DISCRETE EVENT SIMULATION AS A POTENTIAL PROJECT PLANNING AND
CONTROL TOOL FOR CONTOUR CRAFTING PROCESS

By

FARHAN MUHAMMED SALIM

A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE IN CONSTRUCTION MANAGEMENT

UNIVERSITY OF FLORIDA

2017
"In the name of God, the Most Gracious, the Most Merciful"

Dedicated to my father, Mr. P.K. Abdul Salim, my mother, Mrs. Shemmy Salim, my brother, Mr. Adel Salim, my sister, Ms. Sumayyah Salim, all my friends who supported me through the process and Almighty God.
ACKNOWLEDGMENTS

After an intensive period of ten months, today is the day: writing this note of thanks is the finishing touch on my master’s thesis. It has been a period of intense learning for me, not only in the academic arena, but also on a personal level. Writing this thesis has had a big impact on me. I would like to reflect on the people who have supported and helped me so much throughout this period.

I would first like to thank my thesis chair, Dr. Ian Flood and my thesis co-chair, Dr. Bryan Franz for their wonderful collaboration throughout the course of my research. I would also like to thank my committee member, Dr. Masoud Ghiesari. The three of you supported me greatly and were always willing to help me. Your office was always open whenever I ran into a trouble spot or had a question about my research or writing. You consistently allowed this paper to be my own work and definitely provided me with the tools that I needed to choose the right direction and successfully complete my thesis.

I would also like to thank my parents for their wise counsel and sympathetic ear. You are always there for me. Then, there are my friends. We were not only able to support each other by deliberating over our problems and findings, but also happily by talking about things other than just our papers. I want to also thank my favorite sports team, Chelsea Football Club for entertaining me with a great season throughout the year and keep me cheered up during my worst times. Last but not the least, I would like to thank Almighty God for keeping me blessed with health and happiness.

Thank you very much, everyone! GO GATORS!
# TABLE OF CONTENTS

ACKNOWLEDGMENTS........................................................................................................... 4

LIST OF TABLES.................................................................................................................. 8

LIST OF FIGURES.................................................................................................................. 9

LIST OF ABBREVIATIONS.................................................................................................... 11

ABSTRACT............................................................................................................................ 12

CHAPTER

1 INTRODUCTION ............................................................................................................... 14
   1.1 Introduction to the U.S. Construction Industry ....................................................... 14
   1.2 Motivation for Research ......................................................................................... 15
   1.3 Research Objectives ................................................................................................. 17
   1.4 Methodology ............................................................................................................. 17

2 LITERATURE REVIEW ...................................................................................................... 19
   2.1 Future of Construction ............................................................................................. 19
      2.1.1 Design ................................................................................................................ 19
      2.1.2 Material .............................................................................................................. 20
      2.1.3 Construction Process ......................................................................................... 20
   2.2 Autonomous robotic construction – Termes system ............................................. 21
   2.3 Automated layered fabrication technology .......................................................... 21
   2.4 Contour Crafting ........................................................................................................ 23
      2.4.1 Crafting Process .................................................................................................. 25
      2.4.2 Breakdown of A Current Contour Crafting Equipment .................................. 27
      2.4.3 Typical CC Cycle ............................................................................................... 30
      2.4.4 Work Breakdown Structure ............................................................................. 32
   2.5 Important Data from Hwang’s Wall Construction (Hwang 2005) ....................... 33
   2.6 Discrete Event Simulation ....................................................................................... 35
      2.6.1 Stroboscope ....................................................................................................... 36
         2.6.1.1 Resources ..................................................................................................... 37
         2.6.1.2 Links ........................................................................................................... 37
         2.6.1.3 Nodes .......................................................................................................... 37
         2.6.1.4 Activities .................................................................................................... 37
         2.6.1.5 Queues ........................................................................................................ 38
         2.6.1.5 Forks and Dynaforks ................................................................................... 38

3 FACTORS AFFECTING THE CONTOUR CRAFTING CYCLE .................................... 39
APPENDIX

A  STROBOSCOPE MODEL FOR CC CONSTRUCTION OF WALL FOR SINGLE RESIDENTIAL UNIT ................................................................. 86

B  STROBOSCOPE RESULT FOR CC CONSTRUCTION OF WALL FOR SINGLE RESIDENTIAL UNIT ........................................................................... 90

C  STROBOSCOPE RESULT FOR CC CONSTRUCTION OF WALL FOR TWO RESIDENTIAL UNIT ....................................................................................... 93

D  STROBOSCOPE RESULT FOR CC CONSTRUCTION OF WALL FOR THREE RESIDENTIAL UNIT ....................................................................................... 97

E  STROBOSCOPE MODEL FOR CC CONSTRUCTION OF WALL OF 3 RESIDENTIAL UNIT BY RELOCATING LOADING STATION ....................... 104

F  STROBOSCOPE MODEL FOR CC CONSTRUCTION OF WALL OF 3 RESIDENTIAL UNIT BY RELOCATING LOADING STATION ............................ 110

REFERENCES ......................................................................................................................................................... 112

BIOGRAPHICAL SKETCH ........................................................................................................................................ 114
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>Comparison between Termes System and CC</td>
<td>22</td>
</tr>
<tr>
<td>2-2</td>
<td>Summary of Important Data for CC wall construction by Hwang</td>
<td>35</td>
</tr>
<tr>
<td>5-1</td>
<td>Assumptive values for New CC wall construction for residential unit</td>
<td>56</td>
</tr>
<tr>
<td>5-2</td>
<td>Observations form 1 Residential Unit Construction</td>
<td>62</td>
</tr>
<tr>
<td>6-1</td>
<td>Observations form 2 Residential Units Construction</td>
<td>66</td>
</tr>
<tr>
<td>6-2</td>
<td>Observations form 3 Residential Units Construction</td>
<td>73</td>
</tr>
<tr>
<td>7-1</td>
<td>Sensitivity analysis for Capacity of Material Carrying tank</td>
<td>79</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>2-1</td>
<td>Extrusion assembly of the CC equipment</td>
<td></td>
</tr>
<tr>
<td>2-2</td>
<td>Extrusion assembly of the CC equipment</td>
<td></td>
</tr>
<tr>
<td>2-3</td>
<td>Layered pour of Filler Material in 1-hour interval</td>
<td></td>
</tr>
<tr>
<td>2-4</td>
<td>Actual photograph of a layered pour of Filler Material in 1-hour interval</td>
<td></td>
</tr>
<tr>
<td>2-5</td>
<td>CC machine used for wall construction</td>
<td></td>
</tr>
<tr>
<td>2-6</td>
<td>Layered pour of Filler Material in 1-hour interval</td>
<td></td>
</tr>
<tr>
<td>2-7</td>
<td>Path of CC nozzle</td>
<td></td>
</tr>
<tr>
<td>2-8</td>
<td>Typical CC Cycle</td>
<td></td>
</tr>
<tr>
<td>2-9</td>
<td>Work Breakdown Structure for Wall Construction Using CC.</td>
<td></td>
</tr>
<tr>
<td>3-1</td>
<td>Diagrammatical representation of relationship between factors affecting the CC cycle</td>
<td></td>
</tr>
<tr>
<td>4-1</td>
<td>Proposed CC equipment for residential construction</td>
<td></td>
</tr>
<tr>
<td>4-2</td>
<td>A compound Nozzle assembly for commercial construction purposes</td>
<td></td>
</tr>
<tr>
<td>4-3</td>
<td>CC machine printing wall using the compound nozzle</td>
<td></td>
</tr>
<tr>
<td>4-4</td>
<td>New CC cycle</td>
<td></td>
</tr>
<tr>
<td>4-5</td>
<td>Work Breakdown Structure for Wall Construction Using CC.</td>
<td></td>
</tr>
<tr>
<td>5-1</td>
<td>Contour crafting assembly for residential wall construction for 1 unit</td>
<td></td>
</tr>
<tr>
<td>5-2</td>
<td>Top view and cross-sectional view of 1 foot of 1 printed layer. All measurements are in inches</td>
<td></td>
</tr>
<tr>
<td>5-3</td>
<td>Stroboscope model for the New CC Wall Construction for 1 Residential Unit</td>
<td></td>
</tr>
<tr>
<td>6-1</td>
<td>Contour crafting assembly for residential wall construction for 2 unit</td>
<td></td>
</tr>
<tr>
<td>6-2</td>
<td>Contour crafting assembly for residential wall construction for 3 unit</td>
<td></td>
</tr>
<tr>
<td>6-3</td>
<td>Contour crafting assembly for residential wall construction for 3 unit by relocating loading station</td>
<td></td>
</tr>
</tbody>
</table>
6-4  Model for CC wall construction of 3 residential units by relocating loading station. ................................. 71

6-5  Contour crafting assembly for residential wall construction for 3 unit by using to CC machines. ...................................................... 74

6-6  Model for CC wall construction of 3 residential unit by using 2 CC stations. ...... 75

7-1  Capacity of material carrying tank vs. Total time taken for fabrication. ............... 80
# LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>Contour Crafting</td>
</tr>
<tr>
<td>CPM</td>
<td>Critical Path Method</td>
</tr>
<tr>
<td>CYCLONE</td>
<td>Cyclic Operations Network</td>
</tr>
<tr>
<td>DES</td>
<td>Discrete Event Simulation</td>
</tr>
</tbody>
</table>
DISCRETE EVENT SIMULATION AS A POTENTIAL PROJECT PLANNING AND CONTROL TOOL FOR CONTOUR CRAFTING PROCESS

By

Farhan Muhammed Salim

August 2017

Chair: Ian Flood
Co-Chair: Bryan Franz
Major: Construction Management

The increased pressure to improve productivity and cut cost have forced the construction industry to change and adapt to new demands, processes and technologies. With the advance in the in the field of automation, robotics, information technology and construction materials, the future of the construction industry looks bright. One of the most promising new construction innovation “Contour Crafting” (CC), which uses automated layered fabrication technology; commonly known as 3-D printing, has made a huge advancement in the construction industry.

Construction planning is a very critical factor and an integral part of construction project management. In comparison to a typical construction project, CC is more of a cyclic process. The whole construction process functions as a system or a facility. Conventional planning methodologies like Critical Path Method (CPM) is thought to be insufficient to manage a cyclic repetitive system, as it does not handle repetitive work or continuous processes well. An ideal planning technique should be able to account for “what if” situations, to decide the most optimum conditions for the project delivery. The Discrete Event Simulation (DES) technique provides this capability. It allows decision-
makers to test and better understand the process and alternative ways in which the project can be delivered. DES is very versatile and can model most construction processes (Martinez 1996). The aim of the research is to test the effectiveness of DES as an effective planning and control tool for CC Construction Technology. The research was conducted by using Stroboscope software since it was the most powerful freely available DES tool. It is very versatile and can model any type of relationship between two activities or resources.

The primary objectives of the research were to study the Contour Crafting technology and establish parameters that govern the performance of a CC system, and test the effectiveness of DES as a planning tool for CC based construction.

A Stroboscope model for CC based construction was developed and key parameters was incorporated into the DES model as variables, and a study was conducted on the performance of the CC system by altering these factors. Stroboscope was able to model intricate relations between resources and activities in a CC based construction process. The program was also versatile enough to have dynamic timing for each activity, which helped in changing the duration of certain activities during the execution of the DES project file. The research also showcased the versatility of the Stroboscope tool to modify its model based on changing project requirements. The research also successfully reviewed the capacity of the Stroboscope tool to conduct sensitivity analysis for CC based construction. The research was able to justify the use of DES as a powerful project planning tool for CC based construction projects.
CHAPTER 1
INTRODUCTION

1.1 Introduction to the U.S. Construction Industry

The construction industry is the only industry in the U.S. which has failed to record an increase in overall productivity in comparison to the rest of the U.S. industries over the past few decades. Studies show that the major portion of the efficiency and productivity in construction was lost over coordinating labor and material logistics.

The continued advancement in technology has helped improve industrial productivity by quite a significant margin. Unfortunately, the construction industry has traditionally been viewed as technologically stagnant when compared with other industries (Rosefielde and Mills 1979). However, the opportunity to improve construction productivity exists. There is substantial evidence that sectors and processes within the construction industry have experienced productivity gains as a result of utilizing new equipment, material, and information technologies (Goodrum and Haas 2004). The process of digitalization of a construction project through Building Information Modeling (BIM) can be one such example. BIM is revolutionizing the three major processes of construction: design, construction, and operation.

The future of technology in the construction industry looks bright with the advances in robotics, automation and 3-D imaging. These technologies show a great potential for usage in the construction industry. With the implementation of such technology, it helps the construction industry to move from traditionally sequenced operations based processes to more of a manufacturing based approach. Therefore, the currently established planning techniques are inadequate for future construction process planning and control.
1.2 Motivation for Research

The increased pressure to improve productivity and cut cost have forced the construction industry to change and adapt to new demands, processes, and technologies. With the advance in the field of automation, robotics, information technology and construction materials, the future of the construction industry looks bright. Innovative construction techniques are changing the way that we build our structures. The industry is entering an age of the mass-manufactured building. Prefabrication is growing up, reaching a new level of maturity that is now going to change the industry and define new categories of building (Bernstein 2015). Modern construction techniques are changing the way that we build our structures. The construction industry is continuously advancing and adjusting to new demands, procedures, and technology. A prediction to which technology will be the most prominent in the coming future will be a difficult task. However, one technology looks promising is Contour Crafting, which uses an automated layered fabrication technology commonly known as 3-D printing.

Construction planning is a very critical factor and an integral part of construction project management. The success of a project depends upon how well it was planned. Moreover, planning also warrants the feasibility of a project in compliance to project constraints like resources and time. It helps in determining the appropriate design methods and the right combination of resources to finish a project within its contractual time frame. The most common planning technique used today “The Critical Path Method” is calculated using a system that cannot account for resource limits or project deadlines. While resource leveling and time-cost trade-off analysis can be used to mitigate this complication, a resulting issue is that this may create conflicting solutions –
a solution to one constraint may interfere with a solution to another (Hegazy and Menesi 2010). With the advance in technology and use of techniques such as CC, conventional planning techniques like the critical path method and PERT will not be good enough for these construction techniques, the reason for which have been explained in the following paragraph.

In comparison to a typical construction project, CC is more of a cyclic process. The whole construction process functions as a system or a facility. Conventional planning methodologies like Critical Path Method (CPM) is thought to be insufficient to manage a cyclic repetitive system, as it does not account for the nature of the relationship between two activities. Furthermore, CPM procedure can be excessively complex when used to model repetitive tasks. Also, when presented in Gantt chart format, a CPM model provides some insight into how a system’s logic affects its performance but this is limited to event-based logical dependencies and their impact on time-wise performance (Flood 2009a). An ideal planning technique should be able to account for “what if” situations, to decide the most optimum conditions for the project delivery. In order to create a good project plan, a scheduler can use more than one scheduling technique, however, using more than one tool that is not fully compatible with the process can reduce the level of optimization of the procedure and compromise the user ability to plan and control work optimally (Flood 2009a). The ideal way to model a construction process is using a single method which is highly versatile, able to model different situations such as repetitive and non-repetitive construction work, easy to use and able to provide an insight into alternative ways of planning (Flood 2009a). Discrete Event Simulation techniques provide this capability. It allows decision-makers to test
and better understand the process and alternative ways in which the project can be delivered.

1.3 Research Objectives

DES technique is a very versatile planning technique and in principle, can model any interaction between tasks and any type of construction process along with their resource constraints. In DES, the planner creates a model that emulates the construction activities at the site. They then predict the behavior and progress of the project based on the simulations. The assumption in DES is that the state of a system changes instantaneously at specific times marked by events (Martinez 1996). DES is very versatile and can model most construction processes (Martinez 1996). An initial study will be conducted on the upcoming construction technologies. However, the primary goal of this research is to:

- Test the effectiveness of DES as an effective planning and control tool for Contour Crafting Construction Technology

The specific research objectives are to:

- To conduct a brief study on future construction technologies and establish the prominence of Contour Crafting
- To conduct a literature review on Contour Crafting technology and establish the most probable workflow of activities that would be used during CC construction
- Identify and establish parameters that govern the performance of a Contour Crafting system.
- Conduct sensitivity analysis on variables that govern the schedule of a Contour Crafting system
- Test the effectiveness of DES as a planning tool for Contour Crafting by testing the tool in different in ‘what if’ situations.

