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PULL-DRIVEN SCHEDULING FOR PIPE-SPOOL INSTALLATION: SIMULATION OF A LEAN CONSTRUCTION TECHNIQUE

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ABSTRACT: Many construction processes include installation of unique materials in specific locations in the facility being built: materials and locations must match before installation can take place. Mismatches due to delay and uncertainty in supplying materials or completing prerequisite work at those locations hamper field productivity. This is illustrated here using a model of a materials-management process with a matching problem that typifies fast-track process-plant projects. The uniqueness of materials and locations combined with the unpredictability in duration and variation in execution quality of various steps in the supply chain allow for different ways to sequence material delivery and work area completion. Several alternatives are described. Their impact on process execution is illustrated by means of probabilistic process models. One model reflects total lack of coordination between delivery and work area completion prior to the start of construction; a second one describes perfect coordination. The corresponding materials staging buffers and construction progress are plotted based on output from discrete-event simulation models. A third probabilistic model then illustrates the use of the lean construction technique called pull-driven scheduling. Real-time feedback regarding the status of progress on site is provided to the fabricator off site so process steps can be re-sequenced opportunistically. This yields smaller buffers and earlier project completion and, when properly accounted for, increased productivity.

INTRODUCTION

Construction involves installing materials according to project specifications in the facility being built. By tracking the flow of materials through their supply chain (i.e., describing when and where materials are being engineered, fabricated, transported, staged, etc.) installation work can be most effectively planned and executed. Flow data must be more or less detailed depending on whether the material of concern will be available in large quantities of identical, interchangeable units (e.g., concrete blocks, electrical conduit, nuts and bolts); in modest quantities, possibly with some degree of interchangeability (e.g., windows, structural steel, timber in precut lengths), or in small quantities of units with unique properties (e.g., engineered materials such as pipe spools or a custom-designed main entrance door).

Field installation crews, responsible for the final step in the materials flow process, must find resources that match among those available to them; they must ensure that the right material gets put in the right place. For instance, they must identify the location where installation is to take place (e.g., area AR-123), then find the matching material (e.g., pipe spool SP-123) and retrieve the correct installation accessories (e.g., attachments and supports). An integral part of their work, time and again, is to solve the so-called "matching problem." In facilities that comprise thousands of materials of which many are unique, tackling the matching problem is an enormous task. Nevertheless, those performing installation have no way around it.

In contrast, those responsible for engineering and design, fabrication, delivery, and site storage of materials, as well as construction managers overseeing the project often overlook the matching problem that installation crews face. Dealing with materials on an item-by-item basis means paying attention to minute details. It is a tedious task, largely irrelevant to their own. Accordingly, matching-problem details are selectively abstracted away by each party so that they can focus on problems of more direct, contractual concern to them. For example, structural designers do not worry about vendors' ability to deliver specialty valves or nuts-and-bolts because it is outside of their scope of work. Pipe-spool fabricators optimize production schedules to suit their plant's fabrication constraints and other projects' needs. Shipping agents optimize travel by choosing vehicles to meet delivery schedules; they package materials to ensure that loads are stable and meet weight and dimensional constraints during transportation. Laydown yard personnel group materials by shipment, type, or final-installation destination to ease tracking. Project managers control progress based on percentages-of-total of materials engineered, delivered to the site, or installed. The corresponding planning systems must therefore allow for abstraction or detail as needed.

Because of this abstraction, installation crews rarely have the data they need to optimally schedule and thus execute their work. They must rely on the numerous assumptions that are embedded in pre-construction schedules. How much of a problem this creates depends on the extent to which uncertainties in their supply manifest themselves during project execution. If pre-construction schedules were well thought-out and steps preceding installation had no uncertainty in duration or execution quality associated with them, then matching would be easy. In practice, unfortunately, this is not the case. Many projects are executed on a fast track, so construction starts before design has been completed or materials deliveries have been properly sequenced. Installation crews and equipment are often kept waiting because delays in materials supply and delays

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in completing prerequisite site work lead to mis-matches that foul up scheduled work sequences. This lowers the installation crew's productivity and extends the project duration.

In order to increase understanding of these issues, a model was created of a process that is characteristic of the process-plant sector of the construction industry. Alternative strategies for sequencing materials deliveries are presented in this paper and their execution was simulated so computer data supports the comparison between them.

RELATED WORK IN LEAN CONSTRUCTION

Matching problems and process uncertainties pose unique requirements on construction planning systems. An analogy with manufacturing production systems is appropriate to explain what these are. Specifically, the lean production philosophy is relevant (Ohno 1988). Lean production focuses on adding value to a raw material as it proceeds through various processing steps to end up as a finished product. It advocates the avoidance, elimination, or at least reduction of waste from this so-called value stream. By considering waste not only in or produced by individual operations but in the value stream at large, lean production adopts a systems view.

The late Taiichi Ohno first articulated this philosophy and implemented it in Toyota's production system. He classified sources of waste as follows (8 added by Womack and Jones 1996): (1) Defects in products; (2) Overproduction of goods not needed; (3) Inventories of goods awaiting further processing or consumption; (4) Unnecessary processing; (5) Unnecessary movement of people; (6) Unnecessary transport of goods; (7) Waiting by employees for process equipment to finish its work or for an upstream activity to complete; and (8) Design of goods and services that fail to meet user's needs.

The lean production philosophy, since it emerged in the 1950s, has provided major competitive advantage to Japanese manufacturing companies. Its benefits gradually became known outside of Japan. In the 1980s, US manufacturing companies began to convert their operations to implement lean production techniques and, consequently, also improved their operations dramatically (Womack and Jones 1996). Some lean production techniques are: (1) Stopping the assembly line to immediately repair quality defects; (2) Pulling materials through the production system to meet specific customer demands; (3) Reducing overall process cycle time by minimizing each machine's change-over time; (4) Synchronizing and physically aligning all steps in the production process; (5) Clearly documenting, updating, and constantly reporting the status of all process flows to all involved.

Though no one will doubt that there is much waste in construction, lean production has only recently become a subject of interest in our industry. Since the publication of Koskela's (1992) seminal report, researchers around the world have been studying its applicability to construction (e.g., Alarcon 1997). Unfortunately, translating lean concepts from manufacturing to construction is not automatic because of the unique characteristics of the architecture/engineering/construction (AEC) industry in addition to the geographic diversity among projects.

Researchers in construction have begun to realize that construction management must include production control systems (e.g., Bernold and Salim 1993, Melles and Wamelink 1993) to complement the project management systems currently in use. Control systems must include not only activities being performed at the project site but also those that make up the entire supply chain (O'Brien 1995). The work described here belongs to this school of thought.

