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USING SIMULATION TO STUDY THE IMPACT OF IMROVING LOOKAHEAD PLANNING ON THE RELIABILITY OF PRODUCTION PLANNING

Farook Hamzeh
Brandon Langerud

Colorado State University
223 Guggenheim Hall
3rd Floor Spruce Hall
Fort Collins, CO 80523-1584, USA

ABSTRACT

The Last Planner® system (LPS) is used on construction projects to improve the reliability of production planning. A significant process of the LPS is Lookahead planning where activities are broken down into the level of operations, constraints are identified, responsibilities are assigned, and assignments are made ready. The success of Lookahead planning depends on *task anticipation*, which is a result of activity breakdown and design of operations, and *making activities ready* by removing constraints. The purpose of this paper is to show through computer simulation the relationship between improving task anticipated (TA) and the reliability of weekly work planning expressed as percent plan complete (PPC). The paper presents a simulation model for the lookahead planning process starting three weeks before execution and ending in activities executed during the work week. The study findings indicate a positive correlation between TA and PPC where improving lookahead planning can increase reliable work execution.

1 INTRODUCTION

1.1 The Last Planner® System

The Last Planner® System (LPS) for production planning and control is used on construction projects to assist in smoothing variations in workflow and improving the reliability of planning. The system originally addressed reliability issues at the weekly work plan level but soon expanded to cover the full planning and schedule development process from master scheduling to phase scheduling through lookahead planning and weekly work planning. To track the reliability of weekly work planning, the LPS uses metric called percent plan complete (PPC) which measures the percentage of tasks completed relative to those planned (Ballard 2000, Hamzeh 2011).

The LPS comprises four levels of planning processes:

1. *Master scheduling* or front-end planning identifies major milestone dates and describes in general terms work to be performed over the entire duration of a project (Tommelein & Ballard 1997).
2. *Phase scheduling* is collaborative planning exercise that generates a more coarse level-of-detail schedule covering each project phase. The exercise employs reverse phase scheduling and identifies handoffs between the various specialty organizations (Ballard & Howell 2003).
3. *Lookahead planning* looks at activities on the phase schedule within a time frame between two to six weeks. These activities are then broken down into the level of processes/operations, constraints are identified, responsibilities are assigned, and assignments are made ready (Ballard 1997; Hamzeh, Ballard, and Tommelein 2008).

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4. *Weekly work planning* develops the lookahead plan into a weekly work plan by presenting activities in the most detailed level required to drive the production process. At the end of each week, assignments are reviewed to measure PPC. Analyzing reasons for plan failures and acting on these reasons is used for learning and continuous improvement (Ballard 2000).

As a first step in production control, lookahead planning is a vital link between phase scheduling and weekly work planning. Lookahead planning makes scheduled tasks ready to be performed, shields activities on the weekly work plan from variations by removing constraints, sizes capacity to work flow, produces a backlog of workable activities, and designs how operations are performed (Ballard 1997, Ballard 2000, Hamzeh 2009).

To measure the performance of the lookahead planning process two metrics, Tasks Anticipated (TA) and Tasks Made Ready (TMR), are used. TA measures the percentage of tasks anticipated on the lookahead plan two weeks ahead of execution. TMR measures the performance of lookahead planning in identifying and removing constraints to make tasks ready for execution (Ballard 1997; Hamzeh, Ballard, and Tommelein 2008).

Thus TA measures the performance of lookahead planning in anticipating tasks that will take place two or three weeks in the future. Anticipating tasks is a result of breaking down activities into the level of operations, designing those operations (i.e., arranging the sequence, materials, labor, equipment, tools, safety, etc.), identifying constraints, and assigning responsibilities.

Improving lookahead planning is expected to have positive impacts on the reliability of construction workflow. The LPS measures this reliability in terms of PPC by measuring the percentage of tasks completed at the end of a certain week relative to those tasks planned at the beginning of the week. While tracking PPC is necessary on most projects implementing LPS, tracking TA is very rare. This study suggests using computer simulation to study the impacts of increasing TA (i.e., improving the anticipation of tasks) on the reliability of workflow measured in terms of PPC.

1.2 Simulation in Construction

Although the use of simulation to model construction planning is not very common, several researchers have highlighted the use of simulation for construction operations. Martinez and Ioannou (1999) examined simulation programs and found them well suited for various applications within the construction industry. Shi (1999) discussed the benefits of using simulation within construction planning and its potential to improve process performance. A few of the advantages of computer simulation include ability to model resources, create a dynamic process, and being able to instill variability and randomness within the model.

Simulation has been used to improve construction operations. Vanegas et al. (1993) employed simulation for planning construction processes on heavy civil projects and found out that simulation is asimple tool for workflow analysis and its overall implementation costs are relatively low. Huang et al. (2004) reported planning gang formwork operations for building construction, using simulation to improve formwork use, reuse, and resource allocation. They found that depending on the reuse scheme and resource allocation, the project duration and cost can vary substantially.

Other researchers have used simulation for planning and logistics. Wales and AbouRizk (1996) developed a modeling strategy to improve project scheduling and planning by reducing the impacts of weather on productivity and project completion for a bridge construction project. Hamzeh et al. (2007) developed a simulation model to improve the supply of consumables on construction projects by pooling site stores into logistics centers, thus reducing material shortages.

