DISCRETE-EVENT SIMULATION OF LEAN CONSTRUCTION PROCESSES

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Abstract
Little work has been done to date in formally modeling concepts of lean construction, such as uncertainty, waste, flow, conversion, and push vs. pull techniques. This lack of formalization has been blamed in part on the inability of the project-management tools commonly used in industry to describe the construction process and its salient features at a level at which lean production can be studied. However, existing process-level construction models prove to be useful in this regard. Accordingly, this paper describes the use of computer software for discrete-event simulation to represent various construction process characteristics relevant to lean production. Two examples are provided. The first one illustrates the flow and conversion of pipe spools through their design and installation process. Spools exemplify unique materials, measured in discrete quantities. The second one illustrates the flow and conversion of concrete through its batching and placement process. Concrete exemplifies bulk materials, measured by volume. The examples show what types of system-level information can be generated using discrete-event simulation and how this information may be used to redesign construction processes in order to make them leaner.

Keywords: lean construction; materials management; discrete-event simulation; uncertainty; process planning; concrete placement

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INTRODUCTION

The lean construction community has been talking about uncertainty, waste, flow, conversion, and push vs. pull techniques for some time now (Alarcon 1997), yet little work has been done to date in terms of formally modeling those concepts. This has been blamed in part on the inability of the project-level models commonly used in industry practice (critical-path method or CPM scheduling tools, cost control systems, materials management databases, etc.) to describe the construction process and its salient features at a level at which lean production can be studied. However, existing process-level construction models prove to be useful in this regard. Though they are not widely used by construction practitioners, process-level discrete-event simulation models for construction have been available for more than twenty years now (e.g. Halpin and Woodhead 1976). In contrast, similar models are widely used in manufacturing. Because construction process models developed in recent years have the expressiveness and capabilities necessary to model lean production concepts it is worthwhile investigating how they could be used in studying those concepts.

In this paper, one process-level modeling tool, namely the STROBOSCOPE (Martinez 1996) computer software for discrete-event simulation, is being used to represent various construction process characteristics relevant to lean production. This software was chosen because of its expressiveness, speed, and availability. Two examples are provided. The first one illustrates the flow and conversion of pipe spools through their design and installation process. Spools exemplify unique materials, measured in discrete quantities. The second one illustrates the flow and conversion of concrete through its batching and placement process. Concrete exemplifies bulk materials, measured by volume. The examples show what type of system-level information can be generated using discrete-event simulation and how this information may be used to redesign construction processes in order to make them leaner.

UNCERTAINTY AND WASTE

Construction processes are notoriously difficult to plan and control because they are plagued by numerous uncertainties. Making explicit what uncertainties exist, how large they are, and where they may manifest themselves is a first step towards designing a process that will be least impeded by them. It will help in deciding which sources of uncertainties should be tackled first to reduce that uncertainty and improve the process.

Depending on the level of abstraction adopted by the modeler, several sources of uncertainty can be articulated. Here, construction is modeled at the process level, which explicitly represents activities and resources. An activity requires resources as input when it starts, engages those resources during its entire duration of execution, and outputs the same or other resources when it finishes. Resources may be generic or characterized. At this process level, uncertainties pertain to:

1. **Scope of work:** What work is to be performed is not necessarily stated clearly in contract documents. Scope gap or overlap are big issues in subcontract coordination. In addition, a contract’s scope may change during construction to accommodate an owner changing their mind, to correct design mistakes, to deal with unforeseen site conditions, new building regulations, availability of superior materials, etc.
2. **Duration and timing:** Duration gauges the amount of time elapsed from start to finish of an activity. Start and finish events each mark a point in time. These probabilistic though measurable quantities provide a way in which to abstract what

goes on during construction, yet describe how successor activities may be affected when the timing and durations of their predecessors are uncertain.

3. **Quantity:** Variation in quantity results from using imprecise quantity take-offs and estimating rules, procuring and shipping units in quantities that differ from needed quantities, encountering site conditions and worker skill levels that were not anticipated in advance but that result in the consumption of materials at a rate different from what was anticipated, allowing substitutes to be used, changing work to be done, etc. These practices are bound to lead to overages and shortages.
4. **Quality:** Variation in quality may be the result of activities being executed by workers with varying skill levels, using different methods and subject to changing environmental conditions, etc. Inspection will determine which variation in quality is acceptable and whether or not rework will be necessary.
5. **Resource assignment:** Project-level planners tend to ignore the specific assignment of resources to activities. In contrast, process planners—those at the construction site who organize and perform work—must plan for the allocation of resources (i.e. assign resources and sequence their use). Workers who need to install unique materials with specific tools and equipment better know what task is ahead of them, so they can plan how and where the work will be done and make sure all that is needed will be available when needed (Ballard and Howell 1997).