Some lean concepts have already been translated to construction. Howell et al. (1993) discussed how buffers of materials can alleviate the dependencies and worker idle time otherwise incurred when process sub-cycles interact with one another. Ballard formalized the Last Planner to shield installation crews from uncertainties in work flow and demonstrated its successful implementation on actual projects (Howell and Ballard 1996, Ballard and Howell 1997). Phair et al. (1997) reported how equipment manufacturers are reducing set-up time by changing product designs (e.g., buckets and other attachments). In the same vein, this paper describes how the pull technique with feedback regarding progress on site to fabricators off site can improve construction process performance (Tommelein 1997a, 1997b).

PUSH-DRIVEN VS. PULL-DRIVEN PROCESS MANAGEMENT

Push-Driven Process Management

Construction work traditionally is planned by articulating activities and dependencies between them, then assigning durations and resources to each activity. A schedule is developed by calculating early and late activity starts and finishes using the Critical Path Method (CPM). Resource leveling or allocation algorithms may yield some adjustments to the early-start schedule, but upon project execution, activities are expected to start at their earliest possible date in order not to delay succeeding activities or the project as a whole.

Project control aims at adhering to the resulting schedule. It is assumed that all resources required to perform an activity that is about to start will indeed be available at that activity's early-start time. In this so-called "push-driven" approach, each activity passively waits for its ingredients (instructions, labor, materials, equipment, and space) to become available, e.g., by being released upon completion of predecessor activities. When some have become available but others needed at the same time have not, those available will wait in a queue or buffer for the combination of resources—the set of "matching parts"—in its entirety to be ready. While it may be possible to start work with an incomplete set of resources, chances are this will negatively affect productivity (e.g., Thomas et al. 1989, Howell et al. 1993).

Because of uncertainty in duration as well as variation in execution quality and dependency logic of activities, schedules are bound to change as construction progresses. It may be possible to model this uncertainty during the planning stage, as is done by using probabilistic distributions to characterize activity durations in the Program Evaluation and Review Technique (PERT). However, the actual manifestation of uncertainty is known only upon plan execution and must thus be

dealt with in real time. At that point, rigorously adhering to the initial schedule may not be the best approach for successful project completion as network characteristics and resource availability will deviate from those assumed when that schedule was generated.

Moreover, traditional CPM schedules do not necessarily show individual resources and their allocation to activities. Certainly, procurement schedules highlight milestone delivery dates of major items, but most materials will arrive in multi-unit shipments. If a schedule reflects only groupings, then it is too coarse to guide work that involves unique parts. When missing parts are identified during the on-site allocation process, it is much too late to prevent delays.

In addition, current expediting practice is to regularly touch base, e.g., with the engineering design firm or fabricator of whom goods or services are expected. Contact is made prior to the deadline of completion of their work, in order to make sure the target delivery date, e.g., of key materials or pieces of equipment, will be met. Yet, most expediters fail to (e.g., are not authorized to) reschedule activities when it can be anticipated that deadlines will not be met. Accordingly, the traditional, push-driven approach to scheduling prior to the start of construction with no corrective re-scheduling as work progresses leads to process inefficiencies and less-than-optimal project performance.

Pull-Driven Process Management

The main objective of a "pull-driven" approach is to produce finished products as optimally as possible in terms of quality, time, and cost, so as to satisfy customer demand. Achieving high process throughput while minimizing operating expenses including in-process inventories is key. Keeping busy by processing just any one of the resources in the input queue of an activity requiring a combination of resources is insufficient. To pull means that resources must be selectively drawn from queues—so the activity that processes them will be busy just the same—but chosen so that the activity's output is a product needed further downstream in the process, and needed more so than its output using other resources in the queue would have been. Resources' wait time in queues should be minimized.

To implement a pull-driven approach, selective control is needed over which resources to draw for any given activity. This selection is driven by information not solely about resources in the queues immediately preceding the activity under consideration, but also about work-in-progress and resources downstream (successor queues and activities) in the process. Resources will get priority over others in the same queue if they are known to match up with resources forecast to be or already available in queues further downstream in the process. This way, those downstream resources will not unduly await their match and be in process for any time longer than needed, though their planned processing sequence may be violated.

EXAMPLE PROCESS SCENARIO: PIPE-SPOOL INSTALLATION

Constructing an industrial process facility, such as an oil refinery, involves installing many hundreds or thousands of unique pipe spools. This process is simplified here as comprising two chains of activities: pipe spools are designed and fabricated off site while work areas are prepared on site. After spools have been shipped to the site, the chains merge with the installation of spools in their designated areas.

Pipe spools are fabricated off site according to the availability of engineering design information, the fabricator's plant production capacity, etc. Individual tags denote that each spool has unique properties and each has a designated destination in the facility under construction as shown in the project specifications. Spools are subject to inspection before leaving the fabricator's plant. The outcome of the inspection activity is that a spool will be found fit-for-installation with an x% likelihood, and, thus, that there will be a problem with (100 - x)% of them. In the latter case, the fabricator must rework the spool to rectify the problem, prior to shipping.

Concurrently with this off-site process, construction is under way on site. Roads are built, temporary facilities are brought in, foundation systems are put in place, structural steel is being erected, etc. Crews of various trades must complete their work in each area where spools are to be hung, prior to spool installation. When a specific set of ready-for-installation spools is available on site, and all prerequisite work in the matching area has been completed, spools can be installed. Completion of an area's installation work then signals to other trades that subsequent work can start.

INDUSTRY PRACTICE

The Business Roundtable (BRT 1982) identified the piping process as being critical to the success of numerous industrial projects. However, research into improving practice has been lagging until only a few years ago CII conducted a detailed investigation (CII 1996, Howell and Ballard 1996, O'Connor and Liao 1996, O'Connor and Goucha 1996). Major causes for problems were found in the engineering development process, specifically in three areas: (1) piping and instrumentation diagram (P&ID) problems are caused by inefficient sequencing of priotization, inefficient procedures for P&ID development and review, and inefficient communication of P&ID uncertainty; (2) problems in the supplier data process pertain to communication, coordination, and selection duration; and (3) problems in the packaged units process pertain to supplier quality and design. Whereas O'Connor et al. developed policies, procedures, and checklists to enhance the overall efficiency of these processes, Howell and Ballard studied the impact of uncertainty on downstream performance.

Industry practitioners know that construction is plagued by uncertainties. In their most interesting study, Howell and Ballard (1996, p. 6) describe prevailing methods for managing them in the piping function: "Piping success requires minimizing the extent and effects of uncertainty during fabrication and installation. At present, uncertainty in the timing of deliveries of intermediate products from one continuing activity to another defines the production planning and management problem. Lacking tools to minimize the uncertainty in these flows, managers strive for flexibility so that the project can proceed in the face of erratic deliveries and unexpected problems. On piping extensive projects, they rely on

buffers to assure progress despite variations in the timing, sequence, and quality of resources from upstream suppliers. Buffers dampen the effects of variations in the flow of resources and allow flexibility in the choice of work."