1.4 Methodology

The following methodology was adopted for the purpose of this research:
1. A thorough literature review will be completed on CC technology to analyze its prospects and to identify key parameters that govern its performance. The study will also establish the most probable workflow of activities that would be used during a commercial CC construction.

2. A study on DES was conducted, and a DES model for CC was developed on Stroboscope which is an advanced discrete event simulation programming language and system based on Three-Phase Activity Scanning and extended Activity Cycle Diagrams.

3. Key parameters will be incorporated into the DES model as variables, to study the performance of the CC system by altering these factors.

4. Multiple DES models will be developed using different in ‘what if’ situations to test the effectiveness of DES as a planning tool for CC based construction and a comprehensive evaluation will be made to assess the relative adaptability of the tool.

5. To evaluate the ability of the DES, various separate project limitations was assumed, and three separate DES models will be created using the Stroboscope software.
Current construction methods are changing the means by which we construct our buildings. The construction trade is continuously progressing and fine-tuning to new requirements, procedures, and technologies. The standards and limitations to which our structures are built have also progressed with time. Besides giving different occupations to those looking for careers in this field, advancing systems have empowered distinctive living alternatives for individuals to suit their styles and inclinations better. A lot of importance is being given to sustainability, green building standards, lean construction, etc. Prediction of which technology will be the most prominent in the coming future is a difficult task.

There are many dedicated internet articles and journals which attempt to predict the technologies, methods, and materials that could form the future of construction. With regards to technological advances, the potential outcomes are huge for the construction industry, and it shapes the appearance of our future buildings and the way they are built. The advances can be characterized in three different aspects of construction:

1. Design
2. Material
3. Construction Process

2.1.1 Design

While it might be simpler to stick to the currently accustomed construction designs, the industry is changing and the new, creative greener methods are striving to innovate to the point that they get to be distinctly standard (Jone 2014). This new thinking can be exceptionally useful to the nature of the urban environment, and often
can be very attractive with respect urban design. There is a shift from the traditional block buildings to something curvier, which is not only more attractive but also more structurally stable. Architects and designers have given us exciting ideas that will define the way we live, and the living that the next generation will experience (Jone 2014). Architects and designers all across the globe constantly try to come up with new designs, as part of its green design strategy, by trying to create a structure that can minimize solar heat, take advantage of natural daylight, harness wind, and sun energy, etc.

2.1.2 Material

Future on construction materials can be derived from the current advancements in material technology. There are several construction materials that have been invented which show significant potential to replace existing materials. For example, self-healing concrete and permeable concrete are poised to replace existing concrete as it poses several advantages. The self-healing concrete mix is embedded with tiny capsules of sodium silicate. When cracks form, the capsules rupture and release a gel-like healing agent that hardens to fill the void (Roos 2014). This will help eliminate concrete crack and will help to save on concrete maintenance thereby making it economical on the longer run.

2.1.3 Construction Process

Innovative construction techniques are changing the way that we build our structures. The construction industry is continuously advancing and adjusting to new demands, procedures, and technology. With the current advances in robotics and automation, the construction workers of the future could be robots (Jone 2014).
It will be a hard task to exactly predict the dominant construction technology in the future. However, two of the most promising automated construction processes is explained below:

2.2 Autonomous robotic construction – Termes system

Researchers at the Harvard University have developed an autonomous robotic construction crew inspired by termites and their behavior in the construction of termite hills. These small robots can function by communicating with themselves and does not need any additional supervision. The TERMES robots can build towers, castles, and pyramids out of foam bricks, autonomously building themselves staircases to reach the higher levels and adding bricks wherever they are needed. In the future, similar robots could lay sandbags in advance of a flood, or perform simple construction tasks on Mars. (Perry 2014).

2.3 Automated layered fabrication technology

3D printing technologies are transforming the way we think and render ideas to objects. It is beginning to have a significant impact in the construction industry. The technology started small by printing small plastic objects, and now there are huge equipment printing houses in less than 24 hours. The use of 3D printing in has vast potential as a lean construction process, as it provisions the use of advanced green materials and results in lower waste production. Therefore, it maximizes utilization and reduces wastage. Moreover, nearly all 3D printing systems utilize easy setup and operation, faster construction, enabling lower labor costs. Few other significant benefits of 3D printing in comparison to other new construction technologies are better surface finishing and a broader choice of materials. Therefore, the potential of this technology to
alleviate some of the major problems of the construction industry is making 3D printing gain more and more traction.

For this research, 3D printing will be used in order interpret the effectiveness of a simulation-based planning technique. Table 2-1. below shows the comparison between 3D Printing and the Termes system regarding research, advancements and possible uses. Both technologies are being heavily researched in various universities, and a number of articles regarding them can be found online. From the available online resources and the current advancements in research for each of the technology, it can be noticed that 3D Printing is more promising in terms of a technology that can be easily adopted for future construction purposes.

Table 2-1. Comparison between Termes System and CC

<table>
<thead>
<tr>
<th></th>
<th>Termes System</th>
<th>3D Printing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level of automation achieved</td>
<td>High</td>
<td>Medium-High</td>
</tr>
<tr>
<td>Wastage Reduction</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Surface finishing Capability</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Functioning prototype</td>
<td>Miniature Model</td>
<td>Fully Functional Prototype</td>
</tr>
<tr>
<td>Completed life size projects</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Architectural Flexibility</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Current research funding</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Anticipated Uses:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Commercial</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Civil Infrastructure</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Extraterrestrial</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Underwater</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>MEP Installation</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Disaster Relief</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
The table above indicates that 3D Printing is a more established technology and can be used for various purposes such as residential, commercial and disaster relief construction. The early assessment of the technologies also shows that 3D Printing will be a faster construction process. The current functioning prototype of 3D Printing is a fixed structure, and the whole system will have to be dismantled and constructed again when moving from one site to another. However, further research is being done to develop autonomous robots just like Termes system can carry out layered fabrication, thereby increasing the versatility and flexibility of the 3D Printing technology. Hence, this research will be aimed at finding the best-fit planning technique for 3D Printing based construction. The following topic will explain the 3D Printing technology in detail.

2.4 Contour Crafting

In recent years, the 3D printing process has been revolutionizing the manufacturing process. It has been employed in various industries and disciplines such as manufacturing, automobile industry, recreational items, architecture and even the medical industry. The 3D printing process is a material additive manufacturing process by which objects are created by computer controlled, layer by layer sequential material deposition (Hwang and Khoshnevis 2004). With the use of computerized 3D modeling technique, an object or a model is classified into several individual horizontal layers. The mentioned layered geometries are programmed to the machine for controlled deposition of construction material along its path, thereby creating a 3-dimensional solid model in a layer by layer fashion. 3D printing technology has meaningfully reduced the cost and time associated with manufacturing a product. There are many commercialized 3D printing systems that make high-quality models with accurate dimensions and
required surface finish. It can fabricate complex structures with ease. However, 3D printing systems today are not advanced enough for production of large structural components like a wall, footings, etc., except Contour Crafting (CC). This is because in most cases the use of single-task robots to build a structure limits it to smaller sectors of construction since these robots cannot find and fix problems during construction.

Likewise, most of the automated construction systems do not offer much flexibility in with respect to structural design. An equipment proficient in creating variable cross section structure will not be feasible in terms of budget. Additionally, existing automated systems require many prefabricated parts. This factor in as additional costs. Using conventional automation technology, implementing a fully developed automated system that will address the problems facing the construction industry will be expensive (Hwang and Khoshnevis 2004).

The following barriers hinder the efficient implementation of automation technology in construction (Khoshnevis 2004):

- Availability of feasible fabrication technologies for large scale products
- Conventional design approaches not suitable for automation
- Small production quantities compared to other industries Limitation of material choices
- High equipment costs and maintenance fees
- Management issues

Earlier efforts at developing an automated construction equipment have not sufficiently approached these points. Contour crafting pursues alternative methods to tackle the abovementioned points and develop a new fabrication and assembly process.
Contour Crafting is a technology (Khoshnevis 2004) developed by Dr. B. Khoshnevis at the University of Southern California which have been promising in its ability to 3-D print large structures such as houses. CC is an additive fabrication technology that uses computer controls to exploit the superior surface-forming capability of troweling to create smooth and accurate planar and free-form surfaces (Khoshnevis 2004). He first introduced the technology in 2006. With regards to design, it looks very much like the usual 3D printers we see today. However, instead of a plastic resin, it uses a polymer, ceramic slurry, cement, and a variety of other materials and mixes to build large scale objects with the smooth surface finish (Khoshnevis and Dutton 1998). The CC system prints one cementitious layer after the other until the whole structure is complete. This allows it to model complex designs with ease and high construction speed. It leaves almost no waste and uses very less labor thereby making it a prime technology for affordable housing construction.

2.4.1 Crafting Process

Manual layered fabrication has been part of construction for several years. Automating this process in the form of CC is a revolutionary idea. With the help of CC, the construction industry can move from traditional Cast-in-situ method to automated manufacturing. This new way of thinking offers automation a much better chance to penetrate and succeed in the construction field (Hwang and Khoshnevis 2004).

The printing material is secreted between two trowels which act as two solid surfaces. These two trowel surfaces help to create very smooth surfaces with precision. Figure 2-1 and Figure 2-2 shows the extrusion assembly and nozzle structure of the CC equipment.
CC works based on the principles of computer-aided drafting and computer aided manufacturing technology (CAD/CAM). After the model has been developed in CAD, the CC acts as the manufacturing tool and prints the structure. It uses the extrusion technology as mentioned above and will be able to create smooth surfaces by constraining the flow of the cementitious material through the vertical and horizontal
faces of the trowel. The orientation of the side trowel is dynamically controlled to conform to the slope of surface features, and it also allows for thicker material deposition while maintaining smooth surface finish (Khoshnevis et al. 2006). Once the trowels form the exterior edges, the interior can be filled with filler materials such as concrete. This process will allow architects and designers to push the limits of the current structural geometries and design new exotic and contemporary designs.

2.4.2 Breakdown of A Current Contour Crafting Equipment

This CC machine was developed specifically to construct a concrete wall (Hwang and Khoshnevis 2004). The purpose of this wall construction was to establish the feasibility of replacing current construction processes by using CC technology. The main factor which was considered during the construction of the wall was the target geometry of the wall to be constructed. A wall of 6-inch thickness was chosen since it resembles typical concrete wall sections used in residential housing construction. The wall would consist of a concrete form which will then be filled with reinforcement and filler material. The concrete form was constructed by placing the mortar mixture in subsequent layers 0.75 inches (19mm) in width by 0.5 inches (13mm) in height. The final concrete form is a hollow structure with curved radii at each end. Any concrete can be poured in as the filler structural material. The filler material will also be placed in a layer by layer fashion. The time difference between each layer was based on the curing time of the material used. The CC machine was developed by keeping the geometry of the finished product in mind.

The purpose of the wall form is to hold the poured filling material (mostly concrete) and act as mold till the concrete hardens. Once the wall sides of each layer were printed, the middle nozzle pours the filling material into the formed space. The
filling material exerts a lateral pressure on the forms. Therefore, it is required to wait for a certain time for the material to set before the next layer is poured. Research is being conducted in the area of the filling materials. There are several designs that can significantly reduce the amount of filling material to be used. Another reason why the filling material is to be modified is due to the longer setting time. Current experiments conducted on the CC shows that it is required to wait for at least 1 hour before the next batch of concrete is poured. Figure 2-3 and Figure 2-4 shows how the filling material is poured in layer by layer.

![Diagram of layered pour of filling material](image)

Figure 2-3. Layered pour of Filler Material in 1-hour interval. (Photo Courtesy: Hwang and Khoshnevis 2004).

![Actual photograph of layered pour of filling material](image)

Figure 2-4. Actual photograph of a layered pour of Filler Material in 1-hour interval. (Photo Courtesy: Hwang and Khoshnevis 2004).
Figure 2-5 shows the pic of the CC equipment used for the wall construction. The extrusion assembly moves along the X-axis on a rail which rests on the main system frame. The main system frame is stationary. The extrusion assembly also moves up and down along the Z-axis depending upon the layer being fabricated.

Figure 2-5. CC machine used for wall construction. (Photo Courtesy: Hwang and Khoshnevis 2004).

A basic and dedicated CC nozzle system with three-axis motion control was engineered for constructing the full-scale wall demonstrator. This nozzle moves in a predefined path and extrudes a layer of the cementitious material. The nozzle is fitted with two trowels to control both the internal and external surface finish of the extruded rims. Figure 2-6 and Figure 2-7 shows the new CC nozzle assembly. A piston is attached to and driven by the lead screw which turns at constant rotational speed to extrude the mixture (Hwang and Khoshnevis 2004). The thickness of the material is predetermined and is dependent upon several factors such as arm speed of the
machine, properties of the material, etc. The top of the preceding layer should have a smooth finish in order to form a strong bond with the succeeding layer.

Figure 2-6. Layered pour of Filler Material in 1-hour interval. (Photo Courtesy: Hwang and Khoshnevis 2004).

Figure 2-7. Path of CC nozzle.

2.4.3 Typical CC Cycle

The cycle starts with mixing the materials for the fabricating concrete. This material is then loaded into the material carrying the tank. The machine then moves to fabricate a layer. After the system completes fabricating one layer of the wall, the whole extrusion assembly will move vertically upward by a length that is equivalent to the height of the succeeding layer to be fabricated. This cycle is repeated until the whole structure has been fabricated. The main system frame supports and exactly guides the extrusion system during fabrication. In this current system, the movement is possible
only in two directions; X-axis and Z-axis. To print the curved ends of the fall, the nozzle moving in the X-direction stops and it rotates 180 degrees. The Y axis is not used with this configuration; therefore, the machine complexity is significantly (Hwang and Khoshnevis 2004). Also, the geometry of the 3-D objects to be fabricated is limited. After the concrete form has been fabricated, the filling material is poured in layer by layer. An adequate amount of curing time will be given for each layer to avoid excessive lateral pressure. Figure 2-8. shows the diagrammatic representation of a typical CC cycle.

Figure 2-8. Typical CC Cycle
2.4.4 Work Breakdown Structure

A work breakdown structure lets project managers control their work all the more productively. A project is comprised of time and cost restricted activities. Based on that information, the project management team has to prepare a schedule for assigned expenses, resources, and responsibilities. The WBS makes this arranging reliable and accommodates viable project execution. The work breakdown structure for the Contour Crafting construction of a wall constructed by Hwang has a fairly simple WBS which has been represented in Figure 2-9.

![Work Breakdown Structure for Wall Construction Using CC](image)

Figure 2-9. Work Breakdown Structure for Wall Construction Using CC.
2.5 Important Data from Hwang’s Wall Construction (Hwang 2005)

Since there is not enough data for Contour Crafting construction online, it is important to gather certain data from Hwang’s wall construction experiment. These values will be used as-is or modified for the purpose of our research. The breakdown of the Contour Crafting Equipment used for the wall construction has been explained in the previous section. The constructed wall had a thickness of 6 inches, the length of 5 feet and a height of 2 feet. However, some important factors have to be discussed in order to incorporate them to be used when creating a larger structure like a wall construction of a residential unit.

In Hwang’s experiment, numerous iterations were performed before finalizing their variables and constants. For the construction of forming walls, Rapid hardening cement was used. Initially, the mix had an initial setting time of 15 minutes. Various mixes of the rapid set mixture were effectively extruded. However, fabrication of the wall form within the rapid setting times of ~ 15 min was unrealistic and risked paste hardening inside the CC equipment (Hwang and Khoshnevis 2004). It was found that it required 40 minutes to complete one cycle without the risk if paste hardening. The cycle would start from paste mixing through material loading, fabrication and finally machine washing. Therefore, an admixture was added to the paste to increase the initial setting time to 40 minutes.

