4-4-2013

Control Charts as a Productivity Improvement Tool in Construction

Jospeh Hubert Ault
Purdue University, ault1@purdue.edu

Graduate School ETD Form 9
(Revised 12/07)

PURDUE UNIVERSITY
GRADUATE SCHOOL
Thesis/Dissertation Acceptance

This is to certify that the thesis/dissertation prepared

By Joe H. Ault

Entitled
Control Charts as a Productivity Improvement Tool in Construction

For the degree of Master of Science

Is approved by the final examining committee:

James Jenkins
Chair

Randy Rapp

Joseph Orczyk

To the best of my knowledge and as understood by the student in the *Research Integrity and Copyright Disclaimer (Graduate School Form 20)*, this thesis/dissertation adheres to the provisions of Purdue University's "Policy on Integrity in Research" and the use of copyrighted material.

Approved by Major Professor(s): James Jenkins

Approved by: Mark Shaurette 04/04/2013
Head of the Graduate Program Date

CONTROL CHARTS AS A PRODUCTIVITY IMPROVEMENT TOOL IN CONSTRUCTION

A Thesis

Submitted to the Faculty

of

Purdue University

by

Joe Ault

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science

May 2013

Purdue University

West Lafayette, Indiana

TABLE OF CONTENTS

Page

LIST OF TABLES iv
LIST OF FIGURES v
ABSTRACT vii
CHAPTER 1. INTRODUCTION 1
1.1 Introduction 1
1.2 Purpose Statement 2
1.3 Research Hypotheses 3
1.4 Scope 3
1.5 Significance 4
1.6 Definitions 4
1.7 Assumptions 5
1.8 Delimitations 5
1.9 Limitations 6
1.10 Summary 7
CHAPTER 2. REVIEW OF THE RELEVANT LITERATURE 8
2.1 Resources Used for Literature Review 8
2.2 State of Productivity Progress in Construction 8
2.3 Current Best Practices Regarding Productivity in Construction 10
2.4 An Alternative to Technological Investment to Increase Productivity 11
2.5 The Use of Control Charts to Drive Efficiency Improvement 13
2.6 The Success of Process Control in Manufacturing 15
2.7 Performance Measurement in Construction 17
2.8 Summary 20

Page

CHAPTER 3. METHODOLOGY 21
3.1 Research Methodology 21
3.2 Sampling Method 22
3.3 Unit of Measure 23
3.4 Root Cause Analysis Meeting Methodology 24
3.5 Analysis 25
3.6 Research Environment 26
3.7 Researcher Influence 26
3.8 Approvals 27
3.9 Summary 27

CHAPTER 4. DATA AND RESULTS 28
4.1 Foundation Excavation 28
4.1.1 Analysis of Baseline Excavation Data 29
4.1.2 First Excavation Intervention 32
4.1.3 First Excavation Intervention Results 36
4.1.4 Second Excavation Intervention 40
4.1.5 Second Excavation Intervention Results 47
4.2 Foundation Forming and Reinforcing 50
4.2.1 Formwork and Reinforcement Baseline Data Analysis 52
4.2.2 Formwork and Reinforcement Intervention 56
4.2.3 Formwork and Reinforcement Intervention Results 59

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS 63
5.1 Conclusions 63
5.2 Recommendations 65

REFERENCES 68
APPENDICES
Appendix A Excavation Dataset 70
Appendix B Forming and Reinforcing Dataset 74

LIST OF TABLES

Table Page

Table 4.1 Loose Cubic Yards of Soil 29

Table 4.2 Comparison of Basic Statistical Measures for Sites One Thru Four 40

Table 4.3 Comparison of Basic Statistical Measures for Sites Three Thru Six 49

Table 4.4 Comparison of the Mean Productivity Factor for Each Activity 61

LIST OF FIGURES

Figure Page

Figure 4.1 Baseline Excavator Cycle Times by Frequency 30

Figure 4.2 Histogram of Baseline Excavator Cycle Times 31

Figure 4.3 Basic Statistical Measures of Baseline Excavator Cycle Times 32

Figure 4.4 Control Chart of Excavator Cycle Times for Site One 33

Figure 4.5 Control Chart of Excavator Cycle Times for Site Two 34

Figure 4.6 Frequency Counts of Cycle Times for Sites Three and Four 37

Figure 4.7 Independent T-Test Results for the First Excavation Intervention 38

Figure 4.8 Histogram of Cycle Times for Sites Three and Four 39

Figure 4.9 Control Chart for Cycle Times for Site Three 41

Figure 4.10 Control Chart of Excavator Cycle Time for Site Four 42

Figure 4.11 Run Rule Violations for Site Three and Four Control Charts 43

Figure 4.12 Original Approach to the Basement Excavations 44

Figure 4.13 Excavation Plan for the Central Section of Soil 45

Figure 4.14 Excavator Perimeter Positioning and Spoil Pile Location 46

Figure 4.15 Frequency Counts Of Cycle Times for Sites Five and Six 47

Figure 4.16 Independent T-Test Results for the Second Excavation Intervention 48

Figure 4.17 Cycle Times for the Forming and Reinforcing of Site One 53

Figure 4.18 Cycle Times for the Forming and Reinforcing of Site Two 53

Figure 4.19 Group One and Group Two Initial Forming Site One 54

Figure 4.20 Group One and Group Two Reinforcement Site One 54

Figure 4.21 Group One and Group Two Close-Up Formwork Site One 55

Figure 4.22 Initial Side Formwork Installation for Group Two at Site Two 55

Figure Page
Figure 4.23 Group One and Group Two Close-Up Formwork Installations 56
Figure 4.24 Forming and Reinforcing Intervention T-Test 60
Appendix Figure
Figure A.1 Excavation Observations from Site One and Two 71
Figure A.2 Excavation Observations from Site Three and Four 72
Figure A.3 Excavation Observations from Site Five and Six 73
Figure B.1 Forming and Reinforcing Observations from Site One 75
Figure B.2 Forming and Reinforcing Observations from Site Two 76
Figure B.3 Forming and Reinforcing Observations from Site Three 77
Figure B.4 Forming and Reinforcing Observations from Site Four 78

ABSTRACT

Ault, Joe H. M.S., Purdue University, May 2013. Control Charts as a Productivity Improvement Tool in Construction. Major Professor: James Jenkins.

