

Work Structuring LCI White Paper-5 June, 1999

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 chunks¹ 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

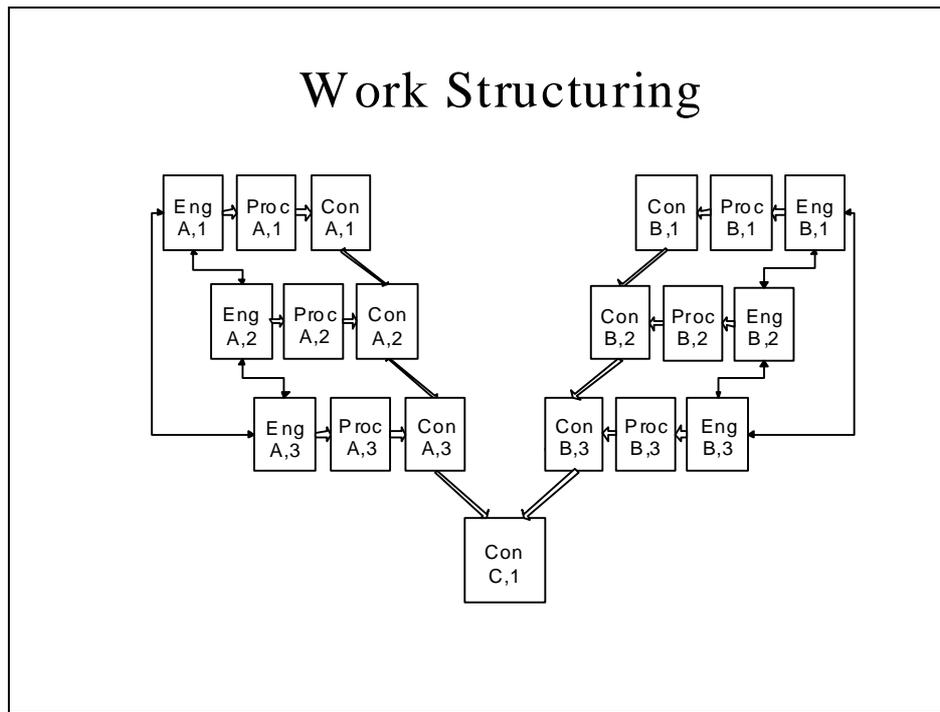
DESIGN FLOW, SUPPLY FLOW, ASSEMBLY FLOW

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."



Work Structuring Model

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

³ 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).

⁴ 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.

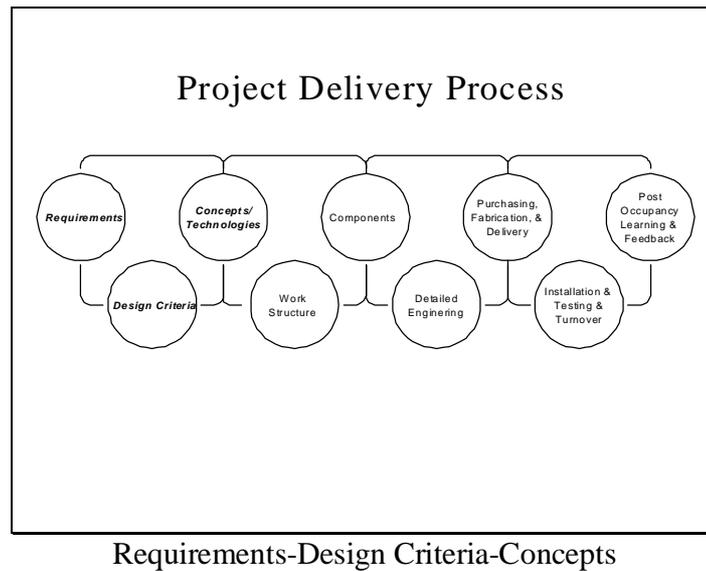
What are the applicable requirements? Codes, standards, and laws are the prime candidates, but even here alternatives often exist. For example, codes specify structural requirements for wind loading, but necessarily are conservative, lacking exact load information for a specific location and facility 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.

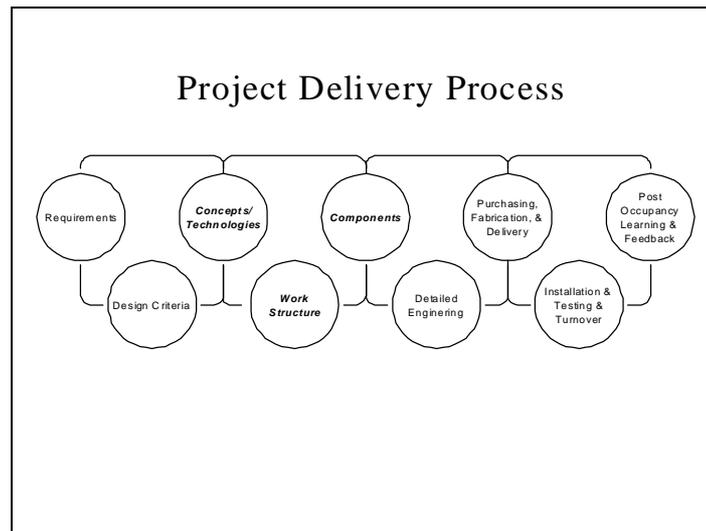
In the delivery process, work flows generally from left to right through linked triads, within which the flow is iterative through multiple loops. For example, Requirements (customer needs, stakeholder demands, etc), Design Criteria, and design Concepts/Technologies are tightly interlinked. Although 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.