During the fabrication process, high pressure was being applied to the mixture inside the material carrying tank. Due to this a significant amount of water seepage was found. This loss of water would affect the workability and strength of the concrete. Another, admixture “Bentonite” was added to the mixture to control this. However, there
should be a limit to what the maximum pour pressure or the deposition speed can be. This based on the mix design.

Another important factor was the extrusion geometry. The concrete form is fabricated by extruding the mortar mixture in incremental layers 0.75 inches (19mm) in width by 0.5 inches (13mm) in height (Khoshnevis et al. 2006). Refer Figure 2-7 to see the path of the extrusion nozzle. In this current system, the movement was possible only in two directions; X-axis and Z-axis. To print the curved ends of the fall, the nozzle moving in the X-direction stops and it rotates 180 degrees. The Y axis is not used with this configuration. The initial material extruded from the nozzle at the start up is rejected till the flow is steadied, and then the system moves to fabricate the wall. Once a whole batch of the mortar blend inside the material conveying tank is printed, the CC framework delays until another batch get loaded. The system continues this process until the entire wall is printed. It was noticed that one batch of fabrication material was consumed in 10 minutes and concrete form was printed to a height on 2.5 inches.

The X-axis velocity of deposition was 0.753 inches/sec. The Z-axis velocity of deposition was 0.515 inches/sec. The rotational speed was 15.888 deg/sec. With these maximum construction velocities, it would result in an unacceptable construction speed for an actual residential or commercial unit. Erecting a 10 feet tall concrete wall for the proposed 2,416 square foot family housing unit would take 12.7 days (Hwang and Khoshnevis 2004). Tests for speedier development times should be composed and arranged since the present outcomes were acquired with the most extreme speeds constrained by the present CC framework.
All the important data from the current wall construction system has been listed in the Table 2-2 below:

Table 2-2. Summary of Important Data for CC wall construction by Hwang

<table>
<thead>
<tr>
<th>Factors</th>
<th>Data from Hwang’s Wall Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Dimensions</td>
<td>Single Wall: 5 feet long, 2 feet tall, 6 inches thick</td>
</tr>
<tr>
<td>Forming Material</td>
<td>Cementitious Mixture</td>
</tr>
<tr>
<td>Filling Material</td>
<td>Concrete filled in after fabricating forming walls</td>
</tr>
<tr>
<td>Initial Setting for forming wall</td>
<td>40 Minutes</td>
</tr>
<tr>
<td>Height of each layer of forming material</td>
<td>0.5 inch</td>
</tr>
<tr>
<td>Width of each layer of forming material</td>
<td>0.75 inch</td>
</tr>
<tr>
<td>X-axis speed (Fabrication speed)</td>
<td>0.753 inch/sec</td>
</tr>
<tr>
<td>Y-axis speed</td>
<td>No Y-axis movement</td>
</tr>
<tr>
<td>Z-axis speed</td>
<td>0.515 inch/sec</td>
</tr>
<tr>
<td>Material Carrying Tank Capacity</td>
<td>Unknown</td>
</tr>
<tr>
<td>Length of 1 layer</td>
<td>10.57 ft.</td>
</tr>
<tr>
<td>Material deposition</td>
<td>One forming surface at a time</td>
</tr>
</tbody>
</table>

### 2.6 Discrete Event Simulation

As mentioned earlier, construction planning is a very important aspect of construction project management. In a CC based construction project the construction activities are characterized by a very broad range of complexity. Analyzing these processes and relations through a conventional planning technique can be very hard
and time consuming. However, with the use of simulation modeling, one can create a model that imitates a real or imaginary dynamic system. By processing these simulation a project management team can predict the end results of the project.

Discrete Event Simulation (DES) is a very advanced simulation technique. The logic used in DES is that the state of a system modifies immediately at specific times marked by specific actions. Simulation-based tools could effectively solve operational construction problems (Lee et al. 2006). DES is very versatile and is able to model most construction processes (Martinez 1996). DES is very versatile in the sense that it can model any type of interaction between tasks and any type of construction process including repetitive and non-repetitive work tasks (Flood 2010). DES could operate in dynamic modeling mode (Sawhney et al. 1998). DES can also use stochastic durations, and incorporate of outside variables like machine down time, labor productivity, learning curves and weather.

2.6.1 Stroboscope

Stroboscope (State and Resource Based Simulation of Construction Processes) (Martinez 1996) was developed by Dr. Martinez at the University of Michigan in 1996. It is currently the most advanced construction simulation software, which can be freely accessed.

Stroboscope is a refinement of CYCLONE (Cyclic Operations Network). CYCLONE (Halpin and Woodhead 1976) was specifically designed for construction by Halpin and Woodhead in (1976). CYCLONE is purely network based which limits the user to model processes at the level of detail required to make decisions (Nowrouzian 2012). Martinez developed Stroboscope (1996) with the objective of enhancing the modeling capabilities of CYCLONE to consider a variety of resources and their specific
21 characteristics, make the state of simulation to control the sequence of tasks and their relative priorities, model resource selection schemes similar to real construction operations, and model material utilization, consumption and production probabilistically (Nowrouzian 2012).

A Stroboscope model is presented by a network. A network consists of resources, links and nodes that are put together (Martinez 1996).

2.6.1.1 Resources

Stroboscope executes simulation based on the movement or usage of resources. Resources move from one activity to another activity through the links. Resources in Stroboscope consist of discrete and bulk resources (Martinez 1996).

2.6.1.2 Links

Links connect network nodes and indicate the direction and type of resources that flow through them. The predecessor is the node located at the tail of the link and the successor is the node located at the head of the link where arrow is located. Only resources with specified characteristic could flow through a link (Martinez 1996).

2.6.1.3 Nodes

Nodes are the elements of a network that hold the resources that are part of the system. There are two types of nodes available for resources to spend their time in: “Activities” and “Queues” (Martinez 1996).

2.6.1.4 Activities

Activities are nodes where resources actively spent time in them to perform the task associated with that activity. In Stroboscope, there are three types of activities; The Normal Activities, Combi Activities and Consolidator Activities.
• Normal Activities are nodes where the tasks start just after the predecessor activities are finished.

• The Combi Activities are nodes where the activities start after some certain conditions are met. Predecessors to a combi must be a Queue.

• Consolidators are activities that based on the resources they receive start and finish their instances.

2.6.1.5 Queues

Queues are nodes within which resources are stored. Resources passively spend time in Queue nodes. Each Queue is associated with a specific resource type. The resources have to wait in Queues until the conditions necessary to start the successor Combi are satisfied (Martinez 1996).

2.6.1.5 Forks and Dynaforks

Fork and Dynaforks are resource-type specific auxiliary network nodes. At the termination of an activity instance, Forks determine which of the successors to be activated and Dynaforks route resources. Auxiliary nodes are drawn smaller than the Normals, Combis and Queues nodes in a network drawing. They are called auxiliary because they do not have duration and resources never spend time in these nodes. Fork and Dynaforks are essentially link accessories. Forks are represented with a small circle that encloses a triangle in a network drawing. Dynaforks are represented with a small circle that encloses five rays in a network drawing.

It is assumed that the reader has a basic understanding of discrete-event simulation and of Stroboscope. Further information on Stroboscope can be found in Martinez (1996).
CHAPTER 3
FACTORS AFFECTING THE CONTOUR CRAFTING CYCLE

The aphorism “Time is money” maybe truer nowhere other than the construction industry, where every day spent building is another day of labor costs and another day of opportunity costs for the owners and future managers who want to operate business or leave space immediately. A CC based construction project follows the same principles.

The key determinants for the pace of the contour crafting (CC) cycle as based in experimental observations are as follows:

3.1 Filling Material Placement

In the wall construction example Hwang, concrete was used as the filling material. Hwang’s system has several setbacks. The maximum pressure of the concrete must be calculated ahead in order to design the concrete form, which requires one to know the pressure, pouring rate, density, temperature, and height of the fresh concrete contained in the mold (Hwang and Khoshnevis 2004). The vertical load on the frame is not as basic as the lateral load, which assumes a key part in the formwork design. At the point when a fresh batch of concrete is set in a form, the solid flows like a viscous fluid and applies a water driven weight. The pressure at any time is a component of the concrete height and thickness and not the volume. The pressure is directly corresponding to the poured concrete height and density.

Once the height of the filling concrete has been decided, the height of form to receive the first batch of concrete is to be decided. The height of the form will be a certain addition to the final height of the filler material.
The final factor to be concerned is the setting time of the filler material. In the concrete wall example, one hour of curing time was given before the next batch of fresh concrete was poured. A batch of concrete of 5 inches’ height was poured initially. An hour delay was found sufficient to contain the lateral pressure of the viscous concrete, by letting it cure and set.

With this time delay, it took a day to complete the fabrication of the wall in Hwang’s experiment. This sort of delay is not feasible in commercial construction. Admixtures that accelerate this setting and curing time might be a good solution when higher concrete placing rates are needed. Other viable solutions will be discussed in further sections.

3.2 Height of Each Layer to be Poured

The nozzle design will depend on the height of each layer to be poured. The nozzle is what will conform the shape of the extruded material. Therefore, the dimensions of the nozzle will be based on the height of each layer. The cross-sectional area of the extruded material is to be decided as per requirement.

Usually, this should be done before the beginning of fabrication. Changing nozzles during the fabrication cycle is not an ideal scenario. The maximum cross-sectional area of the extruded material will depend on the mix design of the fabricating material. If the cross-sectional area crosses the maximum limit, it can result in unstable layers. Therefore, the cross-sectional area, height of each layer and the nozzle design is selected prior to installation of the CC machine. This will remain constant throughout the fabrication.
3.3 Pouring Rate/Pour Pressure and Arm Speed

Pouring rate is a critical component for CC machine. Once the cross-dimensional area of the extrusion material is fixed, the next step will be to decide the pouring pressure and the pouring speed. Depending upon the required schedule, the pouring speed or the arm speed can be increased. The increase of arm speed is directly proportional to the pouring pressure. With the increase in arm speed, it is required to increase the pouring pressure. If the pouring pressure is not increased at the same rate as the arm speed, it will result in shorter layer height than required. Similarly, if the arm speed is not increased at the same speed as the pouring pressure, it will result in irregular forming.

The point to be noted is that there is a maximum limit to which the arm speed and pour pressure can be increased. Superior surface finishing is one of the unique capabilities of the CC technology. This is achieved using simple planar trowels which constrain the extruded flow in the vertical and horizontal directions (Hwang and Khoshnevis 2004). The friction force between the inner surface of the planar trowel and the outer surface of the extruded flow determines the final product surface finish (Hwang and Khoshnevis 2004). If the pouring pressure is increased beyond a certain threshold, it will result in too much friction with the inner surface of the trowel which will drag the extruded material causing irregular flow. This will cause the extruded material to have voids and subpar finish. The increase in pouring pressure can also result in water seepage from the concrete. In the wall construction example, there was a significant amount of water seepage at the nozzle. This should undeniably be avoided since water quantity is critical for governing the mixture’s strength and workability. During the experiments, water seepage prematurely turned the cement mixture into a
high-density viscous mortar paste that frequently restricted or blocked the flow (Hwang and Khoshnevis 2004). In order to maintain constant water content during extrusion, a special admixture “Bentonite” was added into the mortar. The maximum pouring pressure limit is dependent on the mix design. Once the mix design is finalized, the maximum pouring pressure can be then determined. Conveying the appropriate measure of material with consistency and exactness is simple. However, it is hard to control and convey a highly viscous compressible glue through the CC nozzle assembly.

3.4 Maximum Capacity of The Container

The capacity of the material carrying container is another crucial component to the CC assembly. The capacity of the container remains constant throughout the CC process. Therefore, this value should be decided before beginning the entire process. The value of the capacity will depend upon the number of cycles required to complete with one batch of fabricating concrete.

Based upon the required rate of fabrication, the engineers will need to determine the number of cycles needed for each batch of concrete. After each individual batch, it is required to clean the container and nozzle to avoid hardening of the concrete inside the container and the nozzle.

Regardless of the amount of concrete filled in the container, it is required to pump out all the concrete before it reaches its designed initial setting time.

3.5 Mix Design

The mix design is the most crucial factor for the schedule. The entire CC system will function based on the characteristics of the mix design. The characteristics of the mix design cannot be changed during the Contour Crafting process. The required mix
design, based on the structure should be designed prior to the beginning of the process. The compatibility of the mix design with CC equipment should also be taken into account. As mentioned in the previous sections, the mix design will drive the other factors such as maximum arm speed, maximum pour pressure, maximum layer height, etc.

The most crucial factor that the Mix design drives are the minimum and maximum cycle time. Based on the final setting time of the design mix, the cycle time for fabricating one layer of the structure will be decided. In the wall example, 40 minutes was adequate for one batch, which included the fabrication of one layer, cleaning and mixing a new batch. It should also be considered that, even though the concrete does not reach its initial setting time after the first cycle, it should have attained enough strength to carry the succeeding layer of concrete. The wall example showed that the use of admixtures is an economical way to address and control the setting time. A setting retarder will extend the setting time of Portland cement, giving more time to place and finish the mixture (Koshnevis 2014; Hwang and Khoshnevis 2004). From these early experiments with rapid set cement, the conclusion is that the CC system should be designed to complete one material deposition cycle faster than the initial setting time (Hwang and Khoshnevis 2004).

3.6 Summarizing The Factors

All the factors mentioned above have a certain degree of impact on the schedule. Practically, the degree of impact will have to be calculated based on real life values. However theoretically, based on Hwang’s experience and common knowledge of construction these factors can be sorted based on their degrees of impact. The list
below is in descending order with filler material placement being the most important factor:

1. Filler material placement
2. Mix Design
3. Height of each layer to be poured
4. Pouring Rate/Pour Pressure and arm speed
5. Maximum capacity of the Container

The filler material placement has to be decided well in advance. The method used in Hwang's experiment is not feasible in real time construction. Therefore, a more feasible methodology has to be used for commercial construction. The filler material placement methodology will directly impact the Mix design. Based on the initial setting time of the Mix design, the maximum capacity of the container will be decided. The Mix design also governs the Pour Pressure, arm speed and the height of each layer being poured. For a certain Mix design, there will a specific initial setting time, maximum and minimum height of each layer, and maximum and minimum arm speed and pour pressure. For a certain nozzle geometry or layer height, there will be a minimum arm speed and pour pressure. If the nozzle geometry is changed, there be a new minimum arm speed and pour pressure. The arm speed and the pour pressure is directly proportional to each other. Figure 3-1 shows a diagrammatical representation of the relationship between these factors. The size of the box gives the approximate importance of each of the factors. Only the arm speed and pour pressure can be changed during the course of a project. Rest of the factors have to be decided before the start of the project.
Figure 3-1. Diagrammatical representation of relationship between factors affecting the CC cycle.
CHAPTER 4
USING CONTOUR CRAFTING FOR REAL-TIME CONSTRUCTION

Contour Crafting can significantly reduce the cost of commercial construction (Koshnevis 2014). Projections indicate costs will be around one-fifth as much as conventional construction (Koshnevis 2014). Contour Crafting technology helps to reduce wastage during the construction process. It also significantly reduces the construction time; For example, a 1500 square foot building can be built in less than 24 hours. This fast construction time limits the financing expenses of construction activities that regularly take six months or longer to finish. While the expenses of difficult work will be essentially lessened, physical power will be traded for mental aptitude in the construction business.

4.1 New Proposed Model for Contour Crafting Equipment

The primary purpose of developing such technology is to use it in commercial construction. However, the current model of the machine is too slow to be used for real-time construction. Therefore, it is necessary to develop a real-time construction ready model of contour crafting. Khoshnevis has proposed several models that can be used for commercial construction. However, there are not many published articles or journals regarding these newer models. He has several patents on many of his technology. One of the most frequently presented CC equipment is depicted in Figure 4-1.

This equipment shown in Figure 4-1 is a larger scale version of the equipment used in Hwang’s experiment. The main difference to this machine is its ability to move in all three axes; X-axis, Y-axis, and Z-axis. This makes it easier for the machine to print structures with a variety of structural and architectural complexity.
When the filling material and the forming surface are built a long time apart, the overall time of construction is very high. Therefore, Khoshnevis proposed a new extrusion nozzle assembly to print the filler material and forming surface at the same time. Refer Figure 4-2. He has a patent on this assembly.

