ABSTRACT

WANG, CHAO. Causes and Penalties of Variation – A Case Study of a Concrete Slab Prefabrication Shop. (Under the direction of Min Liu and Simon M. Hsiang).

With the current downturn in the economy, the precast concrete components fabricator is under constant pressure from both upstream and downstream clients. It is challenging for concrete prefabricators to reach the goal of producing made-to-order concrete products that can be delivered to a site when needed. One major barrier to the above goal is the variation in task starting time (the difference between the planned and the actual starting time) and the variation in task duration (the difference between the planned and the actual task duration). Based on a concrete slab prefabrication operation, two research questions were raised: 1) What are the causes of variation in task starting time and duration? 2) What are the penalties of not reducing variation? This study found that the top three causes of task starting time variation are prerequisite work, tools/equipment and labor force. The top three causes of task duration variation are tools/equipment, detailed design/working method and materials/components. The penalties associated with not reducing variation are increase in project duration, Work in Progress (WIP) and decrease in labor productivity. Additionally, two execution policies in the face of variation (keeping laborers waiting and keeping laborers busy) were simulated and compared. The results show that keeping busy under this model set up is not the best option if the task accelerated is not on the critical path of the schedule.
Causes and Penalties of Variation – A Case Study of a Concrete Slab Prefabrication Shop

by
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Committee Chair
BIOGRAPHY

Chao Wang was born and grew up in Nanjing, Jiangsu, People’s Republic of China. He received his Bachelor of Management and Master of Management degrees from the Southeast University, Nanjing in August 2004 and May 2008 respectively. Both degrees were in Construction Engineering and Management. In August of 2008, he enrolled in the Construction Engineering and Management program in the Department of Civil, Construction, and Environmental Engineering at North Carolina State University. Given the opportunity to expand his knowledge in construction engineering, he became engaged in a research project with Dr. Min Liu and Dr. Simon M. Hsiang involving lean construction and construction productivity, which resulted in the thesis presented here.
ACKNOWLEDGMENTS

I would like to thank my parents for instilling in me the value of an education, the importance of hard work, and an appreciation for life’s experiences. Thank you very much for all your help both in and out of school.

To my committee, Dr. Min Liu, Dr. Simon M. Hsiang and Dr. Michael L. Leming, thank you for the time and effort you have devoted to make this thesis possible. I would especially like to express my gratitude to Dr. Liu and Dr. Hsiang for guiding me through the whole process.

To Gate Precast, thank you for offering me the opportunity to conduct the field study in the concrete slab prefabrication shop. I would also like to thank Mark Fulcher (Project Manager), Kelvin Downey (Hollow Core Supervisor) and Sammy Roberts (Foreman) for their valuable inputs and comments of my research.

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TABLE OF CONTENTS

LIST OF TABLES........................................................................................................... vii

LIST OF FIGURES ........................................................................................................ ix

1 INTRODUCTION ........................................................................................................ 1

1.1 Background ............................................................................................................. 1

1.2 Problem Statement ................................................................................................. 1

1.3 Research Objectives ............................................................................................... 3

1.4 Research Significance ............................................................................................ 3

2 LITERATURE REVIEW ............................................................................................... 4

2.1 Introduction ............................................................................................................. 4

2.2 Variation, Variance, and Variability ....................................................................... 5

2.3 Factors affecting productivity ................................................................................. 6

2.4 Impact and Penalty of Variation ............................................................................. 11

2.5 Strategies to Reduce Variation and Improve Performance ..................................... 12

3 METHODOLOGY ...................................................................................................... 15

3.1 Research Design .................................................................................................... 15

3.2 Case Study ............................................................................................................. 15

3.2.1 Hypotheses ....................................................................................................... 17

3.2.2 Observation Form Design ................................................................................ 17
3.2.3 Simulation design ........................................................................................................... 20

4 CASE STUDY .......................................................................................................................... 24

4.1 Project Background ............................................................................................................... 24
  4.1.1 Prestressed Hollow Core Slab Fabrication Process ....................................................... 24
  4.1.2 Fabrication Shop Layout .............................................................................................. 31
  4.1.3 Schedule ....................................................................................................................... 32
  4.1.4 Product Mix .................................................................................................................. 36

4.2 Data Analysis ...................................................................................................................... 39
  4.2.1 Starting Time and Duration Variation ............................................................................ 39
  4.2.2 Causes of Starting Time and Duration Variation ............................................................ 40
  4.2.3 Productivity and Variation ............................................................................................ 42
  4.2.4 5-Why Analysis .......................................................................................................... 45

4.3 SIMULATION ..................................................................................................................... 50
  4.3.1 Simulation Model Development ..................................................................................... 50
  4.3.2 Model Input .................................................................................................................. 59
  4.3.3 Different Experiments and Data Analysis .................................................................... 60
  4.3.4 Discussion .................................................................................................................... 64

5 CONCLUSIONS AND RECOMMENDATIONS ...................................................................... 71

5.1 Conclusions ....................................................................................................................... 71

5.2 Recommendations for Future Research ............................................................................ 72
REFERENCES .................................................................................................................. 73

APPENDICES ................................................................................................................ 77

Appendix A Data Collection Sheets ................................................................................. 78

Appendix B Stroboscope Simulation Code .................................................................... 87
LIST OF TABLES

Table 2.1  Literature Review Summary for Variation, Variance and Variability .................... 7
Table 3.1  Observation Form Design 1 .................................................................................. 18
Table 3.2  Observation Form Design 2 .................................................................................. 18
Table 3.3  Observation Form Design 3 .................................................................................. 18
Table 3.4  Observation Form Design 4 .................................................................................. 18
Table 3.5  Variation Causes Coding ...................................................................................... 22
Table 4.1  Task Summary ........................................................................................................ 30
Table 4.2  Slab Product Mix .................................................................................................... 36
Table 4.3  Design/Work Complexity Level of Cutting Slabs ..................................................... 37
Table 4.4  Major Causes of Variation in Task Starting Time ...................................................... 41
Table 4.5  Major Causes of Variation in Task Duration .............................................................. 41
Table 4.6  Daily Productivity .................................................................................................... 43
Table 4.7  Cut & Remove Productivity vs. Complexity Level ..................................................... 44
Table 4.8  Simulation Scenarios ............................................................................................... 52
Table 4.9  Selected Stroboscope Symbols (Martinez 1996) ....................................................... 54
Table 4.10 Task Duration Distribution Based on Least Square Error Criterion ....................... 60
Table 4.11 Task Duration Distribution (α=0.1) ....................................................................... 60
Table 4.12 Simulation Results (1000 Iterations) ...................................................................... 61
Table 4.13 MANOVA Test Result (α=0.05) ............................................................................. 61
Table 4.14  P-Value for T-test Between Duration (α=0.05) ............................................................... 62
Table 4.15  P-Value for T-test Between WIP (α=0.05) .................................................................... 62
Table 4.16  Task Deterministic Duration.......................................................................................... 64
Table 4.17  Task Total Float and Free Float .................................................................................. 65
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Literature Review</td>
<td>4</td>
</tr>
<tr>
<td>2.2</td>
<td>Last Planner System (Ballard 2003)</td>
<td>14</td>
</tr>
<tr>
<td>3.1</td>
<td>Research Design</td>
<td>16</td>
</tr>
<tr>
<td>4.1</td>
<td>Prestressed Hollow-Core Slab Fabrication Process</td>
<td>25</td>
</tr>
<tr>
<td>4.2</td>
<td>Cleaning Bed</td>
<td>26</td>
</tr>
<tr>
<td>4.3</td>
<td>Pulling Strands</td>
<td>26</td>
</tr>
<tr>
<td>4.4</td>
<td>Extruder Being Loaded with Concrete</td>
<td>26</td>
</tr>
<tr>
<td>4.5</td>
<td>Slabs Being Cut</td>
<td>27</td>
</tr>
<tr>
<td>4.6</td>
<td>Slab Being Removed for QC</td>
<td>28</td>
</tr>
<tr>
<td>4.7</td>
<td>Slabs in the QC and Pick-up Area</td>
<td>28</td>
</tr>
<tr>
<td>4.8</td>
<td>Local Storage Yard</td>
<td>29</td>
</tr>
<tr>
<td>4.9</td>
<td>Hollow-Core Slab Fabrication Shop Layout</td>
<td>31</td>
</tr>
<tr>
<td>4.10</td>
<td>Production Schedule</td>
<td>38</td>
</tr>
<tr>
<td>4.11</td>
<td>Cumulative Duration Variation</td>
<td>39</td>
</tr>
<tr>
<td>4.12</td>
<td>Cumulative Starting Time Variation</td>
<td>40</td>
</tr>
<tr>
<td>4.13</td>
<td>Cut &amp; Remove Productivity Based on Beds</td>
<td>45</td>
</tr>
<tr>
<td>4.14</td>
<td>Stroboscope Simulation Model (Scenario 1)</td>
<td>55</td>
</tr>
<tr>
<td>4.15</td>
<td>Stroboscope Simulation Model (Scenario 2, 3, 4)</td>
<td>56</td>
</tr>
<tr>
<td>4.16</td>
<td>Stroboscope Simulation Model (Scenario 5, 6, 7)</td>
<td>57</td>
</tr>
</tbody>
</table>
Figure 4.17  Stroboscope Simulation Model (Scenario 8).......................................................... 58
Figure 4.18  Activity-on-Node (Normal Schedule without Equipment Breakdown).......... 69
Figure 4.19  Gantt Chart (Normal Schedule without Equipment Breakdown...................... 70
1 INTRODUCTION

1.1 Background

Construction precast elements are made at a centralized facility and then transported to the site to be assembled in the facility being constructed. Precast concrete elements offer significant potential advantages in cost, speed of erection, and quality. It is challenging for concrete prefabricators to produce made-to-order concrete products that can be delivered to a site as needed. Concrete prefabricators need to work collaboratively with designer and installer in details, regarding dimensions, material, and structure strength requirements. With the current downturn in the economy, the industry is under constant pressure from both upstream and downstream clients to design fabrication line efficiently with restricted material and labor costs, to fabricate at the last possible moment to maintain business and avoid waste due to change orders, and to make and deliver just-in-time (JIT) to minimize storage and handling costs.

1.2 Problem Statement

In order to reach the above goals, a major challenge that a concrete prefabricator faces is handling variation during the fabrication process in the job shop. In this research, variation is defined as 1) variation in task starting time – the difference between the planned and the actual starting time, and 2) variation in task duration – the difference between the planned and the actual task duration. In reality, many factors (i.e., the late arrival of material, tools or equipment, change orders) contribute to the task starting time variation and duration
variation. These factors may cause the labor force to wait for resources or lead to staging of materials or partially completed products, either of which can generate huge waste and ultimately undermine production performance. Due to the detrimental impact of variation on production performance (Hopp and Spearman 2008, Tommelein 1999), Ballard et al. (2003) argued the first line of defense advocated by lean construction is to reduce variation in an effort to reduce waste and ultimately increase production performance. Little research has been conducted into the causes of variation in construction. Thomas et al. (2002), studied the impacts of work flow variability on daily construction productivity, they concluded that variability in labor productivity is closely correlated to project performance and that reducing variability of daily productivity could improve project performance. They associated variability with categories including sequencing, congestion, weather and rework, but did not further explore these categories to identify the causes of variation. The lack of in-depth understanding of the causes of variation and its impact on production performance result in difficulty in variation control, unreliable construction work plans, and decreased production performance. The existing gap in knowledge is the lack of in-depth understanding of the causes of variation and its impact on production performance. The research questions are: 1) what are the causes of variation? and 2) what are the penalties of not reducing variation? Since variation or variability comes in many forms and types, making the production system very complicated, it is important to define a reasonable research scope. My research focused on the fabrication process in the prefabricator’s job shop and investigated the causes of variation and penalties associated with not reducing variation.
1.3 Research Objectives

Based on the above research questions, the objectives of this study are:

1. Determine the causes of variation in starting time and duration of concrete slab prefabrication tasks based on field observation.
2. Determine penalties associated with not reducing variation.
3. Simulate and compare different execution policies in the face of variation.

1.4 Research Significance

In-depth understanding of the causes of variation during the fabrication process and penalties of not reducing variation can help prefabricators pinpoint the reasons why the work plans were disrupted and put efforts to control and remove the causes in order to provide better variation control, improve reliability of work plans, design execution policies in the face of variation and ultimately improve production performance. Although there is a significant amount of research on variation, there is minimal research directed at understanding the causes of variation and penalties of not reducing it. This gap in the construction related body of knowledge illustrates why this research is significant. In a broader perspective, this research could help prefabricators learn the importance of variation control and planning for performance improvement as opposed to focusing management effort on keeping workers and plant busy.
2 LITERATURE REVIEW

2.1 Introduction

This chapter reviews the relevant professional and research developments affecting this study (Figure 2.1). Section 2.2 and section 2.3 review variation definition and factors affecting productivity respectively. Then variation was defined and potential causes for variation were identified for this case study. Section 2.4 reviews impact and penalty of variation. Section 2.5 reviews strategies to reduce variation and improve performance.

![Diagram](Figure 2.1 Literature Review)
2.2 Variation, Variance, and Variability

Among the many definitions of variation, variance or variability, Rilett (1998) defined variability as the variance associated with a component or end product specification in construction projects. Tommelein et al. (1999) defined work flow variability as the standard deviation from an expected average. Radosavljevic and Horner (2002) defined variance in construction labor productivity as a standard deviation, a measure of dispersion from the mean. Thomas et al. (2002) calculated variation of productivity as the average of the absolute value of the difference between daily productivity and baseline productivity. Howell and Ballard (1994) measured variability of work flow by comparing the tasks assigned (what “will” be done), to those completed (what “did” get done). Koskela (2000) defined variability as the random variation in the processing times or arrival of inputs. Shen and Chua (2005) studied two types of variability, task duration and the availability of resource and information measured by estimated available time (EAT). To summarize, variation is deviation from target (what was planned), variance is deviation from expected, and variability could be either variation or variability. In this study, two types of variation for a construction prefabrication task are examined: 1) the variation in task starting time (the difference between the planned task starting time and the actual task starting time) and 2) the variation in task duration (the difference between the planned task duration and the actual task duration). This definition follows that used by Howell et al. (1998) as it breaks the variation of entire tasks into task staring time and duration. By measuring the time difference
of the starting time and duration, this definition allows more accurate and detailed observation and analysis of the causes of variation.

2.3 Factors affecting productivity

Little research was found that further explored categories to identify causes of variation directly in construction. Thomas et al. (2002) considered variability associated with congestion, sequencing, weather and rework when he studied the impacts of work flow variability on daily construction productivity. Walters et al. (2008) studied thickness of concrete pavement in three concrete paving projects in Iowa. They associated the thickness variability with different material used in the sub base. In order to develop a baseline of factors to consider when examining the causes of variation, literature pertaining to factors affecting construction productivity was reviewed. Rojas and Aramvareekul (2003) identified manpower experience and motivation, scheduling, adverse working conditions, and scope changes as the top factors affecting productivity. Liberda et al. (2003) found lack of detailed planning, inadequate supervision, and lack of information as the three factors that most significantly impacted productivity. Dai et al. (2009) investigated the impacts of 83 different productivity factors by surveying nearly 2000 craft workers nationwide. The factors which have the greatest impact on productivity from the craft workers’ perspective are materials, tools and consumables, engineering drawing management, and construction equipment. Kimpland (2009) divided the top factors into two categories; external and internal. Top external factors were poor quality of plans and specifications, slow responses to questions, unrealistic schedule demands from the customer, and lack of qualified foremen and
<table>
<thead>
<tr>
<th>Reference</th>
<th>Term</th>
<th>Definition</th>
<th>Key Findings</th>
<th>Recommendations</th>
</tr>
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<tbody>
<tr>
<td>Howell and Ballard</td>
<td>Variability</td>
<td>Not directly defined, implied to be the difference between tasks assigned (what “will” be done), and those completed (what “did” get done).</td>
<td>Work flow variation can be reduced by stabilizing all functions through which work flows from concept to completion.</td>
<td>Examine the causes of variation and penalties associated with not reducing variation.</td>
</tr>
<tr>
<td></td>
<td>Variation</td>
<td></td>
<td>Planning systems must be redesigned to include a level for adjusting “SHOULD”, so operations can better match “SHOULD” with “WILL”.</td>
<td></td>
</tr>
<tr>
<td>Rilett (1998)</td>
<td>Variability</td>
<td>The variance associated with a component or end product specification in construction projects</td>
<td>Field density (FD) has significantly higher variability associated with it when compared with the Marshall density (MD) data.</td>
<td>Determine a desirable and quantifiable variability levels for the density.</td>
</tr>
<tr>
<td></td>
<td>Variance</td>
<td></td>
<td>The compaction of the pavement was not as uniform as that of a standard Marshall test.</td>
<td>Examine how the variability associated with the end product specifications (EPS) tests would affect the EPS bonus/penalty schedule.</td>
</tr>
<tr>
<td>Tommelein et al. (1999)</td>
<td>Variability</td>
<td>Standard deviation from an expected average</td>
<td>Throughput will be reduced, project completion delayed, and waste increased by variations in flow.</td>
<td>Examine how we should control variation and create reliable workflow in construction industry</td>
</tr>
<tr>
<td>Authors</td>
<td>Variability</td>
<td>Description</td>
<td>Examples</td>
<td></td>
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<tr>
<td>-------------------------</td>
<td>-------------</td>
<td>------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------</td>
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<tr>
<td>Koskela (2000)</td>
<td>Variability</td>
<td>Random variation in the processing times or arrival of inputs</td>
<td>The transformation-flow-value (TFV) theory of production provides a new, theoretical foundation for construction. More work is needed to further articulate and validate the new foundation, and to develop methods and tools based on it.</td>
<td></td>
</tr>
<tr>
<td>Radosavljevic and Horner (2002)</td>
<td>Variance</td>
<td>Standard deviation - measure of dispersion ( \text{Variance} = S^2 )</td>
<td>Construction labor productivity is not normally distributed. The specific tasks associated with productivity data were not clearly mentioned (only formwork and masonry). Test whether chaos theory is applicable to the analysis of construction labor productivity.</td>
<td></td>
</tr>
<tr>
<td>Thomas et al. (2002)</td>
<td>Variation</td>
<td>( \overline{V} = \sqrt{\frac{\sum (\text{DailyValue} - \text{BaselineValue})^2}{n}} )</td>
<td>There is little correlation between output variability and project performance. Similarly, project waste index a good measurement of project performance. It is hard to know whether flexible capacity is better than improving work-flow reliability if we are not aware of what was planned and what the variations are.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Variability</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Study</td>
<td>Variability</td>
<td>Description</td>
<td>Actions</td>
<td></td>
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<td>---------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------</td>
<td></td>
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<tr>
<td>Horman and Thomas (2005)</td>
<td>Variability</td>
<td>Inventory buffers seem to be related to construction labor performance for the studied projects. Some buffers help achieve the best labor performance in the construction operations studied.</td>
<td>Study the causes of variation.</td>
<td></td>
</tr>
<tr>
<td>Kaplan et al. (2005)</td>
<td>Variability</td>
<td>Just in time model is preferred in the precast pile delivery with less inventory and less handling and storage costs.</td>
<td>Examine the impact of variability on execution and the costs and benefits for driving indicator piles. Analyze what and how much waste there is in current practice, and whether there are product alternatives on the market that are more in line with lean principles.</td>
<td></td>
</tr>
<tr>
<td>Shen and Chua (2005)</td>
<td>Variability</td>
<td>The existing of both types of variations, which represents the common practice in project implementation, usually have detrimental impacts on project performance measured by project duration, average task density, average Percent Plan Impacted (PPI), and average Percent Plan Completed (PPC). EAT related variability should not be ignored.</td>
<td>Examine the causes of variability, and how we should develop strategies for variability control.</td>
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Table 2.1 Continued