This study examined the use of individuals control charts to facilitate the productivity improvement of repetitive construction processes. Cycles times for excavation, forming, and reinforcing processes were observed using stratified random sampling during the construction of six residential home foundations. The cycle time information was plotted on control charts followed by an intervention, with the applicable crew members and management, to analyze the charts and propose solutions to any problems identified. Following the intervention, more samples were collected for comparison to the baseline observations collected before the intervention. The mean cycle times were compared before and after the interventions using an independent t-test.

While the results of the all the interventions showed improvement, only one decrease in the mean cycle time during the excavation process proved to be statistically significant. The statistical power of this significant result was only 0.17 due to the fact that the test only had three degrees of freedom. While reliable significant results were not found, this study demonstrates the principles of using control charts in construction to identify process inefficiencies. The results of the method proposed in this study are highly dependent upon the expertise of the personnel involved in the root cause analysis process.

CHAPTER 1. INTRODUCTION

1.1 Introduction

Poor productivity is a major concern in the construction industry, and high variation in the productivity rate of crews is a “strong indicator of poor labor performance” (Thomas, 2012, p. 13). A process with a high degree of production variation points to an underlying problem with either the design of the system, i.e. management, or with the capabilities of a crew (Cortinas, 1991). Many times the solution for poor performance is to increase the resource inputs of an activity to achieve a higher level of output. While this approach may increase production, the productivity of the process will often worsen.

Increasing the resource input (new technology, more labor) for a poor performing process can magnify the inefficiencies that were already present in the system of construction. Initiating changes to a process using a subjective “hit or miss” approach that does not identify the root cause of production variation will often increase costs without producing the desired results to the degree anticipated (Mann, 2010; Thomas 2012).

Statistical process control (SPC) has been used to great effect in the manufacturing industry to increase productivity in processes by specifically identifying and reducing variation (Deming, 2000). While authors such as Koskela (1992) have proposed that SPC could be applied to the construction industry, the use of the method has been limited to highly repetitive processes like road construction or proposed as a means to track the effect of change initiatives as with Cortinas (1991).

The theory to be tested in the study uses SPC, more specifically control charts, as the first step in the improvement process. Process measurement translated into control charts will specifically identify points in the construction process where variation is occurring. Linking variation with discrete points in time will allow management to better determine the root cause of the variation in an objective manner. The analysis of the data will involve both management and craft labor with the control charts serving as the driver of the process improvement discussion. Modifications to the management of the site can then be made after the analysis to reduce idle time and inefficiency in the production system.

1.2 Purpose Statement

The purpose of this experiment is to test the theory that statistical process control can be applied to the construction industry to reduce special cause variation in the production rate of construction crews leading to an increase in the mean production rate over the duration of the activity. This study will use a multiple measure design where the mean productivity rate of a crew under normal operating conditions will be compared to the mean productivity rate of the same crew under the application of statistical process control. The independent variable in this study is special cause variation which is identified using the rules of interpretation for control charts. The dependant variable in this study is the mean production rate of the crew derived from statistical sampling of a process.

1.3 Research Hypotheses

The null hypothesis for this study (alpha=.05):

There is no significant difference between mean level of productivity under normal operating conditions and the mean level of productivity when the statistical process control improvement cycle is implemented.

The alternative hypothesis for this study (alpha=.05)

The mean level of productivity when the statistical process control cycle is implemented will be greater than the mean level of productivity under normal operating conditions

1.4 Scope

An experiment will be conducted where only excavation and concrete construction activities will be observed and treated. Excavation, in this study, will only include earth removal using a Caterpillar 315C hydraulic excavator. Concrete construction processes will include forming and reinforcing of concrete basement walls. Of the seven types of control charts available, only individuals charts will be used. The data used to construct the chart shall be cycle times in seconds for the excavation activity, and an index ratio actual productivity to estimated productivity for the forming and reinforcing process.

To test if the targeted improvement efforts will significantly increase the production rate of an activity, a p-value will be calculated from an independent t-test comparing a mean level of production from the pre-intervention observations to the mean level of production from post-intervention observations.

1.5 Significance

The benefits of tracking productivity with control charts could be translated to construction companies that have few employees and lack access to the advanced technologies that drive productivity gains in the top firms. By taking random samples of output, variability in a process could be evaluated objectively by managers, as opposed to using subjective techniques to identify activity inefficiencies.

The purpose of this study is to find an objective way to spot inefficiency and fix the problem using the combined expertise of the personnel involved. This tactic could not only keep projects on schedule, but maybe even possibly show that the estimated activity durations were inflated due to consistently inefficient operations in the past. A control chart is essentially a visual aid that objectively reveals where improvement efforts should be directed.

1.6 Definitions

Best Practices- A method or technique that has consistently shown results superior to those achieved with other means, and that is used as a benchmark (www.business dictionary.com, 2012).

Common Cause Variation- Variation inherent to a system of technology that is randomly distributed around the output (Shewhart, 1986).

