The Modeling of Pull-Driven Scheduling for Pipe-Spool Installation as a Lean Construction Method

Rafey Ahmed,Sri Charan, Abdul Ahad,
Department of civil
rafay12385@gmail.com,charansri0123@gmail.com,a.ahad4646@gmail.com
ISL Engineering College.
International Airport Road, Bandlaguda, Chandrayangutta Hyderabad - 500005 Telangana, India.

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 projectspecifications in the facility being built. By tracking the flow ofmaterials through their supply chain (i.e., describing when andwhere materials are being engineered, fabricated, transported,staged, etc.) installation work can be most effectively plannedandexecuted.Flowdatamustbemoreorlessdetaileddependingonwhetherthematerialofconcernwillbeavailableinlargequantitiesofidentical,interchangeableunits(e.g.,concrete blocks, electrical conduit, nuts and bolts); in modestquantities, possibly with some degree of interchangeability (e.g.,windows, structural steel, timber in precut lengths), or in smallquantitiesofunitswithuniqueproperties(e.g.,engineeredmaterialssuchaspipespoolsoracustom-designedmainentrancedoor).

Field installation crews, responsible for the final step in thematerials flow process, must find resources that match amongthose available to them; they must ensure that the right materialgets put in the right place. For instance, they must identify thelocation where installation is to take place (e.g., area AR-123),then find the matching material (e.g., pipe spool SP-123) andretrievethecorrectinstallationaccessories(e.g.,attachmentsand supports).Anintegralpartoftheirwork,timeandagain,istosolvetheso-called"matchingproblem."Infacilitiesthatcomprisethousandsofmaterialsofwhichmanyareunique,tacklingthematchingproblemisanenormoustask.Nevertheless, those performing installation have no way aroundit.

In contrast, those responsible for engineering and design,fabrication, delivery, and site storage of materials, as well asconstruction managers overseeing the project often overlook thematchingproblemthatinstallationcrewsface.Dealingwith materials on an item-by-item basis means paying attention tominute details. It is a tedious task, largely irrelevanttotheirown.Accordingly,matching-problemdetailsareselectivelyabstractedawaybyeachpartysothattheycanfocusonproblemsofmoredirect,contractualconcerntothem.Forexample,structuraldesignersdonotworryaboutvendors'ability to deliver specialty valves or nuts-and-bolts because it isoutside of their scope of work. Pipe-spool fabricators optimizeproduction schedules to suit their plant's fabrication constraintsand other projects' needs. Shipping agents optimize travel bychoosingvehiclestomeetdeliveryschedules;theypackagematerials to ensure that loads are stable and meet weight anddimensionalconstraintsduringtransportation.Laydownyardpersonnelgroupmaterialsbyshipment,type,orfinal-installationdestinationtoeasetracking.Projectmanagerscontrolprogressbasedonpercentages-of-totalofmaterialsengineered, delivered to the site, or installed. The correspondingplanningsystemsmustthereforeallowforabstraction ordetailasneeded.

Because of this abstraction,installation crews rarely havethe data they need to optimally schedule and thus execute theirwork. They must rely on the numerous assumptions that areembeddedinpre-constructionschedules.Howmuchofaproblemthiscreatesdependsontheextenttowhichuncertainties in their supply manifest themselves during projectexecution. If pre-construction schedules were well thought-outandsteps preceding installation had no uncertaintyin durationor execution quality associated with them, then matching wouldbe easy. In practice, unfortunately, this is not the case. Manyprojectsareexecutedonafasttrack,soconstructionstartsbefore design has been completed or materials deliveries havebeen properly sequenced. Installation crews and equipment areoftenkept waitingbecausedelaysinmaterialssupplyanddelays in completing prerequisite site work lead to mis-matches thatfoul up scheduled work sequences. This lowers the installationcrew'sproductivityandextendstheprojectduration.

In order to increase understanding of these issues, a modelwas created of a process that is characteristic of the process-plant sector of the construction industry. Alternative strategiesfor sequencing materials deliveries are presented in this paperand their execution was simulated so computer data supports thecomparisonbetweenthem.

