch sizes, process batch sizes, cycle times for key items or types of fabrication, throughput rates and capacities. Identify bottlenecks and their utilization rates. Document the directives or goals that govern batch sizing. Supplement quantitative measurement data with

1 During our visit to a steel fabricator our host explained that in the early half of the century structural steel was rolled and fabricated by the same firm. He stated that the standard in-process time from rolling to erection for a large structural member averaged forty eight hours. He went on to state that over capacity of mills resulted in fabrication only firms. After awhile the distribution channels evolved to reflect the current state. (mill, fabricator and erector)
interviews of facility personnel. Note quality performance (defect rates), lead time, and on-time performance of vendors providing raw materials to the facility.

Step Three - Compression

Develop a future state map by considering the application of the following actionable items.

1. Clean and clear.
2. Expand bottleneck capacities to increase system capacity.
3. Establish decoupling buffers before and after bottleneck processes to take best advantage of available system capacity.
4. Implement pull techniques such as kanban or conwip to reduce work-in-process (WIP); e.g., reduce the space between machines to limit intermediate inventories and reduce material handling time.
5. Reduce rework by implementing poka-yoke (mistake proofing) techniques.
6. Reduce set-up time through the application of SMED (single minute exchange of die) techniques.
7. Reduce transfer batch sizes.
8. Reduce process batch sizes where appropriate.
9. Organize production in cells using group technology and multi-skilled workers.
10. Improve supplier quality and delivery performance.
11. Increase the accuracy of the demand forecasting system.

Step Four - Prototyping

Though the compression strategies will result in improved profitability and cash flow for the fabricator, the actual cost of the implementation is such that mistakes must be avoided. This can be done through the use of several prototyping tools such as future state Work Maps, mathematical models and discrete event simulation. {EXPAND-add Iris’ pull model as an example of discrete event simulation}

Conclusion

In order to use pull-based systems on AEC projects a window of reliability greater than supplier lead-time must be obtained. This is achieved by improving plan reliability and reducing lead time for supply. This paper presents the conceptual model for Flow Driver, a technique for reducing fabricator lead time based on four tools: work mapping, analysis, compression and prototyping. As with the implementation of any lean production based process the current business drivers must be understood and altered. This is the topic of future white papers. In the meantime your thoughts and ideas are appreciated.
Phase Scheduling
LCI White Paper-7
April 27, 2000
by
Glenn Ballard

LCI recommends using pull techniques and team planning to develop schedules for each phase of work, from design through turnover. The phase schedules thus produced are based on targets and milestones from the master project schedule and provide a basis for lookahead schedules.

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 to only do work that releases work to someone else. Following that rule eliminates the waste of overproduction, one of Ohno's seven types of waste.\(^1\) Working backwards from a target completion date eliminates work that has customarily been done but doesn't 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 work they must perform in order to release work to others or work 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. Usually, planning 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.\(^2\) We first want to produce an 'ideal' schedule.

The team is then invited to reexamine the schedule for logic and intensity (application of resources and methods) in order to generate a bigger gap. Then they decide how to spend that time: 1) assign to the most uncertain and potentially variable task durations, 2) delay start in order to invest more time in prior work or to allow the latest information to emerge, or 3) 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 to deliberately and publicly generate, quantify, and allocate schedule contingency (float).

Once the team has agreed on the phase schedule, the schedule and the activities represented on it have the force of contract and can only be changed under three conditions: 1) the prime contract changes, 2) activities on the schedule cannot be performed without violation of Last Planner system, and 3) workable backlog tasks may not release work, but are only to be used as necessary to maintain resource utilization and continuity, and is not to be used if doing that work now makes later work more difficult or hazardous.

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\(^1\) Workable backlog tasks may not release work, but are only to be used as necessary to maintain resource utilization and continuity, and is not to be used if doing that work now makes later work more difficult or hazardous.

\(^2\) 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.
Planner rules\(^3\), or 3) 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.

Member companies are encouraged to try the following phase scheduling process and to share results. For further information, please contact Glenn Ballard at 888/771-9207 or via email at <ballard@ce.berkeley.edu>.

**Purpose of Phase Scheduling**

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.

**Participants**

Representatives of those with work to do in the phase. For example, a team working to schedule a construction phase would typically involve 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 maybe the contract.

**Process**

1. Define the work to be included in the phase; e.g., foundations, building skin, etc.
2. Determine the completion date for the phase, plus any major interim releases from prior phases or to subsequent phases.
3. 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.
4. Apply durations to each activity, with no contingency or float in the duration estimates.
5. Reexamine logic to try to shorten the duration.
6. Determine the earliest practical start date for the phase.
7. 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.
   Note: this is contingency you intend to spend, unlike budget contingency.

\(^3\) 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.
8. Is the team comfortable that the available buffers are sufficient to assure completion within the milestone(s)? If not, either replan or shift milestones as needed and possible.

9. If there is excess time available, decide whether to accelerate the schedule or use the excess to increase the probability of on-time completion.

Techniques to consider

- reduce batch sizes
- do First Run Studies
- sequence for flow
- structure for resource continuity
- historical PPC analysis
Lean Project Delivery System  
LCI White Paper-8
September 23, 2000 (Revision 1)

by

Glenn Ballard

LCI’s mission is to develop a new and better way to design and build capital facilities. We call that new way the Lean Project Delivery System (LPDS). Our current LPDS model consists of 13 modules, 9 organized in 4 interconnecting triads or phases extending from project definition to design to supply and assembly, plus 2 production control modules and the work structuring module, both conceived to extend through all project phases, and the post-occupancy evaluation module, which links the end of one project to the beginning of the next.

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1 R/1. © Lean Construction Institute, 2000. All Rights Reserved. R/0 published 5/1/00. R/1 adds Work Structuring as a separate module.

2 Research Director, Lean Construction Institute 510-530-8656 or ballard@ce.berkeley.edu
The Project Definition phase consists of the modules: Needs and Values Determination, Design Criteria, and Conceptual Design.


Lean Supply consists of Product Design, Detailed Engineering, and Fabrication/Logistics.

Lean Assembly consists of Fabrication/Logistics, Site Installation, and Testing/Turnover.

Production Control consists of Work Flow Control and Production Unit Control.

Work Structuring and Post-Occupancy Evaluation are thus far only single modules.

The LPDS will be developed as a philosophy, a set of interdependent functions (the systems level), rules for decision making, procedures for execution of functions, and as implementation aids and tools, including software when appropriate.

The domain for the LPDS is defined by the intersection of projects and production systems. We call this domain project-based production systems. Some LPDS modules will be applicable to projects that do not involve the designing and making of artifacts, and possibly also applicable to some types of production systems that are not executed through projects. For example, the production control modules may be applicable to project management generally, and also to all production systems driven primarily by directives rather than by predetermined routings between processing steps or machines. Even so, the LPDS will apply as a whole specifically to temporary production systems such as those used for new product development or capital facilities. Essential features of LPDS include:

- the project is structured and managed as a value generating process
- downstream stakeholders are involved in front end planning and design through cross functional teams
- project control has the job of execution as opposed to reliance on after-the-fact variance detection
- optimization efforts are focused on making work flow reliable as opposed to improving productivity
- pull techniques are used to govern the flow of materials and information through networks of cooperating specialists
- capacity and inventory buffers are used to absorb variability
- feedback loops are incorporated at every level, dedicated to rapid system adjustment; i.e., learning.

Work Structuring

1. "Work Structuring" is a term created by LCI to indicate the development of operation and process design in alignment with product design, the structure of supply chains, the allocation of resources, and design-for-assembly efforts. The purpose of work structuring is to make work flow more reliable and quick while delivering value to the customer.

2. Work structuring is the most fundamental level of process design, answering the questions:
   - In what chunks will work be assigned to specialist production units (PUs)?
   - How will work chunks be sequenced through various PUs?
   - In what chunks will work be released from one PU to the next?
Where will decoupling buffers be needed and how should they be sized?
When will the different chunks of work be done?

Work structuring decisions are made in all project phases. For example, decisions regarding supply chain structure may be made in the project definition phase, while seemingly small details like the selection of a specific component in detailed engineering can impact how work flows within the assembly process.

Production Control

1. "Last Planner" is the name for the LCI's system of production control.
2. Production control governs execution of plans and extends throughout a project. "Control" first of all means causing a desired future rather than identifying variances between plan and actual.
3. Production control consists of work flow control and production unit control. Work flow control is accomplished primarily through the lookahead process. Production unit control is accomplished primarily through weekly work planning.
4. Front end planning belongs to the project definition and design phases of projects. One of the products of front end planning is master schedules. Master schedules serve specific purposes; e.g., demonstrating the feasibility of project completion by target end date. Those purposes or functions do not require a high level of detail, which most often is inappropriate because of uncertainty regarding the future.
5. Master schedules are expressed at the level of milestones, typically by phase.
6. Phase schedules are produced by cross functional teams using pull techniques near in time to the scheduled start of the phase.
7. Phase schedules feed into lookahead windows, usually 3 to 12 weeks in duration.
8. Lookahead processes make scheduled tasks ready for assignment. Such tasks are placed in Workable Backlog.
9. Tasks are allowed to maintain their scheduled starts only if the planner is confident they can be made ready in time.
10. Scheduled tasks are made ready by screening for constraints, then by assigning make ready actions to remove those constraints.
11. The lookahead process generates early warning of problems so there is more time to resolve them.
12. Weekly work plans are formed by selection of tasks from Workable Backlog.
13. Every effort is made to make only quality assignments; i.e., those that are well defined, sound, in the proper sequence, and sized to capacity.
14. The percentage of planned assignments completed (PPC) is tracked and reasons for noncompletions are identified and analyzed to root causes. Action is taken on root causes to prevent repetition.

Project Definition

1. The project definition phase will be managed by the project manager responsible to the client for the entire project, including both designing and building.
2. The project manager may use traditional sources as inputs, such as architectural programming, but such inputs will be integrated with others, including post-occupancy evaluations.

3. Costing and project duration estimating will be integrated with the production of the project definition, rather than being done after the definition is produced.

4. When appropriate\(^3\), a target cost will be established for the facility to be designed. Otherwise, the client will make a decision regarding cost within the definition process.

5. Design criteria for both product and process will be produced.

6. Multiple conceptual designs will be generated and evaluated. When appropriate, more than one will be carried into the Lean Design phase.

7. Conceptual designs will be generated and evaluated in a dialectic with Needs Determination and Design Criteria development.

8. The project definition process will include an explicit information collection and documentation process.

9. Needs will be translated into design criteria using techniques derivative from Quality Function Deployment.

10. Collaborative production and decision making will include clients and stakeholders; e.g., design and construction specialists; suppliers of materials, equipment, and services; facility operators, maintainers, and users; representatives of financiers, insurers, regulators, and inspectors.

11. Work structuring will be applied in the project definition phase in the production of rough cut strategies and plans for project execution, linked to product architecture options, in advance of the more detailed integration of product and process design to be accomplished in subsequent phases.

12. Production control will be applied in the project definition phase once a plan for the phase has been developed. The first plan may be no more than fitting the steps of the project definition process within the available start and completion dates.

13. Project Definition transitions to Lean Design when there is alignment between:
   - customer needs and stakeholder demands
   - design criteria for product and process
   - conceptual design(s)

**Lean Design**

1. The Lean Design phase develops the conceptual design from Project Definition into Product and Process Design, consistent with the design criteria produced in Project Definition.

\(^3\) Target costs are appropriate when the facility is analogous to a product to be sold. Such is the case for clients whose business case is based on a return-on-investment strategy; e.g., commercial building developers. Target costs may be inappropriate for institutional facilities and other situations where the amount of funding is driven more by desired prestige or style, and where funding is often somewhat elastic. Example: Rice U. won't build a Fondren Library unless they can get a facility that meets their desires for a certain impact or statement. If they need more money, they will go back to their alumni and other donors. Should they be unable to get the money, and if they aren't forced by capacity, structural, or code considerations to build a new library, they won't built one at all.
2. Product and process design decisions are made with a view to customer needs as well as to design criteria. Should an opportunity emerge for increasing customer value by expanding customer needs, and if there is sufficient time and money, the project definition process will be reengaged to align needs, criteria, and design concepts.