In the case of commercial construction, the extrusion equipment will have multiple nozzles. In Figure 4-2, a compound nozzle assembly is shown. This nozzle can perform two functions; simultaneously extrude 2 wall sides (forms) and filling material between the formed sides.
Figure 4-2. A compound Nozzle assembly for commercial construction purposes. (Photo Courtesy: Khoshnevis 2006).

A nozzle for extruding a surface comprises of the first outlet configured to extrude the first extrudate of unhardened material controllably; a second outlet configured to controllably extrude a second extrudate of unhardened material that is separated from the first extrudate; a third outlet configured to extrude a third extrudate of unhardened material between the first and the second extrudates that has a width that is substantially less than the distance between the first and second extrudates; and a controller configured to cause the third extrudate to repeatedly traverse between the first and second extrudates (Koshnevis 2014).

As the extrusion nozzle moves according to the predefined material deposition path of each layer, the rims (smooth outer and the top surface of outside edges) are created first (Hwang and Khoshnevis 2004). The desired outer surface finish can be
acquired by using various kinds of trowels. An even top face for every layer is of prime importance for creating a solid bond between the layer being deposited above. Figure 4-3 shows an actual wall printed by the compound nozzle described above.

Figure 4-3. CC machine printing wall using the compound nozzle. (Photo Courtesy: Mankin 2017).

4.2 The Process of Contour Crafting Based Construction

4.2.1 Setup

Figure 4-1 shows how a potential CC machine would like, could be used for commercial construction. The arm of the machine would comprise of the extrusion assembly, and it would move along the X-axis and the Z-axis with the help of rails. The extrusion assembly rests on runway gantry system which moves along the Y-axis. The runway girder will also carry the material carrying tank of a certain capacity.

4.2.2 Process

The contour crafting process would begin with the CC machine waiting at the loading station. Once the machine is ready, the raw materials for concrete are mixed at the mixing station. The design mix will depend on the project requirement and the
design of the building itself. One of the main factors that is dependent on the mix design is the maximum and minimum time that would be required to complete the project.

Once the mixing is complete, the material will be loaded onto the CC machine and will be stored in the material carrying tank which rests on the gantry system. After the completion of loading the CC machine will then haul towards the starting point of the fabrication. This will be a predetermined point based on the project requirements. Once the CC nozzle is positioned at the starting point, it begins to extrude the crafting material along a predefined path. The CC machine will move along X and Y axis to match the required path and design of the building. Once, a layer is completed, the whole extrusion assembly moves upward in along the Z-axis to a height that is equal to the thickness of one layer of extruded crafting material.

The CC machine continues to print until the material in the tank is exhausted. The point at which the fabrication stops is noted. The CC machine then hauls back towards the mixing station. Before a new batch is loaded, the material carrying tank and the nozzle assembly is washed to remove any waste concrete present in the equipment. The washing time required will vary depending on the printing time. If the printing time exceeds the initial setting time, the material will harden inside the tank and the nozzle. Therefore, it is always preferable to start washing before the material in the tank reaches its initial setting time. Once the machine is washed, it will undergo maintenance if necessary. If the machine is working well, it will then proceed to mixing and loading. The whole process is repeated until the required structure is completely built. Since the filler material is fabricated along with the forming surface, the new CC cycle will be much simpler. The new CC cycle is represented in Figure 4-4.
4.3 Work Breakdown Structure for New CC System

The work breakdown structure for the new Contour Crafting that can be used for commercial construction will have a simpler WBS compared to the one using Hwang's system. The WBS has been shown in the Figure 4-5 below:

![Work Breakdown Structure for Wall Construction Using CC](image)

Figure 4-5. Work Breakdown Structure for Wall Construction Using CC.
CHAPTER 5
DISCRETE EVENT SIMULATION OF CONTOUR CRAFTING CYCLE

5.1 The Importance of Analysis of CC Cycle

As it has been mentioned earlier, construction planning is a very critical factor and an integral part of construction project management. The success of a project is dependent upon how well it has been planned. It is through project planning that management decides on the correct amount of cost, resources and time required for a project.

The basic purpose of contour crafting technology is to reduce the time and resources used during a construction project. With the help of this technology, we should able to build a residential unit within a day. Therefore, analyzing the construction speed and the schedule is of prime importance.

The construction speed for CC can be calculated in terms of height of concrete poured per hour. However, there are several factors that affect the construction speed. These factors will have to be taken into consideration while planning a construction project that uses CC technology.

5.2 Using Discrete Event Simulation for CC Based Projects

The Critical Path Method, which is the most commonly used planning technique functions on a system that cannot warrant for resource requirements or project limitations. While resource leveling and time-cost trade-off analysis can be used to mitigate this complication, a resulting issue is that this may create conflicting solutions – a solution to one constraint may interfere with a solution to another (Hegazy and Menesi 2010). In the case of CC technology where planning is heavily resource dependent,
conventional planning techniques like the critical path method and PERT will not be sufficient.

CC is a cyclic process. The whole construction process functions as a system or a facility just like in the manufacturing industry. Each layer being printed can be considered a finished product. The machine will keep producing more finished products until the desired limit is reached. CPM cannot be used to schedule a cyclic repetitive system, as it does not account for the nature of the relationship between two activities. Additionally, the CPM procedure can be excessively complex when used to model repetitive tasks.

An ideal planning technique should be able to account for “what if” situations so as to decide the most optimum conditions for the project delivery. It should be able to analyze the change in resources and give results based on the updated resources and constraints. The ideal way to model a construction process is to use a single method that is highly versatile, able to model different situations such as repetitive and non-repetitive construction work, easy to use and able to provide an insight into alternative ways of planning (Flood 2009b). Discrete Event Simulation techniques provide these capabilities. They allow decision-makers to test and better understand the process and alternative ways in which the project can be delivered. DES is very versatile in the sense that it can model any type of interaction between tasks and any type of construction process including repetitive and non-repetitive work (Flood 2010). DES could operate in dynamic modeling mode (Sawhney et al. 1998). It considers stochastic duration, and incorporation of external factors like weather, labor productivity, and
equipment breakdown (Nowrouzian 2012). DES also allows the construction planner to perform a sensitivity analysis involving resource usage (Nowrouzian 2012).

The several DES tools available has been mentioned in the previous section. For the purpose of this research, we will be using Stroboscope software as a DES tool because it is one of the most sophisticated and versatile tools. The simulation will be done through a command line application through an integrated development environment.

The effectiveness of Stroboscope as a DES tool will be studied by using Stroboscope to model a wall construction process for a single residential unit. Once the model is complete, and results are achieved, a sensitivity analysis will be conducted for the most defining factors of the cycle. This will showcase the various capabilities and versatility of Stroboscope software and the DES technique.

Further, more models will be created with multiple residential units and resources to test the versatility of the software.

5.3 Stroboscope Simulation for Wall Construction of Single Residential Unit

To test the effectiveness of the DES as a planning tool for CC, we will create a simulation model in Stroboscope which will emulate the process of wall construction of a single residential unit.

There will be certain assumptions that we will have to make in order to simplify the modeling process, so as to fit the modeling experiment within the time frame of this research. It should be noted that these experiments do not showcase the capacity of Stroboscope software in its entirety but prove its potential as a definitive planning tool for CC based construction. To learn more about the capabilities of Stroboscope, one should refer to STROBOSCOPE. A Dissertation Submitted in Partial Fulfillment of the
5.3.1 Setup

The setup of the CC based construction for a single home will be as shown in Figure 5-1 below. The process flow for the construction has been explained in the previous section.

Figure 5-1. Contour crafting assembly for residential wall construction for 1 unit.
5.3.2 Assumptions

The assumptive values that will be used for this particular simulation have been listed below in Table 5-1. It also shows these values in comparison to Hwang’s model.

Table 5-1. Assumptive values for New CC wall construction for residential unit

<table>
<thead>
<tr>
<th></th>
<th>Data from Hwang’s Wall Construction</th>
<th>Data for New CC wall construction of Residential Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Dimensions</td>
<td>Single Wall: 5 feet long, 2 feet tall, 6 inches thick</td>
<td>Multiple Walls: Total length: 72 ft., Height: 10 ft. Thickness: 6 inches</td>
</tr>
<tr>
<td>Forming Material</td>
<td>Cementitious Mixture</td>
<td>Cementitious Mixture</td>
</tr>
<tr>
<td>Filling Material</td>
<td>Concrete filled in after fabricating forming walls</td>
<td>Cementitious Mixture (1-inch x 1 inch deposited in a traverse path)</td>
</tr>
<tr>
<td>Initial Setting for forming wall</td>
<td>40 Minutes</td>
<td>40 Minutes</td>
</tr>
<tr>
<td>Height of each layer of forming material</td>
<td>0.5 inch</td>
<td>1 inch</td>
</tr>
<tr>
<td>Width of each layer of forming material</td>
<td>0.75 inch</td>
<td>1 inch (on each side)</td>
</tr>
<tr>
<td>X-axis speed (Fabrication speed)</td>
<td>0.753 inch/sec</td>
<td>2 inch/sec</td>
</tr>
<tr>
<td>Y-axis speed</td>
<td>No Y-axis movement</td>
<td>2 inch/sec</td>
</tr>
<tr>
<td>Z-axis speed</td>
<td>0.515 inch/sec</td>
<td>2 inch/sec</td>
</tr>
<tr>
<td>Material Carrying Tank Capacity</td>
<td>Unknown</td>
<td>0.2 CY</td>
</tr>
<tr>
<td>Length of 1 layer</td>
<td>10.57 ft.</td>
<td>72 ft.</td>
</tr>
<tr>
<td>Material deposition</td>
<td>One forming surface at a time</td>
<td>Two forming surface and filling material in a traverse path deposited all the same time</td>
</tr>
</tbody>
</table>
Furthermore, more assumptions are made to complete the CC cycle. These assumptions are listed below:

- The simulation will only include the construction of the exterior walls
- The simulation is done based on the assumption that the construction of the foundation up to the slab on grade has already been constructed
- The simulation is done based on the assumption that the CC equipment is already set up and ready to use
- The wall will have a structure as shown in Figure 5-2. The wall comprises of two forming surfaces with one filler structure which runs in a traverse path at an angle of 30 degrees to the forming surface. The cross-sectional dimensions of each of the running layer will be 1 inch by 1 inch.

![Cross Sectional View of 1 layer](image)

![Top View of 1 layer](image)

Figure 5-2. Top view and cross-sectional view of 1 foot of 1 printed layer. All measurements are in inches.

- Figure 5-2 shows the top view of the 1 foot of 1 printed layer. Since the filler material is printed in a moving in a traverse pattern, it is longer than the forming surface. For every 12 inches of forming surface printed, 13.7982 inches of filler material gets printed. Therefore, total volume of material printed in 1 foot of 1 layer of the wall will
be 37.7982 inch$^3$. Therefore, the effective cross-sectional area of the 1 printed layer will be $37.7982/12 = 3.14985$ inch$^2$ or 0.02187 ft$^2$. This value will be used in the Stroboscope simulation model.

- It is assumed that the machine will run at a speed of 2 inches/sec in all directions.
- It is assumed that the machine will maintain the speed while turning in corners.
- Total volume of the wall for one house = (Effective cross-sectional area of 1 layer)\*(Total length of wall)\*(No. of layers required to complete the wall) = $0.02187*72*(10*12) = 188.96$ cu.ft or 6.99 cu.yd.
- It is assumed that the time required to mix one batch of material is 5 minutes.
- It is assumed that the time required to load one batch of material is 2 minutes.
- The time required for activities such as Haul, Haul Back, and fabrication is based on the machine speed of 2 inches/sec.
- It is assumed that the material carrying tank has an initial capacity of 0.1 CY.
- It is assumed that the time required to wash the tank is 5 minutes if the printing finishes before reaching the initial setting time of the material inside the tank. If it exceeds this limit, then the material hardens inside the nozzle and the wash time increases to 20 minutes.
- The Stroboscope simulation uses an assumption that the machine will have an uptime of 95% and downtime of 5%. During down time the machine goes into maintenance, and it will take 2 hours to get the machine fully functional again.
- Due to the randomness of the no. maintenance required by the machine all results yielded will be a stochastic value.
- Based on the mixed design, it is assumed that the maximum height that can be printed by one batch is 1 foot.

5.4 Stroboscope Model for New CC Wall Construction Of 1 Residential Unit

Figure 5-3 shows the Stroboscope model for the New CC Wall Construction for 1 Residential Unit. See Appendix A for the detailed text input file for this model in Stroboscope’s own language.
Concrete and the CC printer will be the resources used in the model. The model consists of the following elements:

4 Queues:

- **Concrete Available**: Stores concrete needed for the project
- **Printer Wait**: Stores the CC printer
- **Finished Concrete**: Collects finished concrete
- **Waste Concrete**: Collects finished concrete
❖ 1 Cobmi:

- **Mix Material**: Requires Concrete and 1 free printer at printers wait to activate

❖ 1 Fork:

- **Maintenance Skip**: based on probability diverts printer to maintenance

❖ 7 Normals:

- **Load to Printer**: The fabrication material gets loaded to printer
- **Haul to Fabrication Point**: The CC printer hauls to fabrication point from the loading station.
- **Fabricate/Print**: The CC machine continues to print until material tank is empty
- **Haul Back**: The CC machine hauls back to the loading station.
- **Wash**: The CC machine gets washed
- **Maintenance**: Maintenance of CC machine
- **Haul to Position**: Null activity

❖ 2 Bulk Resources:
- CC Printer: 1 unit
- Concrete for Production: 20 CY
  - All links starting with C carries concrete
  - All links starting with P carries the printer.

The simulation starts with the bulk resources in the queue nodes: Concrete available and CC printer wait. Initially, there is a total of 20 CY in the concrete available queue and 1 CC printer at the CC printer queue. The Mix combi draws one 1 printer from the preceding queue through link P1 and the draws concrete though link C1 by an amount that equals the material carrying tank capacity. The concrete then progresses to Load, followed by Haul and fabrication all the way to finished concrete through links C2, C3, C4 and C5 respectively. Assuming, that there will be a wastage of at least 5% the link C5 will only draw 95% of concrete in the tank. The waste concrete then progresses to haul, wash and the waste concrete queue through links C6, C7, and C8 respectively.

Once the print activity is over, the printer progresses to Load, followed by Haul, fabrication, Haul back and wash though links P2, P3, P4, P5 and P6 respectively. From wash, the printer moves to a fork; maintenance skip through link P7. The maintenance skip fork has two options; link P8 to haul to wait position and finally back to Printer wait queue through link P10. Considering that the CC equipment will have an Uptime of 95% the Printer will pass through link P8 with a probability of 95/100. Or else the printer will move through P9 to Maintenance with a probability of 5/100. The printer will then move from maintenance to printer wait through link P11.
If the time starting from mix until the beginning of wash exceeds the initial setting time of the mix, then the time required for wash will also increase by 15 minutes and in turn increasing the cycle time by a huge time.

5.5 Stroboscope Simulation Result for Wall Construction of 1 Residential Unit

See Appendix B for the detailed output result file for this model in Stroboscope’s own language.

The simulations were conducted using variables and constants that were mentioned in previous sections. Due to the stochastic nature of the Stroboscope model, the simulation was run 12 times. It was found that the average time taken to complete the wall fabrication was 28.13 hrs. It took a total of 48 cycles to complete the wall. The time difference between the beginning of Mix and Wash was 33.49 minutes which was well within the initial setting time of the mix. The average number of time the machine broke down was 2.25 times. The observations from the 12 simulations has been show in Table 5-2 below.