Control Chart- Statistical tool used in quality control to (1) analyze and understand process variables, (2) determine process capabilities, and to (3) monitor effects of the variables on the difference between target and actual performance. Control charts indicate upper and lower control limits, and often include a central (average) line, to help detect trend of plotted values. If all data points are within the control limits, variations in the values may be due to a common cause and process is said to be “in control”. If data points fall outside the control limits, variations may be due to a special cause and the process is said to be out of control (Mann, 2010).

Small Business (construction)- A construction business with gross receipts less than $27 million a year (Small Business Administration, 2012).

Special Cause Variation- Variation that causes a fundamental change in a process that affects the consistency of outcomes which thereby causes a drop in efficiency (Deming, 2000).

Waste- Activity that takes time, resources, or space but does not add value to the end product for the customer (Koskela, 1992).

XmR Control Chart- A control chart that tracks single observations with X represent single observations and mR representing the moving range (Mann, 2010).

1.7 Assumptions

The assumptions for this research study include:

- The historical production data used to calculate the productivity factors is accurate.
- Construction managers involved in the study will be willing and able to learn the principles of evaluating control charts.
- Construction managers involved in the study will have adequate knowledge and experience to make adjustments to an activity to improve the productivity of a process based on the data conveyed in the control charts.
- The activities to be studied will feature crews comprised of the same laborers and operators during the pre-intervention and intervention periods.

1.8 Delimitations

The delimitations of this research study include:

- The studies to be conducted will only occur within one company.

- Only three construction processes will be studied: excavation, concrete forming, and concrete reinforcing.
- Each measurement period for the activities will consist of a two days of pre-intervention measurement and two days of post-intervention measurement. The pre-intervention phase will be used to establish a mean level of production serving as the control group. The post-intervention phase will consist of production rate measurement after process improvements are implemented by management.
- Measurements will only consist of cycle times in seconds or an index of actual output divided by estimated output, where the estimated output will be based upon company historical data.
- Production output will be randomly sampled for six cycles per group.
- The observations will be translated to individual statistical control charts only.
- The individuals control charts will be analyzed by crew members and the project manager following the pre-intervention measurement period where adjustments to the process will be formulated for implementation on the next process.

1.9 Limitations

The limitations of this study include:

- Robust control limits will be used if the data is found to be non-normal.
- The increase in the mean production rate during the post-intervention period is dependent upon the expertise of the personnel involved in the activity to formulate improvements based upon the data.

- The workers in the field will have to recall the working conditions at the points of special cause variation to identify the root cause of the variation.
- The increase in the production rate could be significant simply because the processes will receive closer attention from management.

1.10 Summary

This chapter provided an overview of this research project including background information, a statement of purpose, research question, scope and significance of the study, key definitions, assumptions, and limitations. The following chapter will outline the current research relevant to construction productivity and the use of control charts.

CHAPTER 2. REVIEW OF THE RELEVANT LITERATURE

2.1 Resources Used for Literature Review

Several resources were employed to find relevant material for the literature review. Many professionally reviewed industry level productivity studies were found, but professional journal articles addressing project and task level productivity improvement techniques was found to be lacking. Government publications from research institutions throughout the world provided some applicable information including the National Research Council, the National Institute of Standards and Technology, and the Bureau of Economic Analysis. Informally published manuscripts from universities provided information regarding performance measurement in construction including Stanford University, University of Taiwan, and the University of Alberta. Several books were used that covered extensive research in the areas of statistical process control.

2.2 State of Productivity Progress in Construction

The construction industry is an important factor in the United States (US) economy with construction in place valued at $988.9 billion in 2010. The contribution to the overall US 2010 gross domestic product (GDP) was $511.6 billion, accounting for 3.5% of the total US GDP (Bureau of Economic Analysis, 2012). The construction industry also has an indirect impact on other sectors of the economy such as manufacturing and energy (Chapman & Burty, 2009). Once constructed facilities are ready for use by owners, the structures must be fitted with furnishings and equipment and consumption of utilities continues over the life cycle of the various facilities.

Given the significant impact that the construction industry has on the overall economic vitality of the United States, increasing productivity in the industry is imperative for continued economic growth and to increase the standard of living in the United States (Chapman & Burty, 2009). In sectors with similar or greater economic footprints as construction, efficiency of production continues to show an upward trend mainly due to continued advances in technology (Jorgenson, Ho, & Stiroh, 2008). .

Despite the productivity growth of the nonfarm business sector overall, the construction industry continues to lag other industries in productivity growth. A study published by Preston Haskell in 2004 analyzed productivity increases in construction over the previous 37 years. The measure of productivity in construction can be difficult due to "absence of a consistent measure of aggregate output" (Haskell, 2004, p. 32). For Haskell's study, "aggregate productivity is determined using constant dollars as the input (for both labor and non-labor expenditures) and square feet of building area adjusted for quality changes as the measure of aggregate output" (p. 35). Haskell (2004), asserts that total construction productivity had increased by about 0.78% per year from 1966 to 2003, but the growth is significantly less than the 1.75% productivity growth rate per year in the nonagricultural business sectors over the same time period (Haskell, 2004).

Another analysis of construction productivity by Paul Teicholz (2004), used a different metric (constant dollars of contracts/ work hours of hourly workers) to compare nonagricultural sectors and construction with a decline in field work productivity in construction. One weakness of the findings by Teicholz (2004) is that offsite prefabrication is not accounted for in the calculation. More recently than 2004, studies have found that many companies in the construction industry are nearing counterparts in other economic sectors in productivity improvement through the use of technological and organizational innovation which will be detailed in the following section.

2.3 Current Best Practices Regarding Productivity in Construction

The 2012 U.S. Construction Industry FMI Productivity Report surveyed 122 construction firms from a variety of disciplines with a range of gross yearly revenues. Three key innovations were found to be driving productivity gains in 2011: Building Information Modeling (BIM), integrated project delivery (IPD), and prefabrication/modularization.