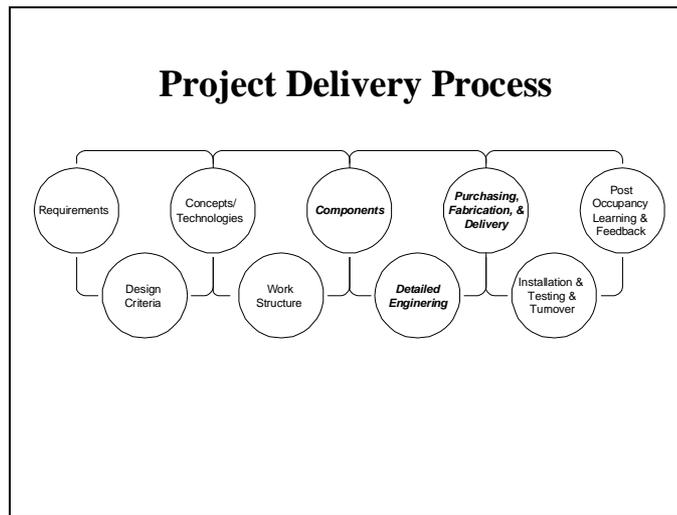
Alternatives can be maintained as long as there is sufficient lead time for acting on them. One reason for understanding supplier lead times is so that design decisions can be made before the alternatives die.

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.



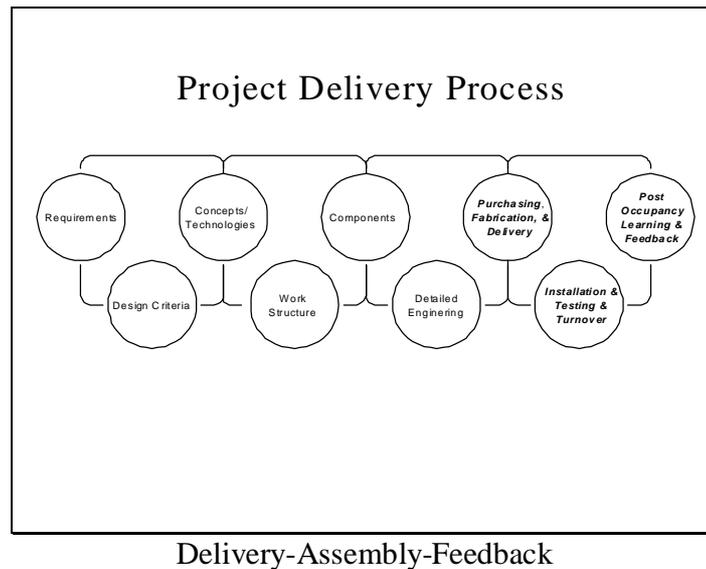
Concepts-Work Structure-Components

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.