<table>
<thead>
<tr>
<th>Observations</th>
<th>No. of breakdowns</th>
<th>Total Runtime (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>31.635</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>27.635</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>27.635</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>27.635</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>27.635</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>29.635</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>29.635</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>27.635</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>25.635</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>27.635</td>
</tr>
<tr>
<td>11</td>
<td>4</td>
<td>31.635</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>23.635</td>
</tr>
<tr>
<td>Average</td>
<td>2.25</td>
<td>28.135</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>1.138</td>
<td>2.276</td>
</tr>
<tr>
<td>Variance</td>
<td>1.295</td>
<td>5.182</td>
</tr>
</tbody>
</table>
There was a total of 82 text entries for this simulation. This simulation also used 75 defining statements in order to define the model. The execution time required for the program was 0.03 secs.
CHAPTER 6
SIMULATING FOR DIFFERENT PROJECT CONDITIONS

The first simulation model has shown that Contour Crafting construction process can be successfully simulated through Stroboscope. However, the efficiency of a modeling technique lies in its capability to incorporate changes based on varying project conditions. Now we will try simulating the model for building two residential units.

6.1 Stroboscope Model for New CC Wall Construction of 2 Residential Units

The model Stroboscope model for simulating the construction of two residential units using Stroboscope will remain as the one shown in Figure 5-3. The haul distance for the second residential unit will differ. The distance between the residential units will be as shown in Figure 6-1 below.

![Diagram of Contour Crafting assembly for residential wall construction for 2 unit.](image)

Figure 6-1. Contour crafting assembly for residential wall construction for 2 unit.
The haul distance from the loading station to the second unit fabrication point will change to 35 ft. This will, in turn, increase the haul and haul back time for wall construction of the second unit.

The text input file for the new model for two units will remain same as the first file except for a few changes (Refer Appendix A). The changes have been listed below:

- **Wall volume will be changed**
  - Total wall volume for two houses will be \(6.99 \times 2 = \sim 14\text{CY}\)
  - **Change:** VARIABLE WallVolume 14; /CY

- **Haul and haul back times will be changed**
  - **Change:** DURATION Haul '((WallVolume-FinishedConcrete.CurCount)>(WallVolume/2) ? (((((DistanceToStartPoint)*36)/CCMachineSpeed)/60) : ((((((DistanceToStartPoint)*36)+312)/CCMachineSpeed)/60))*';
  - **Change:** DURATION HaulBack '((WallVolume-FinishedConcrete.CurCount)>(WallVolume/2) ? (((((DistanceToStartPoint)*36)/CCMachineSpeed)/60) : ((((((DistanceToStartPoint)*36)+312)/CCMachineSpeed)/60))*';

By adding the above listed logic to the Duration of haul and haul back, Stroboscope will automatically increase the time required for Haul and Haul back one the volume for 1 house has been printed.

**6.2 Stroboscope Simulation Result for Wall Construction of 2 Residential Units**

See Appendix C for the detailed output result file for this model in Stroboscope's own language.

The simulations were conducted using variables and constants that were mentioned in previous sections. Due to the stochastic nature of the Stroboscope model, the simulation was run 12 times. It was found that the average time taken to complete the wall fabrication of two residential units were 52.81 hrs. It took a total of 48 cycles to
complete the wall. The time difference between the beginning of Mix and Wash was 38.96 minutes which was well within the initial setting time of the mix. The average number of time the machine broke down was 4.33 times. The observations from the 12 simulations has been show in Table 6-1 below.

There was a total of 82 text entries for this simulation. Changes were made to 3 text input lines. This simulation also used 75 defining statements in order to define the model. The execution time required for the program was 0.03 secs.

<table>
<thead>
<tr>
<th>Observations</th>
<th>No. of breakdowns</th>
<th>Total Runtime (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>50.148</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>54.148</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>54.148</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>52.148</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>60.148</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>52.148</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>50.148</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>50.148</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
<td>54.148</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>54.148</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
<td>48.148</td>
</tr>
<tr>
<td>12</td>
<td>5</td>
<td>54.148</td>
</tr>
<tr>
<td>Average</td>
<td>4.333</td>
<td>52.814</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>1.557</td>
<td>3.114</td>
</tr>
<tr>
<td>Variance</td>
<td>2.424</td>
<td>9.697</td>
</tr>
</tbody>
</table>

**6.3 Stroboscope Model for New CC Wall Construction of 3 Residential Units**

The model Stroboscope model for simulating the construction of 3 residential units using Stroboscope will remain same as the one shown in Figure 5-3. The haul distance for the second and the third residential unit will differ. The distance between the residential units will be as shown in Figure 6-2 below.
The haul distance from the loading station to the second unit fabrication point will change to 35 ft, and the distance to the third unit will be 61 ft. This will, in turn, increase the haul and haul back time for wall construction of the second and third unit.

The text input file for the new model for two units will remain same as the first file except for a few changes (Refer Appendix A). The changes are listed below:

- **Wall volume will be changed**

- Total wall volume for two houses will be $6.99 \times 3 = \sim 21$ CY

- **Change:** VARIABLE WallVolume 21; /CY

- **Haul and haul back times will be changed**

- **Change:** DURATION Haul (WallVolume\(\times\)FinishedConcrete.CurCount)-(WallVolume/3) ? (((DistanceToStartPoint)*36)/CCMachineSpeed)/60) : (WallVolume-FinishedConcrete.CurCount)-(WallVolume/2) ? (((DistanceToStartPoint)*36+312)/CCMachineSpeed)/60) : (((DistanceToStartPoint)*36+312+312)/CCMachineSpeed)/60);
• **Change:** DURATION HaulBack `(WallVolume - FinishedConcrete.CurCount) > (WallVolume/3) ? `(((((DistanceToStartPoint)*36)/CCMachineSpeed)/60) : (WallVolume-FinishedConcrete.CurCount) > (WallVolume/2) ? (((DistanceToStartPoint)*36+312)/CCMachineSpeed)/60) : (((DistanceToStartPoint)*36+312+312)/CCMachineSpeed)/60)`;

By adding the above listed logic to the Duration of haul and haul back, Stroboscope will automatically increase the time required for Haul and Haul back once the volume for 1 house has been printed and again once the volume for the second house has been printed.

### 6.4 Stroboscope Simulation Result for Wall Construction of 3 Residential Units

See Appendix D for the detailed output result file for this model in Stroboscope’s own language.

The simulations were conducted using variables and constants that were used in the simulation model for the construction of 2 residential wall unit. The changes that had been made has been listed in the previous section.

It was found that the time taken to complete the wall fabrication of three residential units were 106.922 hrs. It took a total of 121 cycles to complete the wall.

The time difference between the beginning of Mix and Wash was a minimum of 33.49 minutes and a maximum of 43.89 minutes, which exceeds the initial setting time of the mix.

There were 5 instances where the machine broke down and had to undergo a maintenance time of 120 minutes each.

There was a total of 82 text entries for this simulation. Changes were made to 3 text input lines. This simulation also used 75 defining statements in order to define the model. The execution time required for the program was 0.04 secs.
However, in this cycle the Haul time was excessively long for the third unit. Therefore, the material hardened inside the machine and the wash time increased to 20 minutes for the third residential wall construction. This considerably increased the overall construction time. Due to this reason, the simulation was only run once. This issue can be resolved in two ways:

- Demobilizing and relocating the loading station closer to the third unit after the construction of unit 1 and 2
- Use of two CC printers.

6.5 Stroboscope Model for New CC Wall Construction of 3 Residential Unit by Relocating Loading Station

When simulating the model for CC wall construction of 3 residential units by relocating loading station, several changes will have to be made in comparison to the model used for CC wall construction without relocating the loading station. See Appendix E for the detailed text input file for this model in Stroboscope’s own language.

The CC printer will initially start at the old loading station and will continue to fabricate the first two residential units.

It was evident from the last simulation that the haul distance for the third unit was too long and the concrete will harden inside the material carrying tank. Therefore, in the new model, we will relocate the loading and washing station to a new location which will be in between unit 2 and unit 3. This will reduce the haul distance for the fabrication of the third unit to 1 yard.

Figure 6-3 shows the haul distances and the new assembly for CC wall construction of 3 residential unit by relocating loading station.
The Stroboscope model in itself will change when using the relocating model. However, the base model and the process flow logic will remain the same. Once, the CC printer has been relocated; Stroboscope will have to follow a new route. The Stroboscope model for wall construction for 3 unit by relocating loading station has been shown in Figure 6-4. The blue path will be used for the fabrication of the first two units. The green path will be used for demobilization and relocation process, and the green path will be used for the fabrication of the third unit. Even though the blue and green paths have a similar structure, they have different logics built into them. The green path has only the logic for the construction 1 unit. Whereas, the blue path is built for the construction of two units. If the requirement was to build 4 units, i.e. to relocate after 2 units and to build 2 more units, it would have been possible to use the previous model without adding the green path.
Figure 6-4. Model for CC wall construction of 3 residential units by relocating loading station.
Two additional forks have been built into the model. The properties of the new forks are listed below:

**Unit3Skip**

- : Once the first two units have been printed this skip will help route the CC printer to the green path which will fabricate the third unit

**Demobilize**

- : This fork will reroute the CC printer to the demobilization activity once the fabrication of unit 1 and 2 is completed. In this model, the CC printer will pass through demobilization only once.

### 6.6 Stroboscope Simulation Result for Wall Construction of 3 Residential Units by Relocating Loading Station

Refer Appendix F for the detailed output result file for this model in Stroboscope’s own language.

The simulations were conducted using variables and constants that were mentioned in previous sections. Due to the stochastic nature of the Stroboscope model, the simulation was run 12 times. It was found that the average time taken to complete the wall fabrication of three units were 100.916 hrs. It took a total of 84 cycles to complete the wall. The time difference between the beginning of Mix and Wash was 38.96 minutes which was well within the initial setting time of the mix. The average number of time the machine broke down was 5.833 times. The observations from the 12 simulations has been show in Table 6-2 below.

There were a total of 133 text entries for this simulation. Changes were made to 3 text input lines. This simulation also used 126 defining statements in order to define the model. The execution time required for the program was 0.04 secs.
Table 6-2. Observations for 3 Residential Units Construction

<table>
<thead>
<tr>
<th>Observations</th>
<th>No. of breakdowns</th>
<th>Total Runtime (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>101.249</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>101.249</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>95.249</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>103.249</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>95.249</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>99.249</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>99.249</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>99.249</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>105.249</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>109.249</td>
</tr>
<tr>
<td>11</td>
<td>4</td>
<td>97.249</td>
</tr>
<tr>
<td>12</td>
<td>8</td>
<td>105.249</td>
</tr>
<tr>
<td>Average</td>
<td>5.833</td>
<td>100.916</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>2.125</td>
<td>4.250</td>
</tr>
<tr>
<td>Variance</td>
<td>4.515</td>
<td>18.061</td>
</tr>
</tbody>
</table>

6.7 Stroboscope Model for New CC Wall Construction of 3 Residential Units by Using Two CC Printers

When simulating the model for CC wall construction of 3 residential unit by using two CC printers, it will use similar model the CC wall construction of 3 residential by relocating loading station few changes will have to be made to the model. The demobilization activities will have to be taken out.

A Stroboscope input language for this model has not been created as part of this research. The process setup will be as shown in Figure 6-5. The second CC printer will
be located between unit 2 and unit 3. Both the CC printers will be functioning at the same time. Both the CC printers will use a common loading and washing station.

![Diagram of CC machines working simultaneously]

Figure 6-5. Contour crafting assembly for residential wall construction for 3 unit by using two CC machines.

The washing, maintenance and loading stations will only cater to one CC machine at a time. The stroboscope language will automatically create a queue for the printer and the washing station.

A Stroboscope input language for this model has not been created as part of this research. However, the Stroboscope model for CC wall construction using two printers have been shown in Figure 6-6. The time required for the construction will be equal to the time required for the construction of two units.
Figure 6-6. Model for CC wall construction of 3 residential unit by using 2 CC stations.

There will be few additions and changes to the model in comparison to the model used in Figure 6-4. A new resource will have to be added for space. Wash and Maintenance activities will be changed from Normals to Combis. The will need one space to perform their activities. By adding of the space resource, Stroboscope will only cater to one CC printer at a time at these stations.

This model will initiate with the following resources:

- 1 CC printer at CC printer wait
- 1 CC printer at CC printer wait 2
• 25 CY of Concrete at Concrete Available
• 1 space at Space I for loading and mixing station
• 1 space at Space II for washing station
• 1 space at Space III for maintenance

Even though a running Stroboscope model in its own language has not been created for this particular model; it can be seen that this model can be easily prepared using process flow logic in Figure 6-4. No new additional logic or element knowledge will be required for the new model.
In project management, it is of prime importance to model risk into your projects. One of the ways that you can do this is by using sensitivity analysis. A sensitivity analysis is a technique used to determine how different values of an independent variable impact a particular dependent variable under a given set of assumptions (Investopedia 2015). It can also be explained as “what if” situation analysis, using given a range of variables (Investopedia 2015). We will need to simulate the model with this chosen range of variables and study the outcome. By this process, a project manager and his/her team can control how changes in one variable can change the overall outcome of the project. This will give them the liberty and access to choose the best and the most beneficial variables for their project.

Knowing effects of different variables have on a project can help management with setting needs to all the more rapidly finish the final product. The distinctions among the changing variables can be effectively observed since each end product will have a numerical value. This encourages correlations between the different components to rapidly recognize which risks are worth taking rapidly. Project management team can utilize the affectability examination to make needs in managing basic risks to the project. To summarize the purpose of sensitivity analysis is:

- To categorize the key variables that impact the project performance and the overall project cost
- To examine the effects of changing these key variables using what-if simulation
- To evaluate whether project choices are expected to be impacted by such changes
- To recognize measures that could possibly alleviate the adversarial effects on the project.
7.1 Sensitivity Analysis for CC Based Construction Using DES

In Chapter 5 and 6, we created different Stroboscope models according to different scenarios. We modeled with respect to changing project requirements, and Stroboscope has been shown to be powerful in modeling all the scenarios and changes to the models were easily made with changing project requirements.

At the same time, it is important for a project management tool to be able to conduct sensitivity analysis based on changing variables and what if situations. In Chapter 7, we will test the ability of Stroboscope to conduct sensitivity analysis on a DES model for CC based construction.

In Chapter 3 we were able to identify the factors governing the typical CC cycle. During our modeling process in Chapter 5 and 6, we were able to incorporate these factors into the Stroboscope model as variables. Few of the variables that were used are:

- Height of each layer
- Number of CC printers
- Capacity of material carrying tank
- Arm speed of CC machine
- Initial setting time of design mix

Based on the Stroboscope model for CC based wall construction for 1 residential we will conduct sensitivity analysis for one variable: the capacity of material carrying tank. We will start the capacity of material carrying tank. We will keep all other variables constant and gradually increase the capacity by a value of 0.2 CY. Remember that we will be using the same Stroboscope input language provided in Appendix A. All the assumptions mentioned in section 5.3.2 will be used for this model. Note that all these
limitations have been built into the model in Appendix A. This was evident when the wash time increased its time from five minutes to 20 minutes.

The earlier model used was yielding a stochastic result due to the randomness of the no. of maintenance activity required or the no. of times the CC machine broke down. This stochastic value cannot be used for the sensitivity analysis since each simulation might give a different value for the no. of the maintenance cycle. Therefore, it will be assumed that the simulation is running with a 100% uptime and there will no requirement for maintenance.