<table>
<thead>
<tr>
<th>Study</th>
<th>Type of Variation</th>
<th>Description</th>
<th>Further Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walters et al. (2008)</td>
<td>Variability</td>
<td>Sites that used larger aggregate for the base experienced higher thickness variances. A more suitable sub base model based on the top surface of the aggregate as opposed to an average will reduce the thickness variability. Laser scanning has proved to be a reliable technique in terms of its ability to provide virtual core thickness with low variability.</td>
<td>Further research on the use of lasers should include building a prototype system complete with coordinate control for each of the two scanners that would be needed.</td>
</tr>
<tr>
<td>Hallowell and Gambatese (2010)</td>
<td>Variation</td>
<td>Not directly defined, implied to be a difference from the standard process associated with the application of Delphi method in construction engineering and management (CEM) research. This paper provided CEM researchers with a standard methodology for implementing the Delphi method in rigorous studies intended for publication in journals.</td>
<td>Empirical study is needed to test the validity of the proposed standard methodology for Delphi method implementation in CEM research.</td>
</tr>
</tbody>
</table>
craft workers, while top internal factors involved lack of foreman planning and communication skills, cultural resistance to change, poor communication between foremen and project managers, and lack of technical training at the craft level. Classifying productivity factors provided a baseline of factors to consider when examine causes of variation. How these factors are categorized and tailored for this specific case study is discussed in the following Methodology section.

2.4 Impact and Penalty of Variation

Regarding the impact and penalty of variation, Hopp and Spearman (2008) noted increasing variability always degrades the performance of a production system. Increasing variability impacts the system along three general dimensions: inventory, capacity and time. Higher variability of any sort must harm some measure of performance. In the construction arena, Tommelein et al. (1999) presented a parade game to demonstrate the impact of work flow variability on a single-line production system, which revealed that: (1) throughput will be reduced, project completion delayed, and waste increased by variations in flow, and (2) unreliable work flow results in unutilized production capacity and larger intermediate buffers when high variability prevails. Thomas et al. (2002) compared the impacts of output variability and variability in labor productivity with project performance. The results showed that there is little correlation between output variability and project performance, but that variability in labor productivity is closely correlated to project performance. Liu and Ballard (2008) showed that work flow reliability measured by Percent Plan Complete (PPC) and labor productivity are significantly correlated in the pipe installation project and reducing
work flow variation can help improve labor productivity. No previous research investigated penalties of not reducing variation in the construction prefabrication job shop context. Previous research provided measurements (i.e., throughput, project completion, intermediate buffer) of production system performance for reference. In this research, production system performance is measured by project duration, WIP and labor productivity, and the penalties associated with not reducing variation in concrete prefabrication job shop are studied.

2.5 Strategies to Reduce Variation and Improve Performance

Extensive research has been conducted in reference to the planning strategies to reduce and shield variation, Hopp and Spearman (2008) noted that variability can be buffered by some combination of inventory, capacity and time. Ballard and Howell (1998) reported shielding production from uncertainties is essential, and it can increase productivity up to 30% when higher PPC is achieved. They developed the Last Planner™ System (LPS) focusing on reducing the negative impacts of variability and increasing reliability of workflow. The LPS (Figure 2.2) embodies the following planning practices: (1) planning in greater detail as you get closer to performing the work, (2) developing the work plan with those who are going to perform the work, (3) identifying and removing work constraints ahead of time, as a team, in order to make work ready and increase reliability of work plans, (4) making reliable promises and driving work execution based on coordination and active negotiation with trade partners and project parties, and (5) learning from planning failures by finding the root causes and taking preventive actions (Hamzeh 2009). This system has been successfully implemented on construction projects to improve planning and production performance (Ballard 2000,
Ballard and Howell 2003). Chua et al. (2003) argued project delays due to late availabilities of resource and information prerequisites are one of the major threats to construction management. They proposed a constraint based planning which facilitates identifying and removing constraints from bottleneck activities to reduce uncertainties in construction processes.

Previous research mainly focused on the project planning process to reduce variation and improve project production performance. Little research explored the execution process. Variation is inevitable in reality. When variation occurs, laborers may stop working to wait until the negative effects are remedied, which results in both production and productivity loss. Under this situation, according to common sense, in order to keep the laborers busy, the management may prefer to reallocate the laborers to whatever tasks are being executed or ready to start. However, keeping laborers busy may not be the best option in the face of variability. This study utilized simulation to address this issue.
Figure 2.2 Last Planner System (Ballard 2003)
3 METHODOLOGY

3.1 Research Design

This research utilizes case study and simulation methods to meet the research objectives. Figure 3.1 illustrates the design of this research.

3.2 Case Study

A prestressed hollow core slab prefabrication plant was chosen for the case study because an off-site concrete slab manufacturing system is a typical production system in the construction prefabrication domain. The prefabrication plant was visited, the project manager interviewed and the Stroboscope (Martinez 1996) simulation model designed accordingly. The simulation parameters are based on the initial in-situ observations and the project manager’s interviews. Detailed data collection sheets were tailored for the second site visit, which covered a period of 7 days. The data sheets focused on detailed information including site layout, production planning, actual and planned task starting time and task duration, records of the causes and consequence of the variations, and when and how the production problems are resolved. The data collected during the second site visit was used for analysis of causes of variation on task starting time and duration, and as inputs for simulation to test the impacts of different execution policies on production system performance.
Figure 3.1 Research Design
3.2.1 Hypotheses

The hypotheses for this research are: 1) Variations have detrimental impact on prefabrication production system. Failing to reduce variation causes an increase in project duration and WIP and a decrease in labor productivity; 2) Two execution policies (keeping laborers waiting and keeping laborers busy) have different effects on the production system when variation (i.e. equipment breakdown) occurs during the fabrication process, and keeping laborers busy is the best option.

3.2.2 Observation Form Design

Data collection sheet was designed in order to obtain correct and useful information during the seven-day site observation. During the site observation, many details may happen in the production system every day. It is important to record the right information at the right time. The purpose of observation form design is to effective and efficient documentation of the data needed for the simulation model. Regarding the logic of observation form design, the typical decision making process was considered. When a problem happens, here refereed as variation, the decision maker need to get information and decide with possible alternatives that can be used to solve the problem. The decision maker may ask many “what-if” questions to evaluate the impact of alternatives on the system under different situations before the decision is made. The observation form design follows the logic and put efforts to keep track of the decision making logic and process in the real world. Tables 3.1, 3.2, 3.3, and 3.4 show the design of the observation form.
### Table 3.1 Observation Form Design 1

<table>
<thead>
<tr>
<th>BED</th>
<th>Scheduled Starting Time</th>
<th>Actual Starting Time</th>
<th>Difference</th>
<th>Reason</th>
<th>Idle time before start</th>
<th>Reason</th>
</tr>
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<tbody>
<tr>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>III</td>
<td></td>
<td></td>
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</table>

### Table 3.2 Observation Form Design 2

<table>
<thead>
<tr>
<th>BED</th>
<th>Actual finish time</th>
<th>Scheduled duration</th>
<th>Actual Duration</th>
<th>Difference</th>
<th>Reason</th>
<th>Idle time during the task</th>
<th>Reason</th>
<th>Workforce</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 3.3 Observation Form Design 3

<table>
<thead>
<tr>
<th>BED</th>
<th>Any Rework(Y/N)</th>
<th>Time for Rework</th>
<th>Causes</th>
<th>Time spent finding and getting material and equipment</th>
<th>Any problem regarding equipment, material, labor or design?</th>
<th>when it occurred</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 3.4 Observation Form Design 4

<table>
<thead>
<tr>
<th>BED</th>
<th>What is wrong</th>
<th>Estimated recovery time</th>
<th>Who made decision</th>
<th>What info is needed for decision</th>
<th>Action taken</th>
<th>When is the problem resolved</th>
<th>Alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Based on the literature review, the first site visit, and the inputs from the project manager, 45 causes were tailored for the prestressed hollow core concrete production system to study the prefabrication task starting time and duration variation. The selection of the 45 causes was based on the following procedures:

- Removing factors that are not suitable for this case, for example Dai et al. (2009) found factors such as vehicle traffic routes, shortage of temporary facilities, errors in prefabricated material, availability of forklift and man lift affecting construction productivity from the craft workers’ perspective. The above factors are more related to construction projects and are not suitable for this case. Thus they were removed.

- Adding and detailing factors specific for this case study, for example a common cause, error in material size or type is specified into an error in concrete water content or an error in strand pattern and number, or both.

- Combining similar factors under the same category.

- Grouping the 45 causes into 8 main categories. This definition of different categories follows that used by Wambke et al. (2010). The eight categories, along with a general description of each, are:

  1. Prerequisite Work: Items that must be completed before a task can begin.
  2. Detailed Design / Working Method: Having an accurate and available design/drawing and a feasible working method in order to accomplish a given task.
  3. Labor Force: Labor force available and trained to perform the required task(s).
(4) Tools/Equipment: Required tools and/or equipment available in sufficient quantities and conditions.

(5) Material and Components: Having the correct and necessary materials available when and where you need them.

(6) Work/Jobsite Conditions: Adequate physical space available to perform your job.

(7) Management/Supervision/Information Flow: System exists to develop the work plan/schedule, provide guidance/instruction, and to answer questions when they arise.

(8) Weather or External Conditions: Items that are outside the control of those in the company.

Each category includes a number of potential individual causes for variation. Each individual cause was coded which improves the efficiency when information is documented during the site observation. Table 3.5 lists the 45 individual causes and illustrates how they are divided among the eight categories.

3.2.3 Simulation design

Variation or variability comes in many forms and types, making the production system complicated for decision making in the face of uncertainty. In reality, management may often make decisions based on intuition and experience. They may also evaluate the situation and make decisions by asking and answering some what-if questions in their mind. Discrete Event Simulation (DES) proved to be an effective tool for solving problems and answering what-if questions involved in the above decision making process. Typically, the problems well suited to DES: (1) involve significant uncertainties in the time required to accomplish
tasks or in the amount and quality of materials consumed and produced, (2) are logistically complex with a number of context sensitive dynamic rules and decisions, (3) have interdependent components subject to complex activity start-up conditions where many resources with distinct properties must collaborate according to highly dynamic rules (Hooper 1986).

In this research, the data collected during the second site visit was used as inputs for simulation to test the impacts of different execution policies, that is keeping laborers waiting and keeping laborers busy, in the face of variability on production system performance. The inputs for simulation model mainly included (1) task durations to generate different statistical distributions, (2) cause of variation, (3) parameters associated with the specific type of variation, for example, estimated equipment downtime. The software used to model and simulate the prestressed hollow core concrete slab production system is STROBOSCOPE system, which is a programming language that represents resources as objects that have assignable, persistent, and dynamic properties; and that can actively and dynamically take into consideration the state of simulated process (Martinez 1996).
<table>
<thead>
<tr>
<th>Category</th>
<th>Variation Factors</th>
</tr>
</thead>
</table>
| Prerequisite Work (PW)         | 1. Prerequisite work is not completed.  
2. Prerequisite work is done earlier.  
3. Rework being required due to the quality of previous work.  
4. Poor quality of previous work (though not to a level that requires rework) causes a delay.  
5. Inspections for previously completed work (check slab dimension, strength and cutting, ensure there are no cracks, structure and cosmetic issues) |
| Detailed Design / Working Method (DD/WM) | 1. Quality of documents (errors in design and/or shop drawings)  
2. Turnaround time from engineers when there is a question with a drawing  
3. Strict specification requirements  
4. Quality control requirements  
5. Work complexity |
| Tools/Equipment (TEQ)          | 1. Extruder breakdown  
2. Overhead crane breakdown  
3. Overhead bucket breakdown  
4. Waiting for overhead bucket  
5. Hydro cylinder breakdown  
6. Cutting saw breakdown  
7. Malfunction of cutting saw due to mechanical problem  
8. Other tools not available |
| Material and Components (MC)   | 1. Concrete does not arrive on time  
2. Error in concrete water content  
3. Strands are not available.  
4. Strands are available but there is an error in strand pattern and number |
Table 3.5  Continued

| Labor Force (LF) | 1. Socializing (talking with fellow workers)  
| | 2. Absenteeism  
| | 3. People arriving late and/or leaving early due to illness, injury, family or personal situation, etc.  
| | 4. Low morale and/or lack of motivation  
| | 5. Getting moved to another job/task before the one you were working on was completed and/or before scheduled to move  
| | 6. The crew size being inadequate (i.e. smaller than normal for your company or smaller than what is typical in the industry) for a particular type of work  
| | 7. Inefficiencies associated with personnel turnover (i.e. new employees)  
| | 8. Worker/crew lack of skills/experience to perform the task(s) being asked of them  
| | 9. Adding more labor to accelerate the task  
| Work / Jobsite Conditions (WJC) | 1. Overcrowded work area  
| | 2. Difficult access to work area  
| Management/Supervision/Information Flow (M/S/IF) | 1. To get answers to questions about the design or drawing  
| | 2. For guidance or instruction from supervisor  
| | 3. Lack of foreman skill/knowledge  
| | 4. Coordination between different trades  
| | 5. Over commitment due to a tight work schedule  
| | 6. Foreman availability  
| | 7. Change in the scope of work  
| | 8. Foreman communication skills  
| | 9. Communication between plant supervisor and foreman  
| | 10. Communication between foreman and workers  
| Weather or External Conditions (WEC) | 1. Ceiling electrical cable breakdown due to high humidity  
| | 2. Material storage (concrete) due to harsh weather conditions (extreme cold or rain)  

23
4 CASE STUDY

4.1 Project Background

The case study was undertaken with a precast concrete components fabricator in North Carolina. It is the largest producer of architectural precast concrete in the United States with six architectural precast manufacturing facilities and two structural/prestressed manufacturing facilities.

4.1.1 Prestressed Hollow Core Slab Fabrication Process

The typical process of the prestressed hollow-core slab fabrication is shown in Figure 4.1.

1. Clean Bed (Figure 4.2)

Prestressed hollow-core slabs are produced on casting beds. Before casting, the beds are cleaned and oiled.

2. Pull Strands (Figure 4.3)

A hydraulic cylinder is used for pulling strands. Each strand is tensioned individually. The number and size of the strands vary depending on the slab design.

3. Place Concrete (Figure 4.4)

Zero slump concrete is transported from the batching and mixing plant by an overhead bucket. The bucket brings a one cubic yard batch per cycle automatically to the correct place over an overhead bucket gantry and then discharges the batch into the extruder. The extruder, a key component in the production process, forms the concrete as it rides along the 400-foot-long bed. The extruder vibrates, compacts, and creates the hollow cores within the slab as it
moves along the rails of the bed. As the extruder continues to form the slab, a laborer marks the slab where it needs to be cut (either for an area that needs to be removed or simply at the length of each span).