Components-Detailed Engineering-Purchasing

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

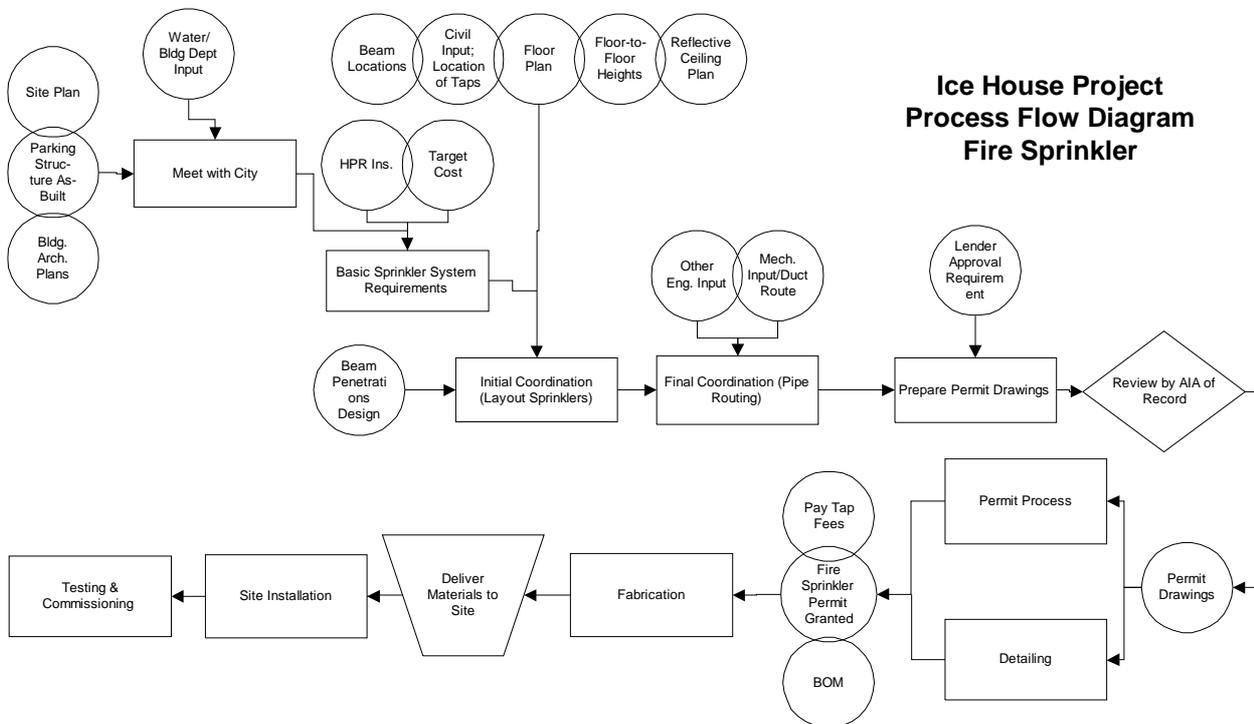
Execution strategies may be directed at a number of different objectives:

- § 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.

- § Design execution
- § Logistics
- § Operations

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 site⁵.



Fire Sprinkler Process Flow Diagram

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 systems⁶, 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.

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.

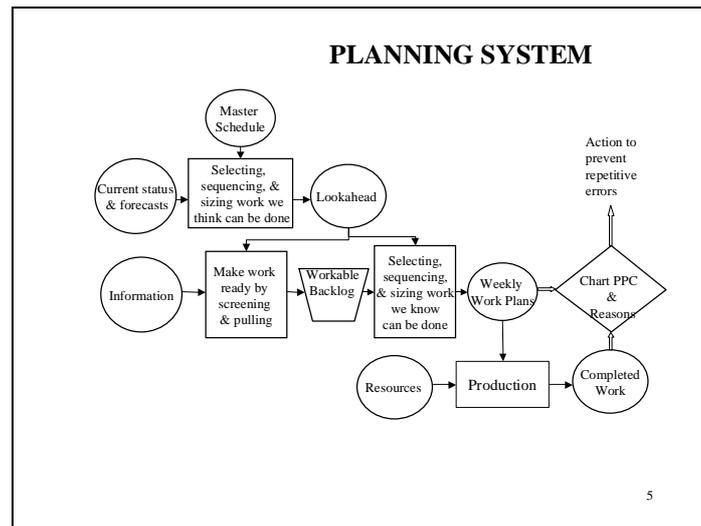
The issue of buffer location, type, and sizing is of enormous importance for our industry. Prior to the advent of lean thinking, it has not been unusual to see buffers located suboptimally as a result of a single PU attempting to protect itself against unreliable work flow. For example, Howell and Ballard (1999) 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.

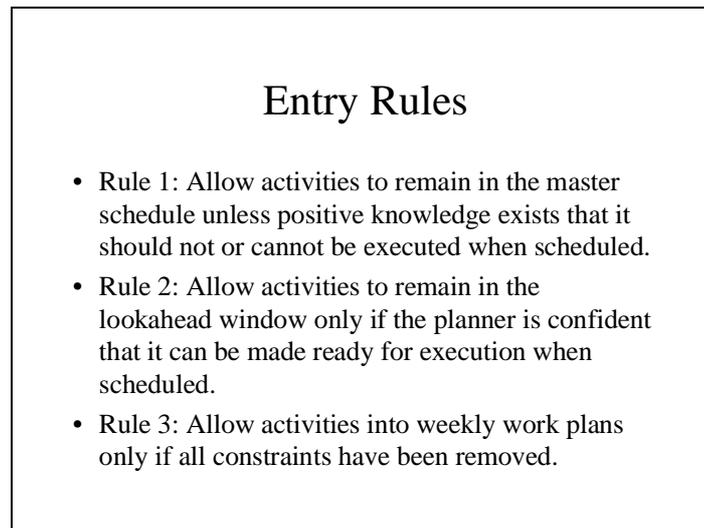
It has been our experience that a single schedule produced at the beginning of the work to be done is insufficient for all but the simplest and shortest projects. A hierarchy of schedules is needed because of uncertainty. In dynamic conditions, detailed scheduling must be done near in time to the activities 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

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.