RELATEDWORKINLEANCONSTRUCTION

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 TaiichiOhno 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-DRIVENVS.PULL-DRIVENPROCESSMANAGEMENT

Push-DrivenProcessManagement

Constructionworktraditionallyisplannedbyarticulatingactivitiesanddependenciesbetweenthem,thenassigningdurationsandresources toeachactivity.Ascheduleisdevelopedbycalculatingearlyandlateactivitystartsandfinishesusingthe CriticalPathMethod(CPM).Resourceleveling or allocation algorithms may yield some adjustments totheearly-startschedule,butuponprojectexecution,activitiesare expected to start at their earliest possible date in order not todelaysucceedingactivitiesortheprojectasawhole.

Project control aims at adhering to the resulting schedule. Itis assumed that all resources required to perform an activity thatis about to start will indeed be available at that activity's early-starttime.Inthisso-called"push-driven"approach,eachactivity passively waits for its ingredients (instructions, labor,materials, equipment, and space) to become available, e.g., bybeing released upon completion of predecessor activities. Whensome have become available but others needed at the same timehave not, those available will wait in a queue or buffer for thecombination of resources— the set of "matching parts"— in itsentirety to be ready. While it may be possible to start work withan incomplete set of resources, chances are this will negativelyaffectproductivity(e.g.,Thomasetal.1989,Howelletal.1993).

dealt with in real time. At that point, rigorously adhering to theinitial schedule may not be the best approachfor successfulprojectcompletionasnetworkcharacteristicsandresource availability will deviate from those assumed when that schedulewasgenerated.

Moreover,traditionalCPMschedulesdonotnecessarilyshowindividualresourcesandtheirallocationtoactivities.Certainly, procurement schedules highlight milestone deliverydates of major items, but most materials will arrive in multi-unitshipments. If a schedule reflects only groupings, then it is toocoarse to guide work that involves unique parts. When missingparts are identified during the on-site allocation process, it ismuchtoolatetopreventdelays.

In addition, current expediting practice is to regularly touchbase,e.g.,withtheengineeringdesignfirmorfabricatorofwhom goods or services are expected. Contact is made prior tothe deadline of completion of their work, in order to make surethetargetdeliverydate,e.g.,ofkeymaterialsorpiecesofequipment, will be met. Yet, most expediters fail to (e.g., are notauthorized to) reschedule activities when it can be anticipatedthatdeadlineswillnotbemet.Accordingly,thetraditional, push-drivenapproachtoschedulingpriortothestartofconstructionwithnocorrectivere-schedulingasworkprogresses leads to process inefficiencies and less-than-optimalprojectperformance.

Pull-DrivenProcessManagement

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

Because of uncertainty in duration as well as variation inexecution quality and dependency logic of activities, schedulesareboundtochangeasconstructionprogresses.Itmaybepossibletomodelthisuncertaintyduringtheplanningstage,asisdoneby usingprobabilisticdistributionstocharacterizeactivitydurationsintheProgramEvaluationandReviewTechnique(PERT).However,theactualmanifestationofuncertaintyisknownonlyuponplanexecutionandmustthusbe

and be in process for any time longer than needed, though their planned processing sequence may be violated.

EXAMPLEPROCESSSCENARIO:PIPE-SPOOLINSTALLATION

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.

INDUSTRYPRACTICE

TheBusinessRoundtable(BRT1982)identifiedthepipingprocess as being critical to the success of numerous industrialprojects. However, research into improving practice has beenlagging until only a few years ago CII conducted a detailedinvestigation (CII 1996,Howell andBallard 1996,O'Connorand Liao 1996, O'Connor and Goucha 1996). Major causes forproblems were found in the engineering development process,specificallyinthreeareas:(1)pipingandinstrumentationdiagram (P&ID) problems are caused by inefficient sequencingofpriotization,inefficientproceduresforP&IDdevelopmentandreview,andinefficientcommunicationofP&IDuncertainty ; (2) problems in the supplier data process pertain tocommunication, coordination, and selection duration; and (3)problemsinthepackagedunitsprocesspertaintosupplierquality and design. Whereas O'Connor et al. developed policies,procedures, and checklists to enhance the overall efficiency ofthese processes,HowellandBallardstudiedtheimpactofuncertaintyondownstreamperformance.

Industrypractitionersknowthatconstructionisplaguedbyuncertainties.Intheirmostinterestingstudy,HowellandBallard(1996,p.6)describeprevailingmethodsformanagingtheminthepipingfunction:"Pipingsuccessrequiresminimizingtheextentandeffectsofuncertaintyduringfabricationandinstallation.Atpresent,uncertaintyinthetiming

bufferstoassureprogressdespitevariationsinthetiming,sequence,andqualityofresourcesfromupstreamsuppliers.Buffers dampen the effects of variations in the flow of resourcesandallowflexibilityinthechoiceofwork."