7.2 Sensitivity Analysis for the Capacity of the Material Carrying Tank

The sensitivity analysis will begin with the value of the capacity of the material carrying tank as 0.1 CY. After each simulation, the total simulation time, the number of cycles required, the time required for each cycle and the maximum print height will be recorded. The simulation will continue until one of the design limitations have been exceeded. The values recorded for the sensitivity analysis was as shown in Table 7-1.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Printer Tank Capacity</th>
<th>Time Taken to complete fabrication</th>
<th>Maximum Print height</th>
<th>No. of cycles</th>
<th>Time required for each cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation 1</td>
<td>0.10</td>
<td>36.505</td>
<td>2</td>
<td>84</td>
<td>26.15</td>
</tr>
<tr>
<td>Simulation 2</td>
<td>0.12</td>
<td>34.239</td>
<td>2</td>
<td>72</td>
<td>28.61</td>
</tr>
<tr>
<td>Simulation 3</td>
<td>0.14</td>
<td>32.539</td>
<td>2</td>
<td>63</td>
<td>31.08</td>
</tr>
<tr>
<td>Simulation 4</td>
<td>0.16</td>
<td>31.777</td>
<td>3</td>
<td>57</td>
<td>33.55</td>
</tr>
<tr>
<td>Simulation 5</td>
<td>0.18</td>
<td>31.121</td>
<td>3</td>
<td>52</td>
<td>36.02</td>
</tr>
<tr>
<td>Simulation 6</td>
<td>0.20</td>
<td>30.694</td>
<td>3</td>
<td>48</td>
<td>38.49</td>
</tr>
<tr>
<td>Simulation 7</td>
<td>0.22</td>
<td>29.939</td>
<td>4</td>
<td>44</td>
<td>40.96</td>
</tr>
<tr>
<td>Simulation 8</td>
<td>0.24</td>
<td>30.302</td>
<td>4</td>
<td>42</td>
<td>43.43</td>
</tr>
<tr>
<td>Simulation 9</td>
<td>0.26</td>
<td>38.985</td>
<td>4</td>
<td>39</td>
<td>60.9</td>
</tr>
</tbody>
</table>

It can be noticed the time taken for fabrication keeps decreasing as we keep increasing the capacity for material carrying tank. Figure 7-1 shows the trend in
reduction. The rate at which the overall time required changes decreases as we keep increasing the capacity of the tank.

Figure 7-1. Capacity of material carrying tank vs. Total time taken for fabrication.

The lowest fabrication time was achieved at a capacity of 0.22 CY. At 0.24 CY the overall fabrication time slightly increases even after the overall no. of cycles required decreases. This is due to that the fact that the time required per cycle has become too large that it, in turn, increases the overall duration. 0.26 CY there is a steep increase in the overall duration. This is because Stroboscope detected that the time from the start of Mix to the start of wash was higher than the initial setting time. Therefore, the concrete has hardened inside the tank, and it increases the overall duration of each cycle.

7.3 Sensitivity Analysis Result

From the above sensitivity analysis, it can be seen that the overall capacity of the material carrying tank can only be increased to a certain extent by keeping all the other
variables constant. If the project management team wants to reduce the fabrication time further, they will have to change another variable. For example, we can try to increase the arm speed of the machine thereby reducing the time required for each cycle. Similarly, with the help of Stroboscope sensitivity analysis, can be conducted on multiple variables. This experiment has shown the capability of Stroboscope in performing successful sensitivity analysis on CC based construction model.
8.1 Conclusion and Key Findings

Contour Crafting is a promising new technology which is a possible answer to the construction industry’s long-term goal to increase productivity and reduce wastage. This requirement is met by the increases use of automation in a controlled work environment. With the help of contour crafting technology, you will be able to be build complex structures with an intricate design. The CC technology fits in this category and has the potential to revolutionize the industry, changing it from the conventional “beam and post” paradigm to a layer by layer approach (Hwang and Khoshnevis 2004). CC is also capable of using a variety of materials with large aggregates and additives such as reinforcement fibre (Khoschnevis 2006). With its high rate of fabrication, and low percentage of wastage, CC can be considered as a viable technology that can be used for full-scale construction in disaster relief construction and low-income housing. There are several studies that are being carried out in the field of contour crafting and automated layer fabrication. The research conducted in this paper attempted to simulate a real life CC based construction. Note, that all the limitations and variables used for the simulation were assumptive and related to the values from Hwang, Dooil, and Behrokh Khoshnevis. "Concrete wall fabrication by contour crafting." 21st International Symposium on Automation and Robotics in Construction (ISARC 2004), Jeju, South Korea. 2004

Like every other construction process, it is important to successfully manage a construction process and the risk associated with it. In comparison to a typical construction project, CC is more of a cyclic process. The whole construction process
functions as a system. Conventional planning methodologies like CPM can be excessively complex when used to model repetitive tasks. Through the course of this research, discrete event simulation technique showcased its potential as a planning tool. Discrete event simulation. Stroboscope, being the most powerful DES tool, was able to model intricate relations between resources and activities in a CC based construction process. With the help of Stroboscope, we were able to represent resources that have different properties. For example, we were able to factor in the initial setting time of the concrete mix into the program. The program was also versatile enough to have dynamic timing for each activity. In the simulation model for CC based wall construction for three residential units, the wash time during the cycle of construction for the third residential unit automatically increased to 20 minutes, since the concrete stayed inside the material carrying tank for too long. Each activity and resources can have an assignable, persistent and dynamic property (Martinez 1996). We were able to model any type of relationship between each activity.

Another important fact observed was the versatility of the Stroboscope tool to modify its model based on changing project requirements. One Stroboscope model was developed for CC based wall construction for 1 residential unit. Only a few minor changes had to be made to this model in order for it to be used for construction on 2 and 3 residential units. With few more changes to the model, we were able to factor in the use of two CC equipment and even demobilizing and relocating the existing CC machine to a new spot. This can be very useful in real life construction project as project managers and engineers can compare the various approaches to completing a
construction project. Various factors like cost and labor can also be integrated to the model with ease.

Chapter 7 showcased the capacity of the Stroboscope tool to conduct sensitivity analysis for CC based construction. Many variables were factored into the Stroboscope input language while developing a model for CC based construction. Sensitivity analysis carried out for the capacity of the material carrying tank with a chosen range of variables and we were able to study the outcome. The distinctions among the changing variables was effectively observed since each end product had a numerical value associated with it. This helped in building correlations between the different components and in recognizing which risks are worth taking. This process will help a project manager understand how changes in certain variable can change the overall outcome of the project and it also gives them the liberty to access and choose the best and the most beneficial variables for their project.

Although Stroboscope has great potential in being a project planning tool for CC based construction, there were a few notable drawbacks. Stroboscope is a very complex software will require expert guidance in learning and using it. The versatility of the software in turn also adds into the complexity of it. There were 75 defining terms that were used to develop the Stroboscope input language for the wall construction model. A Stroboscope user would thoroughly need to learn the various modelling components of Stroboscope. The initial development of a Stroboscope can be quite a strenuous process. The developer should also have a thorough knowledge of the construction process he is trying to model and the logic between each activity.
Stroboscope also has certain limitations when it comes to visual representation. It can provide the user with a basic representation of how the cycle would look like and the process flow logic. However, if the user wants to learn about the relationships and constraints for the activities, they will have to study the input language.

**8.2 Future Research Recommendations**

All the values used in this research are either assumptive or adapted from the wall construction experiment by Hwang (2004). Future research should try to evaluate the same models with more realistic values and study the performance of CC based construction. Since CC is an upcoming and promising construction technology, it is important to find a perfect planning tool for its construction process. Another versatile planning tool is Foresight. Foresight was developed at the Rinker School of Construction Management at the University of Florida. Foresight is a new and innovative approach to modeling the construction processes. Foresight is an enhancement to the type and paradigm of Simulation modeling with the goal of achieving the simplicity of CPM, visual insight of linear scheduling and the power and versatility of simulation (Flood 2009). Foresight is developed with the objective of model having hierarchical structure and interactive development to improve the user’s understanding of the organization and behavior of the system (Flood 2009). Future research should try to model the contour crafting model in Foresight and compare the process and results to that of this research.
Stroboscope Text input file in its own language:

/ Problem Decision Variable

VARIABLE HeightOfLayer 1;
VARIABLE ConcreteAvail 20; /CY
VARIABLE NoOfCCprinters 1; /EA
VARIABLE WallVolume 6.99; /CY
VARIABLE PrinterTankCapacity 0.20; /CY
VARIABLE DistanceToStartPoint 3; /YD
VARIABLE CCMachineSpeed 3; /Inch/Sec
VARIABLE TotalLenghtOfOneLayer 72; /Ft
VARIABLE IniSettingTime 40; /Mins
VARIABLE MixTime 5; /Mins
VARIABLE LoadTime 2; /Mins
VARIABLE CSarea 0.02187;
VARIABLE MaxHeight 8; /Inch
SAVEVALUE WashTime 5;
DISPLAY " ";
DISPLAY "Available Concrete : " ConcreteAvail;
DISPLAY " ";
DISPLAY "No. of Contour Crafting Printers : " NoOfCCprinters;
DISPLAY " ";
DISPLAY "Volume of wall to be constructed : " WallVolume;

DISPLAY " ";

DISPLAY "Capacity of Printer Tank : " PrinterTankCapacity;

DISPLAY " ";

DISPLAY "Arm speed of CC Machine : " CCMachineSpeed;

DISPLAY " ";

DISPLAY "Design Mix Initial Setting Time : " IniSettingTime;

DISPLAY " ";

DISPLAY "Print height (Inches): "

Round[((((PrinterTankCapacity*27)/CSarea)/72),0)*HeightOfLayer;

DISPLAY '
'(Round[((((PrinterTankCapacity*27)/CSarea)/72),0)*HeightOfLayer)>MaxHeight  ? "Simulation not possible" : "Print height within limits"';

GENTYPE CCPrinter;

GENTYPE Concrete;

QUEUE ConcreteForMix Concrete;

QUEUE CCPrinterWait CCPrinter;

QUEUE FinishedConcrete Concrete;

QUEUE WasteConcrete Concrete;

COMBI Mix;

NORMAL Load;

NORMAL Haul;

NORMAL Print;

NORMAL HaulBack;
NORMAL Wash;
NORMAL Maintenance;
NORMAL HaulToPosition;
FORK MaintenanceSkip CCPrinter;
LINK C1 ConcreteForMix Mix;
DRAWAMT C1 '(WallVolume-FinishedConcrete.CurCount)>PrinterTankCapacity ? PrinterTankCapacity : WallVolume-FinishedConcrete.CurCount';
LINK P1 CCPrinterWait Mix;
LINK P2 Mix Load CCPrinter;
LINK C2 Mix Load Concrete;
LINK P3 Load Haul CCPrinter;
LINK C3 Load Haul Concrete;
LINK P4 Haul Print CCPrinter;
LINK C4 Haul Print Concrete;
LINK C5 Print FinishedConcrete;
RELEASEAMT C5 0.95*Print.Concrete.Count;
LINK P5 Print HaulBack CCPrinter;
LINK C6 Print HaulBack Concrete;
RELEASEAMT C6 0.05*Print.Concrete.Count;
LINK P6 HaulBack Wash CCPrinter;
LINK C7 HaulBack Wash Concrete;
LINK C8 Wash WasteConcrete;
LINK P7 Wash MaintenanceSkip;
LINK P8 MaintenanceSkip HaulToPosition;
LINK P9 MaintenanceSkip Maintenance;
STRENGTH P8 0.95;
STRENGTH P9 0.05;
LINK P10 Maintenance HaulToPosition CCPrinter;
LINK P11 HaulToPosition CCPrinterWait;
DURATION Mix 5;
DURATION Load 2;
DURATION Haul '(((DistanceToStartPoint)*36)/CCMachineSpeed)/60)';
DURATION Print '(((PrinterTankCapacity*27)/CSarea)*12)/CCMachineSpeed)/60)';
DURATION HaulBack '(((DistanceToStartPoint)*36)/CCMachineSpeed)/60)';
ONEND HaulBack
  ASSIGN WashTime PRECOND (SimTime-Mix.LastStart)>40 20;
DURATION Wash WashTime;
DURATION Maintenance 120;
INIT ConcreteForMix ConcreteAvail;
INIT CCPrinterWait NoOfCCprinters;
ONEND Wash StdOutput PRECOND (Wash.LastStart-Mix.LastStart)>IniSettingTime
  "Print time exceeded initial setting time. Concrete has hardened inside the Tank.
Heavy Maintenance required";

ONEND HaulToPosition PRINT StdOutput
  "The Current Simulation Time at the end of cycle is %.2f hrs " SimTime/60;
  SIMULATEUNTIL 'FinishedConcrete.CurCount>=WallVolume';
  DISPLAY "Total Simulation Time : "SimTime/60;
REPORT;
APPENDIX B
STROBOSCOPE RESULT FOR CC CONSTRUCTION OF WALL FOR SINGLE RESIDENTIAL UNIT

Stroboscope Model Strobo1 (836283104)
Available Concrete : 20

No. of Contour Crafting Printers : 1

Volume of wall to be constructed : 6.99

Capacity of Printer Tank : 0.2

Arm speed of CC Machine : 2

Design Mix Initial Setting Time : 40

Print height: 3

Print height within limits

The Current Simulation Time at the end of cycle is 0.64 hrs
The Current Simulation Time at the end of cycle is 1.28 hrs
The Current Simulation Time at the end of cycle is 1.92 hrs
The Current Simulation Time at the end of cycle is 2.57 hrs
The Current Simulation Time at the end of cycle is 3.21 hrs
The Current Simulation Time at the end of cycle is 3.85 hrs
The Current Simulation Time at the end of cycle is 4.49 hrs
The Current Simulation Time at the end of cycle is 5.13 hrs
The Current Simulation Time at the end of cycle is 5.77 hrs
The Current Simulation Time at the end of cycle is 6.42 hrs
The Current Simulation Time at the end of cycle is 7.06 hrs
The Current Simulation Time at the end of cycle is 7.70 hrs
The Current Simulation Time at the end of cycle is 8.34 hrs
The Current Simulation Time at the end of cycle is 8.98 hrs
The Current Simulation Time at the end of cycle is 9.62 hrs
The Current Simulation Time at the end of cycle is 10.26 hrs
The Current Simulation Time at the end of cycle is 10.91 hrs
The Current Simulation Time at the end of cycle is 11.55 hrs
The Current Simulation Time at the end of cycle is 12.19 hrs
The Current Simulation Time at the end of cycle is 12.83 hrs
The Current Simulation Time at the end of cycle is 13.47 hrs
The Current Simulation Time at the end of cycle is 14.11 hrs
The Current Simulation Time at the end of cycle is 14.76 hrs
The Current Simulation Time at the end of cycle is 15.40 hrs
The Current Simulation Time at the end of cycle is 16.04 hrs
The Current Simulation Time at the end of cycle is 16.68 hrs
The Current Simulation Time at the end of cycle is 17.32 hrs
The Current Simulation Time at the end of cycle is 17.96 hrs
The Current Simulation Time at the end of cycle is 18.60 hrs
The Current Simulation Time at the end of cycle is 19.25 hrs
The Current Simulation Time at the end of cycle is 19.89 hrs
The Current Simulation Time at the end of cycle is 20.53 hrs
The Current Simulation Time at the end of cycle is 21.17 hrs
The Current Simulation Time at the end of cycle is 21.81 hrs
The Current Simulation Time at the end of cycle is 22.45 hrs
The Current Simulation Time at the end of cycle is 23.09 hrs
The Current Simulation Time at the end of cycle is 23.74 hrs
The Current Simulation Time at the end of cycle is 24.38 hrs
The Current Simulation Time at the end of cycle is 25.02 hrs
The Current Simulation Time at the end of cycle is 25.66 hrs
The Current Simulation Time at the end of cycle is 26.30 hrs
The Current Simulation Time at the end of cycle is 26.94 hrs
The Current Simulation Time at the end of cycle is 27.59 hrs
The Current Simulation Time at the end of cycle is 28.23 hrs
The Current Simulation Time at the end of cycle is 28.87 hrs
The Current Simulation Time at the end of cycle is 29.51 hrs

Total Simulation Time: 32.694753

Statistics report at simulation time 1961.6852

<table>
<thead>
<tr>
<th>Queue</th>
<th>Res</th>
<th>Cur</th>
<th>Tot</th>
<th>AvWait</th>
<th>AvCont</th>
<th>SDCont</th>
<th>MinCont</th>
<th>MaxCont</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCPrinterWait</td>
<td>CCPrinter</td>
<td>0.00</td>
<td>48.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>ConcreteForMix</td>
<td>Concrete</td>
<td>12.64</td>
<td>28.08</td>
<td>1493.44</td>
<td>15.23</td>
<td>2.41</td>
<td>28.08</td>
<td></td>
</tr>
<tr>
<td>FinishedConcrete</td>
<td>Concrete</td>
<td>6.99</td>
<td>6.99</td>
<td>1248.17</td>
<td>4.42</td>
<td>2.34</td>
<td>6.99</td>
<td></td>
</tr>
<tr>
<td>WasteConcrete</td>
<td>Concrete</td>
<td>0.37</td>
<td>0.37</td>
<td>1234.27</td>
<td>0.23</td>
<td>0.12</td>
<td>0.37</td>
<td></td>
</tr>
</tbody>
</table>
Instance            Start     End
========================================
HaulBack(47)        1961.69  1962.59
Total Number of Named Objects : 40
Total Number of Variables : 46
Total Number of Statements : 83