![Diagram of Prestressed Hollow-Core Slab Fabrication Process]

Figure 4.1 Prestressed Hollow-Core Slab Fabrication Process
Figure 4.2 Cleaning Bed

Figure 4.3 Pulling Strands

Figure 4.4 Extruder Being Loaded with Concrete
(4) Cure

Steam pipes located underneath each bed provide heat and accelerate the concrete curing process. The rapid early strength of the concrete could be estimated by stepping on the slab as soon as it has been placed by the extruder. The concrete attains approximately 70% of its ultimate strength (about 3500 psi) between about 6.5 to 10 hours. Typically, the strength level, the release strength, is required prior to transforming load from the strands to the concrete.

(5) Cut & Remove (Figure 4.5 and 4.6)

Once the concrete has reached 70% strength after curing, the tension on the strands can be released and the slab can be cut according to the measured markings. The cutting operation is carried out with a saw that travels on the same rails as the extruder. After cutting, slabs are lifted from the casting bed by an overhead crane with clamps. The slabs are then transferred to the QC and pick up area in the plant for quality checking.

![Figure 4.5 Slabs Being Cut](image-url)
(6) QC (Figure 4.7)

The slab pieces undergo quality check in the QC and pick up area, after which the slabs are marked with project numbers at one end and picked up by an overhead crane and loaded onto a flatbed truck for transportation to the local storage yard.
(7) Transport to Local Storage Yard

After QC, the slabs are transported to a local storage yard. Then they are loaded onto a truck and delivered to a job site, often after an additional 1-2 days.

Table 4.1 summarizes work content, number of labors, equipment, tool and material requirements as well as duration of task. Task duration data is based on discussion with the project manager.
<table>
<thead>
<tr>
<th>Task</th>
<th>Work Content</th>
<th>No. of Laborers</th>
<th>Equipment/Tool</th>
<th>Material</th>
<th>Duration(hr)</th>
<th>Worst</th>
<th>Average</th>
<th>Best</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean Bed</td>
<td>cleaning and oiling bed, placing of strands</td>
<td>1</td>
<td>overhead crane, hollow core slab, sponge</td>
<td>water, oil</td>
<td>4</td>
<td>1</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>Pull Strands</td>
<td>tensioning strands</td>
<td>5*</td>
<td>Hydraulic cylinder</td>
<td>high tensile strand</td>
<td>0.5</td>
<td>0.08</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Place Concrete</td>
<td>setting up extruder, pouring concrete, marking, cleaning extruder, moving extruder to the next available bed</td>
<td>2</td>
<td>hollow core extruder, spade, paint , concrete vibrator</td>
<td>concrete</td>
<td>3</td>
<td>1.5</td>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td>Cure</td>
<td>curing</td>
<td>None</td>
<td>underneath steam heating pipe</td>
<td>----</td>
<td>10</td>
<td>6.5</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>Cut &amp; Remove</td>
<td>cutting bed, removing slabs to the QC and pick up area</td>
<td>3</td>
<td>cutting machine(saw)</td>
<td>----</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>QC</td>
<td>checking quality, marking</td>
<td>1</td>
<td>steel tape, chalk</td>
<td>----</td>
<td>----</td>
<td>0.5</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>Transport to Storage Yard</td>
<td>transporting to local storage yard</td>
<td>1</td>
<td>truck flatbed</td>
<td>----</td>
<td>----</td>
<td>0.3</td>
<td>----</td>
<td></td>
</tr>
</tbody>
</table>

* including the foreman and four laborers
4.1.2 Fabrication Shop Layout

As depicted in Figure 4.9, the facility had three 400-foot-long casting beds available aligned from south to north. A quantity of cables for 2 weeks usage, equipment including cutting saw, extruder, and hydraulic cylinder and hand tools including spade, broom, steel tape, sponge and paint are stored in fixed locations in the shop and are accessible to laborers at the point of use. To the west of the shop, there is a concrete batching and mixing plant, from which concrete materials are transported to the job shop by an overhead bucket through the rails.

![Figure 4.9 Hollow-Core Slab Fabrication Shop Layout](image-url)
4.1.3 Schedule

Due to the current recession, the hollow core plant does not operate under its full capacity. According to the schedule, one plant supervisor (S), one foreman (F) and four laborers (L1, L2, L3, L4), work in the plant every day. In addition there is a QC inspector who is responsible for quality control. The plant supervisor’s schedule and work requirements are flexible, and consist primarily of responsibility for making weekly and daily work plans, doing kitting, that is checking the availability of drawings, materials, and tools for the precast element, and managing and coordinating the whole production process. He usually arrives at the plant at 6:00 am and works 10 hours a day. The foreman, laborer 1 and laborer 2 work from 4:00 AM-2:00PM, and laborer 3 and laborer 4 work from 5:00 AM-3:00PM. Each worker works 10 hours a day and 4 days a week for a 40 hour week. Warszawski (1990) classified the production organization in precast plants as either comprehensive or specialized depending on the scope of operations performed by the work crews. In the comprehensive method, the same crew performs all the different operations for each precast item in turn. Under the specialized method, each crew specializes in a separate activity and repeats that activity for every mold. The specialized method is well suited to a movable production line. In this case study, the prestressed hollow-core fabrication plant utilized the specialized method for organizing the labor and work. Each laborer has fixed quantity of working every day, although he is capable of conducting all the tasks. The schedule and work contents for the laborers could be illustrated as follows.
(1) Foreman (F)

- 4:00 am-2:00pm
- managing and coordinating the operation of different labors
- cutting Bed III before laborer 3 arrives
- marking Bed I, II, and III (where it needs to be cut) when another labor is placing concrete
- putting a piece number representing the slab design on each slab with enamel
- cleaning the extruder
- operating the hydraulic cylinder to tension the strands

(2) Laborer 1 (L1)

- 4:00 am-2:00pm
- de-tensioning the strands before the bed is being cut
- removing slabs from Bed I, II, and III and moving them to the QC and pick up area in the plant
- placing strands on all the three beds for tensioning when the bed is being cleaned
- cleaning the nuts and bolts used in pulling the strands
- assisting with tensioning the strands

(3) Laborer 2 (L2)

- 4:00 am-2:00pm
- de-tensioning the strands before the bed is cut
• removing slabs from Bed I, II, and III and moving them to the QC and pick up area in the plant
• placing strands on all the three beds for tensioning when the bed is being cleaned
• cleaning Bed I, II and III with an oil sponge
• assisting with tensioning the strands

(4)Laborer 3 (L3)
• 5:00 am-3:00pm
• cutting Bed I, Bed II, and part of Bed III
• cleaning the extruder
• assisting with tensioning the strands

(5)Laborer 4 (L4)
• 5:00 am-3:00pm
• operating the extruder and placing concrete on Bed I, II and III
• finishing concrete as it is being placed
• cleaning the extruder
• assisting with tensioning the strands

(6)QC inspector
• 5:00 am-3:00pm
• review all the tensioning and de-tensioning operations
• check slab dimension, strength and cutting
• mark the piece with day/QC accepted or rejected
• check every slab to ensure there are no cracks, structural or cosmetic issues

The operation of tensioning the strands involves the foreman, 4 laborers (L1, L2, L3, L4), and the QC inspector working together, which also improves safety. Everyone in the plant must stop work and stay outside the danger area during the process of pulling the strands. There are also miscellaneous stuff and cleanup work during the day. Any available laborer may conduct these tasks. The management aims to keep the laborer busy during their work time.

Figure 4.10 illustrates a typical production schedule in the prestressed hollow-core slab fabrication plant. By the end of each day, three beds have been placed with concrete. This schedule is used as the benchmark to calculate task starting time and task duration variation. The schedule also indicates that task duration of cut & remove varies among three beds. Two major factors including slab design/work complexity and functioning of the cutting saw, account for this. Every morning, the production starts with cutting Bed III which usually matches the lowest design/work complexity. Thus cutting and removing Bed III could be finished as soon as possible so that placing concrete could start as early as possible. Otherwise laborer 4 will be idle waiting. Cutting and removing Bed I has the longest duration, because cutting saw often malfunctions after cutting Bed III and II; these malfunctions tend to be mechanical problems such as vibration and friction.
4.1.4 Product Mix

The slabs are produced as 6”, 8”, and 10” thick and cut to lengths as specified. In this study, all the slabs produced were 6” in thickness. The product mix is listed in Table 4.2. Piece codes (20, 20A, 20C, 20D, and 29) defined by the concrete slab prefabricator for the convenience of tracking, represent design packages for a particular project. Cutting complexity levels for different slab designs vary. Slab designs 20 and 29 are standard rectangular slabs. The cutting saw cuts along the width direction of the bed only; thus, they are of the lowest complexity level. Designs 20A and 20D are rectangular slabs with a rectangular notch in the corner. The complexity level increases as the cutting saw needs to change the saw direction when it works. Design 20C is of the highest complexity level due to the fact that it has a rip in the middle so the cutting saw needs to both change the saw direction and move back and forth when it moves along the rails of the bed.

Table 4.2 Slab Product Mix

<table>
<thead>
<tr>
<th>Piece Code</th>
<th>Length</th>
<th>Width</th>
<th>Area (SF)</th>
<th>Cutting Complexity Level</th>
<th>No. of Slabs Produced During the Observation Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>15'-2&quot;</td>
<td>4'-0&quot;</td>
<td>61</td>
<td>Low</td>
<td>180</td>
</tr>
<tr>
<td>20A</td>
<td>15'-2&quot;</td>
<td>4'-0&quot;</td>
<td>54</td>
<td>Medium</td>
<td>40</td>
</tr>
<tr>
<td>20C</td>
<td>15'-2&quot;</td>
<td>1'-10&quot;</td>
<td>28</td>
<td>High</td>
<td>280</td>
</tr>
<tr>
<td>20D</td>
<td>15'-2&quot;</td>
<td>4'-0&quot;</td>
<td>54</td>
<td>Medium</td>
<td>40</td>
</tr>
<tr>
<td>29</td>
<td>6'-6&quot;</td>
<td>4'-0&quot;</td>
<td>26</td>
<td>Low</td>
<td>119</td>
</tr>
</tbody>
</table>

Furthermore, the above 5 types of slabs can be combined at each bed for cutting. Mainly 3 types of combinations were used (Design I, II, and III) according to design/work complexity of task cut & remove during the observation period. Design I is a combination of six pieces...
of 29, ten pieces of 20A and ten pieces of 20D. Design II is a combination of six pieces of 29 and forty pieces of 20C. Design III is a combination of six pieces of 29 and twenty pieces of 20. Generally speaking, Design I, II, and III match Bed I, II, and III, although there were exceptions during the observation period as noted in Table 4.3.

Table 4.3 Design/Work Complexity Level of Cutting Slabs

<table>
<thead>
<tr>
<th>Observation Date</th>
<th>BED</th>
<th>Design</th>
<th>Design/Work Complexity Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/27</td>
<td>II</td>
<td>III</td>
<td>Low</td>
</tr>
<tr>
<td>1/28</td>
<td>II</td>
<td>III</td>
<td>Low</td>
</tr>
<tr>
<td>1/25</td>
<td>III</td>
<td>III</td>
<td>Low</td>
</tr>
<tr>
<td>1/26</td>
<td>III</td>
<td>III</td>
<td>Low</td>
</tr>
<tr>
<td>1/27</td>
<td>III</td>
<td>III</td>
<td>Low</td>
</tr>
<tr>
<td>1/28</td>
<td>III</td>
<td>III</td>
<td>Low</td>
</tr>
<tr>
<td>2/2</td>
<td>III</td>
<td>III</td>
<td>Low</td>
</tr>
<tr>
<td>2/3</td>
<td>III</td>
<td>III</td>
<td>Low</td>
</tr>
<tr>
<td>2/4</td>
<td>III</td>
<td>III</td>
<td>Low</td>
</tr>
<tr>
<td>1/25</td>
<td>I</td>
<td>I</td>
<td>Medium</td>
</tr>
<tr>
<td>1/27</td>
<td>I</td>
<td>I</td>
<td>Medium</td>
</tr>
<tr>
<td>1/28</td>
<td>I</td>
<td>I</td>
<td>Medium</td>
</tr>
<tr>
<td>1/25</td>
<td>II</td>
<td>I</td>
<td>Medium</td>
</tr>
<tr>
<td>1/26</td>
<td>I</td>
<td>II</td>
<td>High</td>
</tr>
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<td>2/2</td>
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<td>II</td>
<td>High</td>
</tr>
<tr>
<td>2/3</td>
<td>I</td>
<td>II</td>
<td>High</td>
</tr>
<tr>
<td>1/26</td>
<td>II</td>
<td>II</td>
<td>High</td>
</tr>
<tr>
<td>2/3</td>
<td>II</td>
<td>II</td>
<td>High</td>
</tr>
<tr>
<td>2/4</td>
<td>II</td>
<td>II</td>
<td>High</td>
</tr>
<tr>
<td>2/2</td>
<td>II</td>
<td>II</td>
<td>High</td>
</tr>
</tbody>
</table>
Figure 4.10  Production Schedule
4.2 Data Analysis

4.2.1 Starting Time and Duration Variation

Figure 4.11 provides cumulative duration variation, summed over 7 days. Both positive and negative variations were observed. As depicted in Figure 4.11, Cut & Remove and Place Concrete, two major value-adding activities in this prefabrication process, cause major task duration variation. Cut & Remove was further divided into Design I, II, and III according to design and work complexity. Figure 4.11 shows that the increase of design complexity tends to cause more variation in task duration.

![Cumulative Duration Variation Chart]

Figure 4.11 Cumulative Duration Variation

Figure 4.12 provides cumulative starting time variation, summed over 7 days. Both positive and negative variations were also observed. Clean Bed varies the most. It is the successor of Cut & Remove. That is, a higher duration variation in a predecessor leads to a higher starting time variation in a successor.
4.2.2 Causes of Starting Time and Duration Variation

As discussed in the methodology section, factors in eight categories were reviewed: prerequisite work, detailed design/working method, labor force, tools and equipment, material and components, work/jobsite conditions, management/supervision/information flow, and weather or external conditions. Table 4.4 and Table 4.5 show the major causes of variation in task starting time and task duration based on the site observation. Prerequisite work plays the most important role in causing task starting time variation. Regarding task duration variation, tools/equipment causes variation in task duration, which adds up to about 6.35 hours. Variation in task duration caused by tools/equipment include waiting for overhead bucket (1.12 hours), overhead bucket breakdown (1.4 hours), overhead crane breakdown (1.05 hours), cutting saw breakdown (1.78 hours) and malfunction of cutting saw
due to mechanical problem (1 hour). The second major cause of task duration variation is work complexity (about 3.68 hours).

Table 4.4 Major Causes of Variation in Task Starting Time

<table>
<thead>
<tr>
<th>Category</th>
<th>Factor</th>
<th>Tasks Affected</th>
<th>Cumulative Variation(hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prerequisite Work</td>
<td>Prerequisite work is not completed.</td>
<td>All</td>
<td>19.78</td>
</tr>
<tr>
<td>Prerequisite Work</td>
<td>Prerequisite work is done earlier.</td>
<td>All</td>
<td>-8.08</td>
</tr>
<tr>
<td>Tools/Equipment</td>
<td>Waiting for overhead bucket</td>
<td>Place Concrete</td>
<td>1.00</td>
</tr>
<tr>
<td>Labour Force</td>
<td>People arriving late</td>
<td>Cut &amp; Remove</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Table 4.5 Major Causes of Variation in Task Duration

<table>
<thead>
<tr>
<th>Category</th>
<th>Factor</th>
<th>Tasks Affected</th>
<th>Cumulative Variation(hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tools/Equipment</td>
<td>Cutting saw breakdown</td>
<td>Cut &amp; Remove</td>
<td>1.78</td>
</tr>
<tr>
<td>Tools/Equipment</td>
<td>Overhead bucket breakdown</td>
<td>Place Concrete</td>
<td>1.40</td>
</tr>
<tr>
<td>Tools/Equipment</td>
<td>Waiting for overhead bucket</td>
<td>Place Concrete</td>
<td>1.12</td>
</tr>
<tr>
<td>Tools/Equipment</td>
<td>Overhead crane breakdown</td>
<td>Cut &amp; Remove</td>
<td>1.05</td>
</tr>
<tr>
<td>Tools/Equipment</td>
<td>Malfunction of cutting saw due to mechanical problem</td>
<td>Cut &amp; Remove</td>
<td>1.00</td>
</tr>
<tr>
<td>Detailed Design/Working Method</td>
<td>Work complexity</td>
<td>Cut &amp; Remove</td>
<td>3.68</td>
</tr>
<tr>
<td>Material and Components</td>
<td>Error in concrete water content</td>
<td>Place Concrete</td>
<td>1.12</td>
</tr>
<tr>
<td>Prerequisite Work</td>
<td>Rework</td>
<td>Pull Strands</td>
<td>0.03</td>
</tr>
<tr>
<td>Labor Force</td>
<td>Adding more labour</td>
<td>Clean Bed</td>
<td>-0.86</td>
</tr>
</tbody>
</table>
4.2.3 Productivity and Variation

Table 4.6 shows productivity calculation on a daily basis. Overall productivity, Place Concrete productivity and Cut & Remove productivity were calculated according to Eq. (1), (2), (3), and (4).

Overall Plant Productivity= Cut Slabs (SF) /Labor Hrs \[(1)\]
(Number of labors=5)

Place Concrete Productivity= Placed Concrete (SF) / Labor Hrs \[(2)\]
(Number of labors=2)

Cut & Remove Productivity= Cut Slabs (SF) /Labor Hrs \[(3)\]
(Number of labors=3)

The complexity level of Cut & Remove is mainly associated with three factors; 1) slab thickness, 2) slab span, and 3) volume of slabs with narrow width of less than 4’, plus angle cuts and notches. Therefore, work complexity level need be differentiated when daily productivity is quantified.