Simulation models are powerful analytical tools where uncertainty and variability are embedded to better simulate a system. Tommelein (1997) identified a lack of modeling for the concepts of uncertainty, waste, and flow within lean construction. Developing models to represent the flow of unique materials and bulk volume materials, Tommelein found that simulation is useful in describing lean construction strategies, and providing information required for further improvement. Alves, Tommelein, and Ballard

(2006) utilized simulation to research the interactions between variability, buffers, and batches throughout five scenarios pertaining to the planning, fabrication, shipping and installation of sheet metal ductwork.

Some researchers used simulation for production system design and allocation of buffers. Srisuwanrat and Ioannou (2007) investigated lead-time buffering under uncertainty using simulation and cost optimization. They have found that the process of applying lead-time buffers does provide for increased workflow and project profit, dependent on associated penalty costs. Draper and Martinez (2002) used simulation to evaluate alternative production system designs and recognized that much of the traditional construction processes are lined with waste and "artificial" constraints, making the use of production control difficult. To improve production strategies, Alarcón and Ashley (1999) explored the use of the 'Dice Game', as this game simulation relates to understanding variability and risk analysis. They have found that the use of a simple simulated production model is useful in exploring lean production strategies as they relate to buffers and variability.

Simulation is also used to evaluate alternatives across multiple projects. AbouRizk and Dozzi (1993) used simulation to resolve construction disputes on construction projects by identifying operation cost changes. They also found that simulation can be a very successful tool for construction operations mediation. Liu and Wang (2009) examined the use of simulation modeling with design firms to effectively allocate design participants and resources to multiple projects. It was found that the simulation model could incorporate various design iterations, deliverables and determine the most effective participant allocation for project completion. Schramm et al. (2008) used simulation to support decision-makers in production system design and operations. The authors found that simulation outcomes are helpful in determining a reliable process duration, start time, and the potential impact of changes to production in housing construction.

The previously mentioned studies employed a variety of simulation software to build their simulation models and simulate system performance. These software include @RISK, STROBOSCOPE, CYCLONE, SIGMA, SLAMSYSTEM, and Micro CYCLONE.

2 RESEARCH METHOD

To study the impact of improving tasked anticipated (TA) in lookahead planning on the reliability of weekly work planning and execution requires a detailed study incorporating uncertainty and involving multiple scenarios. The hypothesis suggested is that increasing TA will increase PPC and improve project performance. While performing such a study on a running project is difficult at best, simulation offers an effective inexpensive option to experiment, answer what-if questions, and show the results of various what-if scenarios (Dooley 2002).

There are multiple benefits to using simulation when studying a system including: prediction of what-if scenario results, diagnosis of performance, human-skills training, education, entertainment, proof of solutions (e.g., the pipe spool simulation study by Tommelein (1998)), and theory discovery (Axelrod 2006).

Simulation models representing a system are performed in three different methods: (1) discrete event simulation which models a system in terms of entities and resources changing at discrete time intervals when certain events are triggered, (2) system dynamics which defines the behavior of a system by identifying key-state variables related to each other by differential equations, and (3) agent-based simulation which involves agents that interact with other agents and resources as per certain schema to maximize their utility functions (Dooley 2002, Schruben and Schruben 2005).

This study employs discrete event simulation to study the impact of improving task anticipation in lookahead planning on the performance of weekly work planning. This serves as a laboratory for testing the hypothesis "Improving TA in lookahead planning improves the performance of weekly work planning measured in PPC." The model also helps make predictions about the performance of lookahead planning and its implications on overall project performance such as project duration.

The simulation study includes three main steps: (1) conceptual model design which describes the system to be modeled including variables, resources, and events that trigger changes in the system (as shown later in Figure 1), (2) mathematical model supporting the simulation platform (shown later in Figure 2 although the mathematical details are imbedded within the model and impact the change of events), and (3) experimental design where a set of experiments are tested and evaluated.

3 SIMULATION MODEL

3.1 The Lookahead Planning Process

Lookahead planning is the first step in production control. Lookahead planning involves three main steps: (1) breaking down tasks into the level of processes/operations, (2) identifying and removing constraints to make tasks ready for execution, and (3) designing operations through first run studies (Ballard 1997, Hamzeh 2009).

The common lookahead planning window is six weeks ahead of execution. Activities on the lookahead schedule are systematically broken down into further detail (from boulders to rocks to pebbles) as they move from six weeks away from execution towards execution week. *Six weeks ahead of execution*, tasks enter the six-week lookahead plan from the phase schedule or master schedule. At this stage, tasks are not detailed yet and are represented by boulders. *Between five weeks and four weeks ahead of execution*, task break down starts by decomposing phase-level tasks or "Boulders" into their underlying work elements expressed in terms of processes or "Rocks" (Ballard 2000,Hamzeh 2009).

Three weeks ahead of execution, tasks are broken into operations as shown in Figure 1. At this stage, operations are designed using first run studies where crew workers will perform the operation design on the first run against safety, quality, time and cost criteria. It involves understanding the work involved, the skills and resources needed, and the interactions with other operations (Ballard and Hamzeh 2007, 81). In practice, breakdown can take place earlier than week 3.