   When allocation planning is done in advance of activity execution, opportunities exist to optimally choose which activities to perform first and when. How much in advance of execution this planning process should take place is a function of the complexity of the work to be performed and the uncertainties associated with that work and the process it is part of. Note, however, that even the best plans may fail when uncertainties manifest themselves during process execution, so good process design must include means to recover from those failures.
6. **Flow path and sequencing:** It may not be *a priori* clear what the sequencing is of work to be performed (e.g., whether or not an activity will precede another one), what routing is to be taken when handling materials, etc. Such decisions may have to be postponed and made during construction, when the relevant decision variables take on specific values, or they may have to be decided on stochastically at that time.

Uncertainty is a major culprit for the creation of waste. Waste is created when several resources are needed simultaneously for an activity to start, but a missing one causes the others to pile up. Piles create additional work for those keeping track of what is or is not part of them and they occupy space, thus impeding movement and preventing others from using that space. Waste also is created by the lack of detailed planning and communication of progress. This forces workers downstream in a process to stay flexible, which prevents them from detailing their own plans so as to optimize their own productivity (Ballard and Howell 1997).

However, uncertainty is not the sole culprit for the creation of waste. Waste also is created by doing work not as well as it could be done. It may be the product of poor work methods design (which means deciding which tools or equipment to use, how to sequence processing steps so they can be performed efficiently, what training to provide to people so they will have the knowledge and skills necessary to perform their work, etc.) or poor understanding of how the work fits in with other work in the process as a whole. For example, in moving a material from one location to another, following one path may be better (less wasteful) than another: it may be shorter or easier to travel on (these properties are determined by characteristics of the single flow path and the means used for travel) thus resulting in a shorter travel time or less driver fatigue, or following that path may avoid interference (a system property) with other movement on site.

Clearly, models for lean construction must be able to capture at least the uncertainties outlined here, of not more.

FLOW AND CONVERSION

The application of flow and conversion concepts as a means for identifying waste in construction was advocated early on by Koskela (1992), among others. These concepts refer to possible changes of an “entity,” where “entity” refers to something physical (e.g. a construction material) or abstract (e.g. a piece of information). Flow means a change in location of the entity as is. Conversion means a change in state of an entity possibly because of the entity being combined with others (e.g. a pipe spool being installed during an assembly process), going through a physical or chemical transformation (e.g., concrete sets and cures, during which process it changes from a liquid into a solid), or being altered in terms of information contents (e.g., data being added to a document).

It has been argued that flow adds waste whereas conversion adds value to a process. Unfortunately, the mapping from flow vs. conversion to waste vs. value-adding is not so straightforward. This paper does not provide any new insights regarding this mapping *per se*, but it introduces a system to help distinguish flow from conversion activities and this may contribute to better a understanding of what is or is not desirable.

PUSH- AND PULL-DRIVEN PROCESSES

Push-driven processes

Construction work traditionally is planned and scheduled using CPM. Resource leveling or allocation may yield some adjustments to the early-start schedule, but activities are expected to start at their earliest possible date in order not to delay succeeding activities or the project as a whole. Project controls aim at adhering to the early-start schedule to the largest extent possible. This approach is based on the assumption 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 waits for its resources (instructions, labor, materials, equipment, space) to become available, e.g. by being released by finishing, predecessor activities. When some have become available but others needed at the same time have not, those available will wait 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 uncertainties manifest themselves during process execution, schedule delays occur as construction progresses and remedial action must be decided on 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 differ from those assumed during planning.

Because traditional CPM schedules tend not to show individual resources and their allocation to activities, an opportunity is lost to use the schedule as a guide for field work. Because insufficient detail is shown, the schedule cannot be used to reschedule activities, even when it is known to be likely that deadlines on specific resources will not be met. When missing parts are identified during the on-site allocation process, it is much too late to prevent work delays. Accordingly, the traditional, push-driven approach to scheduling work prior to project commencement with no corrective rescheduling as work progresses leads to waste.

Pull-driven processes

"Pull" techniques aim at producing quality finished products to satisfy customer demand and are driven by the urge to finish partially-completed work in the system. 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.