BIM was reported to have been used on at least one project by 63% of the surveyed firms in 2011 with productivity improvements on the BIM projects being improved by 3% or more in 62% of the projects. IPD was reported to have been used on at least one project by 35% of the surveyed firms in 2011 with productivity being improved on IPD project by more than 3% in 68% of the cases. Prefabrication or modularization showed the most potential for productivity gains according to the FMI report. Sixty-nine percent of firms reported using prefabrication or modularization in 2011 on at least one project with productivity improvements of 5% or more on 82% of the projects.

The gains in productivity on projects employing the tactics above are significant when compared to gains of 1.78% in the combined nonagricultural business sector; however, BIM, IPD, and prefabrication techniques are not being employed by most small construction firms. The U.S. Small Business Administration (SBA) defines a small business in construction as consisting of less than $27.5 million in gross receipts per year. The SBA reported in 2009 that small business construction companies comprised 84% of the industry while contributing 18% of the total GDP from construction operations.

The FMI Productivity Report (2012) classified survey respondents according to gross receipts a year with a convenient segmentation for the lowest class at $26.5 million. Of the firms reporting gains in productivity from BIM of 3% or more, only 7% fit the classification of a small business. Of the firms reporting gains in productivity from IPD of 3% or more, only 9% fit the classification of a small business. Of the firms reporting gains in productivity from prefabrication/modularization of 5% or more, only 3% fit the classification of a small business. This data supports the notion that small construction firms are not employing the sophisticated techniques that are allowing the larger firms to see above average gains in productivity.

2.4 An Alternative to Technological Investment to Increase Productivity

The question then becomes, what is keeping the smaller firms from implementing the best practices to increase productivity in the field? According to Chapman and Burty (2009), a key factor that is contributing to the lack of advancement of best practices in all but top 15% of construction firms is the low reinvestment of returns into organizational development. On average only 0.5% of the value of construction-in-place is invested into organizational development (Chapman and Burty, 2009). Small businesses in construction still predominately operate in the competitively bid environment where return on investment can be as low as 3 to 5% preventing the reinjection of funds into the adoption of the latest information technology and project delivery methods to increase productivity (National Research Council, 2009).

An alternative to the capital investment required by some of the cutting edge best practices to increase productivity described above is to improve the efficiency of traditional processes already in place through better management. According to Tulacz and Armistead (2007), the "common wisdom is that 25% of a project's cost goes to waste and in some cases could go as high as 50%" (p. 1). Waste is often called a non-value adding activity. Koskela (1992) defines a non-value adding activity as an "activity that takes time, resources, or space but does not add value to the end product for the customer" (p. 28). Reducing non-value adding activity is a key to increasing the efficiency of a construction process (Deming, 2000).

The National Research Council (2009) found that four main movements are expected to increase efficiency in the construction industry in the coming decade. Among the movements were the aforementioned use of BIM, IPD, and prefabrication, but the last technique was "effective performance measurement to drive efficiency and support innovation" (National Research Council, 2009, p. 18). Performance measurement can increase efficiency by identifying activity duration variability within a process by which managers can then objectively target aspects of the process needing improvement (Deming, 2000). According to Koskela (1992), activity duration variability increases the amount of non-value adding activity or waste in a process.

2.5 The Use of Control Charts to Drive Efficiency Improvement

The idea of performance measurement driving efficiency is a concept that goes all the way back to Walter Shewhart at Bell Telephone Laboratories. Shewhart realized the importance of identifying and reducing variation in a process which incidentally is the foundation of all lean management concepts (Edmund, 2010). Shewhart developed the control chart by using statistical analysis to monitor the consistency of a process (Shewhart, 1986). A control chart is constructed by measuring some cyclical activity, finding the mean and control limits of the data, and analyzing the orientation of the data points on a control chart which allows management to find where the variation is occurring in a process. Control charts are a foundation of statistical process control (SPC) used in the quality movements in manufacturing (Edmund, 2010).

One version of the seven types of control charts consists of a pair of graphs with the top graph based on X-bar and the bottom graph based on the range of the sample data. With the X-bar graph, the x-axis of the chart labels the sample number of the particular data set while the y-axis of the chart labels the average characteristic of the sample being measured whether a spatial dimension or a time component. The centerline of X-bar graph is the grand average of the averages for each sample. Samples contain two-six measurements in each set. The upper control limit for X-bar graph is calculated by adding the multiple of the average range of the samples by a constant based on the number of observations per sample (A6) to the grand average of the observations. The lower control limit for X-bar graph is calculated by subtracting the multiple of the average range of the samples by a constant based on the number of observations per sample (A6) from the grand average of the observations (Shewhart, 1986).

Each control chart also has another graph showing the average range of data within each particular sample over time. The centerline of the range graph is the average of all the range values for each sample. The upper and lower control limits for an R chart is found by multiplying constants based on the number of observations in each sample (D3 and D4) by the average range (Shewhart, 1986).

The final aspect of the both the X-bar and the R graph is to section the areas between the upper and lower control limits into three equidistant zones above and below the mean (A,B,C). The limits of the two intermediate zones above and below the mean are one and two standard deviations from the centerline respectively (Shewhart, 1986).

Once the control chart is constructed the data points and the line drawn to connect them can be interpreted to identify different types of variation. Before continuing to an explanation of the rules of control chart interpretation a discussion of the two types of variation should be addressed. Common cause variation is defined by Shewhart (1986) as variation “inherent to a system of technology that is randomly distributed around the output” (p.68). In other words, common cause variation is the natural small differences in outcomes that could be expected to occur in a process. Trying to reduce common cause variation is not worth the expenditure of time and effort as the variation natural to any process is not significant enough to greatly impact efficiency (Deming, 2000).