3. Product and process design decisions are made simultaneously rather than first producing a design for the product, then trying to produce a satisfactory design for the process of designing and making that product.

4. The first process designed is the design process itself. That is done by the design team using team planning techniques (stickies on the wall), employing the Activity Definition Model (ADM). See LCI White Paper-7: Phase Scheduling.

5. One set of criteria/objectives for product design will be simplifying site installation to final assembly and testing.

6. Set Based Design (aka Set Based Concurrent Engineering) as practised in Toyota’s product development will be developed into principles for process design.

7. The Design Structure Matrix will be used to resequence design tasks in order to reduce needless iteration.

8. Every effort will be made to maximize customer value in the making of trade-offs between needs and objectives.

9. A single conceptual design will normally be selected before the end of this phase because the last responsible moment for making that decision will have usually passed.

10. Design decisions will be deferred until the last responsible moment if doing so offers an opportunity to increase customer value.

11. Production control is applied to the Lean Design phase using standard Last Planner procedures and techniques. An MS Access-based software developed by James Choo and Iris Tommelein will be tested and refined on member projects.

12. IT tools to be tested in the Lean Design phase include:
   - 3D modeling, shared geometry
   - Collaborative design software, web-based

13. Specialty contractors will either serve as designers or will participate in the design process, assisting with selection of equipment and components and with process design.

14. Where specialty contractors do not perform the design, designers will produce only those deliverables needed for permitting and needed by specialty contractors or other suppliers for detailing. Example: the mechanical engineer will produce only single lines of HVAC duct.

15. We will explore how best to use 3D modeling consistently with a set-based approach, recognizing that current models are not well suited to expressing ranges of values or alternative geometries. 3D/4D may be best used in the design phase as a simulation tool for exploring and evaluating alternatives, whereas it may provide the shared geometry needed to minimize interferences and conflicts in the detailed engineering module.

16. We will explore tools and techniques for process modeling.

17. Operations design is strictly speaking that part of process design that deals with 'making'; i.e., fabrication, assembly and testing. We hope to learn how to design operations to facilitate flow. Operations design is completed in First Run Studies during the Assembly phase.

18. The Lean Design phase transitions into Lean Supply when the product and process design have been developed from the design concept consistently with design criteria, which are themselves adequate expressions of customer needs and stakeholder demands. This
alignment will be explicitly examined and agreed by the design/build team and the client before transition.

Lean Supply

1. The Lean Supply phase consists of detailed engineering of the product design produced in Lean Design, then fabrication or purchasing of components and materials, and the logistics management of deliveries and inventories.
2. All decisions regarding the engineering, production, or delivery of materials and components are made with an eye to maximizing customer value.
3. 3D modeling will be used for detailed engineering.
4. Where possible, fabrication will be driven directly from the 3D model.
5. Collaborative design tools will be used to integrate design inputs developed on different platforms into a single model.
6. Process design will have addressed buffer type, location, and sizing. That will be further detailed and then controlled in this phase, in which the ‘iterative’ relationship among the modules within the phase are more like continuous adjustment than like the generative conversation characteristic of design proper.
7. We will apply lean manufacturing techniques to fabrication shops.
8. It is in this phase that the project, which is a temporary production system, is physically linked to the supply chains that exist independently of the project. Mapping those supply chains is a central research task. Once chains are understood, they may be reconfigured, and both costs and lead times reduced.
9. An objective of process design is to minimize inventories, right sizing them to the flow variability that cannot be eliminated. Where time is of the essence, capacity buffers will be substituted for inventory buffers.
10. This phase transitions into Lean Assembly once site deliveries begin. Site deliveries may be initiated within a fast tracking strategy that decouples facility systems or components so that assembly of one component can begin while detailed engineering of subsequent components is still underway. We will test the hypothesis that a lean version of design-then-build can deliver projects faster than fast tracking. Even so, in no case will all fabrication and procurement of components be completed prior to initiating site installation.

Lean Assembly

1. Lean Assembly begins with the first delivery of tools, labor, materials or components to the site and ends when the keys are turned over to the client.
2. A key issue is coordination of deliveries to ensure soundness of assignments while sizing buffers to residual variability.
3. An objective is to approximate one-touch material handling ideals.
4. We will develop the technique of in-process inspection both in shops and at sites.
5. We will first do descriptive research of testing/turnover processes, looking at ‘zero punch list’ initiatives and at system integration issues. We expect to find considerable waste and value loss.
6. We will encourage incorporation of First Run Studies into assembly lookahead processes, measure their benefits, and link feedback to project definition, design, and supply.
7. We will develop and test the hypothesis that the front line supervisor's role will change from giving orders to coaching and managing improvement.

8. We will learn how to structure and manage intimately connected operations as continuous flow processes.

9. We will promote multiskilling in shops and site installation. Multiskilling is probably best initiated within the context of continuous flow processes, as a means for fine balancing. From there, it could be extended to the objective of minimizing total site head count.
Project Definition
LCI White Paper-9
September 9, 2000
Lean Construction Institute

by
Glenn Ballard and Todd Zabelle

Project definition is the first phase in project delivery (see the Lean Project Delivery System, LCI White Paper-8) and consists of three modules: Determining requirements (stakeholder needs and values), translating those requirements into criteria for both product and process design, and generating design concepts against which requirements and criteria can be tested and developed.

LEAN PROJECT DELIVERY SYSTEM

The movement through these three is necessarily iterative, and need not follow any specific sequence, although requirements seems to be the logical starting point. What’s important is to bring all three into alignment. Only then should the Lean Design phase be launched. But even then, it is possible that subsequent development lead back to project definition and an upgrading of requirements, criteria, or concepts. Such upgrading should be done whenever it adds value and when there is sufficient time and money to make the change. The cycle through the three modules is done to reveal to clients the consequences of their desires and to reveal more and different value generation possibilities than they may previously have conceived.

Architectural programming has much the same objectives as does project definition, but focuses primarily on issues relevant to architectural design such as space planning, and also often does not directly address the task of translating from requirements into design criteria. “Front
end loading” is a term commonly used in the process industries to describe the predesign phase. In some models, “feasibility study” occurs prior to ‘project definition’. In the U.K. and the areas it has influenced, the term “design brief” is used to describe the document capturing the results of requirements determination and exploration of alternative design concepts. LCI’s project definition phase and process draws upon all these traditions, but locates them within the Lean Project Delivery System.

Project definition is best done collaboratively, with the involvement of the project stakeholders themselves. Typical stakeholders include the client (holds the contract; pays the bills), user of the facility, governing agencies (e.g., local building department), designers, fabricators, installers, operators, maintainers, and neighborhood associations. Collaboration takes place in a series of project definition conferences, the desired outcome of which may be a go/no go decision on the part of the client.

### Project Definition Process

Quite a bit of information needs to be collected prior to the first project definition conference. The following are guidelines developed for N.L. Barnes, an LCI contributor:

1. Select team (to be done by the client sponsor, with help from the technical integrator once assigned)
   - Assign Barnes team & prep. for collaborative design meeting
     - technical integrator
     - controls manager
     - engineer
     - superintendent
     - administrative manager

Redraw Figure 2 to reflect the process outlined above.
- Contract with architect & prepare for collaborative design meeting
- Select and prep. specialty contractors & specialty engineering firms
  - civil
  - substructure
  - structure
  - skin
  - mechanical
  - electrical
  - plumbing
  - fire protection
  - vertical transportation
  - other

2. Gather information (the technical integrator is responsible, but may delegate some tasks)
   - Governing entities
     - identify governing entities
     - describe & understand approval and permitting processes
     - determine & understand applicable codes & requirements
   - Site info.
     - site visit by project team
     - location & configuration
     - drainage
     - physical context; e.g., adjacent structures
     - access/egress
     - utility tie-ins
     - soils
     - wind loads
     - seismic
   - Schematic design (if previously produced)
   - Design criteria from model or similar projects

3. Conditions of satisfaction (to be done by the client sponsor and technical integrator)
   - Understand the owner’s business case
   - Determine owner’s conditions of satisfaction (COS)
   - Prepare owner for collaborative design meeting

4. Establish target budget & schedule (to be done by the project controls manager and supt.)
   - State assumptions
   - List issues to address, in priority order
   - Develop an estimating matrix
   - Identify major milestones, including end date, and long lead items

5. Stakeholders (to be done by the technical integrator, with input from the client sponsor)
   - Identify stakeholders; e.g., for Faskin Project:
     - City of San Rafael Dept of Public Works
     - City of San Rafael Building Dept (permitting and inspection entity)
     - Tenants
     - Facilities Manager
     - Leasing Agent
     - Etc.
   - Determine stakeholder demands (find proxies for future tenants; perhaps survey data or post-occupancy evaluations of similar facilities)
   - Invite key stakeholders to participate in the collaborative design meeting
LCI recommends seeking in-depth understanding of location and applicable laws, codes, and standards, in addition to understanding the client’s business case and the demands of other stakeholders. Doing so, we suspect, will drastically narrow the range of possible design solutions. For example, permit requirements may dictate to a considerable degree what documents will be produced during the design process. Codes and standards may dictate or restrict major design decisions.

Brian Lawson, an architect and professor of architecture, tells about a client asking him to design an addition onto his house. A visit makes it apparent that adding space will be very difficult and costly. What’s more, there seems to be plenty of space already. Questioning reveals that the problem is really the noise level in the house, so the design problem appears to be one of providing sound insulation of spaces rather than adding spaces. But Lawson drills deeper and discovers that the noise problem is really the children playing loud music. He solves the problem by suggesting headphones. He loses a commission but gains a friend. This story illustrates the importance of really understanding the client’s situation and not simply accepting their initial statement of needs.

Involvement of the team that is to design and build a facility can occur at very different stages of the client’s project development process. The client may or may not have done a systematic feasibility study, may or may not have already selected a location, may or may not have determined even the type of facility or its intended use. Stakeholders such as tenants and operators may or may not have been previously identified. Consequently, one of the first tasks of the designer-builder is to determine which of these decisions have already been made, to understand those previous decisions (and possibly provoke reconsideration), and to facilitate making those decisions that remain.

Project definition conferences draw on the tradition of architectural charettes, an excellent example of which is the Neenan Company’s Collaborative Design Process. Neenan structures the day in a series of one hour work sessions, in which predetermined teams execute assignments. Between work sessions, each team reports out its findings and questions, and a new set of assignments are made. Teams are formed around building systems; e.g., foundation, superstructure, skin, HVAC, etc. and consist of various specialists representing design, supply, and installation. In some cases, Neenan has been able to get building department inspectors to attend and participate in the sessions, which reportedly has allowed them to explain in advance what requirements they will be applying, and also given the design-build team the opportunity to present their strategy and approach. Client representatives with decision making authority must participate.

Frequently, project definition conferences require more than one day. Between sessions, action items are assigned to collect missing information or explore alternatives. Again, the trigger for moving forward from project definition into design proper is alignment of requirements, criteria, and concepts.

Note that multiple design concepts may be carried forward, either for the entire facility or perhaps for a facility system. For example, multiple building envelopes may deliberately be carried forward without decision, in expectation of making a better decision after more thorough exploration of those alternatives and after further development of interdependent systems. This practice is discussed more thoroughly in White Paper #10 as regards Set Based Design.
Post Occupancy Evaluations (POE)\(^1\)

In the Lean Project Delivery System, POE is shown as a feedback loop from the end of one project to the beginning of the next. As such, it represents the multitude of feedback loops that promote learning throughout the delivery process. POE itself is simply the evaluation of a project delivery process after the facility is in use. In some cases, POE is restricted to facility systems such as HVAC, but more generally, the idea is to determine by inspection, measurement, and questioning, how the facility is actually being used (e.g., how are functional spaces being used compared to the design intent), how the facility is performing (e.g., energy consumption, wear rates, factory yield rates), and how well it meets the needs of its users. This checks both the adequacy of the design process and of the building process.