To implement a pull technique, 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 get priority over others in the queue if they are known to match up with resources already available in queues further downstream in the process. As a result, those available resources will not unduly await their match and be in process for any time longer than needed.

DISCRETE-EVENT SIMULATION USING STROBOSCOPE

Symbols from the STROBOSCOPE (Martinez 1996) discrete-event simulation language have been used in this paper to characterize processes in terms of uncertainty, waste, flow, and conversion, and to describe push vs. pull techniques. STROBOSCOPE makes it easy to model uncertainties pertaining to duration and timing, quantity, resource assignment, and flow path. It makes it possible to model uncertainty regarding scope of work and quality for situations where the (re)work and the likelihood of its occurrence can be identified at the time the model is constructed. In addition, the strong data typing that STROBOSCOPE enforces actually helps in distinguishing flow from conversion.

STROBOSCOPE's modeling symbols and their functionality are outlined in Table 1 but note that their simplicity belies the expressiveness of the programming language that is associated with them. The choice of modeling elements affects the clarity of the model and the models presented in this paper were created specifically to illustrate various lean construction concepts. They certainly do not capture all complexity that could have been modeled using STROBOSCOPE.

Table 1 Selected STROBOSCOPE symbols.

SYMBOL	NAME	EXPLANATION
CutSheet	**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.
Transport	**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.
Fabricate	**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.
AwaitTranspor	**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 out of it.
WA1 →	**Link**	Shows flow logic and 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.
GoodBad	**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. 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.
SpoolInArea A	**Assembler**	Shows that two or more resources are being assembled into a single unit resource which is of the compound (a special kind of characterized) resource type. The assembly base (if there is one) is marked by a double arrowhead.
DumpMix D	**Disassembler**	Shows that a resource is being taken apart or disassembled into its components. The disassembly base (if there is one) is marked by an arrow with a circle at its tail.

EXAMPLE I: PIPE SPOOL INSTALLATION

Process scenario for pipe spool installation

Consider the construction of an industrial process facility, such as an oil refinery, that involves installing thousands of unique pipe spools. Here, this process is characterized 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, these chains merge upon the installation of spools in their designated areas.

Pipe spools are fabricated off-site according to the availability of 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 documents. 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 1 - x% of them. In the latter case, the fabricator must rework this spool to rectify the problem, prior to shipping it to the project site.

Concurrently with this off-site materials handling 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, the spools can be installed. This yields an area completed, ready for another trade to move into.

Problem characteristics for pipe spool installation

Much of the waste in executing processes like this one on actual construction sites stems from the uncertainty in timing and duration of activities and the quality defects that necessitate rework. One obvious place where waste can be observed is in laydown yards where materials pile up and remain for extended time periods. Another place is at the work face where crews should be working but are idle because the materials they need are not available or work prerequisite to theirs has not yet been completed.

Such waste is the consequence of having ill-defined delivery dates and failing to detail specific, on-site needs. In addition, waste is created because materials are installed in combination with several others and need to end up in a designated location of the facility being built, not all of which are available at the same time. Installation crews, responsible for the final step in the materials handling process, must find "matching parts" among those available to them: they must ensure that the right material gets put in the right place. For instance, they must select a specific piece (e.g. pipe spool SP-123), retrieve the correct installation accessories (e.g. various attachments and supports), and match them in accordance with the location where assembly is to take place (e.g. area AR-123). An integral part of their work, time and again, is to solve the so-called "matching problem." When no matching parts are available, no work can be done.

The matching problem usually is abstracted away at the project planning level, because addressing it is tedious and process uncertainties are expected to render any plan created (too long) in advance useless anyway. Because of this abstraction, project managers fail to provide installation crews with the data they need to optimally schedule and thus execute their work. Crews must rely on numerous assumptions in schedules made by others prior to the start of construction. How much of a problem this poses depends on the extent to which uncertainties in the supply of needed resources manifest themselves during project execution. If project schedules were detailed and all steps prior to installation had no uncertainty in duration, flow path, or execution quality associated with them, then matching would be easy. In practice, unfortunately, this is not the case, and mis-matches foul up scheduled work sequences. This lowers the installation crew's productivity and extends the project's duration for construction.

Process model and simulation output for pipe spool installation

Various process uncertainties in the pipe-spool installation process were modeled using STROBOSCOPE (Figure 1). This model also allowed for experimentation by means of simulation of push- and pull-driven sequencing of resources.