Execution    Time = 0.03 seconds
APPENDIX C
STROBOSCOPE RESULT FOR CC CONSTRUCTION OF WALL FOR TWO RESIDENTIAL UNIT

Stroboscope Model Strobo1 (1510074896)
Available Concrete : 20

No. of Contour Crafting Printers : 1
Volume of wall to be constructed : 14
Capacity of Printer Tank : 0.2
Arm speed of CC Machine : 2
Design Mix Initial Setting Time : 40
Print Height: 3
Print height within limits
The Current Simulation Time at the end of cycle is 0.64 hrs
The Current Simulation Time at the end of cycle is 1.28 hrs
The Current Simulation Time at the end of cycle is 1.92 hrs
The Current Simulation Time at the end of cycle is 2.57 hrs
The Current Simulation Time at the end of cycle is 3.21 hrs
The Current Simulation Time at the end of cycle is 3.85 hrs
The Current Simulation Time at the end of cycle is 4.49 hrs
The Current Simulation Time at the end of cycle is 5.13 hrs
The Current Simulation Time at the end of cycle is 5.77 hrs
The Current Simulation Time at the end of cycle is 6.42 hrs
The Current Simulation Time at the end of cycle is 7.06 hrs
The Current Simulation Time at the end of cycle is 7.70 hrs
The Current Simulation Time at the end of cycle is 8.34 hrs
The Current Simulation Time at the end of cycle is 10.98 hrs
The Current Simulation Time at the end of cycle is 11.62 hrs
The Current Simulation Time at the end of cycle is 12.26 hrs
The Current Simulation Time at the end of cycle is 12.91 hrs
The Current Simulation Time at the end of cycle is 13.55 hrs
The Current Simulation Time at the end of cycle is 14.19 hrs
The Current Simulation Time at the end of cycle is 14.83 hrs
The Current Simulation Time at the end of cycle is 15.47 hrs
The Current Simulation Time at the end of cycle is 16.11 hrs
The Current Simulation Time at the end of cycle is 16.76 hrs
The Current Simulation Time at the end of cycle is 17.40 hrs
The Current Simulation Time at the end of cycle is 18.04 hrs
The Current Simulation Time at the end of cycle is 18.68 hrs
The Current Simulation Time at the end of cycle is 19.32 hrs
The Current Simulation Time at the end of cycle is 19.96 hrs
The Current Simulation Time at the end of cycle is 20.60 hrs
The Current Simulation Time at the end of cycle is 21.25 hrs
The Current Simulation Time at the end of cycle is 21.89 hrs
The Current Simulation Time at the end of cycle is 22.53 hrs
The Current Simulation Time at the end of cycle is 23.17 hrs
The Current Simulation Time at the end of cycle is 23.81 hrs
The Current Simulation Time at the end of cycle is 26.45 hrs
The Current Simulation Time at the end of cycle is 27.09 hrs
The Current Simulation Time at the end of cycle is 27.78 hrs
The Current Simulation Time at the end of cycle is 28.51 hrs
The Current Simulation Time at the end of cycle is 29.24 hrs
The Current Simulation Time at the end of cycle is 29.96 hrs
The Current Simulation Time at the end of cycle is 30.69 hrs
The Current Simulation Time at the end of cycle is 33.42 hrs
The Current Simulation Time at the end of cycle is 34.15 hrs
The Current Simulation Time at the end of cycle is 34.88 hrs
The Current Simulation Time at the end of cycle is 35.61 hrs
The Current Simulation Time at the end of cycle is 36.33 hrs
The Current Simulation Time at the end of cycle is 37.06 hrs
The Current Simulation Time at the end of cycle is 37.79 hrs
The Current Simulation Time at the end of cycle is 38.52 hrs
The Current Simulation Time at the end of cycle is 39.25 hrs
The Current Simulation Time at the end of cycle is 39.97 hrs
The Current Simulation Time at the end of cycle is 40.70 hrs
The Current Simulation Time at the end of cycle is 41.43 hrs
The Current Simulation Time at the end of cycle is 44.16 hrs
The Current Simulation Time at the end of cycle is 44.89 hrs
The Current Simulation Time at the end of cycle is 45.62 hrs
The Current Simulation Time at the end of cycle is 46.34 hrs
The Current Simulation Time at the end of cycle is 47.07 hrs
The Current Simulation Time at the end of cycle is 47.80 hrs
The Current Simulation Time at the end of cycle is 48.53 hrs
The Current Simulation Time at the end of cycle is 49.26 hrs
The Current Simulation Time at the end of cycle is 49.98 hrs
The Current Simulation Time at the end of cycle is 50.71 hrs
The Current Simulation Time at the end of cycle is 51.44 hrs
The Current Simulation Time at the end of cycle is 52.17 hrs
The Current Simulation Time at the end of cycle is 52.90 hrs
The Current Simulation Time at the end of cycle is 53.63 hrs
The Current Simulation Time at the end of cycle is 56.35 hrs
The Current Simulation Time at the end of cycle is 57.08 hrs
The Current Simulation Time at the end of cycle is 57.81 hrs
The Current Simulation Time at the end of cycle is 58.54 hrs
The Current Simulation Time at the end of cycle is 59.27 hrs
The Current Simulation Time at the end of cycle is 59.99 hrs
The Current Simulation Time at the end of cycle is 60.72 hrs
The Current Simulation Time at the end of cycle is 61.45 hrs
The Current Simulation Time at the end of cycle is 62.18 hrs
The Current Simulation Time at the end of cycle is 62.91 hrs
The Current Simulation Time at the end of cycle is 63.64 hrs
The Current Simulation Time at the end of cycle is 64.36 hrs
The Current Simulation Time at the end of cycle is 65.09 hrs
The Current Simulation Time at the end of cycle is 65.82 hrs
The Current Simulation Time at the end of cycle is 66.55 hrs
The Current Simulation Time at the end of cycle is 67.28 hrs

Total Simulation Time : 67.862901
Statistics report at simulation time 4071.7741

Contents of the Future Events List at simulation time 4071.7
Instance      Start     End
========================================
HaulBack(83)    4071.77   4075.27

Total Number of Named Objects : 40
Total Number of Variables : 46
Total Number of Statements : 83

-------------------------------------
Execution    Time = 0.03 seconds
APPENDIX D
STROBOSCOPE RESULT FOR CC CONSTRUCTION OF WALL FOR THREE RESIDENTIAL UNIT

Stroboscope Model Strobo1.STR (1227671360)
Available Concrete : 25
No. of Contour Crafting Printers : 1
Volume of wall to be constructed : 21
Capacity of Printer Tank : 0.2
Arm speed of CC Machine : 2
Design Mix Initial Setting Time : 40
Print Height: 3
Print height within limits

The Current Simulation Time at the end of cycle is 0.64 hrs
The Current Simulation Time at the end of cycle is 1.28 hrs
The Current Simulation Time at the end of cycle is 1.92 hrs
The Current Simulation Time at the end of cycle is 2.57 hrs
The Current Simulation Time at the end of cycle is 3.21 hrs
The Current Simulation Time at the end of cycle is 3.85 hrs
The Current Simulation Time at the end of cycle is 4.49 hrs
The Current Simulation Time at the end of cycle is 5.13 hrs
The Current Simulation Time at the end of cycle is 5.77 hrs
The Current Simulation Time at the end of cycle is 6.42 hrs
The Current Simulation Time at the end of cycle is 9.06 hrs
The Current Simulation Time at the end of cycle is 9.70 hrs
The Current Simulation Time at the end of cycle is 10.34 hrs
The Current Simulation Time at the end of cycle is 10.98 hrs
The Current Simulation Time at the end of cycle is 11.62 hrs
The Current Simulation Time at the end of cycle is 12.26 hrs
The Current Simulation Time at the end of cycle is 12.91 hrs
The Current Simulation Time at the end of cycle is 13.55 hrs
The Current Simulation Time at the end of cycle is 14.19 hrs
The Current Simulation Time at the end of cycle is 14.83 hrs
The Current Simulation Time at the end of cycle is 15.47 hrs
The Current Simulation Time at the end of cycle is 16.11 hrs
The Current Simulation Time at the end of cycle is 16.76 hrs
The Current Simulation Time at the end of cycle is 17.40 hrs
The Current Simulation Time at the end of cycle is 18.04 hrs
The Current Simulation Time at the end of cycle is 18.68 hrs
The Current Simulation Time at the end of cycle is 19.32 hrs
The Current Simulation Time at the end of cycle is 19.96 hrs
The Current Simulation Time at the end of cycle is 20.60 hrs
The Current Simulation Time at the end of cycle is 21.25 hrs
The Current Simulation Time at the end of cycle is 21.89 hrs
The Current Simulation Time at the end of cycle is 22.53 hrs
The Current Simulation Time at the end of cycle is 23.17 hrs
The Current Simulation Time at the end of cycle is 23.81 hrs
The Current Simulation Time at the end of cycle is 24.45 hrs
The Current Simulation Time at the end of cycle is 25.09 hrs
The Current Simulation Time at the end of cycle is 25.74 hrs
The Current Simulation Time at the end of cycle is 26.38 hrs
The Current Simulation Time at the end of cycle is 27.02 hrs
The Current Simulation Time at the end of cycle is 27.66 hrs
The Current Simulation Time at the end of cycle is 28.30 hrs
The Current Simulation Time at the end of cycle is 28.94 hrs
The Current Simulation Time at the end of cycle is 29.59 hrs
The Current Simulation Time at the end of cycle is 30.23 hrs
The Current Simulation Time at the end of cycle is 30.87 hrs
The Current Simulation Time at the end of cycle is 31.51 hrs
The Current Simulation Time at the end of cycle is 32.15 hrs
The Current Simulation Time at the end of cycle is 32.79 hrs
The Current Simulation Time at the end of cycle is 33.43 hrs
The Current Simulation Time at the end of cycle is 34.08 hrs
The Current Simulation Time at the end of cycle is 34.72 hrs
The Current Simulation Time at the end of cycle is 35.36 hrs
The Current Simulation Time at the end of cycle is 36.00 hrs
The Current Simulation Time at the end of cycle is 36.64 hrs
The Current Simulation Time at the end of cycle is 37.28 hrs
The Current Simulation Time at the end of cycle is 37.93 hrs
The Current Simulation Time at the end of cycle is 38.57 hrs
The Current Simulation Time at the end of cycle is 39.21 hrs
The Current Simulation Time at the end of cycle is 39.85 hrs
The Current Simulation Time at the end of cycle is 40.49 hrs
The Current Simulation Time at the end of cycle is 41.13 hrs
The Current Simulation Time at the end of cycle is 41.77 hrs
The Current Simulation Time at the end of cycle is 42.42 hrs
The Current Simulation Time at the end of cycle is 43.06 hrs
The Current Simulation Time at the end of cycle is 43.70 hrs
The Current Simulation Time at the end of cycle is 44.34 hrs
The Current Simulation Time at the end of cycle is 44.98 hrs
The Current Simulation Time at the end of cycle is 45.62 hrs
The Current Simulation Time at the end of cycle is 46.27 hrs
The Current Simulation Time at the end of cycle is 46.91 hrs
The Current Simulation Time at the end of cycle is 47.55 hrs
The Current Simulation Time at the end of cycle is 48.19 hrs
The Current Simulation Time at the end of cycle is 48.83 hrs
The Current Simulation Time at the end of cycle is 49.56 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 50.37 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 51.44 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 52.50 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 53.57 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 54.63 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 55.70 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 56.76 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 57.83 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 58.89 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 59.96 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 61.02 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 62.09 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 63.15 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 64.22 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 65.28 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 66.35 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 67.41 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 70.48 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 71.54 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 72.61 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 73.67 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 74.74 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 75.80 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 76.87 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 77.93 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 79.00 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 82.06 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 83.13 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 84.19 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 85.26 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 86.32 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 87.38 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 88.45 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 89.51 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 90.58 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 91.64 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 94.71 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 95.77 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 96.84 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 97.90 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 98.97 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 100.03 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 101.10 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 102.16 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 105.23 hrs
Print time exceeded initial setting time. Concrete has hardened inside the Tank. Heavy Wash required
The Current Simulation Time at the end of cycle is 106.29 hrs

Total Simulation Time: 106.92257

Statistics report at simulation time 6415.3543

Contents of the Future Events List at simulation time 6415.35
<table>
<thead>
<tr>
<th>Queue</th>
<th>Res</th>
<th>Cur</th>
<th>Tot</th>
<th>AvWait</th>
<th>AvCont</th>
<th>SDCont</th>
<th>MinCont</th>
<th>MaxCont</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCPrinterWait</td>
<td>CCPrinter</td>
<td>0.00</td>
<td>121.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>ConcreteForMix</td>
<td>Concrete</td>
<td>2.89</td>
<td>25.00</td>
<td>2858.34</td>
<td>11.14</td>
<td>6.98</td>
<td>2.89</td>
<td>25.00</td>
</tr>
<tr>
<td>FinishedConcreteConcrete</td>
<td>Concrete</td>
<td>21.00</td>
<td>21.00</td>
<td>3988.50</td>
<td>13.06</td>
<td>6.67</td>
<td>21.00</td>
<td></td>
</tr>
<tr>
<td>WasteConcrete</td>
<td>Concrete</td>
<td>1.11</td>
<td>1.11</td>
<td>3976.82</td>
<td>0.69</td>
<td>0.35</td>
<td>0.00</td>
<td>1.11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Activity</th>
<th>Cur</th>
<th>Tot</th>
<th>1stSt</th>
<th>LstSt</th>
<th>AvDur</th>
<th>SDur</th>
<th>MinD</th>
<th>MaxD</th>
<th>AvInt</th>
<th>SDInt</th>
<th>MinI</th>
<th>MaxI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haul</td>
<td>0</td>
<td>121</td>
<td>7.00</td>
<td>6394.56</td>
<td>2.92</td>
<td>2.54</td>
<td>0.99</td>
<td>6.10</td>
<td>53.15</td>
<td>28.96</td>
<td>38.49</td>
<td>183.09</td>
</tr>
<tr>
<td>HaulBack</td>
<td>1</td>
<td>121</td>
<td>32.59</td>
<td>6415.35</td>
<td>2.96</td>
<td>2.55</td>
<td>0.99</td>
<td>6.10</td>
<td>53.19</td>
<td>28.95</td>
<td>38.49</td>
<td>183.09</td>
</tr>
<tr>
<td>HaulToPosition</td>
<td>0</td>
<td>120</td>
<td>38.49</td>
<td>6377.56</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>53.27</td>
<td>29.05</td>
<td>38.49</td>
<td>183.09</td>
</tr>
<tr>
<td>Load</td>
<td>0</td>
<td>121</td>
<td>5.00</td>
<td>6382.56</td>
<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
<td>53.15</td>
<td>28.96</td>
<td>38.49</td>
<td>183.09</td>
</tr>
<tr>
<td>Maintenance</td>
<td>0</td>
<td>120</td>
<td>423.40</td>
<td>6193.67</td>
<td>120.00</td>
<td>0.00</td>
<td>120.00</td>
<td>120.00</td>
<td>1442.57</td>
<td>5186.08</td>
<td>631.13</td>
<td>5685.20</td>
</tr>
<tr>
<td>Mix</td>
<td>0</td>
<td>121</td>
<td>0.00</td>
<td>6377.56</td>
<td>5.00</td>
<td>5.00</td>
<td>5.00</td>
<td>5.00</td>
<td>53.15</td>
<td>28.96</td>
<td>38.49</td>
<td>183.09</td>
</tr>
<tr>
<td>Print</td>
<td>0</td>
<td>121</td>
<td>7.90</td>
<td>6399.66</td>
<td>24.69</td>
<td>24.69</td>
<td>24.69</td>
<td>24.69</td>
<td>53.19</td>
<td>29.05</td>
<td>38.49</td>
<td>183.09</td>
</tr>
<tr>
<td>Wash</td>
<td>0</td>
<td>120</td>
<td>33.49</td>
<td>6357.56</td>
<td>10.63</td>
<td>7.29</td>
<td>5.00</td>
<td>26.00</td>
<td>53.14</td>
<td>29.03</td>
<td>38.49</td>
<td>183.09</td>
</tr>
</tbody>
</table>