Although originating in evaluation of buildings, POE can be used for any type of facility, including factories, bridges, tunnels, etc. Repeated application can build a database of design criteria for various facility types. Such a database can be a valuable input into projects dedicated to designing and building such facilities. For example, POE databases could be a source of information on the needs of users identifiable by type but not specifically, as is the case when a facility is being produced on speculation of future sale or lease. They can also be valuable for improving facility performance from project to project. For example, studies of lighting have related specific physical factors, job satisfaction, and productivity. As part of a comprehensive POE of California prisons, it was discovered that epoxy paint is not a good surface for shower room walls and floors. Although cheaper than ceramic tile at first installation, it requires frequent repainting and costs more in the long run.

POEs are still most commonly used in the facilities management programs of public agencies such as the Naval Facilities Engineering Command and the U.S. Postal Service. However, they offer benefits also to private facilities managers as well as developers and designers of all disciplines.

Cross Functional Teams

A cross functional team is one drawn from multiple specialists. In the product development world, a cross functional team responsible for selecting the design concept for an automobile might consist of representatives from finance, marketing, body design, body and chassis engineering, power train engineering, manufacturing, and key suppliers. As already stated, the cross functional team required for effective project definition consists of representatives from the various stakeholders, which include the client (of which there can be many; e.g., facilities management, marketing, occupants, etc.), the production system representatives (designers, manufacturers, installers), governing agencies (inspectors, neighborhood associations), and sometimes even the general public, as is often the case for public works projects.

A common mistake is to involve such specialists separately, but fail to bring them together. This often occurs because of addiction to a command and control philosophy, and fear of losing control if the specialists actually start talking to one another. The type of control appropriate to the Lean Project Delivery System is achieved through facilitation, not through command. Value is generated through positive iteration of the requirements-criteria-concepts cycle. Only by facilitating conversation among the various specialists in the cross functional team can maximum value be generated for the project stakeholders.

\(^1\) Wolfgang Preiser is among the leading authors on POE. Search his works for references.
Another mistake to avoid is relegating the builders on the team to the task of estimating the
cost of design options produced by others. The intent is rather to simultaneously explore both
product and process design, since both have implications for client satisfaction and value
generation. Further, costing should be done integrally with designing, not thrown over the wall.

QFD

Quality Function Deployment (QFD\(^2\)) is a tool for translating from the Voice of the Customer
into the Voice of the Designer\(^3\); i.e., from requirements into design criteria. The customer may
want to be able to ‘hear a pin drop’ on the stage of a theater when sitting in the back row, but the
designer needs to know what decibel level to use in selection and configuration of materials and
components.

QFD is implemented as a series of translations, moving from the general to the detailed level.
The matrix below correlates a client’s desired characteristics of a roofing system with the
relevant metrics. Consider, for example, the desire that the roof be fire resistant. Exactly what
does that mean as regards design decision making? The metric specifies that the roof system
must meet the requirements of U.L. 790 Class A. Another example: The client wants the roof to
have a 20 year manufacturer’s warranty. The relevant metrics include the requirement that the
membrane be .060 thick, metal must be stainless steel, etc

This translation contributes to the task of helping clients understand the consequences of
their desires. For example, once it is revealed that stainless steel is required to get a 20 year
warranty and the relative cost of stainless steel is determined, that might influence the client to
change their minds about the warranty period.

QFD might also be used to rate various design concepts against desired characteristics of the
facility. That contributes to the goal of revealing more and different opportunities to the client
than they may previously have conceived. As you might suspect, such rectangular matrices can
be used in many different ways to facilitate project definition.

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\(^2\) QFD was developed for use in product development processes. The seminal text is Akao, Y. (1990). *Quality
1990.

\(^3\) In LCI documents, the term “design” and its variants is used to designate design in its larger sense, including
engineering.
Concept Generation

Once requirements have been provisionally determined and target design criteria produced, it becomes possible to evaluate alternative concepts for the facility that will embody those criteria and fulfill those requirements. It should be noted that concepts can be generated as a means for clarification of requirements. As previously stated, there is no right or wrong sequence for moving through the project definition modules. An architect or engineer may hear a bit about what a client wants in a new building or system, then begin generating sketches to explore and sharpen her understanding of those requirements. The key is not sequence but rather the ultimate alignment of requirements, criteria, and concepts.

Ulrich and Eppinger\textsuperscript{4} offer a five step process for concept generation. They stress that the process of concept generation is itself iterative, like the project definition process of which it is a part.

1. Clarify the problem.
2. Search externally (users, experts, benchmarking, etc.)
3. Search internally
4. Explore systematically
5. Reflect on the solutions and the process

Explicit identification of the functions the facility or its systems are to satisfy is almost always important in problem clarification. Ulrich and Eppinger advocate the use of a Concept Classification Tree in Step 4. The idea is to take one function and list the alternatives for performing that function, then the alternatives for realizing each of those, etc. They illustrate with a handheld nailer that is the product being developed. One function of the nailer is to store or accept energy, which can be chemical, pneumatic, hydraulic, electrical, or nuclear. Each of these can be exploded in turn; e.g., chemical energy could come from fuel-air systems or explosive systems; electrical energy could come from a wall outlet, battery, or fuel cell.

Evaluation and selection of concepts occurs through application of requirements and criteria to alternatives. Concepts should be rejected only if they are clearly inferior or impractical and cannot be improved in the time available. The remaining concepts should be maintained and carried forward until the ‘last responsible moment’; i.e., that point in time at which there is no longer sufficient lead time to realize that alternative. This practice is consistent with the lean principle of doing work only when it releases work to others, and is the essence of Set Based Design.

3D Modeling

Although pencil and paper sketches will likely continue to be useful tools for presenting alternative design concepts, 3D models can also play a role. Using a library of objects, limited models can be produced very quickly, allowing better visualization and also making it possible to quickly test appearances, consistency of dimensions, etc.

Summary

The purpose of project definition is to produce and align requirements, criteria, and concepts. Tools used include:

- Post Occupancy Evaluations
- Cross Functional Teams
- Stakeholder, Location, and Regulations Analysis (Information Collection)
- Quality Function Deployment
- Concept Generation (Function Analysis)
- 3D Modeling

Research Questions

LCI has a research project underway on Project Definition. All LCI Platinum Contributors are welcome to participate. Current participants are Barnes and Boldt.

Many questions remain, some a matter of better understanding what has already been done by others, some belonging to descriptive research, and others matters for experimentation. The literature review and descriptive research will be done through PhD students. Descriptive data will also be collected from LCI contributors and experiments will be performed with LCI contributors that wish to participate.

- Literature Review—do a thorough survey of what others have done and are doing that is relevant to the Project Definition phase of the LPDS.

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5 Value Engineering’s function analysis may be useful here.
• Descriptive: To what extent and with what frequency is project definition done on current projects?
• Descriptive: What techniques are successfully used in practice to identify stakeholders and determine stakeholder requirements, to translate requirements into design criteria, and to generate and evaluate facility and facility system concepts?
• Experimental: How to create the conditions needed for successful project definition; e.g., how to persuade clients to allow specialty contractors into pre-design, how to get the participation of suppliers before decision has been made to employ their services?
• Experimental: How can product development techniques from manufacturing be adapted for use in capital facilities project definition?
• Experimental: How to maintain, store, and retrieve project definition information so it is evergreen and accessible, and thus contributes to the goal of system transparency?
• Experimental: What are the measured benefits of implementing project definition within the LPDS?

For further information, please contact Glenn Ballard, 888-771-9207 or gballar@pacbell.net or Todd Zabelle, 415-710-1376 or tzabelle@nlbarnes.com
Within the Lean Project Delivery System, the Lean Design phase begins once Project Definition has aligned purposes, criteria, and concepts. It ends when product and process design have been produced and themselves brought into alignment with the Project Definition elements.

**Figure 1: Lean Project Delivery System**

LCI has been developing a lean approach to the management and execution of design. What we have so far is summarized in Figure 2. In rough order, the steps are to:

- Organize in cross functional teams
- Pursue a set based strategy
- Structure design work to approach the lean ideal
- Minimize negative iteration
- Use the Last Planner system of production control
- Use technologies that facilitate lean design

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1 For a detailed description of the LPDS, see LCI White Paper-8.
In the lean construction community, production is understood as an integrated process of designing and building, which is at the heart of Lean Design. However, designing and building are very different.

- Designing produces the recipe and Building prepares the meal. This is the ancient distinction between planning and doing.
- They also differ in the concept of quality appropriate to each. Design is judged ultimately against its fitness for use; the extent to which it realizes the purposes of those for whom the product is being produced. On the other hand, the product itself is judged by its conformance to the geometry and specifications expressed in the design.
- Variability of outcomes is undesirable for Building--consistent with the concept of quality as conformance to requirements. However, if design products were entirely predictable, the design process would not be adding value.
- Fourth and last, iteration in Building is rework; clearly a type of waste to be avoided. By contrast, designing often requires the production of incomplete or provisional outputs in order to develop understanding of both design problems and alternative solutions.

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.

- Cross Functional Teams (see LCI White Paper #9)
- Pull Scheduling (see LCI White Paper #7)
- Reduce design batch sizes
- Design Structure Matrix
- Strategies for Minimizing Negative Iteration
- Set Based Design
- Share incomplete information
- Work Structuring (See LCI White Paper-5 and Tsao et al. (2000) “Case Study for Work Structuring: Installation of Metal Door Frames”. Available at \url{www.sussex.ac.uk/spru/imichair/iglc8/index.html})
- Simultaneous product and process design
- Shared geometry; unified modeling
- Shift detailed design to specialty contractors
- Produce and inspect outputs based on a definition of quality as ‘fulfillment of purpose’, not ‘conformance to requirements’
- Last Planner system of production control

**Cross Functional Teams**

Cross Functional Teams are the organizational unit for all phases of the Lean Project Delivery System. All stakeholders need to understand and participate in key decisions. However, it is not possible to do work in perpetual mega person meetings, so some division of labor is required. In general, the appropriate pattern to follow is alternation between bigger alignment meetings and work by individuals and smaller teams on the tasks identified and agreed in those meetings.

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. But having representatives of each relevant speciality assigned to each team will always be essential.
Pull Scheduling

Pull Scheduling is really a tool in the Work Structuring toolbox. It is used to do team planning, aka process design. In the Lean Design phase, the plan produced is ultimately for the entire design process. However, the technique can be used by teams of any size to further detail the work for which they are responsible.

Reduce Design Batch Sizes

All too often specialists transmit completed design information with little regard for the needs of other team members and downstream customers. 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 a 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 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. She can decide to defer other decisions or perhaps choose potential 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.

Design Structure Matrix

Lottaz et al. (1999) tell a story illustrating negative (needless) iteration. Holes for refrigeration conduit were required in a beam (Figure 2). Primary dimensions were: 'd' (the diameter of a hole), 'e' (the distance between holes), 'x' (the distance from first hole to 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 mm to 1000 mm and finally involved the HVAC subcontractor, who made further changes. The cycle of changes and transmissions continued. The erection contractor was running out of time, so 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.

Figure 3: Needless Iterations

The beam penetration case is an example of negative iteration; i.e., iteration that could have been avoided without loss of value. Occurrences like this are all too common because of the multiple criteria any one design must meet, and the tradition of sequential processing, aka ‘throw it over the wall’.

Production of a pull schedule by a cross functional team is the first thing to do to minimize negative iteration of this sort. After further detailing of required inputs for the activities included on the pull schedule, the Design Structure Matrix (DSM) can be used to minimize iterative loops. DSM is incorporated in prototype software LCI has produced in conjunction with Loughborough University. The combined software is called DePlan (short for Design Plan) and consists of a front end planning tool called ADePT and a version of Last Planner production control called ProPlan. This software is available currently for experimental use by LCI contributors and others whose involvement can advance the research.
The pull schedule will have sequenced design tasks in some way. In the matrix above, tasks are given letters indicating their place in the original sequence. An x in the matrix indicates that the task in the vertical list is dependent upon the task in the horizontal list. For example, Task F is dependent upon Tasks B, C, P, and R. Since B and C are currently scheduled to be done before F, they pose no problem. However, Tasks P and R are currently scheduled to be done after F. This dependency loop is common in design because of the complexity and interdependence of design decisions. However, the size of such loops can be reduced through use of the DSM software.
DSM contains an algorithm for resequencing tasks to minimize looping. After running the software, a new matrix (shown above) is produced with smaller loops. We suspect that DSM may be used many times over, along with redefining tasks, in order to come to an acceptable design schedule. That schedule will almost certainly contain some loops but they will be smaller and more manageable.