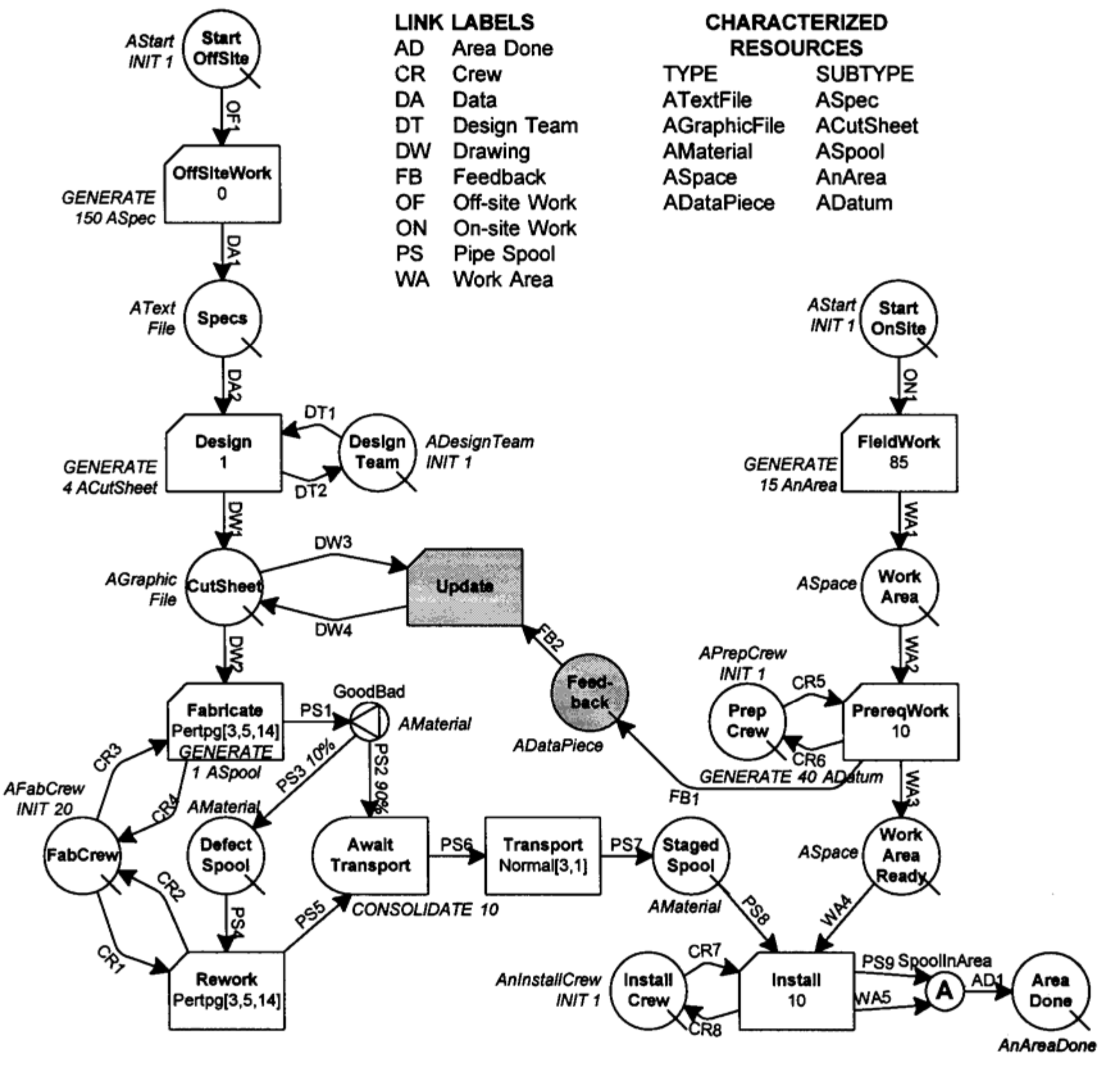

Figure 1 Pipe-spool process model.

Uncertainty and waste

Combi and Normal activity durations reflect one kind of uncertainty. An activity such as Rework models waste; in Figure 1, it is a Combi that follows the GoodBad quality-inspection probabilistic fork and that will be invoked 10% of the time. Waste also will show up in the form of materials piling up on site or crews waiting because the required resources are not available. Such process information is obtained by tracking the number of resources accumulating in queues and the time they reside there (examples are depicted in Figure 2).