Howell and Ballard characterize common practice for moving pipe spools from engineering through off-site fabrication to erection. "When engineering falls behind schedule, fabrication will be delayed, thereby also delaying installation work." "The order in which drawings are provided to the fabricator and the sequencing in which spools are output by the fabrication process may bear little relationship to site needs, therefore requiring re-sequencing for site delivery provided that priority information be available." "Time delays and out-of-sequence work make the supply of materials to the job site unpredictable. This leads to inefficiencies because work cannot be adequately planned and executed, and thus results in low productivity."

Figure 1 charts commodity curves from 1 of 24 projects on which Howell and Ballard collected data. This specific project (Project B) required installation of 2,080 pipe spools in a 57-week duration, measured from start of engineering to end of installation. It was characterized as "Design well established. Rash of client changes late in project." As can be seen, schedule slippages (deviation of actual from planned) occurred in completing isometric drawings (ISOs) and in fabricating spools. Nonetheless, installation work progressed nearly as planned.

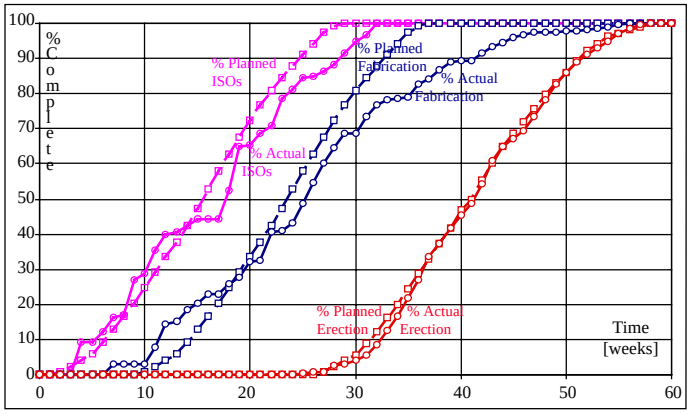


Figure 1: % Planned vs. Actual in Percent of Total of Isometric Drawings (ISOs), Fabricated Spools Delivered to Site, and Spools in Place.
[Data courtesy of Greg Howell and Glenn Ballard]

Commodity curves (which plot time vs. percent complete, also called line-of-balance or velocity charts) do not reveal, however, what resources were needed to adhere to the planned installation schedule. Their usefulness is limited when managing unique materials because they do not help recognize matching problems. This is the case here as pipe spools really are not commodities. "They [spools] differ in specification requirements, physical configuration, and adjacent plant features. These important differences make both establishing performance standards and comparing results very difficult" (Tatum 1985).

Howell and Ballard make no detail available to describe this project's performance, so one cannot be certain of problem causes and possible solutions. They point out "Fast track project. Schedule main concern. Manpower levels above projected." (p. 73). One can only speculate that uncertainty contributed to occurrence of matching problems, hampering installation work, but apparently successfully overcome. In conclusion, Howell and Ballard recommend that piping backlogs be used to buffer on-site from off-site activity ("successful projects have at least 60% of all pipe on hand when 20% has been installed"), and that the principles of the Last Planner be applied to shield installation from remaining uncertainties.

The present paper builds on this work by focusing on two uncertainties in the pipe-spool process: (1) uncertainty in duration of fabrication and transportation and (2) quality failure in fabrication resulting in delay of shipment due to rework. It shows how matching affects the productivity of installation crews and the overall project duration.

PROCESS MODELING

Process-Model Representation

In order to describe and then experiment with alternative planning sequences, the pipe-spool installation process has been modeled using the STROBOSCOPE computer system for discrete-event simulation (Martinez 1996). Table 1 summarizes the functionality of the STROBOSCOPE symbols that are used here, but note that their simplicity belies the expressiveness of the associated programming language.

One major feature of STROBOSCOPE is that resources can be characterized and individually tracked as they reside in various network nodes during a simulation run. When a queue's resources are indistinguishable, there is only one way in which to draw them from that queue; only 1 draw sequence exists. However, when a queue has *n* distinguishable resources, *n!* draw sequences are possible. In general *n* will change in the course of a simulation run as resources join the queue (unless the queue is a source) and leave it (sink). Being able to distinguish resources and to draw those needed for processing when needed is necessary when one sets out to model matching problems and pull techniques.

The sequence in which characterized resources will be drawn from a queue during simulation depends on (1) the ordering of incoming resources relative to those already in the queue, and (2) the criteria applied in selecting resources for withdrawal from the queue. To achieve the desired system behavior, a STROBOSCOPE programmer can define draw sequences by specifying respectively [items in CAPS denote STROBOSCOPE programming statements]: (1) a queue's so-called DISCIPLINE and (2) conditions on the link emanating from the queue (e.g., using RELEASEORDER and DRAWWHERE with FILTER-expressions). Example draw sequences (implemented by ordering, selection criteria, or a combination thereof) are:

1. **First-In First-Out or Last-In First-Out:**

   The ordering criterion is resource time of arrival in the queue. First-in-first-out (FIFO) places resources arriving earlier at the front of the queue, so by default

they will be drawn first (they have been waiting for the longest time). In contrast, last-in-first-out (LIFO) places those arriving later at the front.

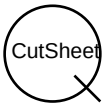
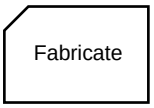
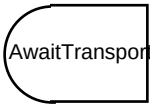
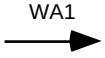
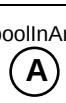
2. **First-in-Order Based on a Property of Resources in Single Queue:**

   When resources can be ordered based on a property or on some externally-defined numbering system, that order can define draw priority. For example, trucks of varying size can be sorted by their loading capacity, where it may have been decided that larger ones will be loaded first; an engineer may have numbered footings to specify the order in which concrete is to be placed, where those with lower numbers will be placed first. Selection is thus based on comparing an individual resource's "capacity" or "placement number" property with that of others in the same queue. Other examples are "easiest to install first" and "highest ratio of earned-to-expended effort first" (Howell and Ballard 1996), "materials covered by or buried in others first," and "those that can easily be damaged last."

3. **Best Match Based on Properties of Resources in Multiple Queues, all Preceding a Single Activity:**

   Resources may be drawn from one or several queues so that the properties of those drawn from one queue match those drawn from the other queue(s). In the worst case, matching fails. This situation typifies matching problems. For example, a water boiler has a designated location in a house under construction; when the boiler is ready to be installed, workers must have access to that designated location to work; no other location will do. Another example is to install only complete pipe runs (Howell and Ballard 1996) or to load various structural steel shapes onto flatbed trucks not to exceed the truck's dimensions or load capacity (Martinez 1996).