In Eq. (3),

Cut Slabs= \(\alpha_1\)*SF of High Level Bed +\(\alpha_2\)*SF of Medium Level Bed +\(\alpha_3\)*SF of Low Level Bed \[(4)\]
\((\alpha_1, \alpha_2, \text{and } \alpha_3 \text{ are coefficients associated with complexity level, } \alpha_1=1, \alpha_2=0.9, \text{ and } \alpha_3=0.8 \text{ based on project manager’s inputs})
Table 4.6 Daily Productivity

<table>
<thead>
<tr>
<th>Observation Date</th>
<th>Duration(hr)</th>
<th>Overtime(hr)</th>
<th>Productivity (SF/Labor Hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Overall</td>
</tr>
<tr>
<td>1/25</td>
<td>12.00</td>
<td>1.00</td>
<td>55.04</td>
</tr>
<tr>
<td>1/26</td>
<td>10.50</td>
<td>-0.50</td>
<td>68.19</td>
</tr>
<tr>
<td>1/27</td>
<td>11.50</td>
<td>0.50</td>
<td>55.34</td>
</tr>
<tr>
<td>1/28</td>
<td>11.00</td>
<td>0.00</td>
<td>58.99</td>
</tr>
<tr>
<td>2/2</td>
<td>11.25</td>
<td>0.25</td>
<td>62.17</td>
</tr>
<tr>
<td>2/3</td>
<td>10.25</td>
<td>-0.75</td>
<td>71.27</td>
</tr>
<tr>
<td>2/4</td>
<td>9.20</td>
<td>-1.80</td>
<td>51.67</td>
</tr>
</tbody>
</table>

Table 4.7 and Figure 4.13 demonstrate Cut & Remove productivity based on different beds.

In Table 4.7,

Productivity = Net SF/ (Cut & Remove Duration *3 laborers) \hspace{1cm} (5)

Mean, standard deviation (SD) and coefficient of variation (CV) of productivity data of different design/work complexity levels were also calculated. As complexity level increases, Cut & Remove productivity decreases and tends to have more variation as indicated by the increase of the CV value (Table 4.7). Productivity decrease is due to increase in duration and decrease in production measured by net SF. More variability in productivity could be explained by the fact that higher design/work complexity tends to cause more variation on task duration as discussed in the previous section. In practice, Bed III (slabs of low complexity level) is cut first. Low complexity means less variation on task duration as well as productivity so that the following Place Concrete on Bed III task could start as early as possible avoiding labor being idle due to variation of Cut & Remove on Bed III.
Table 4.7 Cut & Remove Productivity vs. Complexity Level

<table>
<thead>
<tr>
<th>Date</th>
<th>BED</th>
<th>Design</th>
<th>Complexity Level</th>
<th>Cut &amp; Remove Duration (min)</th>
<th>Net SF</th>
<th>Productivity SF/Labor Hrs</th>
<th>Mean</th>
<th>SD</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/26</td>
<td>I</td>
<td>II</td>
<td>High</td>
<td>160</td>
<td>1250</td>
<td>156.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/26</td>
<td>II</td>
<td>II</td>
<td>High</td>
<td>146</td>
<td>1250</td>
<td>171.23</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/2</td>
<td>I</td>
<td>II</td>
<td>High</td>
<td>212</td>
<td>1276</td>
<td>120.38</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/2</td>
<td>II</td>
<td>II</td>
<td>High</td>
<td>136</td>
<td>1120</td>
<td>164.71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/3</td>
<td>I</td>
<td>II</td>
<td>High</td>
<td>268</td>
<td>1276</td>
<td>95.22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/3</td>
<td>II</td>
<td>II</td>
<td>High</td>
<td>209</td>
<td>1276</td>
<td>122.11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/4</td>
<td>II</td>
<td>II</td>
<td>High</td>
<td>252</td>
<td>1276</td>
<td>101.27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/25</td>
<td>I</td>
<td>I</td>
<td>Medium</td>
<td>203</td>
<td>1210</td>
<td>119.21</td>
<td>134.30</td>
<td>22.02</td>
<td>0.16</td>
</tr>
<tr>
<td>1/25</td>
<td>II</td>
<td>I</td>
<td>Medium</td>
<td>148</td>
<td>1236</td>
<td>167.03</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/27</td>
<td>I</td>
<td>I</td>
<td>Medium</td>
<td>197</td>
<td>1236</td>
<td>125.48</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/28</td>
<td>I</td>
<td>I</td>
<td>Medium</td>
<td>197</td>
<td>1236</td>
<td>125.48</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/25</td>
<td>III</td>
<td>III</td>
<td>Low</td>
<td>97</td>
<td>1376</td>
<td>283.71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/26</td>
<td>III</td>
<td>III</td>
<td>Low</td>
<td>99</td>
<td>1350</td>
<td>272.73</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/27</td>
<td>II</td>
<td>III</td>
<td>Low</td>
<td>112</td>
<td>1324</td>
<td>236.43</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/27</td>
<td>III</td>
<td>III</td>
<td>Low</td>
<td>104</td>
<td>1263</td>
<td>242.88</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/28</td>
<td>II</td>
<td>III</td>
<td>Low</td>
<td>117</td>
<td>1289</td>
<td>220.34</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/28</td>
<td>III</td>
<td>III</td>
<td>Low</td>
<td>101</td>
<td>1376</td>
<td>272.48</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/2</td>
<td>III</td>
<td>III</td>
<td>Low</td>
<td>114</td>
<td>1376</td>
<td>241.40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/3</td>
<td>III</td>
<td>III</td>
<td>Low</td>
<td>103</td>
<td>1376</td>
<td>267.18</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/4</td>
<td>III</td>
<td>III</td>
<td>Low</td>
<td>100</td>
<td>1376</td>
<td>275.20</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
It is interesting to observe that Cut & Remove tasks of high work complexity are mainly put on Bed II rather than Bed I, indicating that project manager does not desire to put tasks with high work complexity level and more variation on task duration and productivity at the end of the production day. This is consistent with the management trying to hold additional time to deal with problems.

**4.2.4 5-Why Analysis**

In order to identify the root causes of task starting time variation and task duration variation and pinpoint specific method to reduce variation and improve productivity. “5 Why” analysis was conducted. Made popular in the 1970s by Shigeo Shingo of Toyota (Leflar 2001), 5 Why involves looking at any problem and asking: “Why?” a number of times to establish the root
cause and then agreeing how to address the root cause. To summarize, the purpose of the analysis is to help determining

- What is the problem?
- What are the root causes of the problem?
- Does the prefabricator identify this problem? What are the remedies and what are the costs?
- Does the prefabricator take any action to remove or minimize the effect of the root cause? If yes, how and how well do they do? If not, why?

(1) Major causes of variation on task duration

- Before and during placing concrete, the overhead bucket often arrived late when every other thing was ready; therefore the operator and extruder had to wait for a few minutes. It caused both starting time and duration variation. What are the reasons for the overhead bucket not arriving on time?

  The possible reasons for the overhead bucket not arriving on time could be: 1) the batch operator not paying attention and getting the bucket started, 2) the material blockage in the hopper, and 3) computer related problems.

- During the process of placing concrete and cut & remove, breakdowns of overhead bucket, overhead crane and cutting saw breakdown resulted in major extensions in task duration.
  - Why did the overhead bucket break down?
  - Why did the cutting saw break down?
• Why did the overhead crane break down?

Bucket shoes coming out of the power line is one possible reason for the overhead bucket break down. Ceiling electrical cable breakdown could be causes for overhead bucket and crane breakdown. Many unrecognized factors also contribute to the breakdown of all the equipment.

• The cutting saw malfunctioned after cutting Bed III and II almost every day. What are the reasons for it?

Vibration and friction are possible causes of cutting saw malfunction. Another cause is the bad burn in the drive. The burn gets loose after the Bed III is being cut. The burn in the drive may have a sticking problem and need freezing up. Meanwhile, the burn is easily malfunctioned and damaged. The whole process repeats even after the burn has been changed.

• How does work complexity affect cut and remove duration?

As discussed in 4.1.4 Product Mix, cutting complexity levels for different slab designs are different. For standard rectangular slabs (i.e., slab designs 20 and 29), the cutting saw cuts along the width direction of the bed only as it moves along the rails; thus, they are of the lowest complexity level. For rectangular slabs with a rectangular notch in the corner (i.e., slab designs 20A and 20D), the complexity level and task duration increase as the cutting saw needs to change the saw direction when it works. Design 20C is of the highest complexity level due to the fact that it has a rip in the
middle so the cutting saw needs to both change the saw direction and move back and forth when it moves along the rails of the bed.

- The operator often stopped the extruder and checked water content during the process of placing concrete. Sometimes error in concrete water content could not be observed with eyes resulting in defected slab products. All above situations would lead to task delay and productivity decrease. What are the reasons for error in concrete water content?

Dynamic and changing daily weather (i.e., temperature, humidity) contribute to the error in concrete water content. Another significant cause is human factor. The human eye is much more sensitive to the concrete water content than a computer is, although the computer technology is widely used to gauge the concrete moisture content. When the production starts in the morning, the batch operator needs to get the right moisture content based on that day’s situation (i.e., weather, humidity) and the extruder operator’s experience. The above process ends until the first 2 batches of concrete are poured. After the second batch, if there is no situation change, the extruder could run smoothly without changing the concrete water content. If the situation changes during the day (i.e., rain), the batch operator would slightly adjust the water content, wait until the concrete is mixed, and send the concrete batch to the extruder to check whether the batch operator made the right or enough decision as the concrete runs through the extruder. The problem is the batch operator has already got another batch of concrete in the mixer being mixed. If adjustments need to be made,
there is one batch coming out of the extruder on the bed plus another one batch in the mixer getting ready to be dropped in the hopper. 2 batches of concrete which equals to about 10 feet of bed may be thrown away, if the adjustments are wrong or not enough.

- Rework in pulling the strands was observed once during the site visit. What are the possible reasons for it?

  The possible reason for it is the human error. Sometimes certain strands break or get crossed. The laborers need to de-tension and remove them. Rework in pulling strands may also cause safety problems. In order to improve the process, the laborers should have periodic retraining which involves reviewing necessary procedures. Besides, the QC man should check carefully during the whole process.

(2) Major causes of variation on task starting time

- Laborers often arrived at the plant 10 or 15 minutes after 4:00am. Is this within the company requirements? If not, what are the reasons for it?

  The company has strict requirements on arriving at the plant and getting ready to work at 4:00 AM. The reason why some laborers are late is they arrive at the company at 4:00 AM and spend about 15 minutes changing clothes, drinking coffee, or simply chatting before they could get to the plant and be ready to work. This could be resolved through enforcement of employee policy. The policy is the laborer would get a verbal warning the first time being late, a written warning the second time, sent home for 3 days the third time and fired the fourth time.
Who is responsible for making work plan, maintain and check equipment, kitting for each precast element (drawings, materials, tools)? How and how well is that done? Hollow core plant supervisor is responsible for making work plan, checking equipment, kitting for each precast element (drawings, materials, and tools). The foreman assists him. The plant supervisor spends about 40% of his working time doing the above tasks, while the rest 60% of time is for monitoring the production. Regarding equipment maintenance, the plant supervisor checks all the equipment every day after all the daily work has been finished. If any problem is detected, the plant supervisor would report to the equipment maintenance and repair team which is responsible for resolving equipment related problems. Besides, the equipment operator would also report to supervisor and the equipment maintenance and repair team if anything wrong occurs during the production process. Furthermore, the project manager is considering replacing worn out parts of extruders on a basis of fixed time interval (i.e., every six months). However it is not implemented because the frequency of extruder usage, which is determined by different type of jobs, varies much, thus the degree of wear varies much too.

4.3 Simulation

4.3.1 Simulation Model Development

Both descriptive analysis and project manager interviews suggest that equipment breakdown is one of the major causes of variation in task duration in this operation. The fabricator has one extra machine for each equipment type except for the overhead bucket; thus once the
equipment breaks down during production, the extra one could be utilized immediately for emergency use. Consequently, there will be not much loss in terms of time and productivity. The simulation in the models examined in this study involved only the breakdown of the overhead bucket, with no extra equipment available. The assumptions of this model are:

1. One overhead bucket is used.
2. Work content is the same in all scenarios: three beds are cut and placed with concrete for each iteration.
3. The overhead bucket breaks down before task Place Concrete starts and the overlap of task Cut & Remove among different beds is not considered.
4. The estimated repair time is 2 hours, which is based on the project manager’s input (during the 7-day observation, 2 breakdowns associated with the overhead bucket were observed; one lasted for about 2 hours, while the other was about 15 minutes).

The laborers only go to help with other tasks during the equipment downtime and will go back whenever the broken equipment is recovered, no matter whether the Cut & Remove task is finished or not. Two execution policies (labor policies) when the overhead bucket breaks down are simulated, namely keeping laborers waiting and keeping laborers busy by sending them to other tasks. In this model, the laborers can be sent to task Cut & Remove to help move the slabs from the casting bed to the QC and pick-up area. According to the project manager’s experience, task duration for Cut & Remove usually could be reduced by 25% when one or two laborers are added. 25% time reduction for task cut & remove is also reasonable considering the data acquired in this study. During the process of removing slabs
with the overhead crane, adding more labors could help arrange wood pads between slabs or hook up the ropes, which will decrease moving time thus reduce the duration of the whole task. One other scenario was included for comparison, assuming that task duration for Cut & Remove could be reduced by 50%.

Nine simulation scenarios were defined as shown in Table 4.8 based on the above descriptions. They are categorized by different overhead bucket breakdown spots. Scenario 1 is the perfect situation when no overhead bucket breaks down.

<table>
<thead>
<tr>
<th>Scenario No.</th>
<th>Bucket Breakdown Spot</th>
<th>Hypothetical Remedy (Labor Policy)</th>
<th>Potential Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>Bed III</td>
<td>Waiting at Bed III</td>
<td>Labor idle</td>
</tr>
<tr>
<td>3</td>
<td>Bed III</td>
<td>Moving to Bed II</td>
<td>Duration of Cut &amp; Remove 2 decreases by 25%</td>
</tr>
<tr>
<td>4</td>
<td>Bed II</td>
<td>Moving to Bed I</td>
<td>Duration of Cut &amp; Remove 2 decreases by 50%</td>
</tr>
<tr>
<td>5</td>
<td>Bed II</td>
<td>Waiting at Bed II</td>
<td>Labor idle</td>
</tr>
<tr>
<td>6</td>
<td>Bed II</td>
<td>Moving to Bed I</td>
<td>Duration of Cut &amp; Remove 1 decreases by 25%</td>
</tr>
<tr>
<td>7</td>
<td>Bed II</td>
<td>Moving to Bed I</td>
<td>Duration of Cut &amp; Remove 1 decreases by 50%</td>
</tr>
<tr>
<td>8</td>
<td>Bed I</td>
<td>Waiting at Bed I</td>
<td>Labor idle</td>
</tr>
<tr>
<td>9</td>
<td>Bed I</td>
<td>Moving to other beds</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Figure 4.14 to 4.17 show the Stroboscope simulation models. Table 4.9 provides explanations for selected Stroboscope symbols, which were used in the simulation model.

Figure 4.14 represents normal production without equipment breakdown. Figure 4.15- 4.17
represent overhead bucket breakdown on Bed III, II and I respectively. Since Place Concrete and Cut & Remove are the two tasks of most interest, only resources including labor, material and equipment, associated with those tasks were made explicit. The nodes are organized by different colors. The blue nodes illustrate activities and resources associated with them on Bed I, the yellow on Bed II and the green on Bed III. The queues of **Bucket**, **Lab** and **CuttingSaw** in red color show the resources of overhead bucket, labor and cutting saw, which are shared among the three beds. The queues of **BedReady** and **SlabReady** provide the end product of a typical day, namely three beds being poured and three beds being cut. Overhead bucket breakdown is modelled by adding a **Repair** node before task Place Concrete. When the **Repair** node activates, it would hold the queue of **Lab** and **Bucket**, the task Place Concrete could not start, which models the keeping labor waiting policy. Keeping labor busy policy is modelled indirectly by changing duration of task Cut & Remove.
Table 4.9 Selected Stroboscope Symbols (Martinez 1996)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Queue" /></td>
<td>Queue</td>
<td>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.</td>
</tr>
<tr>
<td><img src="image" alt="NormalName" /></td>
<td>Normal Activity</td>
<td>Describe 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.</td>
</tr>
<tr>
<td><img src="image" alt="CombiName" /></td>
<td>Combi Activity</td>
<td>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.</td>
</tr>
<tr>
<td><img src="image" alt="Link" /></td>
<td>Link</td>
<td>Shows flow logic and should be labelled to meaningfully describe the resources that flow through it.</td>
</tr>
</tbody>
</table>
Figure 4.14  Stroboscope Simulation Model (Scenario 1)
Figure 4.15 Stroboscope Simulation Model (Scenario 2, 3, 4)
Figure 4.16 Stroboscope Simulation Model (Scenario 5, 6, 7)
Figure 4.17  Stroboscope Simulation Model (Scenario 8)
4.3.2 Model Input

Task duration is estimated from a given statistical distribution. Distribution selection was based on task duration data (Appendix A Tables A.1-A.3) collected from site observations. The Input Analyser module of simulation software Arena (David 2010) was used to determine an appropriate distribution function. The quality of a curve fit is based primarily on the square error criterion, which is defined as the sum of \( \{f_i - f(x_i)\}^2 \), summed over all histogram intervals. In this expression \( f_i \) refers to the relative frequency of the data for the \( i^{th} \) interval, and \( f(x_i) \) refers to the relative frequency for the fitted probability distribution function. This last value is obtained by integrating the probability density across the interval. If the cumulative distribution is known explicitly, then \( f(x_i) \) is determined as \( F(x_i) - F(x_i-1) \), where \( F \) refers to the cumulative distribution, \( x_i \) is the right interval boundary and \( x_i-1 \) is the left interval boundary. If the cumulative distribution is not known explicitly, then \( f(x_i) \) is determined by numerical integration.