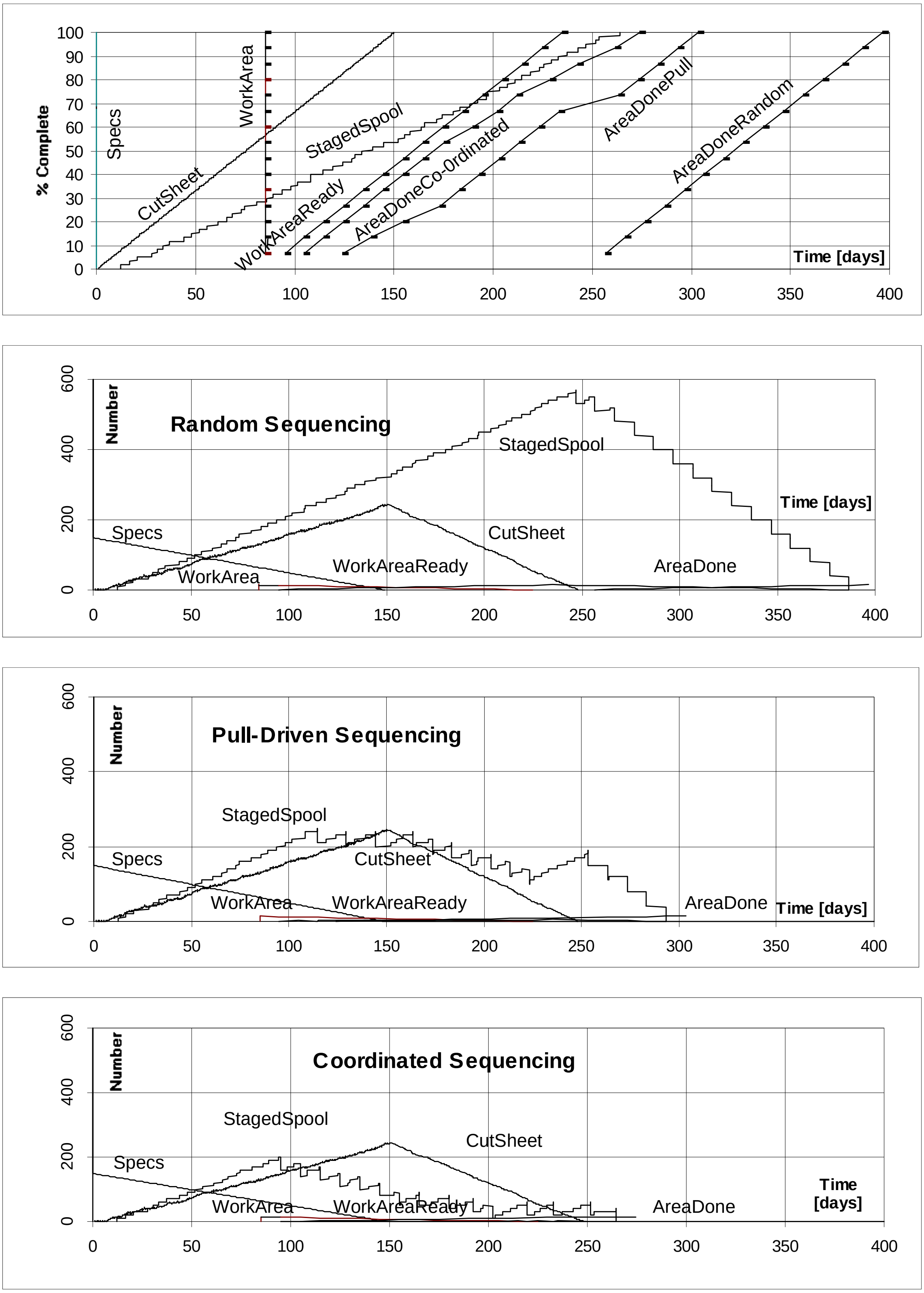

Figure 2 % Complete vs. Time and Number of Resources vs. Time for Specs, WorkArea, CutSheet, StagedSpool, WorkAreaReady, and AreaDone Queues for Random, Coordinated, and Pull-Driven Sequencing.

Flow and conversion

STROBOSCOPE's strong data typing (generic vs. characterized TYPE and SUBTYPE, and compound resources), combined with an appropriate arrow-labeling convention helps reflect which activities represent flow and which conversion. It is good practice to label arrows by combining two (or more) letters that refer to the type of the resource that flows through them with a number to show the sequence in which the resource will traverse the arrows. This convention was consistently applied in Figures 1 and 3.