Table 1: Selected STROBOSCOPE Symbols

SYMBOL	NAME	EXPLANATION
	**Queue**	Is a holding place (buffer) for 0, 1, or several resources waiting to become involved in the succeeding combination activity. Queues may contain generic or characterized resources. The latter are distinct from one another and they can be traced as individuals through various network nodes during simulation. The logic describing the ordering of resources upon entry into a queue of characterized resources is termed a DISCIPLINE.
	**Normal (activity)**	Describes a certain type of work to be done, or a delay, of a known (probabilistic) duration from start to finish. May require a single resource or no resource at all.
	**Combi (-nation activity)**	Like a normal, describes a certain type of work to be done, or a delay, of a known (probabilistic) duration from start to finish. Unlike a normal, requires several resources in combination for its performance and draws what is needed from the queue(s) that precede it.
	**Consolidator**	Acts as a counter up to n (n is an integer value specified with the node): after n resources have been released into the consolidator, the consolidated set will be released from it.
	**Link**	Shows flow logic. Should be labeled to meaningfully describe the resources that flow through it. If the link emanates from a queue, a DRAWORDER may be specified to sequence resources being drawn from the queue.
	**Fork**	Describes a split in a resource's flow path. Incoming resources are routed along one path or another in a probabilistic or deterministic fashion, so the node is called a probabilistic fork or a decision node respectively. Each link emanating from it carries a likelihood or a statement evaluating to true/false for being followed by any specific resource arriving at the fork during simulation. The resource's actual path is determined at run time.
	**Assembler**	Shows that 2 or more resources are being assembled into a single unit resource which is of the compound (a special kind of characterized) resource type.

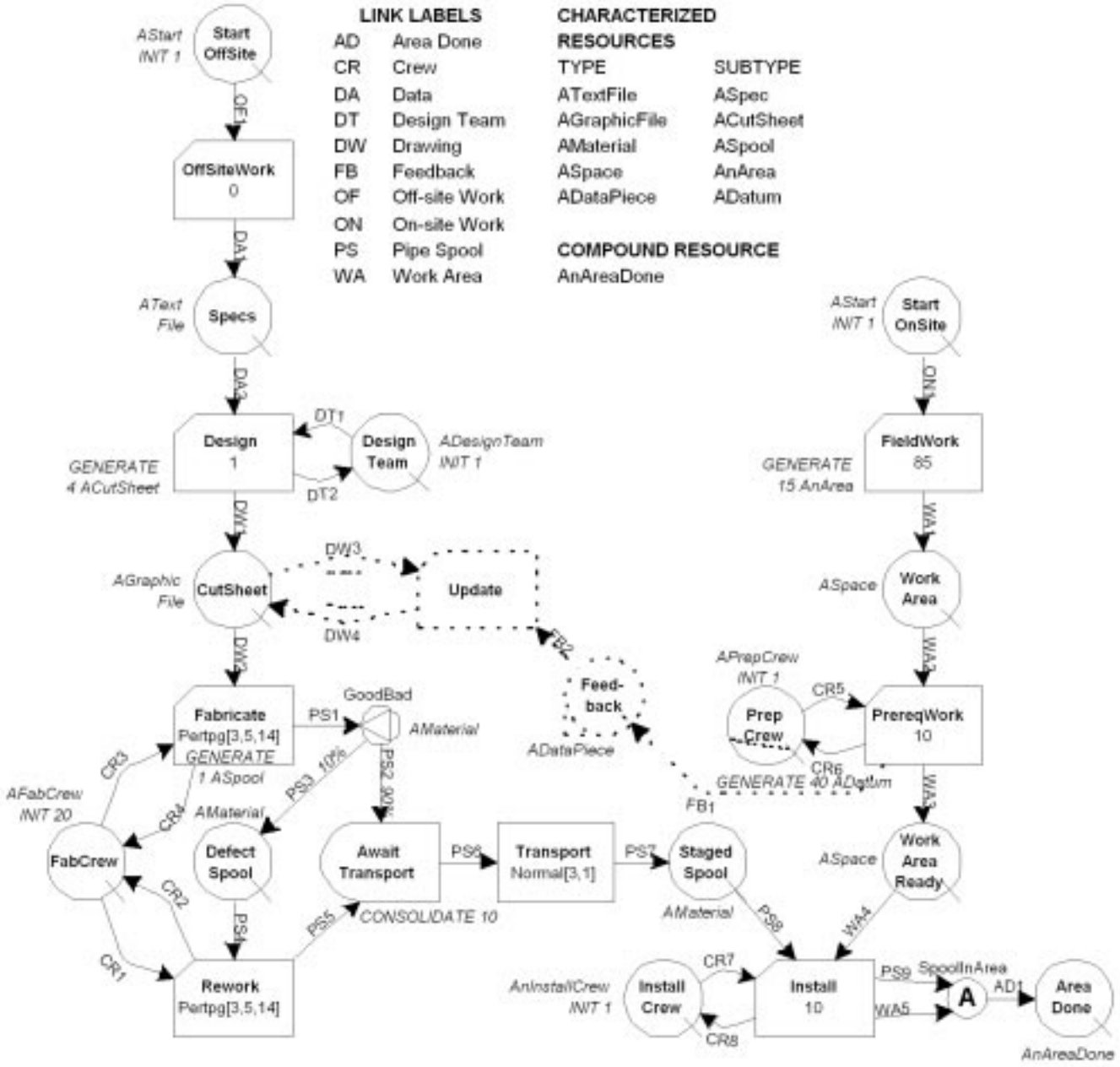


Figure 2: Process Model of Pipe-Spool Installation

4. Random:

Resources are picked at random from those in the queue. This will be appropriate when they are interchangeable. However, when resources are not interchangeable, random drawing (e.g., due to mis-identification of a material) results in erroneous substitution, thus causing problems.

Project managers and field personnel use such draw sequences when planning and executing work. As is to be expected, some sequences will be more advantageous than others. This is illustrated next by simulating alternatives.

Pipe-Spool Process Model

Figure 2 depicts a model of the example pipe-spool installation process. The rationale for selecting modeling elements and their parameters is detailed by Tommelein (1997a). Admittedly, selections were somewhat arbitrary. The writer modeled salient features yet represented only a few system characteristics so that

the model's behavior and output would remain tractable. Simplifications are consistent with the aim of this paper, which is to illustrate (1) the impact coordination planning has on the execution of resource-matching processes and (2) the benefits of pull over push when uncertainty is high. Using the same methodology and tools, more complete, industrial-strength models can easily be developed.