**Instance**

<table>
<thead>
<tr>
<th>Start</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>6415.35</td>
<td>6421.45</td>
</tr>
</tbody>
</table>

**Total Number of Named Objects**: 40  
**Total Number of Variables**: 46  
**Total Number of Statements**: 83  

**Execution Time** = 0.04 seconds
APPENDIX E
STROBOSCOPE MODEL FOR CC CONSTRUCTION OF WALL OF 3 RESIDENTIAL UNIT BY RELOCATING LOADING STATION

/ Problem Decision Variable
VARIABLE HeightOfLayer 1;
VARIABLE ConcreteAvail 25; /CY
VARIABLE NoOfCCprinters 1; /EA
VARIABLE WallVolume 14; /CY
VARIABLE UNIT3Volume 7; /CY
VARIABLE PrinterTankCapacity 0.20; /CY
VARIABLE DistanceToStartPoint 3; /YD
VARIABLE DistanceToStartPoint2 1; /YD
VARIABLE CCMachineSpeed 2; /Inch/Sec
VARIABLE TotalLengthOfOneLayer 72; /Ft
VARIABLE IniSettingTime 40; /Mins
VARIABLE MixTime 5; /Mins
VARIABLE LoadTime 2; /Mins
VARIABLE CSarea 0.02187;
VARIABLE MaxHeight 8; /Inch
SAVEVALUE WashTime 5;
DISPLAY " ";
DISPLAY "Available Concrete : " ConcreteAvail;
DISPLAY " ";
DISPLAY "No. of Contour Crafting Printers : " NoOfCCprinters;
DISPLAY " ";
DISPLAY "Volume of wall to be constructed : ", WallVolume;
DISPLAY " ";
DISPLAY "Capacity of Printer Tank : ", PrinterTankCapacity;
DISPLAY " ";
DISPLAY "Arm speed of CC Machine : ", CCMachineSpeed;
DISPLAY " ";
DISPLAY "Design Mix Initial Setting Time : ", IniSettingTime;
DISPLAY " ";
DISPLAY Round[((PrinterTankCapacity*27)/CSarea)/72),0]*HeightOfLayer;
DISPLAY
'(Round[((PrinterTankCapacity*27)/CSarea)/72),0]*HeightOfLayer)>MaxHeight ?
"Simulation not possible" : "Print height within limits";

GENTYPE CCPrinter;
GENTYPE Concrete;

QUEUE ConcreteForMix Concrete;
QUEUE CCPrinterWait CCPrinter;
QUEUE CCPrinterWait2 CCPrinter;
QUEUE FinishedConcrete Concrete;
QUEUE FinishedConcreteUnit3 Concrete;
QUEUE WasteConcrete Concrete;
COMBI Mix;
NORMAL Load;
NORMAL Haul;
NORMAL Print;
NORMAL HaulBack;
COMBI Mix2;
NORMAL Load2;
NORMAL Haul2;
NORMAL Print2;
NORMAL HaulBack2;
NORMAL Wash;
NORMAL Maintenance;
NORMAL HaulToPosition;
NORMAL DemobilizeRel;
FORK MaintenanceSkip CCPrinter;
FORK Unit3Skip CCPrinter;
FORK Demobilize CCPrinter;
LINK C1 ConcreteForMix Mix;
DRAWAMT C1 "(WallVolume-FinishedConcrete.CurCount)>PrinterTankCapacity
?PrinterTankCapacity : WallVolume-FinishedConcrete.CurCount";
LINK P1 CCPrinterWait Mix;
LINK P2 Mix Load CCPrinter;
LINK C2 Mix Load Concrete;
LINK P3 Load Haul CCPrinter;
LINK C3 Load Haul Concrete;
LINK P4 Haul Print CCPrinter;
LINK C4 Haul Print Concrete;
LINK C5 Print FinishedConcrete;
RELEASEAMT C5 0.95*Print.Concrete.Count;
LINK P5 Print HaulBack CCPrinter;
LINK C6 Print HaulBack Concrete;
RELEASEAMT C6 0.05*Print.Concrete.Count;
LINK P6 HaulBack Wash CCPrinter;
LINK C7 HaulBack Wash Concrete;
LINK C8 Wash WasteConcrete;
LINK P7 Wash MaintenanceSkip;
LINK P8 MaintenanceSkip HaulToPosition;
LINK P9 MaintenanceSkip Maintenance;
STRENGTH P8 0.95;
STRENGTH P9 0.05;
LINK P10 Maintenance HaulToPosition CCPrinter;
LINK P11 HaulToPosition Unit3Skip;
LINK P12 Unit3Skip CCPrinterWait;
LINK P13 Unit3Skip Demobilize;
STRENGTH P12 FinishedConcrete.CurCount<WallVolume;
STRENGTH P13 FinishedConcrete.CurCount>=WallVolume;
LINK P14 Demobilize CCPrinterWait2;
LINK P16 Demobilize DemobilizeRel;
STRENGTH P14 FinishedConcreteUnit3.CurCount>0;

STRENGTH P16 FinishedConcreteUnit3.CurCount==0;

LINK P17 DemobilizeRel CCPrinterWait2;

LINK C99 ConcreteForMix Mix2;

DRAWAMT C99 ' (UNIT3Volume-
FinishedConcreteUnit3.CurCount)>PrinterTankCapacity ? PrinterTankCapacity :
UNIT3Volume-FinishedConcreteUnit3.CurCount';

LINK P18 CCPrinterWait2 Mix2;

LINK P19 Mix2 Load2 CCPrinter;

LINK C9 Mix2 Load2 Concrete;

LINK P20 Load2 Haul2 CCPrinter;

LINK C10 Load2 Haul2 Concrete;

LINK P21 Haul2 Print2 CCPrinter;

LINK C11 Haul2 Print2 Concrete;

LINK C12 Print2 FinishedConcreteUnit3;

RELEASEAMT C12 0.95*Print2.Concrete.Count;

LINK P22 Print2 HaulBack2 CCPrinter;

LINK C13 Print2 HaulBack2 Concrete;

RELEASEAMT C13 0.05*Print2.Concrete.Count;

LINK P23 HaulBack2 Wash CCPrinter;

LINK C14 HaulBack2 Wash Concrete;

DURATION Mix 5;

DURATION Load 2;
DURATION Haul '((WallVolume-FinishedConcrete.CurCount)>(WallVolume/2) ? (((DistanceToStartPoint)*36)/CCMachineSpeed)/60) : (((((DistanceToStartPoint)*36)+312)/CCMachineSpeed)/60)';
DURATION Print '(((PrinterTankCapacity*27)/CSarea)*12)/CCMachineSpeed)/60';
DURATION HaulBack '((WallVolume-FinishedConcrete.CurCount)>(WallVolume/2) ? (((DistanceToStartPoint)*36)/CCMachineSpeed)/60) : (((((DistanceToStartPoint)*36)+312)/CCMachineSpeed)/60)';
DURATION Mix2 5;
DURATION DemobilizeRel 90;
DURATION Load2 2;
DURATION Haul2 '(((DistanceToStartPoint2)*36)/CCMachineSpeed)/60)';
DURATION Print2 '(((PrinterTankCapacity*27)/CSarea)*12)/CCMachineSpeed)/60)';
DURATION HaulBack2 '(((DistanceToStartPoint2)*36)/CCMachineSpeed)/60)';
ONEND HaulBack2
    ASSIGN WashTime PRECOND (SimTime-Mix2.LastStart)>40 20;
DURATION Wash WashTime;
DURATION Maintenance 120;
INIT ConcreteForMix ConcreteAvail;
INIT CCPrinterWait NoOfCCprinters;
SIMULATEUNTIL 'FinishedConcreteUnit3.CurCount>=UNIT3Volume';
DISPLAY "Total Simulation Time : "SimTime/60;
REPORT;
APPENDIX F
STROBOSCOPE MODEL FOR CC CONSTRUCTION OF WALL OF 3 RESIDENTIAL UNIT BY RELOCATING LOADING STATION

Stroboscope Model Strobo1 (1261500168)

Available Concrete : 25

No. of Contour Crafting Printers : 1

Volume of wall to be constructed : 14

Capacity of Printer Tank : 0.2

Arm speed of CC Machine : 2

Design Mix Initial Setting Time : 40

Print height within limits
Total Simulation Time : 99.249321
Statistics report at simulation time 5954.9593

<table>
<thead>
<tr>
<th>Queue</th>
<th>Res</th>
<th>Cur</th>
<th>Tot</th>
<th>AvWait</th>
<th>AvCont</th>
<th>SDCont</th>
<th>MinCont</th>
<th>MaxCont</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCPrinterWait</td>
<td>CCPrinter</td>
<td>0.00</td>
<td>84.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>CCPrinterWait2</td>
<td>CCPrinter</td>
<td>0.00</td>
<td>48.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>ConcreteForMix</td>
<td>Concrete</td>
<td>2.89</td>
<td>14.00</td>
<td>4243.30</td>
<td>14.00</td>
<td>9.98</td>
<td>9.98</td>
<td>14.00</td>
</tr>
<tr>
<td>FinishedConcreteForMix</td>
<td>Concrete</td>
<td>7.00</td>
<td>7.00</td>
<td>1170.74</td>
<td>1.39</td>
<td>2.39</td>
<td>0.00</td>
<td>7.00</td>
</tr>
<tr>
<td>WasteConcrete</td>
<td>Concrete</td>
<td>1.11</td>
<td>1.11</td>
<td>3215.19</td>
<td>0.60</td>
<td>0.32</td>
<td>0.00</td>
<td>1.11</td>
</tr>
</tbody>
</table>

Activity | Cur | Tot  | 1stSt | LstSt | AvDur | SDDur | MinD | MaxD | AvInt | SDInt | MinI | MaxI |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DenomizeRel</td>
<td>0</td>
<td>1</td>
<td>3960.27</td>
<td>3960.27</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td>90.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haul1</td>
<td>0</td>
<td>84</td>
<td>7.00</td>
<td>3923.58</td>
<td>2.35</td>
<td>1.30</td>
<td>0.90</td>
<td>3.50</td>
<td>47.19</td>
<td>25.91</td>
<td>38.49</td>
<td>163.69</td>
</tr>
<tr>
<td>Haul2</td>
<td>0</td>
<td>48</td>
<td>4057.27</td>
<td>5929.97</td>
<td>0.30</td>
<td>0.00</td>
<td>0.00</td>
<td>0.30</td>
<td>39.84</td>
<td>17.50</td>
<td>37.29</td>
<td>157.29</td>
</tr>
<tr>
<td>HaulBack1</td>
<td>0</td>
<td>84</td>
<td>32.59</td>
<td>3951.77</td>
<td>2.39</td>
<td>1.29</td>
<td>0.90</td>
<td>3.50</td>
<td>47.22</td>
<td>25.91</td>
<td>38.49</td>
<td>163.69</td>
</tr>
<tr>
<td>HaulBack1</td>
<td>1</td>
<td>48</td>
<td>4082.27</td>
<td>5954.96</td>
<td>0.30</td>
<td>0.00</td>
<td>0.00</td>
<td>0.30</td>
<td>39.84</td>
<td>17.50</td>
<td>37.29</td>
<td>157.29</td>
</tr>
<tr>
<td>HaulToPosition</td>
<td>0</td>
<td>131</td>
<td>38.49</td>
<td>5922.97</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>45.27</td>
<td>24.51</td>
<td>37.29</td>
<td>163.69</td>
</tr>
<tr>
<td>Load1</td>
<td>0</td>
<td>84</td>
<td>5.00</td>
<td>3921.58</td>
<td>2.00</td>
<td>0.00</td>
<td>2.00</td>
<td>2.00</td>
<td>47.19</td>
<td>25.91</td>
<td>38.49</td>
<td>163.69</td>
</tr>
<tr>
<td>Load2</td>
<td>0</td>
<td>48</td>
<td>4055.27</td>
<td>5927.97</td>
<td>2.00</td>
<td>0.00</td>
<td>2.00</td>
<td>2.00</td>
<td>39.84</td>
<td>17.50</td>
<td>37.29</td>
<td>157.29</td>
</tr>
<tr>
<td>Maintenance</td>
<td>0</td>
<td>5</td>
<td>577.37</td>
<td>5137.12</td>
<td>120.00</td>
<td>120.00</td>
<td>120.00</td>
<td>120.00</td>
<td>1138.59</td>
<td>604.59</td>
<td>312.46</td>
<td>1684.67</td>
</tr>
<tr>
<td>Mix1</td>
<td>0</td>
<td>84</td>
<td>0.00</td>
<td>3915.58</td>
<td>5.00</td>
<td>0.00</td>
<td>5.00</td>
<td>5.00</td>
<td>47.19</td>
<td>25.91</td>
<td>38.49</td>
<td>163.69</td>
</tr>
<tr>
<td>Mix2</td>
<td>0</td>
<td>48</td>
<td>4055.27</td>
<td>5922.97</td>
<td>5.00</td>
<td>0.00</td>
<td>5.00</td>
<td>5.00</td>
<td>39.84</td>
<td>17.50</td>
<td>37.29</td>
<td>157.29</td>
</tr>
<tr>
<td>Print1</td>
<td>0</td>
<td>84</td>
<td>7.90</td>
<td>3927.08</td>
<td>24.69</td>
<td>0.00</td>
<td>24.69</td>
<td>24.69</td>
<td>47.22</td>
<td>25.91</td>
<td>38.49</td>
<td>163.69</td>
</tr>
<tr>
<td>Print2</td>
<td>0</td>
<td>48</td>
<td>4057.57</td>
<td>5930.27</td>
<td>24.69</td>
<td>0.00</td>
<td>24.69</td>
<td>24.69</td>
<td>39.84</td>
<td>17.50</td>
<td>37.29</td>
<td>157.29</td>
</tr>
<tr>
<td>Wash</td>
<td>0</td>
<td>131</td>
<td>33.49</td>
<td>5917.97</td>
<td>5.00</td>
<td>0.00</td>
<td>5.00</td>
<td>5.00</td>
<td>45.27</td>
<td>24.51</td>
<td>37.29</td>
<td>163.69</td>
</tr>
</tbody>
</table>
Contents of the Future Events List at simulation time 5954.96

<table>
<thead>
<tr>
<th>Instance</th>
<th>Start</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>HaulBack2(47)</td>
<td>5954.96</td>
<td>5955.26</td>
</tr>
</tbody>
</table>

Total Number of Named Objects : 68
Total Number of Variables : 65
Total Number of Statements : 124

Execution Time = 0.04 seconds
REFERENCES


constraint-based modeling." Proceedings of the Winter Simulation Conference, Winter
Simulation Conference, 3015-3024.

and manufacturing processes." Winter Simulation Conference, Winter Simulation
Conference, 2583-2592.

and manufacturing processes." Winter Simulation Conference, Winter Simulation
Conference, 2583-2592.

on labor productivity in the US construction industry at the activity level."


21st International Symposium on Automation and Robotics in Construction (ISARC 2004), Jeju, South Korea, .


rib-like interior." US 11/552,885(US7874825 B2),.


BIOGRAPHICAL SKETCH

Farhan Muhammed Salim is a graduate student at the M.E. Rinker Sr. School of Construction Management at the University of Florida. He did his schooling and spent his childhood in Doha, Qatar. He later moved to India to where he received his bachelor’s degree in Civil Engineering from Malaviya National Institute of Technology, Jaipur, India (2013). He then joined one of India’s largest construction firms as a Site Engineer, where he worked for two years, finally resigning in 2015 to pursue his master’s degree in the United States of America. He graduated in August 2017.

Farhan's desired areas of research include, Construction Planning, Construction Project Delivery and Building Information Modeling. In future, Farhan aspires to be working as a top professional in a reputed construction company.