**Strategies for Minimizing Negative Iteration**

The first strategy for minimizing negative iteration is use of pull scheduling and DSM, plus reorganizing the design process as indicated below. Once irreducible loops have been found, they are jointly assigned to the relevant teams of specialists.
Strategies for Reducing Negative Iteration

- Restructure the design process
  - use DSM to resequence
  - use pull scheduling to reduce batch sizes and achieve greater concurrency

- Reorganize the design process
  - make cross functional teams the organizational unit
  - use team problem solving (call a meeting)
  - share ranges of acceptable solutions
  - share incomplete information

- Change how the design process is managed
  - pursue a least commitment strategy
  - defer this decision (defer commitment)
  - practice set-based design
  - use the Last Planner system of production control

- Overdesign (design redundancy) when all else fails, or when reduction in duration is vital and cannot be otherwise achieved

Figure 6: Strategies for Reducing Negative Iteration

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:

- Hold a team meeting to accelerate iteration
- Defer final completion until some critical items of information have been acquired
- Design 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

Set Based Design

"Set-based engineering” has been used to name Toyota's practice of a least commitment strategy in its product development projects. That strategy could not be more at odds with current practice, which seeks to rapidly narrow alternatives to a single point solution, but at the risk of enormous rework and wasted effort. It is not far wrong to say that standard design practice currently is for each design discipline to start as soon as possible and coordinate only when collisions occur. This has become even more common with increasing time pressure on projects.

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Point-based Design

Architects select the 'best' building design & produce sketches & models

Engineers & builders critique the model based on their intuition and experience

Architects revise their models

Key systems are selected & dimensions are fixed asap

Repeat process for subsystems and components

Figure 7: Point-based Design

Toyota is a leader in product development, just as they are in factory production. Toyota's Manager of Body Engineering expressed their perspective well when he said that his job is to prevent premature decision making. Toyota's product development process is structured and managed quite differently even than other Japanese automobile manufacturers.

Set-Based Design

- "Preventing engineers from making premature design decisions is a big part of my job." (Toyota's Manager of Product Engineering)

Figure 8: Set-Based Design
Toyota’s product development:

- Develops multiple design alternatives.
- Produces 5 or more times the number of physical prototypes than their competitors.
- Rejects changes that expand, rather than contract, the space of possible designs.
- Puts new products on the market faster than their competitors.

In all design processes, alternatives are generated, evaluated, and selected. It is common practice to select the best alternative as quickly as possible, then proceed to the next level of detail or decision and repeat the process. Why might this be common practice? Some typical comments that indicate current thinking:

- Why waste time on designs that will not be used?
- We don’t have time to carry forward multiple alternatives.
- Why wait to decide if the best alternative has been identified?

These reasons for practicing point-based design seem plausible, but raise the questions:

- How is it that Toyota "wastes time" on designs not used and yet develops new products faster and cheaper (in development costs) than their competitors?
- How do we decide when we have or do not have time to carry forward multiple alternatives?
- How often can we identify the best alternative immediately, without the benefit of further detailing and development?

We suspect that Toyota's superior performance is a result of reducing negative iteration, and that the reduction is more than sufficient to offset time "wasted" on unused alternatives.

As regards having the time to carry alternatives forward, that would seem to be a function of understanding when decisions must be made lest we lose the opportunity to select a given alternative. We need to know how long it takes to actually create or realize an alternative. Understanding its variability, we can add safety-time to that lead-time in order to determine the last responsible moment. Choosing to carry forward multiple alternatives gives more time for analysis and thus can contribute to better design decisions.

Principles of SBD:

1. Map the design space.
2. Integrate by intersection.
3. Establish feasibility before commitment.

*Mapping the design space* is identifying the set of alternatives or range of values to be carried forward. All design contributors are freed to develop their work, as long as they stay within those boundaries; i.e., within that 'design space'. *Integrating by intersection* means looking for solutions within the intersections of sets or intervals. For example, various interface dimensions

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6 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.
can be specified for mating components such as seats, dashboards, and body panels (see Figure 9). The search for solutions is focused on the shared values for those dimensions. *Establishing feasibility before commitment* refers to the obligation of a design contributor to maintain consistency with the preexisting design. This is radically different from point-based design, in which each design contribution may invalidate all previous work. As an example, consider the beam penetration case presented above.

![Figure 9: Integrate by Intersection](image)

SBD is said to have many benefits: The following list is drawn from the papers by Ward and Sobek:

1. Enables reliable, efficient communication. vs. point-based design, in which each change may invalidate all previous decisions.
2. Waste little time on detailed designs that can’t be built.
3. Reduces the number and length of meetings.
4. Bases the most critical, early decisions on data.
5. Promotes institutional learning.
6. Helps delay decisions on variable values until they become essential for completion of the project.
7. Artificial conflicts and needless iterations of negotiations are avoided.
8. The initiator of a change retains responsibility for maintaining consistency.

**Share 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 judgments 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 categorize 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.

**Work Structuring**

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 structure must anticipate every delivery phase; i.e., how the product 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.

The purpose and complexity of work structuring as conceived within the LPDS reveals the inadequacy of traditional work breakdown structures (WBS), which, being derivative from conversion thinking, share its assumption that work in its entirety can be broken into pieces and those pieces managed as if they were independent.

Work structuring is not itself a tool, but rather a purpose in the pursuit of which tools can be employed. Pull scheduling and cross functional teams are examples of two such tools. LCI has research underway to develop work structuring guidelines beyond advising that consideration be given to all the life cycle stages of the product being designed.

**Simultaneous Product and Process Design**

Integrating design of product and of process is a challenge. Basically this means to consider and decide how to build 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. Besides old habits, we have to overcome specialization and 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 design-build, it is now common to use design-bid-build with specialty contractors, which makes it impossible to involve them in the design process proper.

**Shared geometry; unified modeling**

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 modeling the manufacturing, logistics, assembly, commissioning (startup), and operations of that product or its components. Such tools as IDEAS by Strategic Design Research Corporation have been developed for manufacturing applications and are now being applied to the built environment.
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. A halfway house is to collect design produced in various forms and input it into a single model.

3D modeling 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 insure that the design of systems, subsystems, 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 by group technology they can then use the computer model as a tool to integrate and test components within facility 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 components. 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 modeling.

Shift detailed design to specialty contractors

Specialty contractors are typically required to produce ‘shop drawings’; i.e., detailed instructions for fabrication and installation of materials and components. Design specialists may have previously produced instructions of their own, which most often are discarded by the specialty contractors, who start anew. A simple waste reduction strategy is to stop having design specialists produce detailed design. For example, if there is a mechanical engineer separate from the mechanical contractor, have that engineer produce only single line drawings of duct routing and let the contractor do the detailed routing.

Practice quality control based on a definition of quality as ‘fulfillment of purpose’, not ‘conformance to requirements’

Project production can be abbreviated to the steps: 1) determine customer (and other stakeholder) purposes and needs, 2) translate those purposes and needs into design criteria, 3) apply those criteria to the design of product and process, then 4) 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.

However, the industry habit 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’s missing is reevaluation of the drawings and specifications against stakeholder needs, on the chance that conditions or knowledge has changed, or that a better idea emerges.

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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.

Summary

The steps involved in lean design are:

- Organize in cross functional teams
- Pursue a set based strategy
- Structure design work to approach the lean ideal
- Minimize negative iteration
- Use the Last Planner system of production control
- Use technologies that facilitate lean design

Tools and techniques available for lean design include:

- Cross Functional Teams
- Set Based Design
- Share incomplete information
- Pull Scheduling
- Design Structure Matrix
- Strategies for Minimizing Negative Iteration
- Work Structuring
- Simultaneous Product and Process Design
- Shared geometry; unified modeling
- Shift detailed design to specialty contractors
- Produce and inspect outputs based on a definition of quality as ‘fulfillment of purpose’, not ‘conformance to requirements’
- Last Planner system of production control

Lean Design Research Projects

1. Speciality Contractor participation in predesign and early design (Ballard)
   - Doing exploratory research with Rosendin Electric, Southland Industries, and Gowan Mechanical.
   - Will develop proposals for funding from specialty contractor associations; e.g., NECA, MCAA, SMACNA, NRA

2. Descriptive research: design practice (Ballard and Michael Whelton, UC PhD student)
   - Intent is to document current design practice
   - Plan to work with Burt Hill Kosar Rittelman Associates in Pittsburgh, PA. Whelton is also working as an intern for UC facilities management studying the project definition and design processes on a campus renovation project.
   - Will present findings in March ’01 Research Seminar
3. DePlan implementation by member companies (Ballard and Michael Whelton, UC PhD student)
   - Participants thus far are Southland, Linbeck, Boldt, Gowan, and Mace (U.K.)
   - DePlan is a software package consisting of both ADePT, a tool for planning design projects, and ProPlan, a software incorporating the functionalities of the Last Planner system of production control for application to design.
   - Foci of the study will include
     - use of DSM to minimize iterative loops
     - development of strategies for managing iterative loops
     - application of Last Planner to design production control
   - Will present findings at March '01 Research Seminar

4. Case Study in Project Definition and Lean Design (Zabelle and Ballard)
   - led by Todd Zabelle at Barnes
   - UC student Changwan Kim will do literature survey and support. Next year this will become his PhD research topic
   - findings to be presented at March ’01 Research Seminar

5. Modeling uncertainties in CAD systems-in preproposal stage (Iris Tommelein)

6. Work Structuring-Cynthia Tsao (Cal PhD student working under Tommelein. Greg Howell is also actively involved.)

7. Speciality Contractor involvement in the design of semiconductor facilities-Nuno Gil (PhD student working under Tommelein and Ballard)

8. Descriptive case studies of successful design-build projects from the perspective of lean construction (Ballard and Howell, with support from a PhD student to be named).
   - hope to work with DBIA

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Abstract

A guide is proposed for the design of production systems, which are understood to involve both designing and making products. Production system design is called “work structuring” and serves the three goals of production systems: do the job, maximize value, and minimize waste. For each of the latter two, ends-means hierarchies are proposed that progressively answer the question “What should we do to achieve a goal?”, moving from desired ends to actionable means.

Maximizing Value and Minimizing Waste: Universal Goals

Work Structuring \(^1\) is a primary component of the Lean Project Delivery System \(^2\). Its fundamental purpose is production system design \(^3\), which extends from global organization to the design of operations; e.g., from decisions regarding who is to be involved in what roles to decisions regarding how the physical work will be accomplished. Previously, project planning has focused primarily on organizational structuring and creation of work breakdown structures that divide the work to be done. We propose to include the production system itself, which has been virtually invisible and taken for granted. Doing so necessarily involves moving from a conception of production solely in terms of transformation of inputs to the TFV concept of production advocated by Lauri Koskela \(^4\). TFV adds conceptions of production as consisting of flows of materials and information through networks of specialists, and the conception of production in terms of the generation of customer value.

Creating the conditions for system control and improvement is included in systems design. However, guidelines and techniques for applying control and making improvements lie beyond design and will be treated in later papers.

In the lean approach, products are designed to provide maximum value to their purchasers and users. On the other hand, production systems are designed to achieve the purposes of both their customers and those who ‘deliver’ the system, the producers. Those purposes may vary greatly, but production systems as such have goals that are

\(^1\) See LCI White Paper #5 at www.leanconstruction.org.
\(^3\) For an approach to the design of manufacturing systems (i.e., ‘making’ only), see http://psd.mit.edu/.
appropriate for all such purposes; i.e., maximize value and minimize waste. A brief digression is necessary in order to lay the groundwork for this key idea.

**What is the relationship between the concepts of waste, cost, and value?**

Products have value only to the extent that they can be used to fulfill purposes. A product may be said to be more valuable either if it allows greater fulfillment of purpose or fulfills purpose at less cost. A product that does not fulfill purpose has no value regardless of its cost. The cost of products is what must be sacrificed in exchange for their use and can be divided between cost to acquire and cost to use.