Two weeks ahead of execution (referred to as WK2): tasks at this time will match the level of detail required for production (pebbles) as shown in Figure 1, i.e., they will be expressed as tasks to be performed by specific work crews. Some of the broken pebbles are constraint-free and thus ready for execution whereas others remain constrained. Those that are constrained should be made ready by identifying and removing constraints. This includes making all prerequisites required for task execution available including: previous work, information, human resources, material, equipment, space, and external conditions. Although the model assumes that the majority of constraints are removed between week 2 and week 1, some constraints can be removed earlier and others are removed later on during the execution week. Tasks that are Ready (constraint-free) join the workable backlog (a backlog of workable / constraint-free tasks).

By the end of this period a certain percentage of the tasks are made ready. This percentage is called R. The rest of the tasks (1-R) are not ready. Not-Ready tasks that have the chance to be made ready in the upcoming week are kept in the pool (this percentage is P), the rest (Not-Ready and cannot be made ready or 1-P) are culled out. They will be considered for analysis in the next cycle, one week from now as shown in Figure 1.

The final step to be performed at this stage is the "shielding" step, involving protecting downstream tasks from variability in upstream tasks. It involves analyzing tasks and placing them on the Weekly Work Plan (WWP) if capacity permits or on the fallback / follow-on list (to be performed in case of extra capacity during the week). Since the team's capacity can only accommodate a certain task load, the shielding process prioritizes those tasks selected to go on the WWP as follows: (1) the first tasks to go on the WWP are those that are both critical and ready, (2) if capacity permits, critical and Not-Ready (but can be made ready) tasks go next, (3) non-critical and ready tasks go last if capacity permits; otherwise they are put on the fall-back / follow-on list.

One week ahead of execution (referred to as WWP): At this stage, a provisional weekly work plan is prepared from (WK2) gauging tasks against certain quality criteria of a) definition (do these tasks have a well-defined scope), b) soundness (are they constrained?), c) sequence (are they in proper sequence?), d)

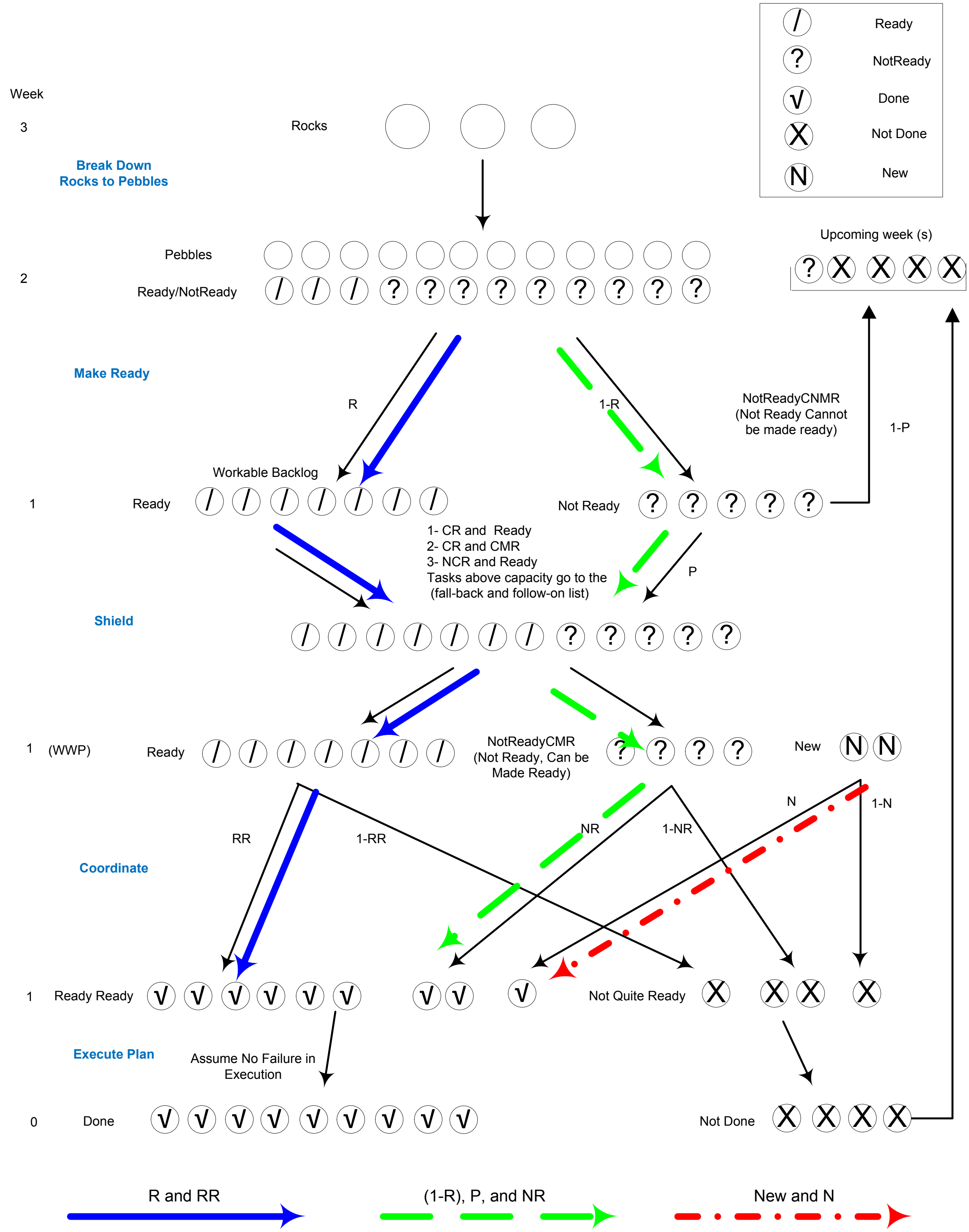

Figure 1: The three possible paths to increasing PPC (adapted from Hamzeh 2009)