Based on minimizing least square errors, Chi-Square and Kolmogorov-Smirnov (KS) goodness-of-fit tests were conducted to test the fit of the function. The null hypothesis (\( H_0 \)) for both tests is the data follow a specified distribution. The alternative hypothesis (\( H_a \)) is the data do not follow a specified distribution. Tables 4.10 and 4.11 show the distributions and characteristic statistics using in the Stroboscope simulation models.
Table 4.10 Task Duration Distribution Based on Least Square Error Criterion

<table>
<thead>
<tr>
<th>Task</th>
<th>Distribution</th>
<th>Function</th>
<th>Square Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean Bed</td>
<td>Triangular[22.5, 30, 35.5]</td>
<td>Triangular</td>
<td>0.061</td>
</tr>
<tr>
<td>Pull Strands</td>
<td>Triangular[12.5, 15, 18.5]</td>
<td>Weibull</td>
<td>0.122</td>
</tr>
<tr>
<td>Place Concrete</td>
<td>Normal[154, 22.9]</td>
<td>Normal</td>
<td>0.096</td>
</tr>
<tr>
<td>Cut &amp; Remove 3</td>
<td>96.5 + Gamma[4.5, 1.35]</td>
<td>Beta</td>
<td>0.091</td>
</tr>
<tr>
<td>Cut &amp; Remove 2</td>
<td>Triangular[117, 130, 252]</td>
<td>Beta</td>
<td>0.164</td>
</tr>
<tr>
<td>Cut &amp; Remove 1</td>
<td>Triangular[160, 191, 268]</td>
<td>Gamma</td>
<td>0.087</td>
</tr>
</tbody>
</table>

Table 4.11 Task Duration Distribution (α=0.1)

<table>
<thead>
<tr>
<th>Task</th>
<th>Distribution</th>
<th>KS Test Conclusion</th>
<th>Chi-Square Test Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean Bed</td>
<td>Triangular[22.5, 30, 35.5]</td>
<td>Accept H&lt;sub&gt;0&lt;/sub&gt;</td>
<td>Reject H&lt;sub&gt;0&lt;/sub&gt;</td>
</tr>
<tr>
<td>Pull Strands</td>
<td>Triangular[12.5, 15, 18.5]</td>
<td>Reject H&lt;sub&gt;0&lt;/sub&gt;</td>
<td>Accept H&lt;sub&gt;0&lt;/sub&gt;</td>
</tr>
<tr>
<td>Place Concrete</td>
<td>Normal[154, 22.9]</td>
<td>Accept H&lt;sub&gt;0&lt;/sub&gt;</td>
<td>Accept H&lt;sub&gt;0&lt;/sub&gt;</td>
</tr>
<tr>
<td>Cut &amp; Remove 3</td>
<td>96.5 + Gamma[4.5, 1.35]</td>
<td>Accept H&lt;sub&gt;0&lt;/sub&gt;</td>
<td>N/A</td>
</tr>
<tr>
<td>Cut &amp; Remove 2</td>
<td>Triangular[117, 130, 252]</td>
<td>Accept H&lt;sub&gt;0&lt;/sub&gt;</td>
<td>N/A</td>
</tr>
<tr>
<td>Cut &amp; Remove 1</td>
<td>Triangular[160, 191, 268]</td>
<td>Accept H&lt;sub&gt;0&lt;/sub&gt;</td>
<td>N/A</td>
</tr>
</tbody>
</table>

4.3.3 Different Experiments and Data Analysis

Table 4.12 shows the simulation result of 1000 iterations for different scenarios addressed in Table 4.8. In this study, penalty is quantified in terms of overtime, overtime percentage, WIP increase and cost overrun (The overtime pay is 15 dollars/Labor Hrs). As depicted in Table 4.12, the overhead bucket breakdown has a negative impact on project duration. It indicates that the later the overhead bucket breakdown occurs during a day, the longer delay it causes.
Multivariate analysis of variance (MANOVA) and pair wise T-test were conducted to determine whether the differences of duration and WIP are significant among different scenarios. Results are shown in Tables 4.13, 4.14 and 4.15.

Table 4.12 Simulation Results (1000 Iterations)

<table>
<thead>
<tr>
<th>Bucket Breakdown Spot</th>
<th>Scenario No.</th>
<th>Duration (min)</th>
<th>WIP</th>
<th>Overall Productivity (SF/Labor Hrs)</th>
<th>Overtime (min)</th>
<th>WIP Increase</th>
<th>Penalty</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A</td>
<td>1</td>
<td>676.53</td>
<td>0.57</td>
<td>74.50</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Bed III</td>
<td>2</td>
<td>732.12</td>
<td>0.73</td>
<td>68.84</td>
<td>55.59</td>
<td>0.16</td>
<td>69.49</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>730.03</td>
<td>0.79</td>
<td>69.04</td>
<td>53.5</td>
<td>0.22</td>
<td>66.88</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>729.51</td>
<td>0.85</td>
<td>69.09</td>
<td>52.98</td>
<td>0.28</td>
<td>66.23</td>
</tr>
<tr>
<td>Bed II</td>
<td>5</td>
<td>750.23</td>
<td>0.61</td>
<td>67.18</td>
<td>73.7</td>
<td>0.04</td>
<td>92.13</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>752.21</td>
<td>0.68</td>
<td>67.00</td>
<td>75.68</td>
<td>0.11</td>
<td>94.60</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>750.9</td>
<td>0.75</td>
<td>67.12</td>
<td>74.37</td>
<td>0.18</td>
<td>92.96</td>
</tr>
<tr>
<td>Bed I</td>
<td>8</td>
<td>797.28</td>
<td>0.49</td>
<td>63.21</td>
<td>120.75</td>
<td>-0.08</td>
<td>150.94</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 4.13 MANOVA Test Result (α=0.05)

<table>
<thead>
<tr>
<th>Source</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependent variable: Duration</td>
<td></td>
</tr>
<tr>
<td>Bed</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Execution policy</td>
<td>0.7056</td>
</tr>
<tr>
<td>Bed * Execution policy</td>
<td>0.2569</td>
</tr>
<tr>
<td>Dependent variable: WIP</td>
<td></td>
</tr>
<tr>
<td>Bed</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Execution policy</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Bed * Execution policy</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>
The tests showed WIP\(^1\) values between any two scenarios are significantly different at the confident level \(\alpha=0.05\). Scenarios could also be divided into four subgroups according to different overhead bucket breakdown spots (N.A., Bed III, Bed II, and Bed I, see Table 4.8). Duration values are significantly different among subgroups at \(\alpha=0.05\), and within-subgroup duration is not significantly different. That is, different labor policies under the model

---

\(^1\) WIP is the summation of all average content of WIP\(_i\), \(i=1,2,3,...9\), which is generated by Stroboscope simulation software.
assumptions have more or less the same effect on total schedule. This could be explained by
the critical path. For example, when the overhead bucket breaks down on Bed III, the project
manager may prefer to send the laborers to help Cut & Remove in Bed II; thus the task
duration for Cut & Remove 2 could be decreased. Under such a model assumption, no matter
how much the task duration for Cut & Remove decreased, it would not affect the total
schedule, because the critical path then is determined by the task Place Concrete. That is,
keeping labor busy can reduce a task’s duration but have no effect on total project duration if
the accelerated task is not on the critical path. Furthermore, in this circumstance, keeping
busy policy increases WIP, the inventory between the start and end points of a product
routing (Hopp and Spearman 2008). WIP represents work accumulating ahead of laborers
waiting to be processed. High WIP can be due to an unbalanced work pace of different
laborers. If not handled, in-progress products may be damaged, requiring rework. Thus, high
WIP indicates more management resources. In this perspective, increase in WIP can lead to
new variation and thus reduce in production system performance. To summarize, keeping
labor busy in the face of variation is an alternative policy but not always the best option.
In addition, the simulation results also demonstrate the trade off between project duration and
WIP. As shown in Table 4.12, among different subgroups, as the project duration increases,
the WIP decreases. For example, the project duration increases about 20 minutes, while the
WIP decreases about 0.1, as the bucket breakdown spot switches from Bed III to Bed II. The
20-minute difference in task duration incurs about 40% increase (from about 67 dollars/day
to 93 dollars/day) in cost overrun. According to the concept of cost benefit analysis, the
management need to consider the project duration and WIP trade-off when they make
decision. And it also indicates that the later the overhead bucket breakdown occurs during a
day, the worse impact it has on the production system in terms of the prefabricator’s money
loss. Thus management effort should be made to detect the potential problem as early as
possible, avoiding the breakdown occurs on Bed II and Bed I under this model set up.

4.3.4 Discussion

The CPM method was used to help assess the simulation results. Deterministic task durations
were utilized in the analysis for simplification purpose. The durations are given in Table 4.16.

Table 4.16  Task Deterministic Duration

<table>
<thead>
<tr>
<th>Task</th>
<th>Duration(min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean Bed</td>
<td>30</td>
</tr>
<tr>
<td>Pull Strands</td>
<td>15</td>
</tr>
<tr>
<td>Place Concrete</td>
<td>150</td>
</tr>
<tr>
<td>Cut &amp; Remove 3</td>
<td>105</td>
</tr>
<tr>
<td>Cut &amp; Remove 2</td>
<td>165</td>
</tr>
<tr>
<td>Cut &amp; Remove 1</td>
<td>205</td>
</tr>
<tr>
<td>Cure</td>
<td>390</td>
</tr>
</tbody>
</table>

Figure 4.18 and 4.19 demonstrate the logic of different tasks when no equipment breakdown
occurs. Under this circumstance, the project duration is 670 minutes.

And the critical path for this project is Cut & Remove 3 → Cut & Remove 2 → Cut &
Remove 1 → Clean Bed 1 → Pull Strands 1 → Place Concrete 1. When the breakdown
occurs, activity duration on the critical path may change, leading to different project duration.
The total float and free float given in Table 4.17 indicate the allowable time change to
maintain the critical path.


Table 4.17 Task Total Float and Free Float

<table>
<thead>
<tr>
<th>Activity</th>
<th>Total Float</th>
<th>Free Float</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut &amp; Remove 3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Clean Bed 3</td>
<td>70</td>
<td>0</td>
</tr>
<tr>
<td>Pull Strands 3</td>
<td>70</td>
<td>0</td>
</tr>
<tr>
<td>Place Concrete 3</td>
<td>70</td>
<td>15</td>
</tr>
<tr>
<td>Cut &amp; Remove 2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Clean Bed 2</td>
<td>55</td>
<td>0</td>
</tr>
<tr>
<td>Pull Strands 2</td>
<td>55</td>
<td>0</td>
</tr>
<tr>
<td>Place Concrete 2</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>Cut &amp; Remove 1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Clean Bed 1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Pull Strands 1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Place Concrete 1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Let overhead bucket breakdown duration= x min (x>0)

Cut & Remove 2 duration after acceleration=y2 min (y2>0)

Cut & Remove 1 duration after acceleration=y1min (y1>0)

(1) Scenario 1

Project duration=670

(2) Scenario 2-4

Project duration=600+x

- Policy I Keep labors waiting (Scenario 2)
  - IF x<=70, then no effect on project duration
  - IF x>70, then project duration is increased by x-70

- Policy II Send labors to Bed II helping cut & remove (Scenario 3-4)
  - IF x<=70, y2<=x+95, then project duration is decreased by 70-x
  - IF x<=70, x+95<y2<=165, then project duration is decreased by 165-y2
- IF \( x > 70 \), then project duration is increased by \( x - 70 \)

(3) Scenario 5-7

Project duration = \( 615 + x \)

- Policy I Keep labors waiting (Scenario 5)
  - IF \( x \leq 55 \), then no effect on project duration
  - IF \( x > 55 \), then project duration is increased by \( x - 55 \)

- Policy II Send labors to Bed I helping cut & remove (Scenario 6-7)
  - IF \( x \leq 55 \), \( y_1 \leq x + 150 \), then project duration is decreased by \( 55 - x \)
  - IF \( x \leq 55 \), \( x + 150 < y_1 \leq 205 \), then project duration is decreased by \( 205 - y_1 \)
  - IF \( x > 55 \), then project duration is increased by \( x - 55 \)

(4) Scenario 8-9

Project duration = \( 670 + x \)

- Policy I Keep labors waiting (Scenario 8)
  - Project duration is increased by \( x \).

- Policy II Send labors to Bed II helping cut & remove (Scenario 9)
  - N.A.

From the deterministic analysis utilizing CPM, we can see that the downtime---overhead bucket breakdown duration used in simulation was 120 minutes which is larger than both 70 and 55. Under these circumstances, keeping labor waiting and sending laborers to other tasks
have same effect on project duration no matter how much the task duration of Cut & Remove could be reduced. It also proved the validity of the simulation model.

To summarize, keeping labor busy in the face of variation is an alternative policy but not always the best option which is different from our intuitive understanding of the process. It indicates that the prefabricators should learn to control variation as opposed to only focusing management efforts on keeping laborers busy. However, in reality, the prefabricators do not consider WIP increase and prefer to keep laborers busy in the face of variability due to 2 considerations. To illustrate this, the situation in the simulation is used. First, keeping laborers busy is a morale issue. The overhead breakdown usually means the laborers responsible for placing concrete need work overtime and thus they can get overtime pay which is higher than normal pay during the day. If the placing concrete laborers are idle and waiting until the equipment problem is resolved in the face of variation, other laborers may feel unsatisfied due to the fact that the placing concrete laborers can have a rest and still work overtime and get overtime pay. Second, keeping laborers busy is a money saving issue. Although the total duration could not be compressed, certain task duration (Cut & Remove) could be decreased by adding more labor. Keeping laborers busy in the face of variation by sending them to help Cut & Remove means the laborers responsible for cutting and removing could finish their job and leave on time or even earlier than usual. All laborers are paid by the total working hours on a weekly basis. Consequently, keeping laborers busy would save money. The above 2 considerations addressed the limitation of my research, that the human
factor which cannot be modeled by simulation also plays an important role in decision making in the practice.
Figure 4.18  Activity-on-Node (Normal Schedule without Equipment Breakdown)
Figure 4.19  Gantt Chart (Normal Schedule without Equipment Breakdown)
5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following observations and conclusions are based on the research conducted in this study.

Part I: Field Study

1. Both positive and negative variations were observed in the field study. Cut & Remove and Place Concrete cause major task duration variation and its successor Clean Bed causes major task starting time variation.

2. Higher design/work complexity tends to cause more variation on task duration and task productivity.

3. The top three causes of task starting time variation are prerequisite work, tools/equipment and labour force.

4. The top three causes of task duration variation are tools/equipment, detailed design/working method and materials/components.

5. The penalties associated with not reducing variation are increases in project duration and Work in Progress (WIP) and a decrease in labor productivity.

Part II: Computer Simulation

6. By simulating and comparing two execution policies in the face of variation, the results show that keeping laborers busy in the face of variation is an alternative policy but not always the best one. Keeping laborers busy can reduce certain task’s duration but have no effect on total project duration reduction if the task accelerated is not on
the critical path. Under this circumstance, keeping laborers busy increases WIP which can lead to new variation and thus damage production system performance.

7. Simulation proved to be an effective tool to solve what-if type of decision making problems. The simulation model has good representation of the reality. Strategy and remedy exhaust the problem and solution domain systematically. Any other strategy and remedy can be a linear combination of the above 9 scenarios. The analysis and simulation can be adopted by other researchers and the conclusion can be used by the company.

5.2 Recommendations for Future Research

Several recommendations for future research were indentified during this study.