HowellandBallardcharacterizecommonpracticeformovingpipespoolsfromengineeringthroughoff-sitefabricationtoerection."Whenengineeringfallsbehindschedule,fabricationwillbedelayed,therebyalsodelayinginstallationwork.""

Theorderinwhichdrawingsareprovidedto the fabricator and the sequencing in which spools are outputby the fabrication process may bear little relationship to siteneeds,thereforerequiringre-sequencingforsitedeliveryprovided that priority information be available." "Time delaysandout-of-sequenceworkmakethesupplyofmaterialstothejob site unpredictable. This leads to inefficiencies because workcannot be adequately planned and executed, and thus results inlowproductivity."

Figure 1 charts commodity curves from 1 of 24 projects onwhich 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 ofinstallation. It was characterized as "Design well established.Rash of client changes late in project." As can be seen, scheduleslippages(deviationofactualfromplanned)occurredincompleting isometric drawings (ISOs) and in fabricating spools.Nonetheless,installationworkprogressednearlyasplanned.

causesandpossiblesolutions.Theypointout"Fasttrackproject.Schedulemainconcern.Manpowerlevelsaboveprojected."(p.73).Onecanonlyspeculatethatuncertaintycontributedtooccurrenceofmatchingproblems,hamperinginstallationwork,butapparentlysuccessfullyovercome.Inconclusion,HowellandBallardrecommendthatpipingbacklogsbeusedtobufferon-sitefromoff-siteactivity("successful projects have at least 60% of all pipe on hand when20% has been installed"), and that the principles of the LastPlannerbeappliedtoshieldinstallationfromremaininguncertainties.

Thepresentpaperbuildsonthisworkbyfocusingontwouncertaintiesinthepipe-spoolprocess:(1)uncertaintyindurationoffabricationandtransporta

they will be drawn first (they have been waiting for thelongesttime).Incontrast,last-in-first-out(LIFO)placesthosearrivinglateratthefront.

First-in-Order Based on a Property of Resources inSingleQueue:

When resources can be ordered based on a property oronsomeexternally-definednumberingsystem,thatorder

ofdeliveriesofintermediateproductsfromonecontinuingactivitytoanotherdefinestheproductionplanningandmanagement problem. Lacking tools to minimize theuncertaintyintheseflows,managersstriveforflexibilitysothattheprojectcanproceedinthefaceoferraticdeliveriesandunexpectedproblems.Onpipingextensiveprojects,theyrelyon

tionand(2)qualityfailureinfabricationresultingindelayofshipmentduetorework.Itshowshowmatchingaffectstheproductivityofinstallationcrewsandtheoverallprojectduration.

PROCESSMODELING

Process-ModelRepresentation

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-InFirst-OutorLast-InFirst-Out:**

   The ordering criterion is resource time of arrival in thequeue.First-in-first-out(FIFO)placesresourcesarrivingearlieratthefrontofthequeue,sobydefault

   can define draw priority. For example, trucks ofvarying size can be sorted by their loading capacity,where it may have been decided that larger ones will beloaded first; anengineer may have numbered footingsto specify the order in which concrete is to be placed,where those with lower numbers will be placed first.Selectionisthusbasedoncomparinganindividualresource's "capacity" or "placement number" propertywith that of others in the same queue. Other examplesare "easiest to install first" and "highest ratio of earned-to-expendedeffortfirst"(HowellandBallard1996), "materials covered by or buried in others first," and"thosethatcaneasilybedamagedlast."

ModelB-CoordinatedSequencing

ModelB'sParameters

Model B describes perfect coordination. The fabrication crewand the installation crew plan before starting their work anddecide on the sequence in which to draw resources. Cutsheetsandareasareassignedsequencenumberssotheycanbedra

B'sPipe-spoolBufferSize

Model B results in minimal space needed to stage spools on site:StagedSpool peaks at 200 in Figure 3 (Right, Lower-middle).Nonetheless,somespoolswillaccumulateonsitebecausedeliveries get out of sequence when uncertainty manifests itselfduring fabrication and shipping, and the need for rework arisesoccasionally.