When arrows pointing into an activity have the same letters as those emanating from it, then that activity denotes flow. Examples are Transport in Figure 1 and TruckDeparts in Figure 3. When the arrows pointing into an activity differ from those emanating from it, then that activity denotes conversion. Assemblers and disassemblers are auxiliary nodes to the Combi that precedes them; they also denote conversion. Thus, examples of conversion are Design, Fabricate, and Install in Figure 1, and BatchAndLoad and HoistAndEmpty in Figure 3.

It is difficult to judge on the basis of flow or conversion alone whether or not an activity is "desirable" from a lean production viewpoint. Obviously, transportation activities represent flow, but at least some of that flow is likely to be a necessary part of the process and therefore value-adding. Assembly may be value-adding provided that no disassembly immediately succeeds it and reverses its effect, but rather, that disassembly occur - if at all - only after some value has been added to the assembly. The same applies to disassembly.

Push and pull

STROBOSCOPE can track resources individually as they reside in various network nodes during a simulation run. This makes it feasible to implement sequencing rules that specify the order in which Combis should draw resources from Queues, and to study the impact those rules have on process execution.

A STROBOSCOPE programmer can define sequencing rules such as:

1. First-In First-Out (FIFO) or Last-In First-Out (LIFO)
2. First-in-Order Based on a Property of Resources in Single Queue
3. Best Match Based on Properties of Resources in Multiple Queues
4. Random

Three alternative sequencing rules were investigated (Table 2). A model for each was implemented using the same basic template (Figure 1) that was crafted to illustrate the occurrence of various kinds of process uncertainty. Industry data was obtained to estimate orders of magnitude for activity durations and percent rework (Howell and Ballard 1995). Some uncertainty was not modeled (OffSiteWork is assumed to be complete and thus all Specs are available at time 0; FieldWork results in all WorkAreas being available at time 85) so as to not complicate interpretation of the simulation results. Obviously, modeling uncertainties further upstream in the off- or on-site activity chains and including those regarding Design, PrereqWork, and Install will further exacerbate the effects described below.

Figure 2 shows results from one individual simulation run for each alternative. The chart at the top uses the line of balance to depict time vs. percent complete in terms of number of resources that entered into various queues. It combines the AreaDone output from the three alternatives. The other three charts, one for each alternative, depict the total number of resources in the queue at any one time during simulation. Note that these runs, in and by themselves, provide mere data points. They do not characterize ranges of uncertainties associated with variables, though STROBOSCOPE provides the means to collect statistics over multiple runs (Tommelein 1997a gives details).

Table 2 Alternative sequencing rules.

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

The models differ from one another in two ways: (1) they use a different sequencing rule for Fabricate to draw resources from the CutSheet queue (Table 2), and (2) only Case C includes the Feedback queue, the Update activity, and links FB1, FB2, DW3, and DW4 (Figure 1). The basic template describes the installation of 600 pipe spools in 15 areas, 40 spools are designated to each area, and work cannot start until all 40 are available.

Cases A and B reflect two extremes in degree of pre-construction planning. **Case A** reflects total lack of coordination. CutSheets (or Spools) and WorkAreas are processed in an order independent of one another. Thus, the likelihood for mismatches to occur at installation time is high. This leads to a huge build-up of spools on site waiting for the areas where they are to be installed to open up, and vice versa. StagedSpool peaks at 570 in Figure 2 (upper-right). However, an advantage of these buffers is that they enable the installation crew to delay their start and then get work done at their highest possible production rate, though this comes at the expense of delayed project completion (397 days). For the crew to have the opportunity to be optimally productive, their delayed start date—a function of the uncertainty of the system—will need to be estimated during planning and a time buffer or lag preceding the Install activity may be added to the precedence network.

Case B describes perfect coordination. It is an idealized case, which, for many reasons will be impossible to achieve in reality. CutSheets 1 through 40 go to fabrication before 41 through 80, etc. Similarly, Area 1’s prerequisite work is performed prior to Area 2’s, etc. This results in minimal space needed to stage spools on site: StagedSpool peaks at 200 in Figure 2 (lower-right). Nonetheless, some spools will accumulate due to asynchrony of the two activity sequences and uncertainty and defects in their activities.