size (is the amount of task matched by enough capacity?), and e) learning (are metrics tracked to monitor and improve performance?). Tasks that are critical, made ready, or can be made ready in the upcoming week are incorporated in the weekly work plan within available capacity. Made ready and non-critical tasks are placed on the fall back / follow on work list to be performed in case of extra capacity, either from completing critical tasks sooner than expected, or from discovering a constraint that cannot be removed in the plan period. In addition, a certain number of new tasks (New) that have not been broken down from rocks or boulders are introduced in this stage to cater for tasks that were not thought of before.

The last step of the process is During *Execution Week* where a percentage of Ready Ready tasks (RR) is executed and moved to the Done pile as shown in Figure 1. The rest of these activities (1-RR) are actually constrained and cannot be executed due to constraints that were neither discovered in the previous week nor removed during the execution week. Hence, these tasks join the Not Done pile. For tasks that were Not Ready at the beginning of execution week coordination is very crucial to remove constraints (i.e., make sure all prerequisites are available). A certain percentage of those Not-Ready tasks (NR) will be made ready and executed. Thus, they will join the Done pile. The remaining (1-NR) Not-Ready tasks will remain constrained, not be executed, and join the Not Done pile. Furthermore, a certain percentage of the New tasks (N) will be made ready, be executed, and join the Done pile. The remaining percentage (1-N) of tasks will be constrained, not executed, and join the Not Done pile. At the end of the week, PPC is calculated by dividing the number of executed tasks, i.e., those in the Done pile over the total number of tasks planned (i.e., Done + Not Done). Tasks in the Not Done pile will be candidates to join next week's weekly work plan.

The whole lookahead planning process mentioned above will be repeated on the project until all the tasks on the project are complete.

3.2 Graphical Model

A mathematical model was first built to represent the process shown in Figure 1. The model tracks pebbles between week 3 and the execution week. It takes into account all rework tasks that have to go in again and pass the shielding process, weekly work planning, and weekly execution. This mathematical model was then reconstructed using SIGMA in a discrete event simulation environment. Figure 2 shows the graphical model built in SIGMA to simulate the process shown in Figure 1. This model is a surrogate of the real system used in a simulation environment to analyze a system and provides insights into its performance and limitations.

However, the model also incorporates some assumptions including: (1) 40 rocks (i.e., activities on the process level such as construct walls, columns, etc.) are introduced each week. These rocks are then divided into pebbles. Each rock is divided into a certain number of pebbles that range between 2 and 4. It is represented stochastically in the model as equal to (2 + 2 * RND) where RND is a randomly generated number between 0 and 1; (2) Capacity constraints are not considered, all tasks passing the "Shield" step make it to the weekly work plan and no tasks go on the fall-back / follow-on list; and (3) There is no priority when executing activities.

3.3 Simulation Experiment

The goal of this simulation is to study the relationship between increasing tasks TA in lookahead planning on the performance on weekly work planning measured in terms of PPC. The hypothesis underlying this research is "increasing TA will increase PPC and improve the project performance". To setup experiments to analyze this hypothesis, the authors looked at the three different paths to increasing PPC. These three paths are shown with the blue, green, and red arrows in Figure 1. However, one path corresponds with an increased TA, which is the path through the solid arrows.

TA measures the performance of the planning team in anticipating tasks that should go on the weekly work plan two weeks ahead of execution. It is a measure of successful comprehensive task breakdown, and operations design. Referring to Figure 1, TA can be calculated as the total number of pebbles at

WK2 to the total number of pebbles on the WWP, i.e., TA = (Total Pebbles at WK2 **-** Not Ready that cannot be made ready)/ (Total Pebbles at WK2 **-** Not Ready that cannot be made ready + New (tasks added to the WWP that were not on the lookahead schedule).

One method to increase TA is to increase R, which is the percentage of tasks that are ready two weeks ahead of execution. Although increasing R will slightly impact the increase of TA, this scenario was used to study the impact of increasing TA on PPC. Consequently, the experiment used the following parameters:

- The project has 2080 *Rocks* (general tasks in the form of processes).
- Each rock is broken down into 2 to 4 *Pebbles* (tasks detailed to the level of production crews).
- *P,* the percentage of Not-Ready tasks that can be made ready is 0.3.
- *RR,* the percentage of Ready tasks that are actually unconstrained is 0.85.
- *NR,* the percentage of Not-Ready tasks that will be made ready during the execution week is 0.6.
- *New*, number of tasks added to the weekly work plan from outside the lookahead plan is 40 tasks per week.
- *N,* the percentage of *New* tasks the can be made ready during the execution week is 0.5.
- *R,* the percentage of *Pebbles* that are made ready two weeks ahead of execution is varied between 0.1 and 0.9.
- *TA*, *PPC*, and the number of weeks required to finish the project are outputs of the model.