Special cause variation causes a fundamental change in the process that affects the consistency of outcomes which thereby causes a drop in efficiency. The control chart can be used to identify special cause variation that produces inefficiency in a process, and then the root cause of the special cause variation can be identified and designed out of the process thereby increasing productivity (Deming, 2000).

Special cause variation is indentified in the chart by using six rules. The six rules include: one point outside of the upper or lower control limit, two out of three consecutive points in zone A, four out of five consecutive points in zone B, seven consecutive points in zone C, six consecutive points on one side of the mean, or fourteen consecutive points alternating above and below the mean (Deming, 2000). Data below the mean when using time based data is a sign of positive production, and a manager should find the root cause of why the samples performed better than average and try to replicate the conditions throughout the system (Deming, 2000).

To summarize, a control chart can lead to efficiency of process performance by identifying special cause variation in a system. Once a manager can locate points in a process that are out of statistical control by checking the six rules, the root cause of the variation can be analyzed and designed out of the system. It should be noted that the causes of special cause variation in a construction activity will often be due to the planning and organization of activity by management rather than labor incompetence (Adrian & Adrian, 1995). Conducting SPC through the use of control charts can facilitate the recommendation by the National Research Council (2009) to implement "effective performance measurement to drive efficiency and support innovation" (p. 14). This claim is supported by the effectiveness of SPC to increase productivity in manufacturing in the 20^{th} century.

2.6 The Success of Process Control in Manufacturing

When looking at the evolution of increasing efficiency of industry in the last century, one must look to the production advances made in manufacturing beginning in World

War II. The United States government was focused on providing military organizations and personnel with high quality products that would operate as intended in the field. A crucial factor in movement to increase quality in wartime production was the Emergency Technical Committee, of which, Edwards Deming was a key member (Mann, 2010).

Deming had a background in statistics, and was exposed to statistical process control early in his career by working at Bell Telephone Laboratories with Walter Shewhart the innovator of the Shewhart control chart (Mann, 2010). During World War II, Deming was instrumental in applying SPC to wartime production to reduce variation in production processes. After the war, the techniques developed to control quality were largely abandoned in the US due to the insatiable demand for mass produced American products (Deming, 2000).

By 1947, Deming had become involved with the 1951 Japanese census. While in Japan, Deming was recognized by the Japanese Union of Scientists and Engineers (JUSE) for his wealth of understanding of production process and quality techniques refined during the war. With some working knowledge of Shewhart, JUSE invited Deming to become a key consultant in the rebuilding of Japan's manufacturing sector (Mann, 2010).

Deming would speak to groups of managers and engineers across Japan, and soon his techniques of using control charts to spur the continuous improvement process lead Japanese manufacturers to achieve the highest standards of production efficiency in the history of manufacturing (Mann, 2010). Deming continued to expand his principles to find a focus on finding the root cause of waste in processes whether managerial or production orientated.

By the late 1950s, others were beginning to build on the work of Deming, such as Kichiro Toyoda the founder of what would become the Toyota Motor Corporation. Toyoda had a unique view of the factors that hampered efficiency in manufacturing. These factors were distilled into three words “muri” (overburden), “mura” (inconsistency), and “muda” (waste). The main concept that later developed into the Toyota Production System focused on designing out the three factors by locating the sources of variation in production systems using control charts to objectively identify process inefficiencies (Deming, 2000).

By the end of the 1970s, Toyota’s production of vehicles had increased from 154,770 in 1960 to 3,293,344 in 1980 with unsurpassed efficiency. American manufacturers had already begun to take notice throughout the 1970s, but the 1980 NBC special, *If Japan Can….Why Can’t We?*, awakened many American businesses to the rampant waste occurring in a variety of industries (Deming, 2000). Many different efficiency and quality movements began in American business, such as Total Quality Management and Six Sigma which all at their core have the foundation of SPC (Mann, 2010).

2.7 Performance Measurement in Construction

While control charts have been shown to be a valuable tool for process improvement, performance measurement in construction lacks a set of widely accepted standards on the task level (Chapman & Burty, 2009). Koskela (1992) puts forward several hallmarks of good measurement to facilitate process improvement in construction including: measures should capture time data, measures should be able to pinpoint improvement potential, measures should be physical rather than financial, and measures should be customized to fit the situation.

The AACE International Recommended Practice No. 25R-03 (2004) makes a distinction between production and productivity. Production is a measure of output regardless of labor hours while a measure of productivity should include output (units completed) divided by input (work or equipment hours). Following this definition, full production can be reached without achieving a high level of productivity; therefore a measure of productivity should include labor hours as part of the metric.

Dozzi and AbouRizk (1993) also suggest using a more traditional productivity measure of a ratio of outputs to inputs with the main focus being labor productivity. Task metrics using output/input ratios are common in publications for estimating such as R.S. Means. The Construction Industry Institute has an alternative input/output ratio where outputs are fixed and the amount of labor hours to complete the set level of output is measured.

Stalk and Hout (1990) suggest that the construction task measurement includes more metrics than just output divided by input. For instance, performance measurement can include inventory turnover, value added time as a percent of total time, lead time, or percent of schedule complete in a given period.

Chapman and Burty (2009), put forth a “task productivity index” as an alternative to traditional measures (p. 6). An index is ratio of actual performance over a reference number. The indices proposed are similar to the earned value management productivity calculations of budgeted cost of work performed divided by budgeted cost of work scheduled (Leu, Lin, Chen, & Ho, 2006). Both indexes give construction managers indications about project efficiency related to cost. AACE International (2004) also outlines a productivity factor for tracking the efficiency of a process where actual productivity is divided by planned productivity without consideration of cost.