Markets are mechanisms for exchange and a means for determining product prices. Although many factors may influence what price a buyer actually pays for a product (not least, having the means to pay!), generally what a buyer is willing to pay for a product is a measure of its value to the buyer—the more valuable, the more a buyer is willing to pay, and vice versa. Paying more than necessary to acquire a product is considered to be waste, one type of which is ‘avoidable cost’. This is the concept of ‘cost to acquire’.

There is also a concept of ‘cost to use’, which is related to how well the product fulfills the purposes of its user (which may or may not also be its buyer). A product that costs more to maintain or has a shorter useful life is considered less valuable. Environmental impacts of use and disposal are included in ‘cost to use’.

Finally, there is the concept of cost to produce. The concept of waste is most firmly related to the cost to produce, minimization of which is desirable. However, minimization of production time is also desirable and in ways that are not always easily monetized.

Maximizing value gives the producer the greatest leverage over pricing. Maximizing value and minimizing waste generates the greatest profit, the difference between price and cost. Consequently, regardless of specific business strategies, profit-seeking producers should strive to maximize value and minimize waste. This also holds true for so-called non-profit organizations.

In what circumstances would it not be in the interest of producers to maximize value or minimize waste? A few come to mind: 1) When producers make money from waste, and 2) When generating value for customers reduces value for producers. For example, producers make money from waste when changes are exploited as a primary source of profit. Inadequate design combined with design-bid-build may leave the construction contractor no alternative but to rely on design errors and omissions to make the contract profitable. As regards the second circumstance, generating value for customers reduces value for producers when there is a choice between increasing the producer’s profit and investing some of that potential profit in upgrading the product through selection of systems, equipment, or parts. Does the fact that producer and customer interests sometimes conflict in the traditional production system invalidate the claim that value and waste are universal goals? We suggest that the conclusion should rather be to structure production systems to avoid such contradictions, which arise because of the way production systems are structured.

Customer purposes may vary widely, from immediate profit generation to market expansion to ease of operation to wanting to delight your mother with a birthday gift. Generating value for customers is to better enable them to realize their purposes.
Minimizing waste in the production may reduce the customer’s cost or may increase the producer’s profit. Either way, it is an appropriate goal.

Clearly there can be conflicts between the values of producers and customers, between various customers, or between various producers as we face production system design decisions. Aligning interests is a critical element in production system design, but tradeoffs are unavoidable, just as they are unavoidable in product design when there are multiple customers. The unending pursuit of perfection is in large part driven by the desire to elevate the level at which tradeoffs must be made. An example: The level at which time-cost tradeoffs are made is determined by the degree of variability in the system, which can be represented by PPC (percent plan complete). Higher PPC (lower variability) allows greater resource utilization at a given pace of production, or a faster production rate at a given level of resource utilization, thus ‘elevating’ the level at which the time-cost tradeoff is made.

A warning: Even though maximizing value and minimizing waste are universal goals of project-based producers, nonetheless it is vitally important for producers to decide on business objectives and strategies. As producers get better at designing, operating, and improving (aka, managing) production systems, they often must change the commercial structures in which they work in order to reap those gains. For example, if a producer conceives itself as a service provider and structures contracts to be paid for time provided, the commercial incentive is to spend more time rather than less. As it learns how to do more in less time, this contradiction between commercial objectives and production system capabilities must be resolved. Typically it is resolved by moving from service provider to product provider. But that is a story for another day.

**A 3rd Goal for Production Systems**

Lauri Koskela proposes a third production system goal. Along with maximizing value and minimizing waste, he adds producing the product, a goal so obvious that it can easily be overlooked. This goal is principally pursued in traditional project design through the development of a work breakdown structure. This ‘WBS’ divides the total work scope into its elements, and typically is mated with an organizational breakdown structure, which assigns responsibility for ‘delivery’ of those elements. This guide to production system design is intended to be an alternative to WBS/OBS, appropriate for the TFV (task-flow-value) concept of production as distinct from task only.

The assumptions behind WBS/OBS are flawed: work scope is not divisible into independent elements. Project elements are typically interdependent. Value is delivered because the whole is more than the sum of the parts; i.e., value emerges from interdependence. That flawed conception is the result of a truncated concept of production. However, the task view is a legitimate part of the TFV concept. We suggest that this is, considered within the TFV concept, the realm of contracts between

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production systems; contracts being the means for coordinating the actions of multiple
systems. In the case of project-based production systems, contracts link the temporary
system to the larger complex of production systems that exist independently of the
project.

It is inappropriate to conceive contracts exclusively in terms of transactions; i.e., the
exchange of commodities. Contracts can also be relational; e.g. getting married versus
buying a loaf of bread. The contracts that stitch together the elements of project
production systems are relational. Misconceiving them in terms of transactions promotes
enforcing conformance to contractual agreements, regardless of changes in project
objectives, and neglecting the interdependence of production system members.

In any case, in this paper, we neglect the third production system goal, which we intend
to treat in future papers.

Uses of this design guide

The following guide for design of project-based production systems differs from those
developed for manufacturing systems primarily in the conceptualization of production to
include both the designing and making of products. System design is obviously the
primary application for this design guide. However, there are also two additional
applications. One is for identifying where there are gaps in the research agenda. What do
we need to learn how to do or how to do better? Another application is for those
implementing the concepts, processes, and techniques developed in research. What are
the competencies that need to be developed or strengthened by a producer?

What follows are ends-means hierarchies arranged in outline form. We present the
hierarchies for each of the production system goals separately, initially presenting the
first three levels, then adding more detailed, actionable levels one at a time.

ENDS-MEANS HIERARCHIES

Maximize Value: Levels 1-3 (Level 1=Maximize Value)

- Deliver products that enable customers to better accomplish their purposes
  - Structure work for value generation
  - Understand, critique, & expand customer purposes
  - Increase system control (ability to realize purposes)
- Deliver projects on time/Reduce cycle time variation
  - Minimize production disruptions
  - Respond rapidly to production disruptions

How maximize value? By delivering products that enable customers to better accomplish
their purposes and by delivering those products when they are needed.
How deliver products that…? By structuring work for value generation, by understanding, critiquing, and expanding customer purposes, and by increasing the ability to realize purposes.

Each of these can in turn be expanded into a hierarchy of means that progressively become less goal-like and more actionable.

Maximize Value: Levels 1-4

- Deliver products that enable customers to better accomplish their purposes
  - Structure work for value generation
    - Align stakeholder interests
    - Organize in cross functional teams
    - Increase positive iteration
  - Understand, critique, & expand customer purposes
    - Use a collaborative project definition process
    - Use a set based strategy in design
    - Design for all life cycle stages
    - Inspect against purposes
  - Increase system control (ability to realize purposes)
    - Focus control on the complete system
    - Simplify the system (reduce the number of parts and linkages)
    - Increase system transparency
    - Use Last Planner system of production control
    - Reduce variability, including latent product defects
- Deliver products on time/Reduce cycle time variation
  - Minimize production disruptions
    - Increase system control
    - Reduce variability
  - Respond rapidly to production disruptions
    - Use the Last Planner system of production control

For example, how might we “understand, critique, and expand customer purposes”? By using a collaborative project definition process, by using a set based strategy in design, by designing for all life cycle stages (and the customers of our product in each of those

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6 Project control is usually conceived with the purpose of minimizing negative variance from planned cost and schedule, typically within a contract management perspective, but sometimes dedicated to reducing waste. We suggest that the purpose of control is not only to reduce waste, but more actively, to cause a desired rate and sequence of work to be done so those various work flows are coordinated. It is the coordination of work flows that reduces waste and also increases the ability to realize purposes; i.e., generate value.

7 See “Shielding Production” at www.leanconstruction.org.

8 Variability can be either of product or process, both understood as variation from an expected or desired state. Some variation is a result of how products and processes are designed and controlled. Some is natural and unavoidable, but only quantifiable within the context of management action. Consequently, the pursuit of perfection progressively minimizes variation, approaching ever more closely its natural limits.
stages), and by inspecting/evaluating prospective or actual system outputs against customer purposes.

A similar ends-means hierarchy can be generated for the goal of minimizing waste, of which there are four basic types: defective products, lack of flow, lost capacity, and avoidable cost.

**Minimize Waste: Levels 1-3**

- Reduce defective products
  - Improve supplier quality and on-time delivery
  - Improve the quality of intermediate products within the production process, either design or construction
- Make materials and information flow/reduce cycle times (i.e., minimize time mtls or info spend being inspected, reworked, waiting in queues, being processed, or moving)
  - Structure work for flow
  - Control work for flow
  - Reduce inventories (time spent waiting in queues)
  - Reduce inspection time
  - Reduce processing times
  - Reduce rework time
  - Reduce time materials and information spend being moved and not processed
- Get more from less
  - Increase resource productivity, aka realized capacity (but subordinate to value, defect minimization, & flow)
  - Reduce the cost of acquiring resources, materials, and information
  - Reduce the cost of using materials and information

Defects may linger hidden in products after they are delivered to customers. Such defects are categorized under the value heading in this analysis because they reduce the value provided customers. Defects within the production process may be attacked within the suppliers’ production systems or within the project production system.

Flow is a fundamental concept indicating the production system’s striving for instant delivery. As such, it incorporates both continuity (not stopping) and speed. The coordination of multiple flows is important in all production systems, but especially in project-based production systems like construction because of the complexity of products and the number of suppliers. Coordination of flows obviously reduces delays and rework, but is largely achieved through planning and control. Consequently coordination of multiple flows is considered on the value side of the hierarchy.

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9. The first three of these categories of waste are groupings of the types of waste proposed by Ohno. Avoidable cost is an added category.
10. An example: “Critical Success Factors” adopted by Malling Products in the U.K. are defined as 100% Reliability, Lead Time Towards Zero, Six Sigma Quality, Zero Safety Incidents & Suggestions for Improvement by Team Members. All are in support of the ideals outlined in this paper. None address traditional measurements such as cost, ROI, etc.
Resources are things that can bear load and have limited capacities; e.g., labor, tools, equipment, space, and time. Resource management can be divided between acquisition and use. Getting the most out of resources once they have been acquired has traditionally been pursued under the rubric of ‘productivity improvement’. Minimizing the cost of acquiring those resources also reduces waste, but is subordinate to productivity improvement because of the latter’s impact on production system performance.

A caution about resource productivity: In the construction industry, there has been a tendency to optimize resource productivity locally to the detriment of system performance. Within the lean framework, resource productivity improvement is subordinate to the goals of value generation and waste reduction.

The first task is to achieve a certain level of flow (speed) and defect performance (quality), including the location of capacity buffers as needed to absorb variability without sacrificing cycle time, should minimizing delivery time be valuable. Then, a follow-on task is to reduce the resources needed to maintain or improve that level of flow and defect performance. In no case should flow or defect rate be allowed to worsen in order to improve resource utilization or productivity.

It may also be useful to note that the above hierarchy applies equally well to both designing and making. For example, improving the quality and on-time delivery of design ‘products’ from external suppliers is certainly appropriate. As is increasing the flow of information in design by reducing batch sizes, reducing rework, etc.