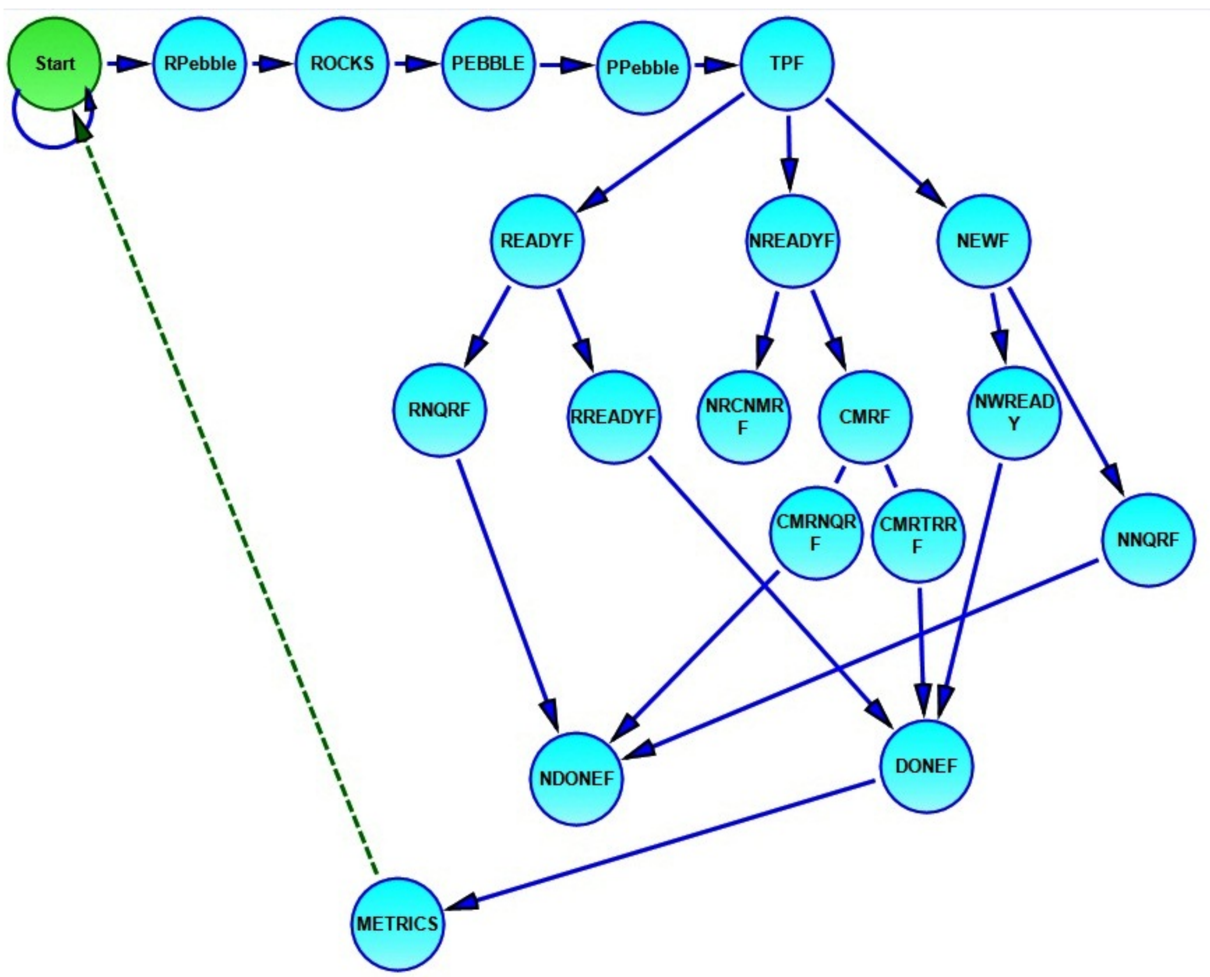

Figure 2: A graphical model in SIGMA simulating the lookahead process shown in Figure 1

4 SIMULATION RESULTS

Using the parameters mentioned above, nine experiments (varying R between 0.1 and 0.9) are run each 100 times. For each run, TA and PPC are measured on a weekly basis for the whole duration of the project and an average TA and PPC number for the whole project is calculated. An average TA and PPC for the 100 runs is then calculated and reported. Table 1 shows results for TA and PPC averaged over all the project weeks and over 100 runs.

Table 1 also shows an average duration for the project over 100 runs rounded for a full week. Standard deviations for TA and PPC over 100 runs are also reported. Each experiment was run 100 times to reduce the impact of 'warm-up' effects at the beginning of the project and the 'close down' effects at the end of the project. The standard deviation figures show consistency in the results.

Table 1: TA, PPC, and Completion Weeks' results for nine experiments each run 100 times

R	TA Avg.	St. Dev.	PPC Avg.	St. Dev.	Avg. Completion Weeks
0.1	0.741	0.048	0.623	0.009	74
0.2	0.743	0.043	0.658	0.009	68
0.3	0.745	0.039	0.683	0.010	65
0.4	0.746	0.037	0.702	0.010	63
0.5	0.746	0.036	0.717	0.011	61
0.6	0.747	0.036	0.729	0.011	60
0.7	0.747	0.036	0.739	0.012	59
0.8	0.747	0.038	0.747	0.013	58
0.9	0.746	0.040	0.754	0.014	57

Figure 3 shows results of TA and PPC for the nine experiments. The results indicate an increase in TA with the increase of R which means that improving the way project teams plan their tasks make them ready is related to tasks anticipation and breakdown. Results also show an increase in PPC when increasing TA even if that increase is small. This means investing in lookahead planning can pay dividends in terms of task completion.