IMPLEMENTATION AND SIMULATION OF ALTERNATIVES

One deterministic and three probabilistic models were implemented. All models describe that 600 spools are to be installed in 15 areas, at 40 spools per area. It has been assumed that spools are delivered to site in loads of 10 and installation in an area will not start until all 40 matching spools are available.

Deterministic Model

Model Construction and Parameters

The deterministic model is based on the process chart with all characteristics shown in Figure 2 except for those listed in Table 2. All durations take on their most likely value and there are no quality failures (no rework). This model illustrates how the project progresses when everything in the system is certain, perfectly coordinated, and synchronized.

Perfect coordination means that cutsheets 1 through 600 are used for fabrication in numerical order, resulting in spools 1 through 600 arriving at the site in numerical order. Similarly, work areas 1 through 15 are prepared in numerical order, so that installation of spools 1 through 40 starts without delay as soon as area 1 is ready, installation of spools 41 through 80 starts as soon as area 2 is ready, and so on.

By construction, all CutSheets are available on day 0, at the start of simulation, and WorkAreas on day 85. The durations of activities Design, Fabricate, PrereqWork, and Install, combined with their production resources DesignTeam, FabCrew, PrepCrew, and InstallCrew respectively, were chosen so that their throughput is equivalent to 4 spools/day. Consequently, synchronization means that all commodity curves for CutSheet, StagedSpool, WorkAreaReady, and AreaDone are parallel (Figure 3, Left, Top).

Pipe-spool Buffer Size

Figure 3 (Right, Top) illustrates that pipe spools accumulate on site at a steady pace until day 95, when the first area opens up for installation. The StagedSpool buffer peaks at 340. It gradually gets depleted over time as subsequent areas open up, yet continues to get replenished until all spools have been delivered to the site.

Note that at 20% of work done (AreaDone), more than 70% of all spools have been delivered to the site. According to Howell and Ballard's rule of thumb, this is a favorable indicator for project success. As will be shown later, it is no guarantee for project success, however, particularly when out-of-sequence work leads to mismatches.

Productivity of Installation Crew

Since all activities in this model are synchronized and there is no uncertainty, the installation crew's productivity is optimal. Each area gets completed in 10 days and work progresses uninterruptedly.

Project Duration

The project duration is 245 days (95 days until work in the first area can start plus 15 times the installation of 40 spools in each area where work progresses at 10 days/area: 95 + 15*10 = 245).

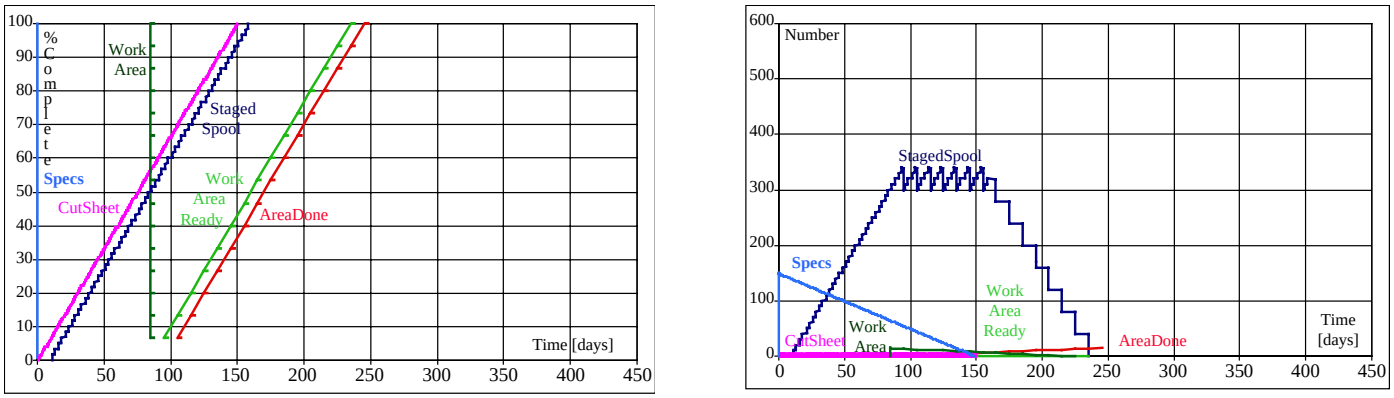
Alternative Probabilistic Models

Model Construction

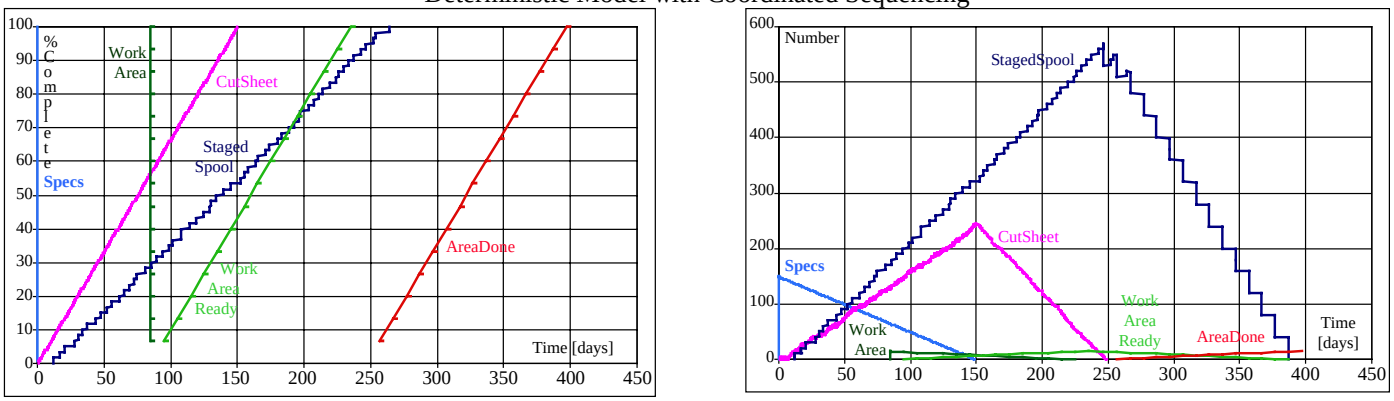
The three probabilistic models also are based on the process chart as depicted, but they include all its uncertainties in durations and likelihood of rework. The variability in fabrication duration was taken from Howell and Ballard (1996). A piping industry rework rate ranging from 1 to 10% was quoted by Ballard and the worst value is used here. Lacking other data, rework is assumed to take the same amount of time as fabrication. The three models differ from one another (1) in the draw order of cutsheets for fabrication and (2) only the last model includes the Feedback queue, the Update activity, and links FB1, FB2, DW3, and DW4 (shown in dotted lines in Figure 2).