Minimize Waste: Levels 1-4

- Reduce defective products
  - Improve supplier quality and on-time delivery
    - Reduce the number of suppliers and engage them in pursuit of the lean ideal
    - Actively learn with suppliers from project to project
    - Require evidence of product compliance from suppliers
  - Improve the quality of intermediate products
    - Improve design constructability
    - Use in-process inspection
    - Pay after inspection/quality assurance
    - Use commissioning processes\(^{11}\) to demonstrate system and facility functionality and capacity

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\(^{11}\) Commissioning is a set of formal procedures for assuring that what is delivered to customers meets their needs. It typically includes some means for assessing the adequacy of design, conformance of products to the design (including testing and integration of subsystems into functional facility systems), and preparation of the customer for assuming custody and control, as in operator training. It may also include some type of post occupancy evaluation. Commissioning has long been done in industrial facilities, especially those involving continuous flow processes (pharmaceuticals, petroleum, etc.), but is now becoming popular in commercial building, especially as buildings go more high-tech. For more information, see the website of the Building Commissioning Association: http://www.bcxa.org/.
• Make materials and information flow/reduce cycle times (i.e., minimize time mts or info spend being inspected, reworked, waiting in queues, being processed, or moving)
  o Structure work for flow
    ▪ type, size, & locate buffers to absorb variability & match the value of time vs cost for this customer
    ▪ Make throughput=demand rate (avoid overproduction [waste] and underproduction [loss of value])
    ▪ Structure work in continuous flow processes when feasible
    ▪ Layout for flow
    ▪ Simplify site installation to final assembly and commissioning
    ▪ Minimize negative iteration in design
  o Control work for flow
    ▪ Use the Last Planner system of production control
  o Reduce inventories (time spent waiting in queues)
    ▪ Reduce variability (a primary reason for inventories)
    ▪ Reduce transfer batch sizes (get stuff out of queues asap)
    ▪ Reduce setup times (a ‘cost’ that constrains inventory reduction)
    ▪ Pull mats & information through the production system
  o Reduce inspection time
    ▪ Make inspection unnecessary or automatic; aka, pokayoke
    ▪ Incorporate inspection in processing time
  o Reduce processing times
    ▪ Reduce process batches
    ▪ Redesign products to require less processing time
    ▪ Apply technology that reduces processing time
  o Reduce rework time
    ▪ Do in-process inspection
    ▪ Identify and act on causes of defective work
  o Reduce time materials and information spend being moved and not processed
    ▪ Reduce ‘distances’ over which materials and information are to be moved
    ▪ Increase movement speed
    ▪ Reduce the number of moves; e.g., strive for ‘one touch’ matl hdlg on site
• Get more from less
  o Increase resource productivity, aka realized capacity (but subordinate to value & flow)
    ▪ Increase resource utilization
    ▪ Increase resource fruitfulness

12 Pull is not a universal means, but rather requires satisfaction of the condition that lead times fall within the window of reliability; i.e., the time in advance that future states of the production system can be accurately forecast. Given the long lead times for many components and services, together with the small windows of reliability now characteristic of the construction industry, push mechanisms will inevitably be needed for some time to come, and perhaps always in some degree. The structuring of pull/push mechanisms is a much needed area for research.
- Assign tasks where they can best be done; e.g., shift detailed eng. to suppliers
  - Reduce the cost of acquiring resources, materials, and information
    - Reduce transaction costs
    - Reduce purchase prices
  - Reduce the cost of using materials and information
    - Reduce material scrap
    - Reduce unneeded workspace
    - Reduce ‘emissions’

Minimize Waste: All Levels

- Reduce defective products
  - Improve supplier quality and on-time delivery
    - Reduce the number of suppliers and engage them in pursuit of the lean ideal
    - Actively learn with suppliers from project to project
    - Require evidence of product compliance from suppliers
  - Improve the quality of intermediate products
    - Improve design constructability
    - Use in-process inspection
    - Pay after inspection/quality assurance
    - Use commissioning processes to demonstrate system and facility functionality and capacity

- Make materials and information flow/reduce cycle times (i.e., minimize time mtls or info spend being inspected, reworked, waiting in queues, being processed, or moving)
  - Structure work for flow
    - type, size, & locate buffers to absorb variability & match the value of time vs cost for this customer
    - Make throughput=demand rate (avoid overproduction [waste] and underproduction [loss of value])
      - Match bottleneck capacity to demand rate
      - Pull materials and information through the production system
  - Structure work in continuous flow processes when feasible
    - Balance processing times of the production units
    - Use multiskilled workers to smooth work flow between production units
  - Layout for flow
  - Simplify site installation to final assembly and commissioning
  - Minimize negative iteration in design
    - Use the Design Structure Matrix (DSM)\textsuperscript{13} to eliminate avoidable iteration

\textsuperscript{13} See LCI White Paper #10 at www.leanconstruction.org.
• Use strategies for reducing negative iteration at team assignment level
  o Accelerate iteration through team sessions
  o Design to the upper end of interval estimates; e.g., loads
  o Shift overdesign where estimates can best be made or overdesign can be done at least cost
  o Control work for flow
    ▪ Use the Last Planner system of production control
    ▪ Try to make only assignments with the following quality characteristics: definition, soundness, sequence, size, learning
    ▪ Measure plan reliability
    ▪ Identify and act on root causes of plan failure
    ▪ Explode scheduled tasks as they enter the project lookahead window (typically 3-12 weeks)
    ▪ Analyze lookahead tasks for constraints and act to remove those constraints
    ▪ Allow lookahead tasks to maintain their scheduled dates only if they can be made ready in time
    ▪ Balance load and capacity by retarding/advancing scheduled tasks and/or reducing/increasing resources
  o Reduce inspection time
    ▪ Make inspection unnecessary or automatic; aka, pokayoke
    ▪ Incorporate inspection in processing time
  o Reduce inventories (time spent waiting in queues)
    ▪ Reduce variability (a primary reason for inventories)
      • Underload resources
      • Identify & act on causes of variability
        ▪ Reduce transfer batch sizes (get stuff out of queues asap)
        ▪ Reduce setup times (a ‘cost’ that constrains inventory reduction)
        ▪ Pull matls & information through the production system
  o Reduce processing times
    ▪ Reduce process batches
    ▪ Redesign products to require less processing time
    ▪ Apply technology that reduces processing time
  o Reduce rework time
    ▪ Do in-process inspection
    ▪ Identify and act on causes of defective work
  o Reduce time materials and information spend moving
    ▪ Reduce ‘distances’ over which materials and information are to be moved
    ▪ Increase movement speed

14 Strictly speaking, underloading is a means for reacting to or accommodating variability at the work station where it is implemented, but also reduces work flow variability at downstream work stations.
• Reduce the number of moves; e.g., strive for ‘one touch’ matl hdlg on site

• Get more from less
  o Increase resource productivity, aka realized capacity (but subordinate to value & flow)
    ▪ Increase resource utilization
      - Match load & capacity (have sufficient load to utilize available capacity)
      - Reduce system variability (allows greater utilization for a given throughput rate)
    ▪ Increase resource fruitfulness
      - Develop skills
      - Improve design for fabrication and installation
      - Assign tasks where they can best be done; e.g., shift detailed eng. to suppliers
  o Reduce the cost of acquiring resources, materials, and information
    ▪ Reduce transaction costs
    ▪ Reduce purchase prices
  o Reduce the cost of using materials and information
    ▪ Reduce material scrap
    ▪ Reduce unneeded work space
    ▪ Reduce ‘emissions’

APPLICATION OF THE DESIGN GUIDE

Priorities

Considering tradeoffs, value generation has priority over waste reduction. In other words, when faced with a choice between generating value and reducing waste, choose value generation. Granted, waste may make the product prohibitively expensive; i.e., despite its value, the customer either cannot afford to pay for it or system waste delays its delivery beyond the point that the product is needed by the customer. When that occurs, the best way to generate value may be to reduce waste. Clearly the priority of value generation over waste reduction is not a simple matter of choosing between alternative actions, as is perhaps clear from the number of instances in which the same means are listed for both ends. However, in all cases, value generation has the higher priority as a goal. Waste reduction emerges as a goal in its own right, rather than a means for achieving the goal of value delivery, for producers rather than customers.

Moving from value generation to waste reduction is also typically the temporal order of design, implementation, and improvement. Within waste reduction, flow and defect reduction have priority over getting more from less, because of the greater impact of the former on system performance.
Metrics

Measurements at lower levels may be useful, but the primary measures of production system performance are at Level 2:

- Deliver products that enable customers to better accomplish their purposes: customer surveys and post-occupancy evaluations
- Deliver products on time: on-time delivery rates
- Make materials and information flow: process flow analysis and project durations (cycle times)
- Get more from less: productivity measurements, costs, scrap rates, etc.
- Reduce defective products and process: % product defects discovered at various process stages and % process defects such as safety and health incidents.

Of the above, some work remains to be done on post-occupancy evaluations and on process flow analysis. Equally important is to instill the discipline of analyzing defects and failures to root causes and acting on those causes.

Designing a Project-Based Production System

Now that we have a hierarchy of ends and means, how might it be used in production system design—especially of project-based production systems?

One use is to answer specific questions of technique; e.g., ‘How do we go about reducing inventories?’. Another use is as a guide to making investment decisions; e.g., ‘Which is more important on this project, keeping the client’s cost within his budget or accelerating project completion?’ Further, like all checklists, the hierarchy can serve as a reminder lest something vital be overlooked. For example, has sufficient consideration been given to minimizing environmental impacts from operation of the facility? Lastly, the hierarchy can be used as a template for construction of system models for simulating alternative designs.

INNOVATIONS PROPOSED IN THIS PAPER

- Conceptualization of work structuring as production system design.
- Maximizing value and minimizing waste are universal goals for producers, regardless of their specific business objectives and strategies.
- Conceptualization of value generation in terms of producer as well as customer purposes.
- Understanding of control as a means for generating greater value, based on control being better accomplishment of purposes.
- Conceptualization of flow as the progression of intermediate products (materials or information) through the production system, as opposed to the traditional lean production/manufacturing conceptualization of flow as all temporal states of materials other than processing; i.e., as non-value-adding states of materials.
• Categorization of waste into defective products, lack of flow, lost capacity, and avoidable cost.
• Conceptualization of flow as the system’s innate striving for instantaneous delivery and hence minimization of cycle time.
• Creation of the category: Get More From Less.

**NEEDED RESEARCH**

Given the above ends-means hierarchies, what do they reveal about needed research? Are there ends for which means need to be developed, tested, or improved? We suggest the following areas where research is needed right away and also show where LCI’s current research projects fit into the systems design model:

• *Understand, critique, and expand customer purposes.*
  LCI’s research project *Lean Design* is dedicated to experimental implementation of the processes outlined in LCI White Papers 9 (Project Definition) & 10 (Lean Design).

• *Organize in cross functional teams.*
  Experimentation is needed in bringing downstream players into upstream phases, structuring commercial relationships, aligning interests, specifying roles and responsibilities, etc. LCI’s research project *Specialty Contractors in Design* is tackling this problem as regards involvement of specialty contractors in preconstruction processes.

• *Increase system transparency.*
  While many things can be done to increase system transparency, including organizing in cross functional teams and aligning stakeholder interests, a primary area needing development is the application of information technology for this purpose. LCI is allied, along with other organizations, with Reality Capture Technologies in a proposal to NIST’s Advanced Technology Program for funding to apply IT to increasing system transparency.

• *Matching buffer type, location, and size to actual variability.*
  What’s needed is measurement of actual variabilities: processing durations, on-time deliveries, defect rates, etc. Buffer engineering itself doesn’t appear to be problematic. This topic is included in Todd Zabelle’s research on *Taking Fab Shops Lean*.

• *Structure work in continuous flow processes.*
  Experimental work is needed to see what work can be structured as continuous flow processes and how such processes are best managed. LCI’s research project *Incorporating First Run Studies into Make Ready Processes* will involve structuring continuous flow processes, as will LCI’s research project *Cycle Time Reduction in Residential Construction* and Todd Zabelle’s *Taking Fab Shops Lean*. The latter two projects explicitly consider multiskilling and self-directed work teams.

• *Simplify site installation to final assembly and commissioning.*
  Obviously modularization and prefabrication are critical elements here. Research is needed to determine the fabrication precision needed, explore the interaction of tolerances, and develop strategies for developing needed supply chain capabilities.
• Minimize negative iteration in design.
Experimental application of the Design Structure Matrix and the strategies for team management of looped design tasks is included in LCI’s Lean Design research project.

• Reduce inspection time.
This is one of the foci of LCI’s research project on Project Completion.

• Reduce rework time.
This is one of the foci of LCI’s research project on Project Completion.

• Improve supplier quality and on-time delivery.
Research is needed on the formation and management of teams of specialists dedicated to the lean ideal. Some work is being done by LCI on this topic in conjunction with N.L. Barnes, Inc. It is also part of LCI’s research project Cycle Time Reduction in Residential Construction.

• Improve installation quality.
This is one of the foci of LCI’s research project on Project Completion.