The concept behind the cost indexes could be modified to allow indexes based on schedule performance rather than cost performance. Actual amount of work performed divided by the amount of work scheduled would give an index that could indicate time performance without cost data required. Another advantage of such an index would be "dimensionless" nature of the values allowing different activity indexes to be plotted on the same control chart to see variation in time performance among different activities. Plotting the time indexes mentioned above on control charts to evaluate variation has been employed successfully in software engineering (Limpke, 2002).

Another important consideration when applying SPC to find improvement opportunities is to understand the sub-process impact on the overall duration of the project. It was discovered in manufacturing that the traditional conversion model of looking at production line as a series of unique processes that converted inputs to outputs could lead to improvements of individual sub-processes that actually produce more waste in the system while increasing the utilization rate of the individual process (Koskela, 1992). The extra waste originates from the need to increase supply buffers, the need to store more product if the successive process cannot utilize the production of the proceeding process at the same rate, and the expenditure of time and cost to improve the sub-process that does not increase overall system efficiency (Deming, 2000).

In construction, this concept is well understood through the use of critical path scheduling. When a project timeline needs to be compressed, only activities that will actually affect the system as a whole i.e. reduce the completion date are targeted for compression. Reducing variation in any construction activity may produce labor and equipment cost savings through greater speed of production; however a subjective method of choosing activities for analysis would not produce the greatest value. The greatest value would come from measuring and improving processes that have a relatively high budgeted cost and affect the final completion date.

2.8 Summary

Increases in productivity in construction have traditionally lagged other industries in the past. Technological innovation is driving the top firms in the industry to higher levels of productivity, but small businesses in construction are lagging due to financial constraints. Eliminating waste by using control charts to target opportunities for improvement may offer a cost effective way for small business contractors to better manage labor in the field. Time indexes may be a metric of productivity that when used in conjunction with a control chart will spur efficiency of production by demonstrating variability in the construction system. The following research will investigate the validity of the proceeding claims.

CHAPTER 3. METHODOLOGY

3.1 Research Methodology

The foundation of this research study is collect quantitative data related to excavation and concrete construction processes. Many sub-processes are included in the broad term of concrete construction, but the nature of the unit of measure for this study allows different sub-processes to be tracked on the same control chart. The study will be a quasi-experiment using multiple measures with crews (labor, equipment, tools) performing work that is to be measured pre-intervention and post-intervention.

The first step of the experiment is to establish a baseline mean level of production for the processes. This pre-treatment phase will consist of taking random samples of productivity rates over the course of two days for a total of 72 samples. The details of the sampling technique and unit of measure will be detailed in sections to follow. With the individual sample observations a pre-intervention mean production rate can be calculated for both processes. During the pre-intervention period, operations will be conducted under ordinary procedural conditions expect for the presence of the observer.

Following the pre-intervention phase of measurement, an intervention will be made based upon conclusions drawn from the control charts. Control charts will be constructed daily based on the samples. The control charts can then be used to identify variation in the production of the crew as outlined in the literature review. The project manager will hold a daily meeting at the end each pre-intervention period to identify the root causes of the variation. The expertise of the project manager and crew members will then be applied to identify possible improvements that could be made to reduce the variation in the production process. The meeting will follow a procedure that will be detailed in a following section.

3.2 Sampling Method

One of the main goals of this experiment is to investigate if statistical sampling of cycle times can capture change in production over time. The samples need to adequately represent the population of production cycles on a daily basis to allow managers to make informed decisions about the state of a process. For an independent one-tailed hypothesis t-test using an anticipated effect size of 0.6, desired statistical power level of 0.8, and a probability level of 0.05; the minimum sample size per day equals 36.

The control chart being used in this study requires samples to be taken in batches ranging from two to six consecutive observations. This study will use six samples per group requiring six sampling periods per day. In general, crews only are adding value at the workface for six hours per day after a 60 minute lunch period and approximately two 30 minute periods of preparation and shutdown activities are performed. The total time at the workface will be stratified into six one hour periods of which random times for sampling will be selected using a random sample generator. For example, the first hour of work from 8:30-9:30 will have each minute in the hour entered into the random sample generator with the time selected being where the six cycle observation will begin.

3.3 Unit of Measure

The dependent variable in this case is the mean production rate for a particular process. The excavation activity can be easily measured using the cycle time in seconds without any conversion. Rather than measure productivity with a typical measure of work hours per unit for the forming and reinforcing activities, an index of performance will be used to allow comparison of activities with different base output measures. The index will be the actual productivity rate divided by the scheduled or predicted productivity rate. The scheduled productivity rate will be determined for a given time period using historical performance data for different activities recorded at the company.

The current estimations of productivity used for scheduling are based upon historical production per hour and the evaluation of the unique aspects of each project. For the purposes of this study, the estimated output per hour will be converted into output per second for comparison with cycle times that are to be measured in seconds.

The index value will consist of the observed average output per second for each six cycle period divided by historical output per second. This technique will give a “dimensionless” ratio with 1.00 being a performance where the actual output equals the estimated output. Under performance by the crew will give a value under 1.00 while outpacing the estimated performance by the crew will yield a value over 1.00. The control chart displaying the values for each observation period will give managers a visual control where performance can be quickly appraised.

3.4 Root Cause Analysis Meeting Methodology

To translate the data contained in the individuals control charts into process improvements, a daily meeting will occur after each pre-intervention period. The meeting will be conducted on site with the project manager and members of the crew. Prior to the meeting the sampling data from the both pre-intervention periods will be graphed on a control chart, and the researcher will identify the areas of special cause variation before the meeting begins. The goal of the meeting is to identify the root causes of the variation and then generate improvements for the design and execution of the next project. This root cause analysis process will follow a problem solving action plan with five procedural steps.