Although Figure 3 shows a slightly positive impact of increasing TA on PPC (correlation is 0.94), Figure 4 sheds a new light on this relationship. While the correlation between TA and PPC is 0.94 which is quite high, the fact that the curve drops down after reaching a certain TA level indicate diminishing returns for increasing TA beyond a certain limit. This result indicates that successfully anticipating tasks on the lookahead plan might not be enough on its own to ensure a high PPC result.

In addition to increasing PPC, the results of the experiments show an overall project improvement. Figure 5 shows a decrease in project completion duration when increasing TA and PPC. Improving lookahead planning by increasing task anticipation (TA) and the percentage of tasks made ready two weeks ahead of execution (R) produced positive results in terms of weekly task completion PPC and overall project completion duration. The results also show diminishing returns for improving the performance of lookahead planning.

5 RECOMMENDATIONS AND FURTHER RESEARCH

This paper presented a simulation model built to study the relationship between TA and PPC. The results indicate that increasing TA by improving the team's ability to plan and design tasks for execution can have a positive influence on improving task execution or PPC. While TA expresses foresight in anticipating tasks and identifying constraints, establishing foresight is only one part of lookahead planning. The other important aspect is making tasks ready by removing constraints. This other aspect is measure by an-other metric called Task Made Ready (TMR). Further research is required to incorporate TMR and study its impact on PPC and overall project performance.

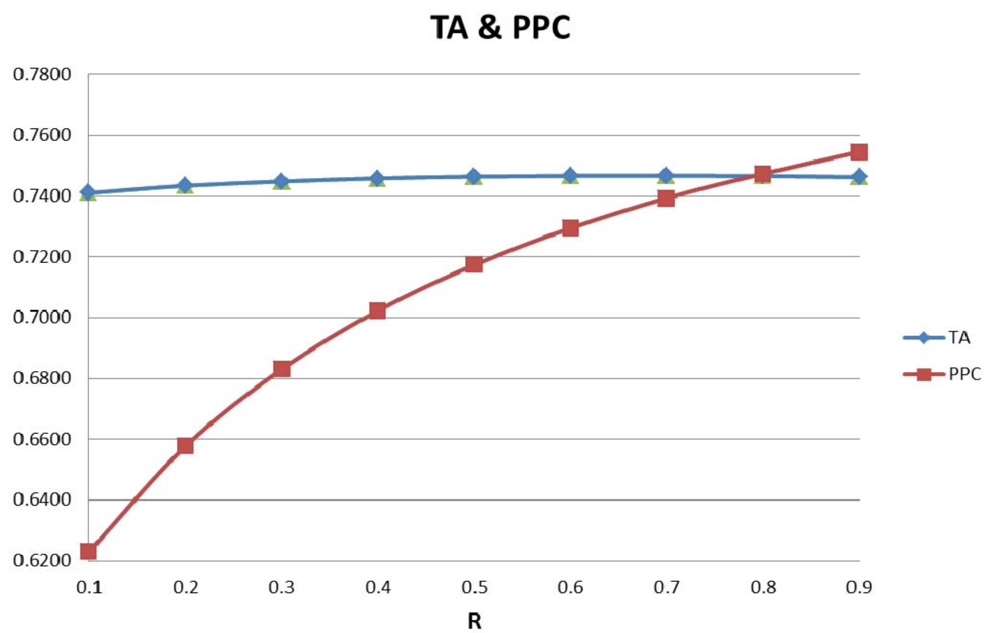

Figure 3: TA and PPC project results for nine experiments varying R between 0.1 and 0.9