Table 2: Deterministic vs. Probabilistic Models

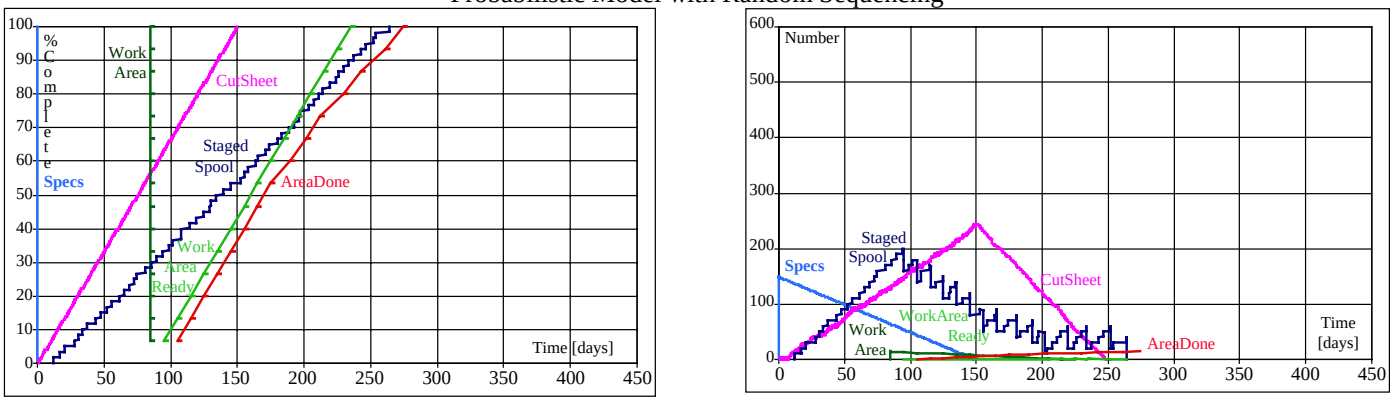
MODELING SYMBOL	DETERMINISTIC MODEL (Model D)	PROBABILISTIC MODEL (Models A, B, and C)
STRENGTH PS2	100%	90%
STRENGTH PS3	0% (no rework)	10%
DURATION Fabricate [days]	5	Pertpg [3, 5, 14]
DURATION Rework [days]	N/A	Pertpg [3, 5, 14]
DURATION Transport [days]	3	Normal [3, 1]



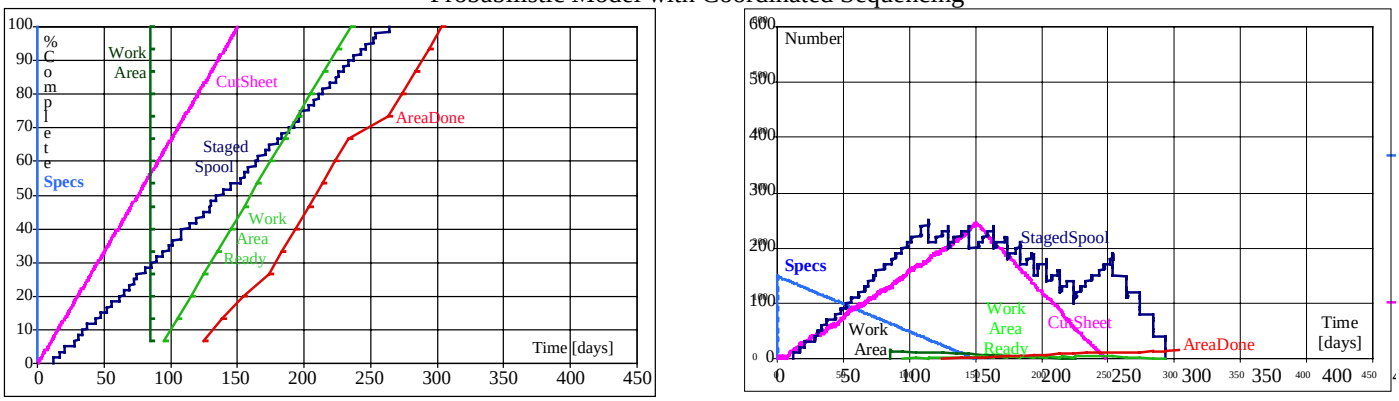
Deterministic Model with Coordinated Sequencing



Probabilistic Model with Random Sequencing



Probabilistic Model with Coordinated Sequencing



Probabilistic Model with Pull-driven Sequencing

Figure 3: Commodity Curves (Left) and Buffer Sizes (Right) for Simulation of Single Iteration

Different draw orders for each model can be discerned in the STROBOSCOPE source code (Tommelein 1997a) but not in Figure 2 as the graphical representation reflects only a limited number of model parameters. Draw sequencing does not affect throughput of the fabrication process (by construction of the model, all spools are characterized by the same duration distribution for fabrication), so in terms of percent of pipe spools having been fabricated, transported, and delivered to the site, all three probabilistic models will exhibit the same behavior: their StagedSpool commodity curves look the same.

The duration variables were chosen so that the *most likely* or *mean* value of the off-site sequence is synchronized with the on-site sequence. Thus, the most likely values of Design, Fabricate (ignoring Rework), and Transport add up to have the right number of pipe spools—though not necessarily the right spools—being staged on site for a desired number of days prior to the most likely completion of FieldWork and PrereqWork. In addition, the throughput (average number of resources output per time unit) off site matches the throughput on site (40 spools get produced on average in the same amount of time needed to complete prerequisite work in an area). That way, presumably (if all instances of each activity had a duration close to the mean value of that activity and no quality failure such as rework manifested itself), field production should not be delayed by a shortage of materials. Nevertheless, it could be delayed due to mismatches. Table 3 lists the alternative draw sequences used in each probabilistic model (A, B, and C). For the sake of completeness, it also includes those of the deterministic model described previously (model D).

The first two probabilistic models illustrate the traditional, push-driven process-management approach, but they present extremes in effort put into pre-construction planning. The third model exemplifies a pull-driven approach.

Output Representation

Selected simulation outputs were charted for a single iteration to show what a specific instance of each model might look like (Figure 3). Simulation of each probabilistic model was then repeated for 1,000 iterations to illustrate the extent to which buffer sizes and progress of activities vary. Figure 4 (Top Left) shows the superimposed commodity curves. Value ranges on percent complete of AreaDone at any time are denoted by a solid line for the mean value, and long and short dashes respectively for the mean plus-or-minus 1-or-2 standard deviations. Figure 4 (Top Right, Bottom Left, and Bottom Right) shows the mean plus-or-minus 1-or-2 standard deviations for the number of StagedSpool, and, as labeled, the standard deviation (SD). Values were collected every 25 days.