The AACE International Recommended Practices *25R-03: Estimating Lost Labor Productivity in Construction Claims* (2004), lists the common causes of lost productivity which will be used to identify, define, and categorize the variation indentified in the control charts. On-site personnel will be asked to link the problems causing productivity variation on the job site to the common causes of lost productivity listed in the AACE International report. Using the common causes of lost productivity should allow the meeting participants to more clearly assess and communicate what the perceived problems on the job are. Once the root causes of variation are contained within a category, appropriate recommendations and solutions that address the particular category can be applied.

The list of the common causes of lost productivity cited by the AACE International includes: absenteeism, acceleration, adverse weather conditions, availability of skilled labor, change orders and rework, competition for craft labor, craft turnover, stacking of trades, defective engineering, dilution of supervision, excessive overtime, failure to coordinate trades, fatigue, labor relations, learning curve, material shortages, tool and equipment shortages, over manning, poor morale of craft labor, project management, out of sequence work, site restrictions, site conditions, and untimely approvals.

One potential flaw of this process, outlined in the limitations, is the workers must be able to recall what was happening during the points indicating negative or positive variation. To combat the recall problem, workers will be asked to take brief notes during the day when they perceive that the pace of work is unusually productive or unproductive for use in the meeting at the end of the shift. Another important aspect when generating solutions is to look at points when production was greater than expected. Identifying the conditions that supported greater than expected performance could lead to better solutions for under performance situations.

3.5 Analysis

To test the effectiveness of control charts to facilitate productivity improvement, an independent t-test will be used to test the null hypothesis that the mean level of production for the pre-treatment period will equal the mean level of production for the treatment period using an alpha value of 0.05. The alternative hypothesis for this experiment is that the mean level of production for the pre-treatment period will be less than the mean level of production for the treatment period.

In addition to the significance test, effect size will be calculated using the standardized mean equation when a significant result is found. Effect size will go beyond the "did we get an effect" results of the significance test to reveal how much effect the treatment provided. The estimated total cost of the treatment will be combined with effect size as well to reveal the cost of the effect of the treatment.

3.6 Research Environment

The construction of six new speculative homes with similar configurations will be the focus of the study. This series of projects provides the opportunity to study processes under very similar conditions which is essential when using control charts to make improvements that will translate from one jobsite to another. The excavation of each home site can be completed in one day under most conditions. The forming and reinforcing process for each site is projected to take three days. Anywhere from seven to fourteen days will elapse between each individual project.

3.7 Researcher Influence

There are two key ways that the researcher will influence this study. The "Hawthorne Effect" is one troubling aspect of work observation that will need to be mitigated to some degree. The "Hawthorne Effect" is a phenomenon where workers change their behavior when they know they are being observed. Dummy observation periods will occur prior to the actual commencement of the pretest period to try to reduce sensitivity of workers to the presence of the observer.

Another important effect the researcher will have on this study is the ability of the researcher to train the construction managers to be able to interpret the data displayed in the control charts. The case for the researcher being able to adequately inform the managers about the important indicators in the charts is demonstrated in the literature review where the rules for interpreting control charts is covered in detail citing the leading authorities on the subject in industry.

3.8 Approvals

The Internal Review Board (IRB) of Purdue University was consulted about approvals needed for the study. An IRB analyst concluded that the nature of the study outlined in this proposal was not considered human subjects research according to the federal guidelines.

3.9 Summary

This chapter covered the key aspects of an experiment designed to test the effectiveness of statistical control charts to facilitate targeted productivity improvement. The experiment consists of a pre-intervention period followed by a post-intervention period where mean levels of production will be calculated for each period. The intervention consists of using the control charts data to identify and reduce special cause variation in excavation and concrete construction processes through targeted management improvements. The significance of the improvements will be tested using an independent t-test comparing the mean level of production for the two periods

CHAPTER 4. DATA AND RESULTS

4.1 Foundation Excavation

This section will describe the process improvement cycle for a series of foundation excavations for six speculative homes with similar configurations and site conditions. A Caterpillar 315C hydraulic excavator with a 36" wide bucket was observed excavating each home foundation with approximately 7-14 days elapsing between each job.

The jobsite conditions overall were excellent. Access to the area of development was optimal as a concrete street was already in place to accommodate the houses built in the area several years ago. The lot configurations of the sites allowed sufficient room for material and equipment storage. Spoil piles were maintained on each site as the excavated soil was appropriate for backfill. The ground breaking of one site was delayed due to rain, but the surface conditions were dry when the excavation began. The water table around the area was low enough to not require any extra procedures for drainage within the excavations. In all cases, the sites were cleared of organic material before the excavation operation started. The configuration of the foundation for each home was designed for economy and speed of construction. Each basement consisted of a basic 32' by 40' rectangle at a maximum digging depth of approximately 9' to accommodate an 8' high finished ceiling.

Additional excavations were required to a depth just below the frost line for the attached garage and porch footings. The orientation of the garage and porches for each home in relation to basic basement shape was slightly different to avoid a repetitive design in the development. The excavation sequence started with the basement followed by the footings for the garage and porches with the trenches for utilities being excavated last. In this study, only the basement excavations were observed. Table 4.1 lists the loose cubic yard cut and fill quantities for each basement space calculated using “Earthworks” estimating software.