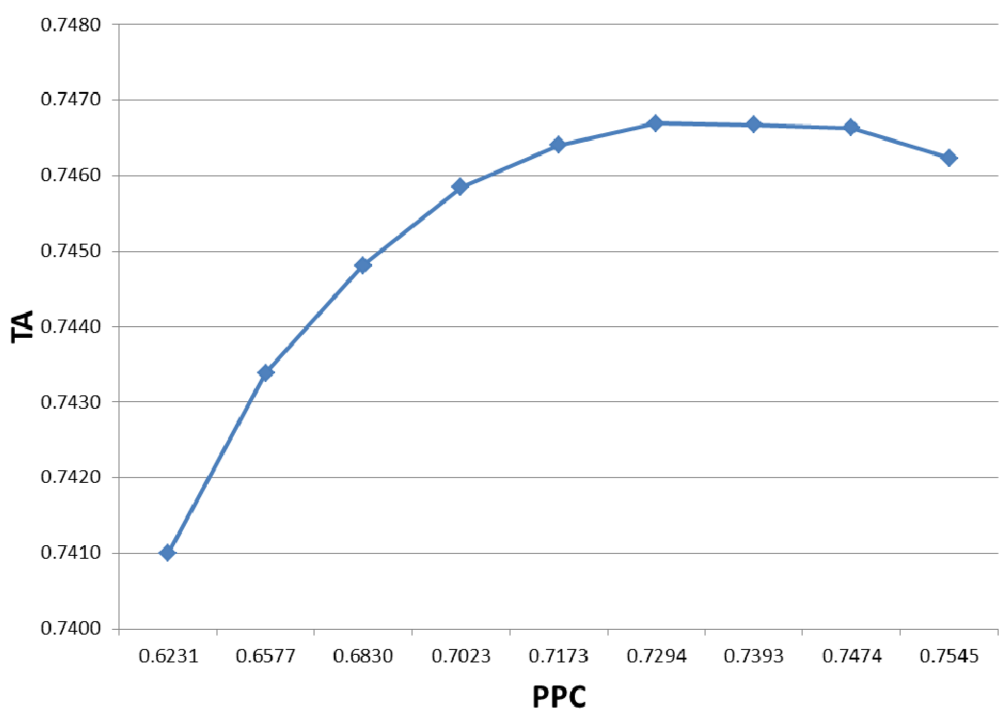

Figure 4: TA and PPC project results for nine experiments

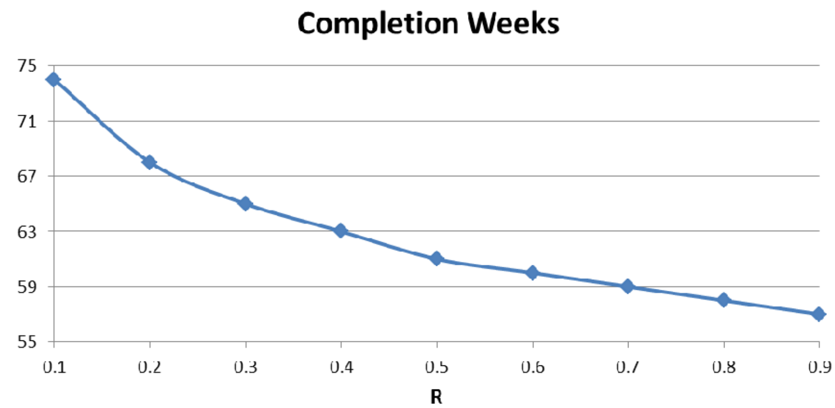

Figure 5: Completion Weeks for nine experiments varying R between 0.1 and 0.9

The study results show that even a small change in TA may have an impact on PPC. More research is required before confirming the hypotheses that increasing TA will increase PPC. This would require running more future experiments and changing parameters such as N and New. While this paper presents preliminary results, performing more experiments can help solidify the conclusions and better describe the relationship between TA and PPC.

The results shown in Figure 4 suggest that there are limitations to team planning. The diminishing returns suggest that extreme investments in planning will fail to pay proper dividends when it comes to task execution. However, the authors believe that the construction industry is still falling far behind that frontier and can enjoy the benefits of improving lookahead planning by finishing projects earlier and may be cheaper.

The results shown in this study will be useful to construction planners, superintendents, and managers. However, the results can be further emphasized and validated if they can be reproduced experimentally on a construction project. The results coming out of this study are exploratory results that can help support the hypothesis that increasing TA can increase PPC. However, future experiments on construction projects are required to accept the hypothesis. The authors are exploring those opportunities on two current construction projects and hope to successfully design and implement experiments similar to emulate those presented in this paper.

REFERENCES

Abourizk, S. M., and S. P. Dozzi. 1993. "Application of Computer-Simulation in Resolving Construction Disputes." *Journal of Construction Engineering and Management-ASCE* 119(2):355-373.

Alarcón, L. F., and D. B. Ashley. 1999. "Playing Games: Evaluating the Impact of Lean production Strategies on Project Cost and Schedule." In *Proceeding of the 7th Annual Conference of the International Group for Lean Construction*, edited by I. Tommelein, 263-274. University of California, Berkeley, CA, USA.

Alves, T. d. C. L., I. D. Tommelein, and G. Ballard. 2006. "Simulation as a Tool for Production System Design in Construction." In *Proceedings of the 14th Annual Conference of the International Group for Lean Construction*, edited by L. Alarcon, 341-353. Santiago, Chile.

Axelrod, R. 2006. "Advancing the Art of Simulation in the Social Sciences." In *Handbook of Research on Nature Inspired Computing for Economy and Management,* edited by J.-P. Rennard, 90-100. Hershey, PA: Idea Group.

Ballard, G. 1997. "Lookahead Planning: The Missing Link in Production Control." In *Proc. 5th Annual Conf. Int'l. Group for Lean Constr., IGLC 5*, edited by L. Alarcon, 13-26. Gold Coast, Australia.

Ballard, G. 2000. "The Last Planner System of Production Control." Ph.D. Dissertation, Faculty of Engineering, School of Civil Engineering, The University of Birmingham, UK.

Ballard, G., and F. R. Hamzeh. 2007. *The Last Planner Production Workbook- Improving Reliability in Planning and Workflow*. 2nd Edition. San Francisco, California: Lean Construction Institute.

Ballard, G., and G. Howell. 2003. "An Update on Last Planner." *Proc. 11th Annual Conf. Intl. Group for Lean Construction*, edited by J. Martinez. Blacksburg, Virginia, USA.

Dooley, K. 2002. "Simulation Research Methods." In *Companion to Organizations*, edited by J. Baum, 829-848. London, UK: Blackwell.

Draper, J. D., and J. Martinez. 2002. "The Evaluation of Alternative Production System Designs with Discrete Event Simulation." In *Proceedings of the 10th Annual Conference of the International Group for Lean Construction*, edited by C. Fromoso and G. Ballard. Gramado, Brazil.