1. Using probabilistic models to generate production schedule which will be more realistic when used as a benchmark to calculate variation

2. Modelling repair time and task duration reduction as distributions, because in reality, the repair time changes thus task duration reduction potential changes accordingly. This needs longer time observation on site

3. Generalizing beyond the conditions at the concrete slab prefabrication shop

4. Viewing barriers in a broader context (i.e., how the prefabrication shop better can adapt to demands variability which is an external source for variation)
REFERENCES


APPENDICES
## Appendix A Data Collection Sheets

Table A.1 Task Starting Time and Duration Variation-Clean Bed and Pull Strands (min)

<table>
<thead>
<tr>
<th>Date</th>
<th>BED</th>
<th>Clean Bed</th>
<th>Pull Strands</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Duration</td>
<td>Starting Time Variation</td>
</tr>
<tr>
<td>1/25</td>
<td>I</td>
<td>30</td>
<td>-39</td>
</tr>
<tr>
<td>1/25</td>
<td>II</td>
<td>35</td>
<td>-27</td>
</tr>
<tr>
<td>1/25</td>
<td>III</td>
<td>30</td>
<td>-8</td>
</tr>
<tr>
<td>1/26</td>
<td>I</td>
<td>29</td>
<td>-20</td>
</tr>
<tr>
<td>1/26</td>
<td>II</td>
<td>32</td>
<td>-29</td>
</tr>
<tr>
<td>1/26</td>
<td>III</td>
<td>27</td>
<td>-11</td>
</tr>
<tr>
<td>1/27</td>
<td>I</td>
<td>31</td>
<td>57</td>
</tr>
<tr>
<td>1/27</td>
<td>II</td>
<td>30</td>
<td>28</td>
</tr>
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<td>1/27</td>
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<td>-3</td>
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<td>1/28</td>
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<td>II</td>
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<td>2/2</td>
<td>I</td>
<td>29</td>
<td>26</td>
</tr>
<tr>
<td>2/2</td>
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<td>31</td>
<td>-9</td>
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Table A.1 Continued

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<td>2/2</td>
<td>III</td>
<td>30</td>
<td>12</td>
<td>PW1</td>
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<td>17</td>
<td>12</td>
<td>PW1</td>
</tr>
<tr>
<td>2/3</td>
<td>I</td>
<td>23</td>
<td>142</td>
<td>PW1</td>
<td>-7</td>
<td>LF 9</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2/3</td>
<td>II</td>
<td>23</td>
<td>48</td>
<td>PW1</td>
<td>-7</td>
<td>LF 9</td>
<td>15</td>
<td>45</td>
</tr>
<tr>
<td>2/3</td>
<td>III</td>
<td>27</td>
<td>4</td>
<td>PW1</td>
<td>-3</td>
<td>LF 9</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>2/4</td>
<td>I</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>15</td>
<td>-16</td>
</tr>
<tr>
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<td>II</td>
<td>34</td>
<td>137</td>
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<td>4</td>
<td>PW1</td>
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<td>N/A</td>
</tr>
<tr>
<td>2/4</td>
<td>III</td>
<td>29</td>
<td>-5</td>
<td>PW2</td>
<td>-1</td>
<td>15</td>
<td>20</td>
<td>PW1</td>
</tr>
</tbody>
</table>

* Indicates no variation or no obvious reason captured.
Table A.2 Task Starting Time and Duration Variation—Place Concrete (min)

<table>
<thead>
<tr>
<th>Date</th>
<th>BED</th>
<th>Duration</th>
<th>Starting Time Variation</th>
<th>Reason</th>
<th>Duration Variation</th>
<th>Reason</th>
<th>Set Up Extruder</th>
<th>Pouring</th>
<th>Clean Extruder</th>
<th>Move Extruder</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/25</td>
<td>I</td>
<td>233</td>
<td>-8</td>
<td>PW2</td>
<td>83</td>
<td>TEQ3</td>
<td>10</td>
<td>107</td>
<td>29</td>
<td>0</td>
</tr>
<tr>
<td>1/25</td>
<td>II</td>
<td>151</td>
<td>-12</td>
<td>PW2</td>
<td>1</td>
<td>TEQ3</td>
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Appendix B Stroboscope Simulation Code

/***********************************************
/* Stroboscope source file generated from Visio drawing C:\Users\Wang Chao\Desktop\simulation\Scenario 1.vsd
***********************************************
/* General section for problem parameters
VARIABLE CurrentHour Mod[4+SimTime/60,24];
VARIABLE WorkingHours 'CurrentHour>=4 & CurrentHour<15';
VARIABLE NrIterations 1000;
SAVEVALUE CurrentIteration* 1;
/***********************************************
/* Definition of resource types
GENTYPE Bed; /BE
GENTYPE Cable; /ST
GENTYPE Concrete; /CO
GENTYPE Crane; /CR
COMPTYPE CRCrew; /CU
GENTYPE Equipment; /EQ
GENTYPE Extruter; /EX
GENTYPE Hopper; /HO
GENTYPE Hydrcylinder; /HY
GENTYPE labor; /LA
GENTYPE OverheadBucket; /OV
COMPTYPE PCCrew; /CR
GENTYPE Run; /RU
GENTYPE Saw; /SA
GENTYPE Seq; /SE
GENTYPE slab; /SL
GENTYPE Ticket; /TI
/***********************************************
/* Definition of network nodes
COMBI CleanBed1;
COMBI CleanBed2;
COMBI CleanBed3;
QUEUE WIP1 Run;
QUEUE WIP4 Run;
QUEUE WIP7 Run;
COMBI PullStrands1;
COMBI PullStrands2;
COMBI PullStrands3;
QUEUE WIP2 Run;
QUEUE WIP5 Run;
QUEUE WIP8 Run;
COMBI PlaceConcrete1;
COMBI PlaceConcrete2;
COMBI PlaceConcrete3;
NORMAL Cure1;
NORMAL Cure2;
NORMAL Cure3;
QUEUE WIP3 Run;
QUEUE WIP6 Run;
QUEUE WIP9 Run;
COMBI CutandRemove1;
COMBI CutandRemove2;
COMBI CutandRemove3;
QUEUE SlabReady slab;
QUEUE Bucket OverheadBucket;
QUEUE Extr Extruter;
QUEUE Rbed1 Bed;
QUEUE Rbed2 Bed;
QUEUE Rbed3 Bed;
QUEUE Lab labor;
QUEUE CuttingSaw Saw;
QUEUE Concre1 Concrete;
QUEUE Concre2 Concrete;
QUEUE Concre3 Concrete;
QUEUE BedReady Bed;
/
*************************************************************************/
********
*********
/* Definition of network Links */
LINK Link1 CleanBed1 WIP1;
LINK Link2 WIP1 PullStrands1;
LINK Link3 PullStrands1 WIP2;
LINK Link4 WIP2 PlaceConcrete1;
LINK Link5 PlaceConcrete1 Cure1 Run;
LINK Link6 Cure1 WIP3;
LINK Link7 WIP3 CutandRemove1;
LINK Link8 CutandRemove1 SlabReady;
LINK Link9 CleanBed2 WIP4;
LINK Link10 WIP4 PullStrands2;
LINK Link11 PullStrands2 WIP5;
LINK Link12 WIP5 PlaceConcrete2;
LINK Link13 PlaceConcrete2 Cure2 Run;
LINK Link14 Cure2 WIP6;
LINK Link15 WIP6 CutandRemove2;
LINK Link16 CutandRemove2 SlabReady;
LINK Link17 CleanBed3 WIP7;
LINK Link18 WIP7 PullStrands3;
LINK Link19 PullStrands3 WIP8;
LINK Link20 WIP8 PlaceConcrete3;
LINK Link21 PlaceConcrete3 Cure3 Run;
LINK Link22 Cure3 WIP9;
LINK Link23 WIP9 CutandRemove3;
LINK Link24 CutandRemove3 SlabReady;
LINK HP5 Bucket PlaceConcrete3;
LINK HP6 PlaceConcrete3 Bucket;
LINK EX3 Extr PlaceConcrete2;
LINK EX4 PlaceConcrete2 Extr;
LINK RB1 Rbed1 CleanBed1;
LINK RB2 CutandRemove1 Rbed1;
LINK RB3 Rbed2 CleanBed2;
LINK RB4 CutandRemove2 Rbed2;
LINK RB5 Rbed3 CleanBed3;
LINK RB6 CutandRemove3 Rbed3;
LINK EX1 Extr PlaceConcrete1;
LINK EX2 PlaceConcrete1 Extr;
LINK EX5 Extr PlaceConcrete3;
LINK EX6 PlaceConcrete3 Extr;
LINK HP3 Bucket PlaceConcrete2;
LINK HP4 PlaceConcrete2 Bucket;
LINK HP1 Bucket PlaceConcrete1;
LINK HP2 PlaceConcrete1 Bucket;
LINK LA1 Lab PlaceConcrete2;
LINK LA2 PlaceConcrete2 Lab;
LINK LA3 Lab PlaceConcrete1;
LINK LA4 PlaceConcrete1 Lab;
LINK LA5 Lab PlaceConcrete3;
LINK LA6 PlaceConcrete3 Lab;
LINK CM1 CuttingSaw CutandRemove3;
LINK CM2 CutandRemove3 CuttingSaw;
LINK CM3 CuttingSaw CutandRemove2;
LINK CM4 CutandRemove2 CuttingSaw;
LINK CM5 CuttingSaw CutandRemove1;
LINK CM6 CutandRemove1 CuttingSaw;
LINK Cr3 Concre3 PlaceConcrete3;
LINK Cr2 Concre2 PlaceConcrete2;
LINK Cr1 Concre1 PlaceConcrete1;
LINK   Link30 PlaceConcrete1 BedReady;
LINK   Link31 PlaceConcrete2 BedReady;
LINK   Link32 PlaceConcrete3 BedReady;

/*******************************************************************************/
/* Definition of global variables and programing objects */
COLLECTOR ProjectDuration*;
COLLECTOR WIP*;

/*******************************************************************************/
/* Startup of CleanBed1 */
PRIORITY   CleanBed1 '1';
DRAWAMT    RB1 '1';
DURATION   CleanBed1 'Triangular[22.5, 30, 35.5]';

/*******************************************************************************/
/* Termination of CleanBed1 */
RELEASEAMT  Link1 '1';

/*******************************************************************************/
/* Startup of CleanBed2 */
PRIORITY   CleanBed2 '2';
DRAWAMT    RB3 '1';
DURATION   CleanBed2 'Triangular[22.5, 30, 35.5]';

/*******************************************************************************/
/* Termination of CleanBed2 */
RELEASEAMT  Link9 '1';

/*******************************************************************************/
/* Startup of CleanBed3 */
PRIORITY   CleanBed3 '3';
DRAWAMT    RB5 '1';
DURATION   CleanBed3 'Triangular[22.5, 30, 35.5]';

/*******************************************************************************/
/* Termination of CleanBed3 */
RELEASEAMT  Link17 '1';

/*******************************************************************************/
/* Startup of PullStrands1 */
DRAWAMT    Link2 '1';
DURATION   PullStrands1 'Triangular[12.5, 15, 18.5]';

/*******************************************************************************/
/* Termination of PullStrands1 */
RELEASEAMT Link3 '1';

/* Startup of PullStrands2 */
DRAWMAT  Link10 '1';
DURATION  PullStrands2 'Triangular[12.5, 15, 18.5]';

/* Termination of PullStrands2 */
RELEASEAMT Link11 '1';

/* Startup of PullStrands3 */
DRAWMAT  Link18 '1';
DURATION  PullStrands3 'Triangular[12.5, 15, 18.5]';

/* Termination of PullStrands3 */
RELEASEAMT Link19 '1';

/* Startup of PlaceConcrete1 */
DRAWMAT  Link4 '1';
DRAWMAT  EX1 '1';
DRAWMAT  HP1 '1';
DRAWMAT  LA3 '2';
DRAWMAT  Cr1 '1';
DURATION  PlaceConcrete1 'Normal[154, 22.9]';

/* Termination of PlaceConcrete1 */
RELEASEAMT Link5 '1';
RELEASEAMT EX2 '1';
RELEASEAMT HP2 '1';
RELEASEAMT LA4 '2';
RELEASEAMT Link30 '1';

/* Startup of PlaceConcrete2 */
DRAWMAT  Link12 '1';
DRAWMAT  EX3 '1';
DRAWMAT  HP3 '1';
DRAWMAT  LA1 '2';
DRAWMAT  Cr2 '1';
DURATION  PlaceConcrete2 'Normal[154, 22.9]';
 Termination of PlaceConcrete2
RELEASEAMT    Link13 '1';
RELEASEAMT    EX4 '1';
RELEASEAMT    HP4 '1';
RELEASEAMT    LA2 '2';
RELEASEAMT    Link31 '1';

 Startup of PlaceConcrete3
DRA W AMT    Link20 '1';
DRA W AMT    HP5 '1';
DRA W AMT    EX5 '1';
DRA W AMT    LA5 '2';
DRA W AMT    Cr3 '1';
DURATION    PlaceConcrete3 'Normal[154, 22.9]';

 Termination of PlaceConcrete3
RELEASEAMT    Link21 '1';
RELEASEAMT    HP6 '1';
RELEASEAMT    EX6 '1';
RELEASEAMT    LA6 '2';
RELEASEAMT    Link32 '1';

 Startup of Cure1
DURATION    Cure1 '390';

 Termination of Cure1
RELEASEAMT    Link6 '1';

 Startup of Cure2
DURATION    Cure2 '390';

 Termination of Cure2
RELEASEAMT    Link14 '1';

 Startup of Cure3
DURATION    Cure3 '390';
/******************************************
***************************************
*****************
/* Termination of Cure3
RELEASEAMT  Link22 '1';
/* Startup of CutandRemove1
PRIORITY  CutandRemove1 '1';
DRAWAMT  Link7 '1';
DRAWAMT  CM5 '1';
DURATION  CutandRemove1 'Triangular[160, 191, 268]';
/****************************
**************
/* Termination of CutandRemove1
RELEASEAMT  Link8 '1';
RELEASEAMT  RB2 '1';
RELEASEAMT  CM6 '1';
/****************************
**************
/* Startup of CutandRemove2
PRIORITY  CutandRemove2 '2';
DRAWAMT  Link15 '1';
DRAWAMT  CM3 '1';
DURATION  CutandRemove2 'Triangular[117, 130, 252]';
/****************************
**************
/* Termination of CutandRemove2
RELEASEAMT  Link16 '1';
RELEASEAMT  RB4 '1';
/****************************
**************
/* Startup of CutandRemove3
PRIORITY  CutandRemove3 '3';
DRAWAMT  Link23 '1';
DRAWAMT  CM1 '1';
DURATION  CutandRemove3 '96.5 + Gamma[4.5, 1.35]';
/****************************
**************
/* Termination of CutandRemove3
RELEASEAMT  Link24 '1';
RELEASEAMT  RB6 '1';
RELEASEAMT  CM2 '1';
/****************************
**************
/* Initialization of Queues, Running the Simulation, Presenting Results
/Print the header of the output table
PRINT StdOutput "

93
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<th>Iteration</th>
<th>ProjectDuration</th>
<th>WIP</th>
</tr>
</thead>
<tbody>
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</table>

```
/* Iteration
***************
WHILE CurrentIteration<=NrIterations;
CLEAR;
INIT Rbed1 0;
INIT Rbed2 0;
INIT Rbed3 0;
INIT Extr 1;
INIT Bucket 1;
INIT SlabReady 0;
INIT WIP1 0;
INIT WIP2 0;
INIT WIP3 1;
INIT WIP4 0;
INIT WIP5 0;
INIT WIP6 1;
INIT WIP7 0;
INIT WIP8 0;
INIT WIP9 1;
INIT Lab 2;
INIT CuttingSaw 1;
INIT Concre1 1;
INIT Concre2 1;
INIT Concre3 1;
SIMULATEUNTIL BedReady.CurCount==3;
COLLECT ProjectDuration SimTime;
COLLECT WIP
/ Print row with results
PRINT StdOutput
"%6.0f %15.2f %15.2f\n"
CurrentIteration
SimTime
ASSIGN CurrentIteration CurrentIteration+1;
WEND;
/***************
*/ Reporting
/***************
```
PRINT StdOutput "Ave\n" ProjectDuration.AveVal WIP.AveVal;
PRINT StdOutput "SD\n" ProjectDuration.SDVal WIP.SDVal;
PRINT StdOutput "Min\n" ProjectDuration.MinVal WIP.MinVal;
PRINT StdOutput "Max\n" ProjectDuration.MaxVal WIP.MaxVal;
/* Stroboscope source file generated from Visio drawing C:\Users\Wang Chao\Desktop\simulation\Scenario 2 3 4 .vsd

*****************************************************************************************

General section for problem parameters
VARIABLE CurrentHour Mod(4+SimTime/60.24);
VARIABLE WorkingHours 'CurrentHour>=4 & CurrentHour<15';
VARIABLE NrIterations 1000;
SAVEVALUE CurrentIteration* 1;
*****************************************************************************************

Definition of resource types
GENTYPE Bed; /BE
GENTYPE Cable; /ST
GENTYPE Concrete; /CO
GENTYPE Crane; /CR
COMPTYPE CRCrew; /CU
GENTYPE Equipment; /EQ
GENTYPE Extruter; /EX
GENTYPE Hopper; /HO
GENTYPE Hydrcylinder; /HY
GENTYPE labor; /LA
GENTYPE OverheadBucket; /OV
COMPTYPE PCCrew; /CR
GENTYPE Run; /RU
GENTYPE Saw; /SA
GENTYPE Seq; /SE
GENTYPE slab; /SL
GENTYPE Ticket; /TI
*****************************************************************************************

Definition of network nodes
COMBI CleanBed1;
COMBI CleanBed2;
COMBI CleanBed3;
QUEUE WIP1 Run;
QUEUE WIP4 Run;
QUEUE WIP7 Run;
COMBI PullStrands1;
COMBI PullStrands2;
COMBI PullStrands3;
QUEUE WIP2 Run;
QUEUE WIP5 Run;
QUEUE WIP8 Run;
COMBI PlaceConcrete1;
COMBI PlaceConcrete2;
COMBI PlaceConcrete3;
NORMAL Cure1;
NORMAL Cure2;
NORMAL Cure3;
QUEUE WIP3 Run;
QUEUE WIP6 Run;
QUEUE WIP9 Run;
COMBI CutandRemove1;
COMBI CutandRemove2;
COMBI CutandRemove3;
QUEUE SlabReady slab;
QUEUE Bucket OverheadBucket;
QUEUE Extr Extruter;
QUEUE Rbed1 Bed;
QUEUE Rbed2 Bed;
QUEUE Rbed3 Bed;
QUEUE Lab labor;
QUEUE CuttingSaw Saw;
QUEUE Concre1 Concrete;
QUEUE Concre2 Concrete;
QUEUE Concre3 Concrete;
QUEUE BedReady Bed;
COMBI Repair;
QUEUE WIP10 Run;