Case B results in the shortest project duration (275 days), though the installation crew faces a materials shortage (by construction of the model!) and was not able to work as productively as before (the AreaDone line of balance is not straight). This is no coincidence! The author 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 processes results in a StagedSpool slope much smaller than the CutSheet or WorkAreaReady slope. The AreaDone slope is smaller as well, except in Case A. Because FieldWork starts 85 days (by construction) after OffSiteWork, the StagedSpool and WorkAreaReady lines of balance cross (in all three Cases).

Case C augments Case A with a pull mechanism. Upon project execution, CutSheets are first processed in random order relative to work areas, but as soon as areas are ready for spool installation, the CutSheet’s priorities are updated with that feedback and “pulled” to the site. A total of 291 updates were performed (Figure 2, lower-left).

Thus, relatively few spools accumulate (250 maximum). Note that the average spool buffer size is larger here than it was in Case B. The project duration remains fairly short (304 days). However, there is a penalty in terms of field productivity, though this can be improved by reducing the crew size to match resource availability or ordering the crew to start later (as in Case A) so they can work at their fastest possible rate.

EXAMPLE II: CONCRETE PLACEMENT

Process scenario for concrete placement

Consider the process of placing concrete using a crane and bucket. This process is here characterized as comprising two main cycles: (1) concrete is batched, loaded into a ready-mix truck, and delivered to the site and (2) a bucket is filled with concrete, hoisted by crane, emptied, and returned to the fill area.

The batch plant produces the requested mix design. Assuming the truck's nominal capacity is 10 yd^3 (13.70 m^3) and provided that it has been fully loaded, approximately that amount of concrete will be available to fill buckets. The bucket's assumed nominal capacity is 2 yd^3 (2.74 m^3) so each delivery will fill about 5 buckets. Not included in this model, for the sake of simplicity, is the formwork in which concrete will be placed.

PROBLEM CHARACTERISTICS FOR CONCRETE PLACEMENT

The uncertainties in this model are characteristic of processes that involve bulk materials handling. However, planning the delivery of ready-mix concrete requires extra care (as compared to sand, for instance). A batch will start to set about 0.5 hour after water has been added to the mix. If it has not been placed in its final position by then, it will have to be discarded as stirring up the concrete any time thereafter would destroy the development of its structure and result in reduced ultimate strength. Thus, one source of uncertainty is the duration needed to bring concrete to the site and place it; if that duration exceeds a threshold value, then the mix is wasted.

Another source of uncertainty is estimating, i.e., determining with reasonably accuracy what quantities are needed. An order of concrete will reflect not only the amount to be placed in forms (ignoring the volume of reinforcing bars, chairs, spacers, and other embedments), but also losses of material incurred on a daily basis. Handling quantities are limited in size but they must add up to the required placement quantity as it is important that construction joints be executed as planned rather than be created haphazardly as the result of materials shortage.

Some concrete will be wasted in the handling process because it is a material without packaging of its own. While measuring systems in computer-controlled batch plants are quite accurate, there will always be some concrete adhering to the ready-mix truck's revolving drum, the shoot, and the bucket with its placement attachments; some concrete may be cast in cylinders for testing; some may be spilled when filling buckets or forms, etc. Because concrete is an expensive material and shortages can be very costly, quite a few waste factors are an integral part of the estimate and orders tend to be conservative.

PROCESS MODEL AND SIMULATION OUTPUT FOR CONCRETE PLACEMENT

With no exception, all aforementioned characteristics can be represented using STROBOSCOPE. A simple process model for concrete placement is shown in Figure 3. Additional detail can be obtained from the author.

Uncertainty and waste

As was the case for the pipe spool model, simulation output can be collected to describe the amount of time resources spend being idle in queues vs. being productively engaged in activities (e.g. CraneReady), to determine space needed for trucks to get positioned for off-loading (EmptySpace), to find out what amount of concrete can be expected to have been put in place (MixInPlace) as opposed to wasted (MixWasted), etc.

Flow and conversion

The numerous assembly and disassembly nodes in this model show that concrete gets put from one container into another one prior to placement. In adhering to the arrow-in arrow-out convention, these nodes denote conversion. However, one may question the extent to which changing containers (especially several times) truly is value adding. As for conversion, given that concrete is a chemically reactive material, one should recognize that the mix flowing through MX1 will be different in nature from that flowing through MX5.