Hamzeh, F.R. 2011. "The Lean Journey: Implementing the Last Planner System in Construction." In *Proceedings of the 19th Annual Conference of the International Group for Lean Construction (IGLC 19)*, edited by J. Rooke and B. Dave, 379-390. Lima, Peru.

Hamzeh, F. R. 2009. "Improving Construction Workflow – The Role of Production Planning and Control." PhD Dissertation, University of California at Berkeley, Berkeley, CA.

Hamzeh, F. R., G. Ballard, and I. D. Tommelein. 2008. "Improving Construction Workflow- The Connective Role of Lookahead Planning." In *Proceedings of the 16th Annual Conference of the International Group for Lean Construction (IGLC 16)*, edited by P. Tzortzopoulos and M. Kagioglou, 635-646. Manchester, UK, 16-18 July.

Hamzeh, F. R., I. D. Tommelein, G. Ballard, and P. Kaminsky. 2007. "Logistics Centers to Support Project-Based Production in the Construction Industry", In *Proceedings of the 15th Annual Conference of the International Group for Lean Construction (IGLC 15)*, edited by C. Pasquire and P. Tzortzopoulos, 181-191. East Lansing, Michigan, USA, 18-20 July.

Huang, R. Y., J.-J. Chen, and K. S. Sun. 2004. "Planning Gang Formwork Operations for Building Construction Using Simulations." *Automation in Construction* 13(6):765-779.

Liu, J. J., and W.-C. Wang. 2009. "Simulation-Based Scheduling Model for Multiple Design Projects." In *Proceedings of the 17th Annual Conference of the International Group for Lean Construction*, edited by Y. Cuperus and E. H. Hirota, 523-532. Taipei, Taiwan.

Martinez, J. C., and P. G. Ioannou. 1999. "General-Purpose Systems for Effective Construction Simulation." *Journal of Construction Engineering and Management-ASCE* 125(4):265-276.

Schramm, F. K., G. L. Silveira, H. Paez, H. Mesa, C. T. Formoso, and D. Echeverry. 2007. "Using Discrete-Event Simulation to Support Decision-Makers in Production System Design and Operations." In *Proceedings of the 15th Annual Conference of the International Group for Lean Construction*, edited by T. Abdelhamid, 131-141. Michigan, USA.

Schruben, D. L., and L. W. Schruben. 2005. *Event Graph Modeling: Using Sigma*. 5th Edition. Berkeley, CA: Custom Simulations.

Shi, J. J. 1999. "Computer Simulation in AEC and its Future Development." In *Stanford Construction Engineering and Management Workshop*. Stanford University, Standford, CA.

Srisuwanrat, C., and P. G. Ioannou. 2007. "The Investigation of Lead-Time Buffering Under Uncertainty using Simulation and Cost Optimization." In *Proceedings of the 15th Annual Conference of the International Group for Lean Construction*, edited by C. Pasquire and P. Tzortzopoulos, 580-589. Michigan, USA.

Tommelein, I. D. 1997. "Discrete-Event Simulation of Lean Construction Processes." In *Proceedings of the 5th Annual Conference of the International Group for Lean Construction*, edited by L. Alarcon, 121-136.

Tommelein, I. D. 1998. "Pull-driven Scheduling for Pipe-spool installation: Simulation of a Lean Construction Technique." *Journal of Construction Engineering and Management-ASCE* 124(4):279-288.

Tommelein, I. D., and G. Ballard. 1997. "Look-ahead Planning: Screening and Pulling." *Technical Report No. 97-9,* Construction Engineering and Management Program, Civil and Environmental Engineering Department, University of California, Berkeley, CA, USA.

Vanegas, J. A., E. B. Bravo, and D. W. Halpin, D. W. 1993. "Simulation Technologies for Planning Heavy Construction Processes." *Journal of Construction Engineering and Management-ASCE* 119(2):336-354.

Wales, R. J., and S. M. AbouRizk, S. M. (1996). "An Integrated Simulation Model for Construction." *Simulation Practice and Theory* 3(6):401-420.

AUTHOR BIOGRAPHIES

FAROOK HAMZEH is an Assistant Professor at the Department of Construction Management, Colorado State University. Before moving to academia, he worked for more than seven years on heavy civil, building construction, high rise, historical renovation, health care, and industrial projects in California, Dubai, Qatar, and Lebanon. He earned his Ph.D. in Civil and Environmental Engineering with an emphasis on Engineering Project Management from the University of California, Berkeley. He has a Master's degree in Engineering Management and a Bachelor's degree in Civil Engineering from the American University of Beirut. His research interests include lean construction, productivity improvement, and production planning. His email address is fh35@aub.edu.lb.

BRANDON LANGERUD is originally from Devils Lake, North Dakota. He received his undergraduate degree in Construction Management from North Dakota State University. He has a degree from the Community College of the Air Force (CCAF) in aircraft maintenance technology. Brandon has worked primarily in the residential construction and remodeling industry within the Fargo-Moorhead, ND region. He is a veteran of the ND Air National Guard where he served as an Aircraft Maintenance Crew Chief for the F-16 and C-21 aircraft. Brandon's research interests include lean construction methods and construction organizational learning. His e-mail address is blangeru@lamar.colostate.edu.