/**************************
**********
/* Definition of network Links
LINK Link1 CleanBed1 WIP1;
LINK Link2 WIP1 PullStrands1;
LINK Link3 PullStrands1 WIP2;
LINK Link4 WIP2 PlaceConcrete1;
LINK Link5 PlaceConcrete1 Cure1 Run;
LINK Link6 Cure1 WIP3;
LINK Link7 WIP3 CutandRemove1;
LINK Link8 CutandRemove1 SlabReady;
LINK Link9 CleanBed2 WIP4;
LINK Link10 WIP4 PullStrands2;
LINK Link11 PullStrands2 WIP5;
LINK Link12 WIP5 PlaceConcrete2;
LINK Link13 PlaceConcrete2 Cure2 Run;
LINK  Link14 Cure2 WIP6;
LINK  Link15 WIP6 CutandRemove2;
LINK  Link16 CutandRemove2 SlabReady;
LINK  Link17 CleanBed3 WIP7;
LINK  Link18 WIP7 PullStrands3;
LINK  Link19 PullStrands3 WIP8;
LINK  Link20 WIP8 Repair;
LINK  Link21 PlaceConcrete3 Cure3 Run;
LINK  Link22 Cure3 WIP9;
LINK  Link23 WIP9 CutandRemove3;
LINK  Link24 CutandRemove3 SlabReady;
LINK  HP5 Bucket PlaceConcrete3;
LINK  HP6 PlaceConcrete3 Bucket;
LINK  EX3 Extr PlaceConcrete2;
LINK  EX4 PlaceConcrete2 Extr;
LINK  RB1 Rbed1 CleanBed1;
LINK  RB2 CutandRemove1 Rbed1;
LINK  RB3 Rbed2 CleanBed2;
LINK  RB4 CutandRemove2 Rbed2;
LINK  RB5 Rbed3 CleanBed3;
LINK  RB6 CutandRemove3 Rbed3;
LINK  EX1 Extr PlaceConcrete1;
LINK  EX2 PlaceConcrete1 Extr;
LINK  EX5 Extr PlaceConcrete3;
LINK  EX6 PlaceConcrete3 Extr;
LINK  HP3 Bucket PlaceConcrete2;
LINK  HP4 PlaceConcrete2 Bucket;
LINK  HP1 Bucket PlaceConcrete1;
LINK  HP2 PlaceConcrete1 Bucket;
LINK  LA1 Lab PlaceConcrete2;
LINK  LA2 PlaceConcrete2 Lab;
LINK  LA3 Lab PlaceConcrete1;
LINK  LA4 PlaceConcrete1 Lab;
LINK  LA5 Lab PlaceConcrete3;
LINK  LA6 PlaceConcrete3 Lab;
LINK  CM1 CuttingSaw CutandRemove3;
LINK  CM2 CutandRemove3 CuttingSaw;
LINK  CM3 CuttingSaw CutandRemove2;
LINK  CM4 CutandRemove2 CuttingSaw;
LINK  CM5 CuttingSaw CutandRemove1;
LINK  CM6 CutandRemove1 CuttingSaw;
LINK  Cr3 Concrete3 PlaceConcrete3;
LINK  Cr2 Concrete2 PlaceConcrete2;
LINK  Cr1 Concrete1 PlaceConcrete1;
LINK  Link30 PlaceConcrete1 BedReady;
LINK Link31 PlaceConcrete2 BedReady;
LINK Link32 PlaceConcrete3 BedReady;
LINK HP7 Bucket Repair;
LINK HP8 Repair Bucket;
LINK Link40 Repair WIP10;
LINK Link41 WIP10 PlaceConcrete3;

/* Definition of global variables and programe objects
COLLECTOR ProjectDuration*;
COLLECTOR WIP*;

/* Startup of CleanBed1
PRIORITY CleanBed1 '1';
DRAWAMT RB1 '1';
DURATION CleanBed1 'Triangular[22.5, 30, 35.5]';

/* Termination of CleanBed1
RELEASEAMT Link1 '1';

/* Startup of CleanBed2
PRIORITY CleanBed2 '2';
DRAWAMT RB3 '1';
DURATION CleanBed2 'Triangular[22.5, 30, 35.5]';

/* Termination of CleanBed2
RELEASEAMT Link9 '1';

/* Startup of CleanBed3
PRIORITY CleanBed3 '3';
DRAWAMT RB5 '1';
DURATION CleanBed3 'Triangular[22.5, 30, 35.5]';

/* Termination of CleanBed3
RELEASEAMT Link17 '1';

/* Startup of PullStrands1
DRAWAMT Link2 '1';
DURATION PullStrands1 'Triangular[12.5, 15, 18.5]';
RENTERMINATION of PullStrands1
RELEASEAMT Link3 '1';

**/ STARTUP of PullStrands2
DRAWAMT Link10 '1';
DURATION PullStrands2 'Triangular[12.5, 15, 18.5]';

**/ TERMINATION of PullStrands2
RELEASEAMT Link11 '1';

**/ STARTUP of PullStrands3
DRAWAMT Link18 '1';
DURATION PullStrands3 'Triangular[12.5, 15, 18.5]';

**/ TERMINATION of PullStrands3
RELEASEAMT Link19 '1';

**/ STARTUP of PlaceConcrete1
DRAWAMT Link4 '1';
DRAWAMT EX1 '1';
DRAWAMT HP1 '1';
DRAWAMT LA3 '2';
DRAWAMT Cr1 '1';
DURATION PlaceConcrete1 'Normal[154, 22.9]';

**/ TERMINATION of PlaceConcrete1
RELEASEAMT Link5 '1';
RELEASEAMT EX2 '1';
RELEASEAMT HP2 '1';
RELEASEAMT LA4 '2';
RELEASEAMT Link30 '1';

**/ STARTUP of PlaceConcrete2
DRAWAMT Link12 '1';
DRAWAMT EX3 '1';
DRAWAMT HP3 '1';
DRAWAMT LA1 '2';
DRAWAMT Cr2 '1';
DURATION  PlaceConcrete2 'Normal[154, 22.9]';
/
/* Termination of PlaceConcrete2
RELEASEAMT  Link13 '1';
RELEASEAMT  EX4 '1';
RELEASEAMT  HP4 '1';
RELEASEAMT  LA2 '2';
RELEASEAMT  Link31 '1';
/ *******************
**********
*********

/*/ Startup of PlaceConcrete3
DRAWAMT  HP5 '1';
DRAWAMT  EX5 '1';
DRAWAMT  LA5 '2';
DRAWAMT  Cr3 '1';
DRAWAMT  Link41 '1';
DURATION  PlaceConcrete3 'Normal[154, 22.9]';
/****************************
**********
*********

/*/ Termination of PlaceConcrete3
RELEASEAMT  Link21 '1';
RELEASEAMT  HP6 '1';
RELEASEAMT  EX6 '1';
RELEASEAMT  LA6 '2';
RELEASEAMT  Link32 '1';
/****************************
**********
*********

/*/ Startup of Cure1
DURATION  Cure1 '390';
/****************************
**********
*********

/*/ Termination of Cure1
RELEASEAMT  Link6 '1';
/****************************
**********
*********

/*/ Startup of Cure2
DURATION  Cure2 '390';
/****************************
**********
*********

/*/ Termination of Cure2
RELEASEAMT  Link14 '1';
/****************************
**********
*********

/*/ Startup of Cure3

101
DURATION  Cure3 '390';
/*.................................................................................................................................
   * Termination of Cure3
RELEASEAMT   Link22 '1';
/*.................................................................................................................................
/* Startup of CutandRemove1
PRIORITY   CutandRemove1 '1';
DRAWAMT   Link7 '1';
DRAWAMT   CM5 '1';
DURATION  CutandRemove1 'Triangular[160, 191, 268]';
/*.................................................................................................................................
   * Termination of CutandRemove1
RELEASEAMT   Link8 '1';
RELEASEAMT   RB2 '1';
RELEASEAMT   CM6 '1';
/*.................................................................................................................................
/* Startup of CutandRemove2
PRIORITY   CutandRemove2 '2';
DRAWAMT   Link15 '1';
DRAWAMT   CM3 '1';
DURATION  CutandRemove2 'Triangular[117, 130, 252]';
/* DURATION  CutandRemove2 '0.75'Triangular[117, 130, 252]'; /*for scenario 3
/* DURATION  CutandRemove2 '0.5'Triangular[117, 130, 252]'; /*for scenario 4
/*.................................................................................................................................
   * Termination of CutandRemove2
RELEASEAMT   Link16 '1';
RELEASEAMT   RB4 '1';
/*.................................................................................................................................
/* Startup of CutandRemove3
PRIORITY   CutandRemove3 '3';
DRAWAMT   Link23 '1';
DRAWAMT   CM1 '1';
DURATION  CutandRemove3 '96.5 + Gamma[4.5, 1.35]';
/*.................................................................................................................................
   * Termination of CutandRemove3
RELEASEAMT   Link24 '1';
RELEASEAMT   RB6 '1';
RELEASEAMT   CM2 '1';
/* Startup of Repair
DRAWAAMT   Link20 '1';
DRAWAAMT   HP7 '1';
DURATION   Repair '120';
ائهم
**********

/* Termination of Repair
RELEASEAMT   HP8 '1';
RELEASEAMT   Link40 '1';
اتهم
**********

/* Initialization of Queues, Running the Simulation, Presenting Results

/Print the header of the output table
PRINT StdOutput "
Iteration    ProjectDuration    WIP
hr
=================================================================================
";
/******
/* Iteration
/******
WHILE CurrentIteration<=NrIterations;
CLEAR;
INIT Rbed1 0;
INIT Rbed2 0;
INIT Rbed3 0;
INIT Extr 1;
INIT Bucket 1;
INIT SlabReady 0;
INIT WIP1 0;
INIT WIP2 0;
INIT WIP3 1;
INIT WIP4 0;
INIT WIP5 0;
INIT WIP6 1;
INIT WIP7 0;
INIT WIP8 0;
INIT WIP9 1;
INIT Lab 2;
INIT CuttingSaw 1;
INIT Concre1 1;
INIT Concre2 1;
INIT Concre3 1;
SIMULATEUNTIL BedReady.CurCount==3;
COLLECT ProjectDuration SimTime;
COLLECT WIP
/ Print row with results
    PRINT StdOutput 
        "%6.0f %15.2f %15.2f\n"
    CurrentIteration SimTime 
ASSIGN CurrentIteration CurrentIteration+1;
WEND;
/***************
/* Reporting
/***************
PRINT StdOutput "Ave
    ProjectDuration.AveVal WIP.AveVal;
PRINT StdOutput "SD
    ProjectDuration.SDVal WIP.SDVal;
PRINT StdOutput "Min
    ProjectDuration.MinVal WIP.MinVal;
PRINT StdOutput "Max
    ProjectDuration.MaxVal WIP.MaxVal;
# Stroboscope source file generated from Visio drawing C:\Users\Wang Chao\Desktop\simulation\Scenario 5 6 7.vsd

/* General section for problem parameters
VARIABLE CurrentHour Mod[4+SimTime/60,24];
VARIABLE WorkingHours 'CurrentHour>4 & CurrentHour<15';
VARIABLE NrIterations 1000;
SAVEVALUE CurrentIteration* 1;

/* Definition of resource types
SEQ\TYPE Bed; /BE
SEQ\TYPE Cable; /ST
SEQ\TYPE Concrete; /CO
SEQ\TYPE Crane; /CR
COMPTYPE CRCrew; /CU
SEQ\TYPE Extruder; /EX
SEQ\TYPE Hopper; /HO
SEQ\TYPE Hydrcylinder; /HY
SEQ\TYPE labor; /LA
SEQ\TYPE OverheadBucket; /OV
COMPTYPE PCcrew; /CR
SEQ\TYPE Run; /RU
SEQ\TYPE Saw; /SA
SEQ\TYPE Seq; /SE
SEQ\TYPE slab; /SL
SEQ\TYPE Ticket; /TI

/* Definition of network nodes
COMBI CleanBed1;
COMBI CleanBed2;
COMBI CleanBed3;
QUEUE WIP1 Run;
QUEUE WIP4 Run;
QUEUE WIP7 Run;
COMBI PullStrands1;
COMBI PullStrands2;
COMBI PullStrands3;
QUEUE WIP2 Run;
QUEUE WIP5 Run;
QUEUE WIP8 Run;
COMBI PlaceConcrete1;
COMBI PlaceConcrete2;
COMBI PlaceConcrete3;
NORMAL Cure1;
NORMAL Cure2;
NORMAL Cure3;
QUEUE WIP3 Run;
QUEUE WIP6 Run;
QUEUE WIP9 Run;
COMBI CutandRemove1;
COMBI CutandRemove2;
COMBI CutandRemove3;
QUEUE SlabReady slab;
QUEUE Bucket OverheadBucket;
QUEUE Extr Extruter;
QUEUE Rbed1 Bed;
QUEUE Rbed2 Bed;
QUEUE Rbed3 Bed;
QUEUE Lab labor;
QUEUE CuttingSaw Saw;
QUEUE Concre1 Concrete;
QUEUE Concre2 Concrete;
QUEUE Concre3 Concrete;
QUEUE BedReady Bed;
COMBI Repair;
QUEUE WIP10 Run;

/****************************

// Definition of network Links
LINK Link1 CleanBed1 WIP1;
LINK Link2 WIP1 PullStrands1;
LINK Link3 PullStrands1 WIP2;
LINK Link4 WIP2 PlaceConcrete1;
LINK Link5 PlaceConcrete1 Cure1 Run;
LINK Link6 Cure1 WIP3;
LINK Link7 WIP3 CutandRemove1;
LINK Link8 CutandRemove1 SlabReady;
LINK Link9 CleanBed2 WIP4;
LINK Link10 WIP4 PullStrands2;
LINK Link11 PullStrands2 WIP5;
LINK Link12 WIP5 Repair;
LINK Link13 PlaceConcrete2 Cure2 Run;
LINK Link14 Cure2 WIP6;
LINK Link15 WIP6 CutandRemove2;
LINK Link16 CutandRemove2 SlabReady;
LINK Link17 CleanBed3 WIP7;
LINK Link18 WIP7 PullStrands3;
LINK Link19 PullStrands3 WIP8;
LINK Link20 WIP8 PlaceConcrete3;
LINK Link21 PlaceConcrete3 Cure3 Run;
LINK Link22 Cure3 WIP9;
LINK Link23 WIP9 CutandRemove3;
LINK Link24 CutandRemove3 SlabReady;
LINK HP5 Bucket PlaceConcrete3;
LINK HP6 PlaceConcrete3 Bucket;
LINK EX3 Extr PlaceConcrete2;
LINK EX4 PlaceConcrete2 Extr;
LINK RB1 Rbed1 CleanBed1;
LINK RB2 CutandRemove1 Rbed1;
LINK RB3 Rbed2 CleanBed2;
LINK RB4 CutandRemove2 Rbed2;
LINK RB5 Rbed3 CleanBed3;
LINK RB6 CutandRemove3 Rbed3;
LINK EX1 Extr PlaceConcrete1;
LINK EX2 PlaceConcrete1 Extr;
LINK EX5 Extr PlaceConcrete3;
LINK EX6 PlaceConcrete3 Extr;
LINK HP3 Bucket PlaceConcrete2;
LINK HP4 PlaceConcrete2 Bucket;
LINK HP1 Bucket PlaceConcrete1;
LINK HP2 PlaceConcrete1 Bucket;
LINK LA1 Lab PlaceConcrete2;
LINK LA2 PlaceConcrete2 Lab;
LINK LA3 Lab PlaceConcrete1;
LINK LA4 PlaceConcrete1 Lab;
LINK LA5 Lab PlaceConcrete3;
LINK LA6 PlaceConcrete3 Lab;
LINK CM1 CuttingSaw CutandRemove3;
LINK CM2 CutandRemove3 CuttingSaw;
LINK CM3 CuttingSaw CutandRemove2;
LINK CM4 CutandRemove2 CuttingSaw;
LINK CM5 CuttingSaw CutandRemove1;
LINK CM6 CutandRemove1 CuttingSaw;
LINK Cr3 Concrete3 PlaceConcrete3;
LINK Cr2 Concrete2 PlaceConcrete2;
LINK Cr1 Concrete1 PlaceConcrete1;
LINK Link30 PlaceConcrete1 BedReady;
LINK Link31 PlaceConcrete2 BedReady;
LINK Link32 PlaceConcrete3 BedReady;
LINK HP7 Bucket Repair;
LINK HP8 Repair Bucket;
LINK Link40 Repair WIP10;
LINK Link41 WIP10 PlaceConcrete2;

/* Definition of global variables and programming objects */
COLLECTOR ProjectDuration*;
COLLECTOR WIP*;

/* Startup of CleanBed1 */
PRIORITY CleanBed1 '1';
DRAWAMT RB1 '1';
DURATION CleanBed1 'Triangular[22.5, 30, 35.5]';

/* Termination of CleanBed1 */
RELEASEAMT Link1 '1';

/* Startup of CleanBed2 */
PRIORITY CleanBed2 '2';
DRAWAMT RB3 '1';
DURATION CleanBed2 'Triangular[22.5, 30, 35.5]';