Model A - Random Sequencing

Model A's Parameters

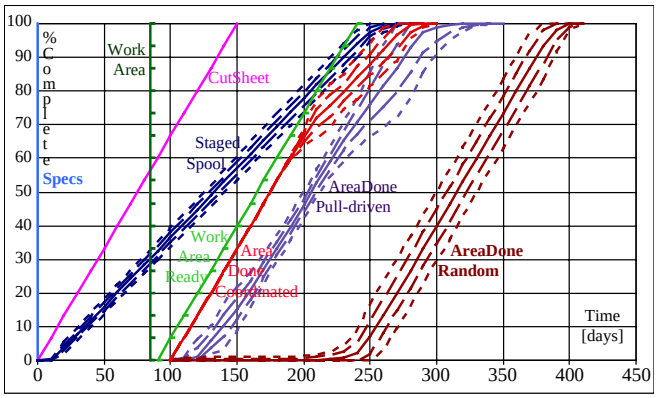
The worst-case pre-construction plan is to have no coordination at all. The order in which pipe spools are fabricated bears no relationship to the order in which areas are being prepared on site. With no communication between fabrication and installation to coordinate their respective work with one another, each crew will draw resources from the queue available to them in the order that suits them best. The fabrication crew may select spools based, perhaps, on the order in which cutsheets are provided to the fabrication shop. This order may have nothing to do with installation sequencing. The preparation crew may select one area after the other based, perhaps, on which one is nearest to their present location. This situation has been implemented by defining the DRAWORDER for choosing resources in the CutSheet queue through link DW2 to be random, and leaving the discipline in the WorkArea queue as the default FIFO (anything else would appear equally random relative to the randomness in drawing cutsheets).

Model A's Pipe-spool Buffer Size

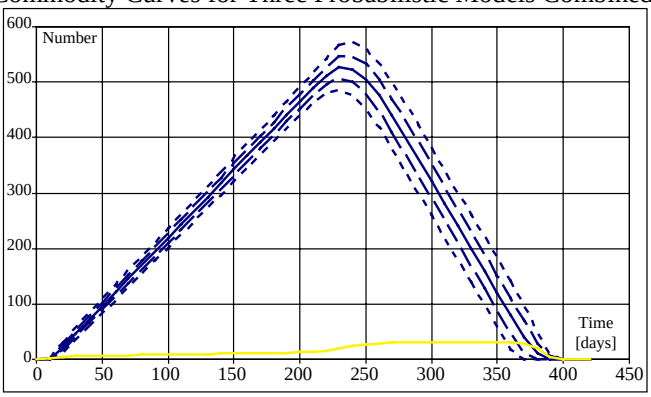
Because of lack of coordination, the likelihood for mismatches to occur is high. When spools in StagedSpool and work areas in WorkAreaReady cannot be matched for installation, staging areas will fill up with spools of no immediate use, and work areas remain unfinished. The peak at 570 for StagedSpool in Figure 3 (Right, Upper-middle) confirms this to be the case (590 spools on site is the maximum, as there are 600 spools in total, 15 areas requiring 40 spools each, and the next-to-last shipment of 10 should at the very latest complete five required sets of 40 spools).

Table 3: Alternative Sequencing Strategies

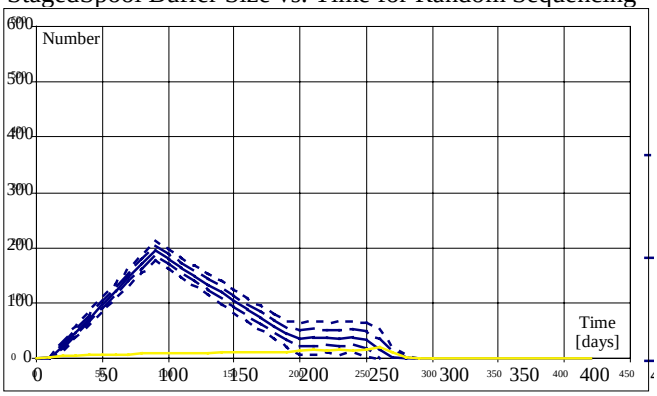
CASE	DESCRIPTION	CutSheet DRAW SEQUENCE	WorkArea DRAW SEQUENCE
A	Probabilistic Model Random Sequencing	Random	FIFO
B	Probabilistic Model Coordinated Sequencing	FIFO	FIFO
C	Probabilistic Model Pull-driven Sequencing	Priority to spools that match area(s) ready	FIFO
D	Deterministic Model Coordinated Sequencing	FIFO	FIFO



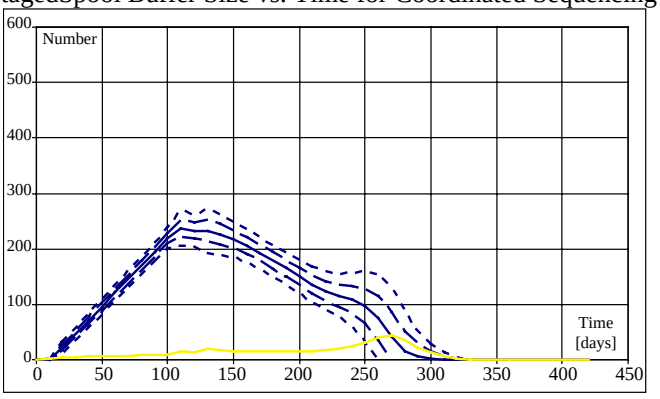
Commodity Curves for Three Probabilistic Models Combined



StagedSpool Buffer Size vs. Time for Random Sequencing



StagedSpool Buffer Size vs. Time for Coordinated Sequencing



StagedSpool Buffer Size vs. Time for Pull-Driven Sequencing

Figure 4: Simulation Output of 1,000 Iterations

In reality (not in the model), spools on site for a long time (at worst, a spool could be the first one delivered and last one installed) are more likely to sustain damage. Additional preparation work (e.g., erecting scaffolds or, at least, checking if previous preparation work still meets specifications and if there are no new obstructions) may be required when installation crews finally move into an area where work is to be completed. Real project costs are incurred for keeping track of and rehandling materials on site, for working in obstructed areas, and for performing out-of-sequence work.

Model A's Productivity of Installation Crew

As mentioned previously, it has been assumed that installation in an area does not start until all 40 spools for that area are available. This is not necessarily industry practice (management pressure to start work and produce "show pipe" even though work cannot be executed optimally, usually is very high) but the line of balance labeled AreaDone in Figure 3 (Left, Upper-middle) confirms that accumulating a huge buffer makes it possible for the installation crew to achieve its highest possible production rate (also see Howell et al. 1993). At 20% of spools installed, nearly all spools have been delivered to site; vice versa, at 60% of spools delivered, barely any installation work has started (also see Figure 4 Top Left). For the crew, this will be an effective way of getting work done, provided that they need not be idle prior to starting to install.