This is certainly not an exhaustive list of research needs or of research initiatives. We have only listed research projects being carried out directly by LCI, excluding even PhD research being done under Tommelein or Ballard. As for needs, almost every item in the hierarchy could be further developed. However, for the most part, we believe that the conceptual model has been developed and what is now needed is systematic experimentation with concepts and techniques. We offer this model to the international research community as a framework within which to further develop lean construction.

Please communicate comments and questions to Glenn Ballard at gballar@pacbell.net.
**Last Planners™** prepare assignments for people who do work. Last Planners™ can be found throughout construction organizations where they are called “Foremen”, “General Foremen” or “Superintendent”. This is a complex and difficult job because Last Planners™ must plan and prepare for the future, and supervise work underway. Keeping peace in the crew, assuring work is safe, coping with shortages, solving problems, and finding ways to make progress are all part of the job. Asking these people in this environment to do a better job planning seems like asking a lot and it would be if nothing else changed. But the situation does change when projects are managed under the **Last Planner System™ (LPS)** of Production Control. Last Planners™ working in this system report they spend far less time fighting fires and looking for work. This guide explains both the operation of the planning system and the Last Planner’s role in it.

Last Planners™ make assignments to crews and these assignments largely determine performance of that crew. This is obvious and important. Less obvious and often more important is the impact of one planner’s work on crews that follow down stream. If upstream plans are reliable, work is released to the next crew at the time and in the sequence to best support the overall project. In effect, assignments prepared by Last Planners™ are directions for their crew and promises (commitments) to others that makes close coordination possible. Creating and maintaining reliable workflow between crews is the first objective of the system. The LPS supports this objective both by providing a way for Last Planners™ to make reliable assignments, and by making work ready so that it can be assigned when required. Finally, the system provides feedback to improve performance.

**System Overview**

The Last Planner System™ provides the planning and control tools necessary to manage work on projects even when they are complex, uncertain and quick. Planning is defining what is to be done and how, control is a making it happen. A project is under control when we can do what we say we are going to do. Keeping commitments in the short term is essential if the project is to achieve its objectives. This is a very different definition of control than used in current practice. The design of the LPS makes it possible but people make the system work by how they make and keep commitments. Making and keeping promises is the essential skill required in this system. Plans prepared at each level are promises to someone; at the highest level to the client, at the Last Planner™ level to crews that follow and work in parallel. Coordination is tough when workflow is unreliable, impossible when people don’t keep their promises. Making reliable promises sometimes means saying “no”. The importance of commitments and saying “no” will become more obvious in the discussion about lookahead and last planning practice.

The LPS has four levels of planning. The degree of detail in plans is refined and uncertainty is reduced through each level by careful consideration of what **SHOULD** and **CAN** be done. Planning this way keeps objectives firmly in front of the project.
team and helps them identify and remove obstacles to their achievement. Coordination happens through the continuous process of making and keeping commitments for action. Planning in this system is not dreaming or hoping, rather it is the active hard work of creating the future. The resulting predictable flow of work from one crew to the next reduces waste, simplifies further planning and finally is the key to delivering value to the clients.

The master or project schedule is developed from design criteria that support the client’s project objectives. The basic structure of work, that is the big chunks that make up the project, is determined by breaking the project into pieces and establishing their sequential relationships. Current planning practice produces good enough master schedules for use in the LPS but we advocate reducing the level of detail in the master schedule to key milestones and then developing phase schedules as the milestones approach.

The master schedule must demonstrate the feasibility of completing the work in the available time, develop and display execution strategies, determine when long lead items are needed, and identify milestones important to clients and stakeholders. It cannot and should not be used as the tool for managing activities except on relatively small and simple projects. More detail schedules are developed in the phase schedule to support completion of master schedule milestones. While we believe overly detailed master schedules are not needed to manage the project, their...
preparation early in the project is vital to developing the best understanding of the project.

The master schedule should be developed in as much detail as possible early in the project so as to learn as much as possible about the relationship between the pieces, to determine when long lead items are required, to identify areas of greater uncertainty and those subject to change, and to gain confidence that project objectives are achievable. This is an essential exercise but it does not design the way work will be done, that is the production process that will complete the project. Highly detailed master schedules cannot be used to manage the work itself as they rest on an incomplete model of the work. By this we mean that schedules identify activities but do not portray the flow of requirements within and between tasks or activities beyond simple sequential relationships.

Phase schedules are prepared by the team of people who manage the work in the phase. While phase schedules may not be required on small less complex jobs, their function should not be overlooked. Master schedules can be understood as a sort of exploded assembly drawing of the project showing how the big pieces come together over time. This view of the project is important but does not show the way work will be done to complete the work within each piece or to coordinate the details of their assembly. This is the role of a phase schedule. Developed by those responsible for the work, a phase schedule identifies the rules for release of work from one activity to the next and sets the sequence and timing of activities in finer detail than the master schedule. Activities from the phase schedule enter the lookahead process where they are magnified into task level detail, screened for to assure all requirements are made ready for the assignment. The Last Planner™ then completes the assignment to meet specific criteria, and after the work is performed measures the percent of tasks complete. Reasons for incomplete tasks are identified and action taken to prevent recurrence.

**Phase Scheduling**

Activities on the master schedule will sooner or later need to be magnified and posted to a lookahead schedule. When projects are large and complex, a single master schedule should represent activities only in broad terms. In these cases, a single lookahead to cover all tasks will be unwieldy. Accordingly, the master schedule should be maintained at the milestone level. Phase schedules developed to achieve the milestones should be prepared closer to action but early enough to make work ready and assure coordination. Phase schedules should be prepared at least 6 weeks prior to the start of their first activity or even sooner if longer lead times have been identified.

The best practice is to gather the work management team, review the master schedule and appropriate milestones and then working back from that milestone to identify the work needed to complete of the phase. This back-to-front process identifies the conditions required for work to be released from one activity to the next and the coordination necessary to allow multiple activities to proceed concurrently. This process is best done on a blank wall where people can add cards for each activity and move them as new work is revealed. A rough time scale should be established so people have a sense of the timing involved. This is a highly participative process often rich in horse-trading and negotiation. Activities in a phase
schedule are highly dependent on each other. They involve routine and repetitive interfaces between trades and therefore require close coordination.

A typical phase scheduling process will take a few hours although the time can be shortened if the team is experienced and/or templates from similar work are available. Near the end of the process, durations should be established for each activity. The durations themselves should represent the most likely duration for the task given the circumstances on the project and the teams estimate of their ability to be reliable. The durations will establish the critical path through the phase and in most cases float within the phase will be apparent. This time should be allocated by the team to the most uncertain activities in order to assure the timing of activities within the phase is stable. If the project is pressed for speed and early achievement of milestones is valuable, the team should explore how the phase can be accelerated, what actions will be required and how the group will respond to early completions.

By contrast, if the work in a phase exceeds the available duration, the team must carefully consider alternatives and their cost and then open negotiations at the project level in order to best achieve project objectives.

In summary, master schedule activities are magnified in phase scheduling. Each phase includes activities that in turn must be further magnified and screened in the lookahead plan that typically includes work for the next 6 weeks. This effectively means that 5 weeks of work are visible on the lookahead. The first week of the so-called 6 week lookahead, in effect, becomes the weekly work plan that is being executed as of the data date.

### Lookahead Planning

If the master schedule is a sort of time based assembly drawing of the project and phase scheduling designs the details of the production process, then lookahead planning assures the requirements are in place to make it run. The process is straightforward; activities fall into the lookahead schedule, typically 6 weeks before the work is supposed to start. As time passes, the level of detail is magnified as specific tasks within the larger activity are identified. Each task is screened to assure requirements are identified and pulled into readiness to maintain a backlog of work available to the Last Planner.

The lookahead period is used to
- shape workflow sequence and rate; for example to adjust the time and sequence of work to conform with known availability of resources.
- match workflow to the amount of labor and equipment available.
- prepare and maintain a backlog of ready work to assure continuous work when rates of production vary from planned.
- develop detailed plans for how work is to be done considering safety, environmental, and quality issues.

Thus lookahead planning assures the flow of work through the production system. Commitment planning by the Last Planner™ involves committing to what will be done based on actual receipt of resources and completion of prerequisites.
What time frame does the lookahead cover?

As mentioned, the Master schedule identifies the project milestones over the life of the entire project. Phase schedules detail the production process to support those milestones and may cover several months. Lookahead schedule typically look 6 or 8 weeks into the future. Both the lookahead and the Weekly Work Plan increasingly magnify tasks to be performed, taking into account actual circumstances. The lookahead and, in turn, the Weekly Work Plan cover shorter time spans into the immediate future but reflect higher degrees of confidence that work will be executable.

Which activities get posted on the lookahead?

The lookahead window determines how far ahead of the scheduled start date activities in the phase schedule are considered for entry into the lookahead plan.

Once in the lookahead schedule the activities are -

**Magnified:** A greater amount of detail is needed during lookahead planning regarding the activity’s inputs and outputs so that the planner can screen the activity to assure that the activity can be made ready by its scheduled start date.

**Screened:** Determining the status of tasks in the lookahead window relative to their readiness, then choosing to advance them into the lookahead schedule or delay tasks on the master schedule based on their status and the probability they can be made ready prior to the activity’s scheduled start.

**Made ready:** taking actions needed to remove constraints from activities to make them sound so they will be ready at the scheduled time for assignment in a weekly work plan by the Last Planner.

SCREENING

Screening is the process of preparing activities for advancement into the lookahead schedule or delaying entry of activities from the phase or master schedule based on the known status of constraints (requirements necessary for work) and the probability of removing them prior to the task’s scheduled start. Screening does not prevent an activity with outstanding constraints from moving forward as long as the person responsible believes there enough time remaining before action to remove the constraints. Screening is first done when activities are considered for entry into the lookahead. It is then repeated in each planning cycle, when the planner updates the lookahead and advances tasks into the next week.

CONSTRAINTS ANALYSIS

A constraint is anything that stands in the way of a task being executable or sound. Constraints concern directives such as specifications and procedures, prerequisite work done by others whether on or off site, or resources such as labor and equipment and space – things that carry load. Typical constraints on construction tasks are the completion of design or prerequisite work; availability of materials, information, and labor or equipment resources.
Constraints Analysis aids in systematically identifying and tracking activity status. Identifying and removing constraints is one of the most important steps in reliable production planning and control.

**REMOVING CONSTRAINTS**

Planners remove constraints to advance activities into weekly work plan assignments. An activity with its constraints removed is available to enter the weekly work plan. There are two groups of constraints that must be considered by planners at every level. The first are those normally within their control. For a foreman these might include the tools kept in a gang box. Each planner should assure that the constraints within his control will be on hand. The second category of constraints is any constraint that require action of others (in the case of gang box tools, a shortage may put tools in this category.) The second category is removed by making a request to someone else. Planners should not assume that their requests will be filled until they receive a promise of delivery. Even then should be wary if they are not confident of the supplier will deliver.

The first step is to make a request of the supplier to deliver what is needed to make the task ready. The second is to assure a promise has been received and to assess its reliability. This may include assuring the lead time for supplies is shorter than the time remaining. However, unforeseen events may always come up, so contacting the supplier is the typical make-ready step. Confirming lead times is part of the screening process and may be repeated during weekly updating of the lookahead schedule.

Expediting may be required if the constraint (supply) does not appear to be forthcoming. In most cases this will require action by more senior people and they should be alerted as soon as the planner looses confidence.

Making work ready during the lookahead period is the key action then for Last Planners™ and their supervisors. The system can cope with delays and problems if they are identified early enough in planning and elevated to those with authority to cause action.

**The Last Planner**

Telling people what should be done isn’t enough. The planning system must assure they have what it takes to do the job. Discovering what CAN be done only after the crew arrives won’t assure reliable workflow between crews.
A reliable assignment, one that gets done at the required time, determines what “WILL” be done, after considering both what “SHOULD” from higher-level schedules and what “CAN” be done based on the situation at hand. Assignments are likely to get done when they are well defined, resource sound, in the right sequence, and within the capacity of the crew. The Last Planner’s job is to make certain the task in the assignment meets these criteria, and to reject assignments that do not. Last Planners™ can reasonably commit to completing the tasks on weekly work plans that meet these criteria.