/* Termination of CleanBed2 */
RELEASEAMT Link9 '1';

/* Startup of CleanBed3 */
PRIORITY CleanBed3 '3';
DRAWAMT RB5 '1';
DURATION CleanBed3 'Triangular[22.5, 30, 35.5]';

/* Termination of CleanBed3 */
RELEASEAMT Link17 '1';

/* Startup of PullStrands1 */
DRAWAMT Link2 '1';
DURATION PullStrands1 'Triangular[12.5, 15, 18.5]';

//*********************************************************
// Termination of PullStrands1
RELEASEAMT Link3 '1';
//*********************************************************

// Startup of PullStrands2
DRAWAMT Link10 '1';
DURATION PullStrands2 'Triangular[12.5, 15, 18.5]';
//*********************************************************

// Termination of PullStrands2
RELEASEAMT Link11 '1';
//*********************************************************

// Startup of PullStrands3
DRAWAMT Link18 '1';
DURATION PullStrands3 'Triangular[12.5, 15, 18.5]';
//*********************************************************

// Termination of PullStrands3
RELEASEAMT Link19 '1';
DRAWAMT Link4 '1';
DRAWAMT EX1 '1';
DRAWAMT HP1 '1';
DRAWAMT LA3 '2';
DRAWAMT Cr1 '1';
DURATION PlaceConcrete1 'Normal[154, 22.9]';
//*********************************************************

// Termination of PlaceConcrete1
RELEASEAMT Link5 '1';
RELEASEAMT EX2 '1';
RELEASEAMT HP2 '1';
RELEASEAMT LA4 '2';
RELEASEAMT Link30 '1';
//*********************************************************

// Startup of PlaceConcrete2
DRAWAMT EX3 '1';
DRAWAMT HP3 '1';
DRAWAMT LA1 '2';
DRAWAMT Cr2 '1';
DRAWAMT Link41 '1';
DURATION PlaceConcrete2 'Normal[154, 22.9]';
/*-------------------------------------------------------------------------------------------*/
/* Termination of PlaceConcrete2 */
RELEASEAMT Link13 '1';
RELEASEAMT EX4 '1';
RELEASEAMT HP4 '1';
RELEASEAMT LA2 '2';
RELEASEAMT Link31 '1';
/*-------------------------------------------------------------------------------------------*/
/* Startup of PlaceConcrete3 */
DRAWAMT Link20 '1';
DRAWAMT HP5 '1';
DRAWAMT EX5 '1';
DRAWAMT LA5 '2';
DRAWAMT Cr3 '1';
DURATION PlaceConcrete3 'Normal[154, 22.9]';
/*-------------------------------------------------------------------------------------------*/
/* Termination of PlaceConcrete3 */
RELEASEAMT Link21 '1';
RELEASEAMT HP6 '1';
RELEASEAMT EX6 '1';
RELEASEAMT LA6 '2';
RELEASEAMT Link32 '1';
/*-------------------------------------------------------------------------------------------*/
/* Startup of Cure1 */
DURATION Cure1 '390';
/*-------------------------------------------------------------------------------------------*/
/* Termination of Cure1 */
RELEASEAMT Link6 '1';
/*-------------------------------------------------------------------------------------------*/
/* Startup of Cure2 */
DURATION Cure2 '390';
/*-------------------------------------------------------------------------------------------*/
/* Termination of Cure2 */
RELEASEAMT Link14 '1';
/*-------------------------------------------------------------------------------------------*/
/* Startup of Cure3 */
DURATION  Cure3 '390';
/******************************************************************************************/
/* Termination of Cure3*/
RELEASEAMT  Link22 '1';
/* Startup of CutandRemove1*/
PRIORITY CutandRemove1 '1';
DRAWAMT  Link7 '1';
DRAWAMT  CM5 '1';
DURATION  CutandRemove1 'Triangle[160, 191, 268]';
/* DURATION  CutandRemove1 '0.75*Triangle[160, 191, 268]'; */for scenario 6
/* DURATION  CutandRemove1 '0.5*Triangle[160, 191, 268]'; */for scenario 7
/******************************************************************************************/
/* Termination of CutandRemove1*/
RELEASEAMT  Link8 '1';
RELEASEAMT  RB2 '1';
RELEASEAMT  CM6 '1';
/******************************************************************************************/
/* Startup of CutandRemove2*/
PRIORITY CutandRemove2 '2';
DRAWAMT  Link15 '1';
DRAWAMT  CM3 '1';
DURATION  CutandRemove2 'Triangle[117, 130, 252]';
/******************************************************************************************/
/* Termination of CutandRemove2*/
RELEASEAMT  Link16 '1';
RELEASEAMT  RB4 '1';
/******************************************************************************************/
/* Startup of CutandRemove3*/
PRIORITY CutandRemove3 '3';
DRAWAMT  Link23 '1';
DRAWAMT  CM1 '1';
DURATION  CutandRemove3 '96.5 + Gamma[4.5, 1.35]';
/******************************************************************************************/
/* Termination of CutandRemove3*/
RELEASEAMT  Link24 '1';
RELEASEAMT  RB6 '1';
RELEASEAMT  CM2 '1';
/******************************************************************************************/

111
/* Startup of Repair
DRAWAMT Link12 '1';
DRAWAMT HP7 '1';
DURATION Repair '120';

/* Termination of Repair
RELEASEAMT HP8 '1';
RELEASEAMT Link40 '1';

/* Initialization of Queues, Running the Simulation, Presenting Results
/Print the header of the output table
PRINT StdOutput "
Iteration  ProjectDuration  WIP
hr
===================================\n";

/* Iteration
/*/
WHILE CurrentIteration<=NrIterations;

CLEAR;

INIT Rbed1 0;
INIT Rbed2 0;
INIT Rbed3 0;
INIT Extr 1;
INIT Bucket 1;
INIT SlabReady 0;
INIT WIP1 0;
INIT WIP2 0;
INIT WIP3 1;
INIT WIP4 0;
INIT WIP5 0;
INIT WIP6 1;
INIT WIP7 0;
INIT WIP8 0;
INIT WIP9 1;
INIT Lab 2;
INIT CuttingSaw 1;
INIT Concre1 1;
INIT Concre2 1;
INIT Concre3 1;
SIMULATE UNTIL BedReady.CurCount==3;
COLLECT ProjectDuration SimTime;
COLLECT WIP

/ Print row with results
PRINT StdOutput
"%6.0f %15.2f %15.2f\n"
CurrentIteration
SimTime
ASSIGN CurrentIteration CurrentIteration+1;
WEND;

/***************
/* Reporting
/***************
PRINT StdOutput "Ave %15.2f %15.2f\n"
ProjectDuration.AveVal
WIP.AveVal;
PRINT StdOutput "SD %15.2f %15.2f\n"
ProjectDuration.SDVal
WIP.SDVal;
PRINT StdOutput "Min %15.2f %15.2f\n"
ProjectDuration.MinVal
WIP.MinVal;
PRINT StdOutput "Max %15.2f %15.2f\n"
ProjectDuration.MaxVal
WIP.MaxVal;
**Stroboscope source file generated from Visio drawing C:\Users\WangChao\Desktop\simulation\Scenario 8.vsd**

/*****************
/* General section for problem parameters
VARIABLE CurrentHour Mod[4+SimTime/60,24];
VARIABLE WorkingHours 'CurrentHour>=4 & CurrentHour<15';
VARIABLE NrIterations 1000;
SAVEVALUE CurrentIteration* 1;
/*****************/

/** Definition of resource types
GENTYPE Bed; /BE
GENTYPE Cable; /ST
GENTYPE Concrete; /CO
GENTYPE Crane; /CR
COMPTYPE CRCrew; /CU
GENTYPE Equipment; /EQ
GENTYPE Extruter; /EX
GENTYPE Hopper; /HO
GENTYPE Hydrcylinder; /HY
GENTYPE labor; /LA
GENTYPE OverheadBucket; /OV
COMPTYPE PCCrew; /CR
GENTYPE Run; /RU
GENTYPE Saw; /SA
GENTYPE Seq; /SE
GENTYPE slab; /SL
GENTYPE Ticket; /TI
/*******************/

/** Definition of network nodes
COMBI CleanBed1;
COMBI CleanBed2;
COMBI CleanBed3;
QUEUE WIP1 Run;
QUEUE WIP4 Run;
QUEUE WIP7 Run;
COMBI PullStrands1;
COMBI PullStrands2;
COMBI PullStrands3;
QUEUE WIP2 Run;
QUEUE WIP5 Run;}
QUEUE WIP8 Run;
COMBI PlaceConcrete1;
COMBI PlaceConcrete2;
COMBI PlaceConcrete3;
NORMAL Cure1;
NORMAL Cure2;
NORMAL Cure3;
QUEUE WIP3 Run;
QUEUE WIP6 Run;
QUEUE WIP9 Run;
COMBI CutandRemove1;
COMBI CutandRemove2;
COMBI CutandRemove3;
QUEUE SlabReady slab;
QUEUE Bucket OverheadBucket;
QUEUE Extr Extruter;
QUEUE Rbed1 Bed;
QUEUE Rbed2 Bed;
QUEUE Rbed3 Bed;
QUEUE Lab labor;
QUEUE CuttingSaw Saw;
QUEUE Concre1 Concrete;
QUEUE Concre2 Concrete;
QUEUE Concre3 Concrete;
QUEUE BedReady Bed;
COMBI Repair;
QUEUE WIP10 Run;
/* Definition of network Links
LINK Link1 CleanBed1 WIP1;
LINK Link2 WIP1 PullStrands1;
LINK Link3 PullStrands1 WIP2;
LINK Link4 WIP2 Repair;
LINK Link5 PlaceConcrete1 Cure1 Run;
LINK Link6 Cure1 WIP3;
LINK Link7 WIP3 CutandRemove1;
LINK Link8 CutandRemove1 SlabReady;
LINK Link9 CleanBed2 WIP4;
LINK Link10 WIP4 PullStrands2;
LINK Link11 PullStrands2 WIP5;
LINK Link12 WIP5 PlaceConcrete2;
LINK Link13 PlaceConcrete2 Cure2 Run;
LINK Link14 Cure2 WIP6;
LINK Link15 WIP6 CutandRemove2;*/
LINK HP7 Bucket Repair;
LINK HP8 Repair Bucket;
LINK Link40 Repair WIP10;
LINK Link41 WIP10 PlaceConcrete1;
/*********************************************************************************
*****************
/* Definition of global variables and programe objects 
COLLECTOR ProjectDuration*;
COLLECTOR WIP*;
/*********************/
**********************************************
*****************
/* Startup of CleanBed1
PRIORITY CleanBed1 '1';
DRAWAMT RB1 '1';
DURATION CleanBed1 'Triangular[22.5, 30, 35.5]';
/*********************************************************************************
*****************
/* Termination of CleanBed1
RELEASEAMT Link1 '1';
/*********************/
*****************
/* Startup of CleanBed2
PRIORITY CleanBed2 '2';
DRAWAMT RB3 '1';
DURATION CleanBed2 'Triangular[22.5, 30, 35.5]';
/*********************************************************************************
*****************
/* Termination of CleanBed2
RELEASEAMT Link9 '1';
/*********************/
*****************
/* Startup of CleanBed3
PRIORITY CleanBed3 '3';
DRAWAMT RB5 '1';
DURATION CleanBed3 'Triangular[22.5, 30, 35.5]';
/*********************************************************************************
*****************
/* Termination of CleanBed3
RELEASEAMT Link17 '1';
/*********************/
*****************
/* Startup of PullStrands1
DRAWAMT Link2 '1';
DURATION PullStrands1 'Triangular[12.5, 15, 18.5]';
/*********************/
*****************
/* Termination of PullStrands1
RELEASEAMT Link3 '1';
/********************************************************************************************
*****************
/* Startup of PullStrands2
DRAWAMT Link10 '1';
DURATION PullStrands2 'Triangular[12.5, 15, 18.5]';
/********************************************************************************************
*****************
/* Termination of PullStrands2
RELEASEAMT Link11 '1';
/**********************************************************************
*************
*****************
/* Startup of PullStrands3
DRAWAMT Link18 '1';
DURATION PullStrands3 'Triangular[12.5, 15, 18.5]';
/********************************************************************************************
*****************
/* Termination of PullStrands3
RELEASEAMT Link19 '1';
/*/ Startup of PlaceConcrete1
DRAWAMT EX1 '1';
DRAWAMT HP1 '1';
DRAWAMT LA3 '2';
DRAWAMT Cr1 '1';
DRAWAMT Link41 '1';
DURATION PlaceConcrete1 'Normal[154, 22.9]';
/********************************************************************************************
*****************
/* Termination of PlaceConcrete1
RELEASEAMT Link5 '1';
RELEASEAMT EX2 '1';
RELEASEAMT HP2 '1';
RELEASEAMT LA4 '2';
RELEASEAMT Link30 '1';
/********************************************************************************************
*****************
/* Startup of PlaceConcrete2
DRAWAMT Link12 '1';
DRAWAMT EX3 '1';
DRAWAMT HP3 '1';
DRAWAMT LA1 '2';
DRAWAMT Cr2 '1';
DURATION PlaceConcrete2 'Normal[154, 22.9]';
/********************************************************************************************
*****************
/* Termination of PlaceConcrete2 */
RELEASEAMT Link13 '1';
RELEASEAMT EX4 '1';
RELEASEAMT HP4 '1';
RELEASEAMT LA2 '2';
RELEASEAMT Link31 '1';

/* Startup of PlaceConcrete3 */
DRAWAMT Link20 '1';
DRAWAMT HP5 '1';
DRAWAMT EX5 '1';
DRAWAMT LA5 '2';
DRAWAMT Cr3 '1';
DURATION PlaceConcrete3 'Normal[154, 22.9]';

/* Termination of PlaceConcrete3 */
RELEASEAMT Link21 '1';
RELEASEAMT HP6 '1';
RELEASEAMT EX6 '1';
RELEASEAMT LA6 '2';
RELEASEAMT Link32 '1';

/* Startup of Cure1 */
DURATION Cure1 '390';

/* Termination of Cure1 */
RELEASEAMT Link6 '1';

/* Startup of Cure2 */
DURATION Cure2 '390';

/* Termination of Cure2 */
RELEASEAMT Link14 '1';

/* Startup of Cure3 */
DURATION Cure3 '390';
/** Termination of Cure3 */
RELEASEAMT Link22 '1';

/** Startup of CutandRemove1 */
PRIORITY CutandRemove1 '1';
DRAWAMT Link7 '1';
DRAWAMT CM5 '1';
DURATION CutandRemove1 'Triangular[160, 191, 268]';

/** Termination of CutandRemove1 */
RELEASEAMT Link8 '1';
RELEASEAMT RB2 '1';
RELEASEAMT CM6 '1';

/** Startup of CutandRemove2 */
PRIORITY CutandRemove2 '2';
DRAWAMT Link15 '1';
DRAWAMT CM3 '1';
DURATION CutandRemove2 'Triangular[117, 130, 252]';

/** Termination of CutandRemove2 */
RELEASEAMT Link16 '1';
RELEASEAMT RB4 '1';

/** Startup of CutandRemove3 */
PRIORITY CutandRemove3 '3';
DRAWAMT Link23 '1';
DRAWAMT CM1 '1';
DURATION CutandRemove3 '96.5 + Gamma[4.5, 1.35]';

/** Termination of CutandRemove3 */
RELEASEAMT Link24 '1';
RELEASEAMT RB6 '1';
RELEASEAMT CM2 '1';

/** Startup of Repair */
DRAWAMT Link4 '1';
DRAWAMT HP7 '1';
DURATION Repair '120';

REDIT Termination of Repair
RELEASEAMT HP8 '1';
RELEASEAMT Link40 '1';

REDIT Initialization of Queues, Running the Simulation, Presenting Results
PRINT StdOutput "
Iteration ProjectDuration WIP
hr
========================================
\n";

REDIT Iteration
REDIT
WHILE CurrentIteration<=NrIterations;

CLEAR;
INIT Rbed1 0;
INIT Rbed2 0;
INIT Rbed3 0;
INIT Extr 1;
INIT Bucket 1;
INIT SlabReady 0;
INIT WIP1 0;
INIT WIP2 0;
INIT WIP3 1;
INIT WIP4 0;
INIT WIP5 0;
INIT WIP6 1;
INIT WIP7 0;
INIT WIP8 0;
INIT WIP9 1;
INIT Lab 2;
INIT CuttingSaw 1;
INIT Concre1 1;
INIT Concre2 1;
INIT Concre3 1;
SIMULATEUNTIL BedReady.CurCount==3;
COLLECT ProjectDuration SimTime;
COLLECT WIP
/ Print row with results
    PRINT StdOutput
      "%6.0f %15.2f %15.2f\n"
    CurrentIteration
    SimTime
ASSIGN CurrentIteration CurrentIteration+1;
WEND;
/********************
/* Reporting */
***************
PRINT StdOutput "Ave  %15.2f %15.2f\n"
  ProjectDuration.AveVal
  WIP.AveVal;
PRINT StdOutput "SD  %15.2f %15.2f\n"
  ProjectDuration.SDVal
  WIP.SDVal;
PRINT StdOutput "Min  %15.2f %15.2f\n"
  ProjectDuration.MinVal
  WIP.MinVal;
PRINT StdOutput "Max  %15.2f %15.2f\n"
  ProjectDuration.MaxVal
  WIP.MaxVal;