In this single iteration, the crew's start time is 247 days. However, during pre-construction planning, one can only estimate this start date. Given the uncertainty in getting matching spools to site, it may make sense to build in a time buffer or lag preceding the Install activity to enable the crew to be optimally productive once they mobilize (e.g., start Install no earlier than day 250). Buffering protects the installation crew from upstream process uncertainties and buys time for them to plan and get ready, or do other work in the mean time.

Model A's Project Duration

The delay in starting installation, forced here by a shortage of matching materials, leads to a project duration of 397 days. This is by far the longest one of all scenarios shown in Figure 3.

Model B - Coordinated Sequencing

Model B's Parameters

Model B describes perfect coordination. The fabrication crew and the installation crew plan before starting their work and decide on the sequence in which to draw resources. Cutsheets and areas are assigned sequence numbers so they can be drawn in FIFO order (STROBOSCOPE's default discipline). CutSheets 1 through 40 will go to fabrication before 41 through 80, and so on. Similarly, Area 1's prerequisite work will be performed prior to Area 2's, and so on.

While perfect coordination reflects an idealized situation, for many reasons it will never materialize. It seldom is a contractual requirement and it also is too restrictive to the various parties involved in the process (e.g., fabrication shops are not set up to tolerate one-piece flows, that is, to change machine setups in order to meet each spool's unique fabrication requirements).

Model B's Pipe-spool Buffer Size

Model B results in minimal space needed to stage spools on site: StagedSpool peaks at 200 in Figure 3 (Right, Lower-middle). Nonetheless, some spools will accumulate on site because deliveries get out of sequence when uncertainty manifests itself during fabrication and shipping, and the need for rework arises occasionally.

Model B's Productivity of Installation Crew

Despite expedient project completion, the installation crew (which starts to work as soon as work is available and stays idle in-between activities, when materials are in short supply) was not able to work as productively as before (the AreaDone line of balance is not straight but bends to the right). This is no coincidence! The writer crafted the model's basic template to show how materials shortages might arise so that their impact on production could be shown. While the activities Design, Fabricate, PrereqWork, and Install can process resources at the same average rate of 1 area/10 days or 4 spools/day, uncertainty in the Fabricate, Rework, and Transport activities results in a StagedSpool slope much smaller than the CutSheet or WorkAreaReady slope. Consequently, the AreaDone slope is smaller as well (note that in Model A the AreaDone slope was not really affected by the slow delivery rate because of the large build-up of spools prior to its start). Because FieldWork starts 85 days after OffSiteWork, the StagedSpool and WorkAreaReady lines of balance cross.

Model B's Project Duration

Perfect coordination leads to project completion in the shortest duration of 275 days (Figure 3, Left, Lower-middle).

Model C - Pull-driven Sequencing

Model C's Parameters

Model C augments model A's random sequencing with a pull mechanism, which includes the Feedback queue, the Update combination activity, and four links to tie them into the existing network. CutSheets initially are processed in random order relative to work areas, but as soon as an area is ready for spool installation, area-availability feedback is transmitted and used to update their status. Cutsheets that match this feedback are checked accordingly so that they will get priority over others to be fabricated, that is, they are "pulled" to the site. In the single iteration that is depicted, a total of 291 updates were performed.

Model C's Pipe-spool Buffer Size

Relatively few spools accumulate on site (250 maximum, Figure 3, Right, Bottom). The buffer is not as small as it was with perfect coordination, but it certainly does not get as much out of hand as it did with random sequencing either!

Model C's Productivity of Installation Crew

Starting off with random sequencing and then improving the sequencing based on feedback penalizes the crew in terms of field productivity relative to the perfect-coordination case. The slope of AreaDone has decreased further than it already had in model B. Luckily, this performance can be anticipated and improved. The crew can be ordered to start later (e.g., start at time 150 or 175, see Figure 4, Top Left), when more spools are on site so workers will be able to progress at their fastest possible rate, or it can be scaled down in size.

Model C's Project Duration

The project duration remains fairly short, at 304 days (Figure 3, Left, Bottom).

IMPLEMENTATION HARDWARE AND SOFTWARE

All models were run in STROBOSCOPE (version 1, 2, 2, 0) on a Pentium 200-MHz computer running Windows® 95. A single iteration takes on the order of 1 minute. Source code is available (Tommelein 1997a) so readers can reproduce and further experiment with alternative inputs to this model.

Other draw sequences and feedback mechanisms could have been implemented and their impact studied on, for instance, crew productivity and project completion. The feedback mechanism as shown does not lead to optimal system performance. Readers may accept this observation as a challenge.

DISCUSSION AND CONCLUSIONS

The lean-production "pull" technique has been shown to improve performance of a construction process. It is particularly well-suited for fast-track projects that require assembly of unique parts and that are plagued by uncertainties. Such projects are difficult to schedule accurately and in detail in advance. The nature of the anticipated matching problems must determine the complexity and detail required of the planning system. As uncertainties manifest themselves during project execution, the pre-construction schedule will have to be adjusted in a flexible manner for field work to progress efficiently and for work-in-progress inventories to remain small.

The pull technique suggests that real-time feedback from construction be used to drive the sequencing of off-site work, and vice versa. By choosing upstream to process "matching parts" first, the downstream process will proceed in a more expedient fashion, and completed units will be available sooner than would be the case otherwise. Wireless communication technologies, appropriate to implement this technique, are readily available today.

The pull technique assumes that all participants in the project supply chain are willing and able to respond to each other's needs in order to optimize overall project performance, not just their own. This requires rethinking of contractual relations and providing appropriate incentives. Processes also must become more transparent. Participants who can 'see' the other's needs, can better plan to accommodate them. A somewhat paradoxical situation exists today, with the proliferation of specialist firms believing that they have optimized their own operations. Local optima may have been reached, but at best, those are based on numerous assumptions about other project participants' performance. Many process uncertainties and resulting waste stems from ignorance. Increased process transparency among participants may aid not just the project's but also the individual firm's performance.

Only one pull link was shown in the model discussed here. Obviously, choosing where, when, and how to pull is an

important issue. Many pull links could be created, but each costs money to implement and the effects of one may offset those of another. Investigation of this issue must be supported by collection of process data that describes activities and durations, resources, and path-flow uncertainties of the system that is to be improved. Discrete-event simulation can help the decision maker understand the system's behavior and gauge the impact pull links may have. Using the simulated data, a cost-benefit analysis can then be performed prior to physically establishing those links.

The collection of process data in and by itself is a worthwhile endeavor. Knowing where uncertainties exist and how large they are will help focus on reducing those uncertainties. It should be obvious from the limited work that has been conducted to date on implementing production control in construction as is advocated by the lean production philosophy, that process-level analysis of construction is promising area of research, development, and application.

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