ModelB'sProductivityofInstallationCrew

Despiteexpedientprojectcompletion,theinstallationcrew(which starts to work as soon as work is available and stays idlein-betweenactivities,whenmaterialsareinshortsupply)wasnot able to work as productively as before (the AreaDone line ofbalanceisnotstraightbutbendstotheright).Thisisnocoincidence! The writer crafted the model's basic template toshowhowmaterialsshortagesmightarisesothattheirimpactonproductioncouldbeshown.WhiletheactivitiesDesign,Fabricate, PrereqWork, and Install can process resources at thesame average rate of 1 area/10 days or 4 spools/day, uncertaintyin the Fabricate, Rework, and Transport activities results in aStagedSpoolslopemuchsmallerthantheCutSheetorWorkAreaReady slope. Consequently, theAreaDone slope issmaller as well (note that in Model A the AreaDone slope wasnot really affected by the slow delivery rate because of the largebuild-upofspoolspriortoitsstart).BecauseFieldWorkstarts 85daysafterOffSiteWork,theStagedSpoolandWorkAreaReadylinesofbalancecross.

ModelB'sProjectDuration

Perfect coordination leads to project completion in the shortestduration of275days(Figure3,Left,Lower-middle).

ModelC-Pull-drivenSequencing

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!

wnin FIFO order (STROBOSCOPE's default discipline). CutSheets1 through 40 will go to fabrication before 41 through 80, and soon. Similarly, Area 1's prerequisite work will be performed priortoArea2's,andsoon. Whileperfectcoordinationreflectsanidealizedsituation,formanyreasonsitwillnevermaterialize.Itseldomisacontractualrequirementanditalsoistoorestrictivetothevariouspartiesinvolvedintheprocess(e.g.,fabricationshopsare not set up to tolerate one-piece flows, that is, to changemachine setups in order to meet each spool's unique fabricationrequirements).

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).

IMPLEMENTATIONHARDWAREANDSOFTWARE

AllmodelswereruninSTROBOSCOPE(version1,2,2,0)ona Pentium 200-MHz computer running Windows® 95. A singleiteration takes on the order of 1 minute. Source code is available(Tommelein1997a)soreaderscanreproduceandfurtherexperimentwithalternativeinputstothismodel.

Otherdrawsequencesandfeedbackmechanismscouldhave beenimplementedandtheirimpactstudiedon,forinstance,crewproductivityandprojectcompletion.Thefeedback mechanism as shown does not lead to optimal systemperformance.Readersmayacceptthisobservationasachallenge.

DISCUSSIONANDCONCLUSIONS

Thelean-production"pull"techniquehasbeenshowntoimprove performance of a construction process. It is particularlywell-suitedforfast-trackprojectsthatrequireassemblyofunique parts and that are plagued by uncertainties. Such projectsare difficult to schedule accurately and in detail in advance. Thenature of the anticipated matching problems must determine thecomplexityanddetailrequiredoftheplanningsystem.Asuncertainties manifest themselves during project execution, thepre-construction schedule will have to be adjusted in a flexiblemanner for field work to progress efficiently and for work-in-progressinventoriestoremainsmall.

The pull technique suggests that real-time feedback fromconstruction be usedto drive the sequencing of off-site work,andviceversa.Bychoosingupstreamtoprocess"matchingparts"first,thedownstreamprocesswillproceedinamoreexpedient fashion, and completed units will be available soonerthanwouldbethecaseotherwise.Wirelesscommunicationtechnologies,appropriatetoimplementthistechnique,arereadilyavailabletoday.

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.

ACKNOWLEDGMENTS

I am most indebted to James C. Goodwin, Manager of Materials Management at H.B. Zachry, for letting me study industry practices at the Lyondell-Citgo Refinery Expansion Project site in Houston, Texas. This study increased my awareness and understanding of the complexity of construction materials management.

Thanks are due to Professor Julio C. Martinez, at the Virginia Polytechnic and State University, for making STROBOSCOPE readily available. Thanks to him as well as his dissertation advisor, Professor Photios G. Ioannou at The University of Michigan, this expressive and especially fast discrete-event simulation system now lets us model construction processes effectively and efficiently.

Last, but not least, I owe thanks to my Berkeley colleague, Glenn Ballard, for introducing me to the "Last Planner" and discussing field implementations of lean construction, which has sharpened my own thinking about this subject. Glenn also provided valuable feedback on drafts of this paper.