The Last Planner’s Weekly Work Plan is a commitment plan. By committing only to work that CAN be done, the Last Planner™ SHIELDS crews from uncertainty. The crew will be more likely to accomplish what they set out to do with this kind of assignment. Increased plan reliability improves performance of the crew and simplifies coordination with others because they will be better able to organize their work and plan the methods to be applied.

Thus the certainty of workflow from one crew to the next is a key to improving project performance.

(Flexibility is the only alternative strategy. This means mobilizing resources sufficient to do whatever work happens to be available, allowing for multiple stops and starts of operations best performed as a whole, inefficient sequencing of tasks, and inability to do detailed advance planning. When the flexibility strategy is applied, workflow uncertainty increases multiplying the project uncertainty and the expense. In the short term, the flexibility strategy seems relatively easy to carry out! Responsibility for poor performance can be avoided by blaming others for failing to keep their commitments.)

Lets look in more detail at the criteria because assignments that meet these criteria will most likely be done. If they are not, the reason for failure can be traced to its root cause and action taken to prevent recurrence. Experience in construction shows that poor information on the availability of resources is often the most frequent source of planning failures.)

**Quality Criteria for Assignments**

The Last Planner™ makes the Weekly Work Plan by identifying tasks that both SHOULd be done and CAN be done because they meet the planning criteria. Activities that do not meet these criteria will have to be made ready first.

Choosing what work WILL be performed in the next week from what CAN be performed is termed making reliable assignments. Weekly Work Plans are effective when assignments meet these four specific quality criteria;

**Definition:** Are assignments specific enough that the right type and amount of information or materials can be collected, work can be coordinated with other disciplines or trades, and it is possible to tell at the end of the week if the assignment has been completed?

**Soundness:** Are all assignments workable? Do you understand what is required? Do you have what you need from others, are all materials on hand; is design complete; is prerequisite work complete, etc.? Note that some
make-ready work will remain to be done during the week, e.g., meeting with other designers or fabricators, coordinating with trades working in the same area, moving materials to the point of installation, etc. Nonetheless, the intent is to do whatever can be done to get the work ready before the week in which it is to be done.

**Sequence:** Are assignments selected from those that are sound in priority order and in order of workability? Will doing these assignments release work needed by someone else? Are additional lower-priority assignments identified as workable backlog, that is, are additional quality tasks available in case assignments fail or productivity exceeds expectations?

**Size:** Are assignments sized to the productive capability of each individual or crew while still being achievable within the plan period?

Only tasks that meet these quality criteria should be put on a Weekly Work Plan.

**Workable Backlog**

Workable backlog is work that is ready to do but not assigned because it is beyond what the crew can reasonably be expected to do. If it were placed on the Weekly Work Plan, the assignment would overload the crew and thus break the sizing criteria. Ready work that cannot be assigned is recorded as **Workable Backlog** on the Weekly Work Plan. Workable Backlog provides ready work that can keep the crew working in the right sequence when they are not be able to complete an assignment on their Weekly Work Plan, or when they complete assignments sooner than expected. Workable Backlog prevents the crew from doing work that makes later work more costly or difficult. Items in workable backlog must meet all quality criteria except sizing.

Remember that the Last Planner™ aims to assure reliable work for their crew as well as crews downstream. Plan reliability is key to system performance. Accordingly, the Last Planner™ should **under load** the crew, that is, make assignments that absorb less than 100% of its capacity to do work required downstream. This assures it will get done even when small things go wrong. Workable backlog will provide work to use any time not applied to produce the work required downstream. Remember, reliable workflow is the first objective of the planning system and is more important than the short-term productivity of your crew. Maintaining workable backlog allows you to keep productivity high while serving those who rely on your crew.

**Measuring Planning System Performance with PPC**

Planning is always an exercise in judgment. Last Planners™ will be using their judgment in lookahead planning when they assess the likelihood that constraints will be removed and when they make assignments. The information planners rely upon is often incomplete and seldom certain. Supervisors should take active role in lookahead planning and review weekly work plans to minimize errors. But mistakes will be made by the best of planners because their work often relies on long strings of commitments by others and of course, projects are uncertain and complex. So it is
important to measure the success of the entire planning system and to take action to improve its performance. Measuring reliability is the first step. The Last Planner™ System measures reliability in terms of Percent Plan Complete or PPC.

**PPC is the number of actual task completions divided by the number assigned for a given week.**

PPC assesses the extent to which the Last Planner™ was able to anticipate what work would get done in the upcoming week. It measures if WILL matches DID. PPC thus reflects the reliability of planning system.

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**Complete or Not Complete? That is the PPC Question.**

Whether or not an assignment has been completed requires a YES or NO answer. The Last Planner™ only marks those tasks complete that are in fact complete. Work is not complete even though it may have been started or even nearly complete. This no-partial-credit rule means credit is taken only for completed work that can be handed off to the next crew. If any part remains incomplete, no clean handoff can take place. In order to create reliable flow from one crew to the next, end-of-week completion commitments must be met.

The Last Planner™ System normally allows some leeway regarding schedule variation by assessing completion only once per week. In cases where timing is critical, PPC can be measured to the day or hour. In any case incompletion of work may be caused by -

- failure to deliver perquisites as promised,
- unclear or inapplicable procedures,
- failing to understand the effort required,
- unforeseen site conditions or bad weather,
- conflicts with other crews for space or equipment.

**Learning from Plan Failures**

When an assignment is not completed by the end of the plan week, the Last Planner™ must record the reasons for non-completion. Reasons for plan failure fall into categories pertaining to directives, prerequisite work, resources, and process or output failures. Construction people will recognize some of those commonly mentioned.
### CONSTRUCTION

<table>
<thead>
<tr>
<th>Directives</th>
<th>Design Changes</th>
<th>Not informed of performance standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prerequisite Work</td>
<td>Submittal approval not received</td>
<td>Materials did not arrive as promised</td>
</tr>
<tr>
<td></td>
<td>Request for information unanswered</td>
<td>Other contractor still in area</td>
</tr>
<tr>
<td></td>
<td>No access to work area</td>
<td></td>
</tr>
<tr>
<td>Resources</td>
<td>Crane not available due to breakdown</td>
<td>Unexpected absentees</td>
</tr>
<tr>
<td>Process or Output</td>
<td>Planned too much work</td>
<td>Inadequate coordination</td>
</tr>
<tr>
<td></td>
<td>Emergency</td>
<td></td>
</tr>
</tbody>
</table>

Reasons for plan failure can be plotted based on their frequency of occurrence. This highlights which failures are predominant and where process improvement efforts may be most beneficial.

After noting reasons for non-completion, a root cause analysis must be performed. The reason that is first apparent may in fact be a consequence of other actions and events that took place on the project. Each company should establish a process to determine the source of the action or event chain in order to learn how repeat failures can be prevented. The purpose of this effort is to discover the action needed to prevent future failures and not to assign blame to any individual. The Reasons Analysis Hierarchy may help you determine root causes.

For instance:

If you did not have something you needed as a prerequisite to your process,

- Did you request those needed prerequisites?
- Was your request specific and complete?
- Were you promised the prerequisite but did the provider not deliver? or
- Were you not able to reach agreement with the supplier of the prerequisite?

Each of these in turn leads to further questions that will let you pin down the cause of failure, so you may be able to prevent it from reoccurring.

### Weekly Planning Cycle

Weekly Work Planning is done shortly before performing work. Assuming that the plan week begins on Mondays—though other plan weeks are possible—planning for...
next week should begin this week and coordination with others completed during a mid-week meeting. This meeting involves a meeting coordinator and all Last Planners™ on a project whose work is related by prerequisites, shared resources, directives, or other potential constraints. The purpose of the meeting is threefold:

- Assess and learn from last week's PPC,
- Create the work plan for the following week, and
- Determine make ready needs for the remainder of the week.

The Weekly Work Plan developed during this mid-week meeting can be adjusted at the end of the week, when last-minute information is available regarding completion of make ready work and likely completion of work scheduled for that week.

**WEEKLY PLANNING CYCLE**

<table>
<thead>
<tr>
<th>WEEK A</th>
<th>WEEK B</th>
<th>WEEK C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friday</td>
<td>Monday</td>
<td>Friday</td>
</tr>
<tr>
<td>Midweek Planning Meeting</td>
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<td></td>
</tr>
<tr>
<td>Institute 11</td>
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</tbody>
</table>

Last Planners™ must bring to the mid-week meeting their actual PPC data from last week with reasons identified for assignments that were not completed. This week’s meeting is for all Last Planners™ to report the root causes for their plan failures and to identify how these can be prevented in the future. Prevention often requires
consideration and action by other crews or higher levels of supervision, so the meeting is to clarify who must take action.

The review of the current week's Weekly Work Plan and information on the status of work is to communicate how things are going, to allow other crews to gain insight into plan changes or request adjustments from others, and finally to determine what action can be taken to increase PPC in this week.

Finally, each Last Planner™ then puts forward their Weekly Work Plan for the next week. This information exchange combined with negotiation among Last Planners™ will help resolve sequencing alternatives where shared resources are involved.

<table>
<thead>
<tr>
<th>Last Planners™ bring to the Weekly Work Planning meeting:</th>
<th>The coordinator brings:</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ Last week's Weekly Work Plan with PPC and reasons for plan failure identified;</td>
<td>□ The project’s Master/Phase and Lookahead Schedules</td>
</tr>
<tr>
<td>□ This week’s Weekly Work Plan and information on the status of work;</td>
<td>□ Status information from the client, regulators, designers, suppliers, project managers, crews, or others with a stake in the project.</td>
</tr>
<tr>
<td>□ A first cut at next week's Weekly Work Plan and a list of make ready needs; and</td>
<td>□ A Proposed Weekly Work Plan to support Phase Milestones. (if needed.)</td>
</tr>
<tr>
<td>□ The Lookahead Schedule with the status of constraints as they are known.</td>
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</tbody>
</table>

The Weekly Work Planning meeting can be followed by a second meeting held on the last day of the week. The time between the two work planning meetings enables Last Planners™ to take care of some make ready needs. At the second meeting, they will adjust and finalize the next week's Weekly Work Plan after reviewing the actual status of their Weekly Work Plan of the current week.

In addition, all Last Planners™ must check on the completion of make ready work for next weeks’ assignments. Some may yet have to be completed in the upcoming week and will thus require timely tracking. If this make-ready work is not done in time, the corresponding assignment is doomed to fail. The crew should therefore not even start this work, but rather, select an alternative assignment on their workable backlog.

Before the end of work Friday, all Last Planners™ finalize their Weekly Work Plans and distribute them to their crews as well as supervisors.
The Weekly Work Planning Adjustment meeting is for Last Planners™ to determine:

- Which assignments will likely be completed later that day and so increase PPC?
- Which assignments will remain incomplete when the day is over?
- Will incomplete work be made up by working overtime that Friday or over the weekend, or should it be assigned for the next week?
- What make ready work remains to be done during the next week?
- If a make ready task or any assignment were to fall through, how will the work plan be affected?
- Is alternative work available in the workable backlog?

RECAP
The Last Planner™ system includes three levels of planning, each serving a very specific purpose. The purpose of the **master schedule** is to:

- Demonstrate the feasibility of completing the work within the available time.
- Display an execution strategy that can serve as a basic coordinating device
- Determine when long lead items will be needed.

The purpose of the **lookahead schedule** is to:

- Shape workflow in the best achievable sequence and rate for achieving project objectives that are within the power of the organization at each point in time.
- Match labor and related resources to work flow
- Produce and maintain a backlog of assignments for each frontline supervisor and crew, screened for constraints.
- Group together work that is highly interdependent, so the work method can be planned for the whole operation.
- Identify operations to be planned jointly by multiple trades

The purpose of the **weekly work plan** is to:

- Identify make ready actions and assessing their feasibility prior to making assignments so as to shield crews or design teams from uncertainty.
- Making best use of the crew or team’s capacity, acknowledging individuals’ differences, in light of the scheduled loads.
Step 1 - List Criteria

Step 2 - List Inputs

Step 3 - Determine Resources

Step 4 - Determine Deliverable

Step 5 - Upon Completion of Work Determine Match of Criteria to Deliverable