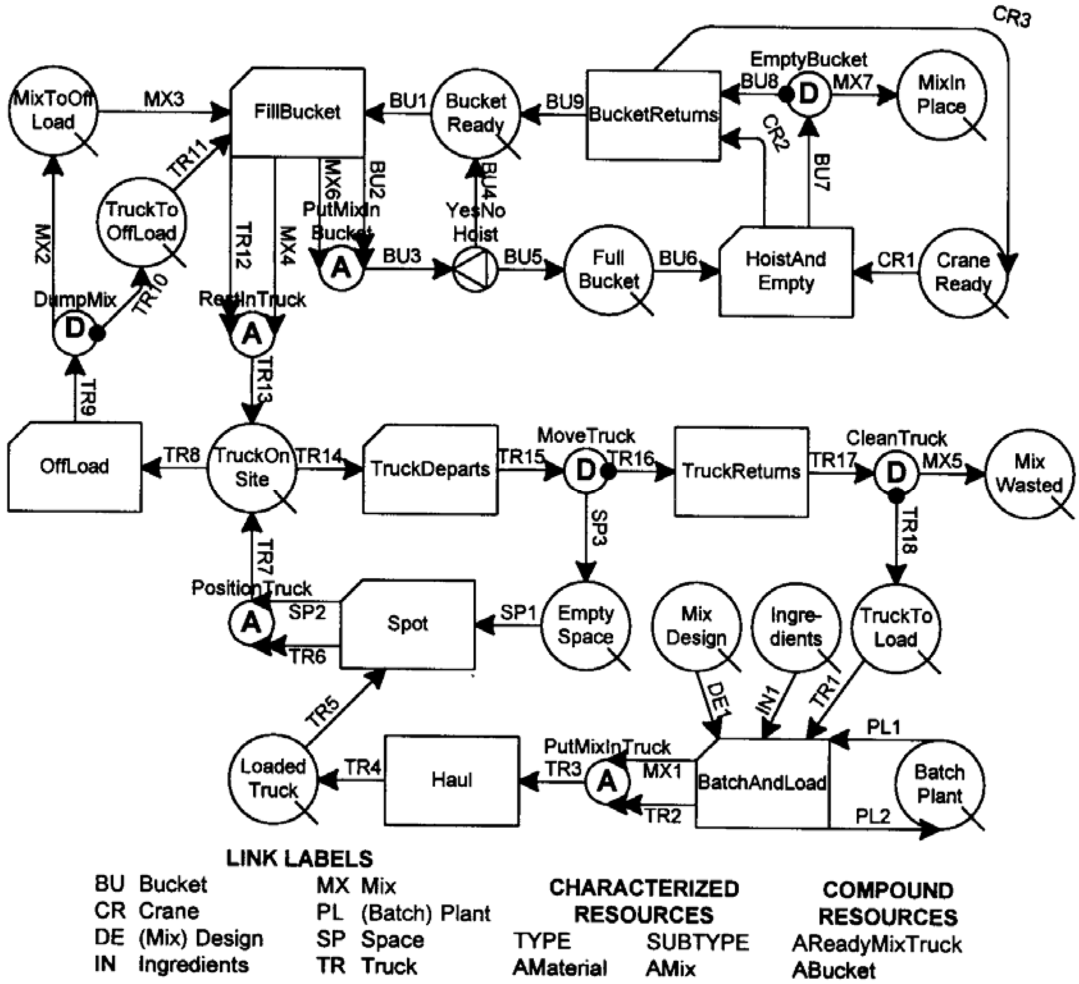

Figure 3 Process model for concrete placement.

Pull vs. Pull

To allow for process uncertainties in terms of timing as well as adjustments in quantity, concrete delivery systems will include some form of a pull mechanism, so that mixes are not unduly batched when timely delivery is too uncertain or the site is not ready for placement. In this simplified model, however, no pull mechanism is shown.

CONCLUSIONS

Examples in this paper have illustrated how modeling concepts used in discrete-event simulation also can be used to describe lean construction concepts. Various forms of uncertainty, waste, flow, conversion, and push vs. pull-driven sequencing were described. Discrete as well as bulk resources were modeled.

Discrete-event simulation of the pipe-spool process model showed how data characteristic of the system as whole can be generated and lead to insights into process waste. In turn, these insights can direct further experimentation and redesign of construction processes in order to make them leaner.

Such process models can characterize prevailing industry practices or individual projects. Any one construction project is unique, of course, and a considerable amount of field data (on- or off-site) will have to be collected regarding duration, timing, quantity, quality, etc. when one sets out to model its constituent processes and quantify process uncertainties of any kind. Neither academics nor practitioners in construction have made it part of their routine practice to collect such process data and develop process models, yet doing so is a necessary step towards understanding and optimizing construction systems.

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