This research was funded by grant CMS-9622308 from the National Science Foundation, whose support is gratefully acknowledged. Any opinions, findings, conclusions, or recommendations expressed in this report are those of the author and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

Alarcon, L. (ed.) (1997). *Lean Construction*. Balkema, Rotterdam, The Netherlands, 497pp.

Ballard, G. and Howell, G. (1997). "Shielding Production from Uncertainty: First Step in an Improvement Strategy." *Technical Report 97-1*, Constr. Engrg. and Mgmt. Program, Civil &Envir. Engrg. Dept., Univ. of Calif., Berkeley, CA.

Bernold, L.E. and Salim, Md. (1993). "Placement-oriented design and delivery of concrete reinforcement." *J. Constr. Engrg. and Mgmt.*, ASCE, 119(2) 323-335.

BRT (1982). *Construction Technologies Needs and Priorities.* The Business Roundtable, Construction Industry Cost Effectiveness (CICE) Project Report B-3, New York, NY.

CII (1996). "Piping: Improving P&IDs, Supplier Data, and Packaged Units." Research Summary 47-1, Constr. Industry Institute, Univ. of Texas, Austin, TX, Dec., 28pp.

Howell, G.A. and Ballard, H.G. (1996). *Managing Uncertainty in the Piping Process*. RR 47-13, Constr. Industry Institute, Univ. of Texas, Austin, TX, September, 103pp.

Howell, G., Laufer, A., and Ballard, G. (1993). "Interaction between sub-cycles: one key to improved methods." *J. Constr. Engrg. and Mgmt.*, ASCE, 119(4) 714-728.

Koskela, L. (1992). *Application of the New Production Philosophy to Construction*. Technical Report 72, CIFE, Stanford Univ., Stanford, CA, September, 75pp.

Martinez, J.C. (1996). *STROBOSCOPE State and Resource Based Simulation of Construction Processes.* Ph.D. Diss., Civil &Envir. Engrg. Dept., Univ. of Michigan, Ann Arbor, MI, 518pp.

Melles, B. and Wamelink, J.W.F. (1993). *Production Control in Construction*. Delft Univ. Press, Delft, The Netherlands, 320pp.

O'Brien, W.J. (1995). "Construction Supply Chains: Case Study and Integrated Cost and Performance Analysis." *Proceedings IGLC-3*, held in Albuquerque, NM, 187-222 in Alarcon (1997).

O'Connor, J.T. and Liao, S.-J. (1996). "Enhancement of the Piping and Instrumentation Diagram, Development Process." RR47-12, Constr. Industry Institute, Univ. of Texas, Austin, TX, Aug., 136pp.

O'Connor, J.T. and Goucha, H.Y (1996). "Improving Industrial Piping Through Vendor Data and Packaged Units Processes." RR47-11, Constr. Industry Institute, Univ. of Texas, Austin, TX, May, 164pp.

Ohno, T. (1988). *Toyota Production System: Beyond Large-Scale Production.* Cambridge, MA: Productivity Press, translation not credited.

Phair, M., Tulacz, G.L., and Angelo, W.J. (1997). "Cushier Controls, Cabs, Make Cash: Ergonomics and Comfort Go Hand-in-Hand with Productivity." *ENR*, Feb. 10, 34-39.

Tatum, C.B. (1985). "Evaluating Construction Progress." *Project Mgmt. Journal*, Spec. Summer Issue, August, 52-57.

Thomas, H.R., Sanvido, V.E., and Sanders, S.R. (1989). "Impact of Material Management on Productivity— a Case Study." *J. Constr. Engrg. and Mgmt.*, ASCE, 115(3) 370-384.

Tommelein,IrisD.(1997a).*Discrete-EventSimulationofaPull-DrivenMaterials-HandlingProcessthatRequiresResourceMatching:ExampleofPipe-SpoolInstallation*.Tech. Report 97-2, Constr. Engrg.& Mgmt. Program, Civil &Envir.Engrg.Dept.,Univ. of California, Berkeley, CA.

Tommelein,IrisD.(1997b)."ModelsofLeanConstructionProcesses:ExampleofPipe-SpoolMaterialsManagement."In Anderson, S. (Editor). "Managing Engineered Constructionin Expanding Global Markets." *Proc. Construction CongressV,*Oct.5-7in Minneapolis, MN,ASCE, 156-164.

Womack, J.P. and Jones, D.T. (1996).*Lean* Thinking*: BanishWasteandCreateWealthinYourCorporation.*Simon&Schuster,NewYork,NY,350pp.