Table 4.1

Loose Cubic Yards of Soil

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Cut	839.5	868.1	915.8	887.2	906.3	944.5
Backfill	198.6	205.1	216.9	210.2	214.7	223.7

4.1.1 Analysis of Baseline Excavation Data

Excavator cycle times were collected in subgroups of six over the course of the first two jobs for a total 72 samples. These figures were used to establish a baseline for comparison to observations collected after the first intervention. The combined frequency counts of the cycle times observed from site one and two are displayed in Figure 4.1.

Frequency Counts			
		Percents	
Value	Count	Cell	Cum
14	1	1.4	1.4
15	5	6.9	8.3
16	6	8.3	16.7
17	5	6.9	23.6
18	8	11.1	34.7
19	7	9.7	44.4
20	10	13.9	58.3
21	5	6.9	65.3
22	3	4.2	69.4
23	5	6.9	76.4
24	5	6.9	83.3
25	3	4.2	87.5
26	2	2.8	90.3
27	1	1.4	91.7
28	1	1.4	93.1
34	1	1.4	94.4
40	1	1.4	95.8
61	1	1.4	97.2
76	1	1.4	98.6
78	1	1.4	100.0

Figure 4.1. Baseline excavator cycle times by frequency.

A histogram of the data shown in Figure 4.2 shows a lognormal distribution with a high peak centered on the median cycle time of 20 seconds. With a lognormal distribution, the median cycle time can be thought of as the typical amount of time it takes the excavator to complete a cycle during ordinary conditions.

.

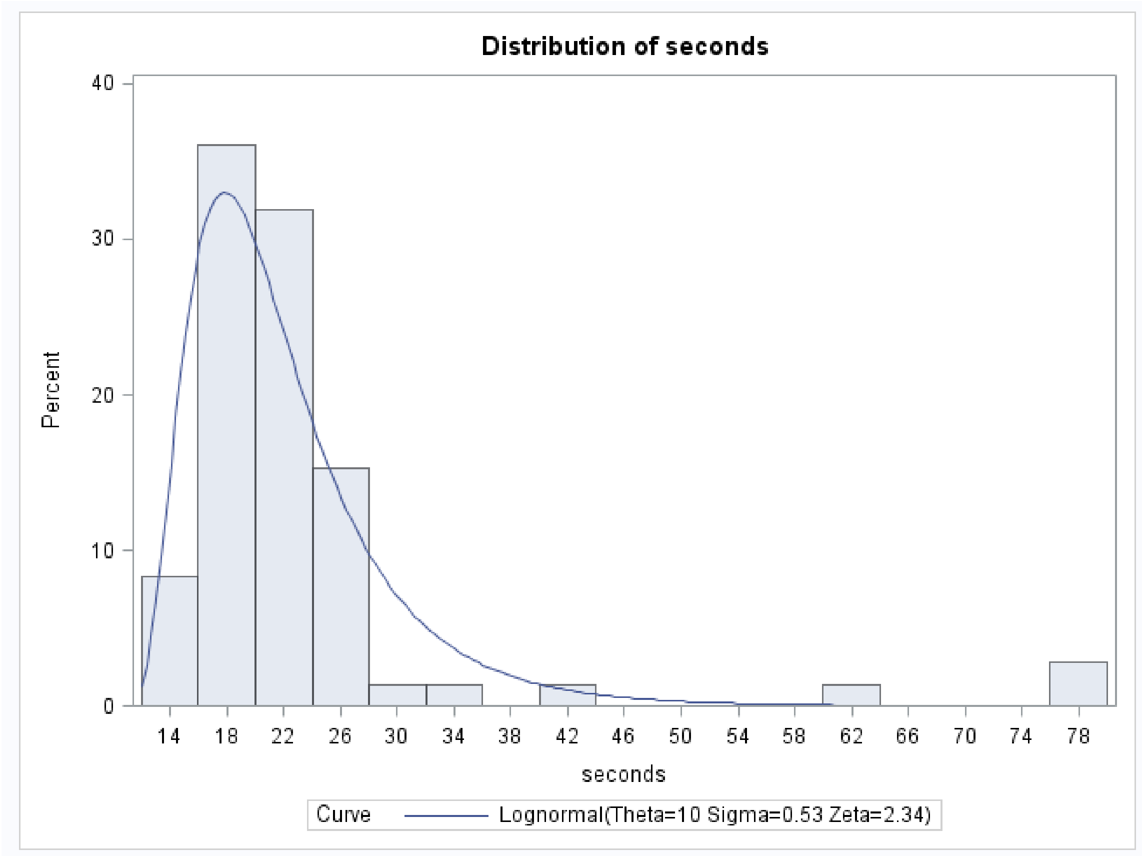

Figure 4.2. Histogram of baseline excavator cycle times.

The mean cycle time is being pulled from the median towards the skewed right tail of the distribution by several observations with relatively long cycle times. A normal distribution will have the same value for median and mean unlike a lognormal distribution where values will be different. Figure 4.3 shows a summary of the descriptive statistics for the data.

Basic Statistical Measures			
Location		Variability	
Mean	22.55556	Std Deviation	11.28989
Median	20.00000	Variance	127.46166
Mode	20.00000	Range	64.00000
		Interquartile Range	5.00000

Figure 4.3. Basic statistical measures of baseline excavator cycle times.

A simple interpretation of these figures listed above leads to three concerns. Significant shifts in the process accounted for the 2.6 second discrepancy between the average cycle time and the median cycle time. The median time of 20 seconds per cycle is at the low end of estimates for the cycle time for the Caterpillar 315C excavator, and cycle times are highly variable with a standard deviation of 11.3.

4.1.2 First Excavation Intervention

Using the data from site one and two, control charts were constructed using robust control limits to evaluate the process patterns and performance. An on-site meeting was conducted after the completion of site two with the operator of excavator and the manager in charge of this phase of the project. Figure 4.4 and 4.5 display the control charts from the first two operations.

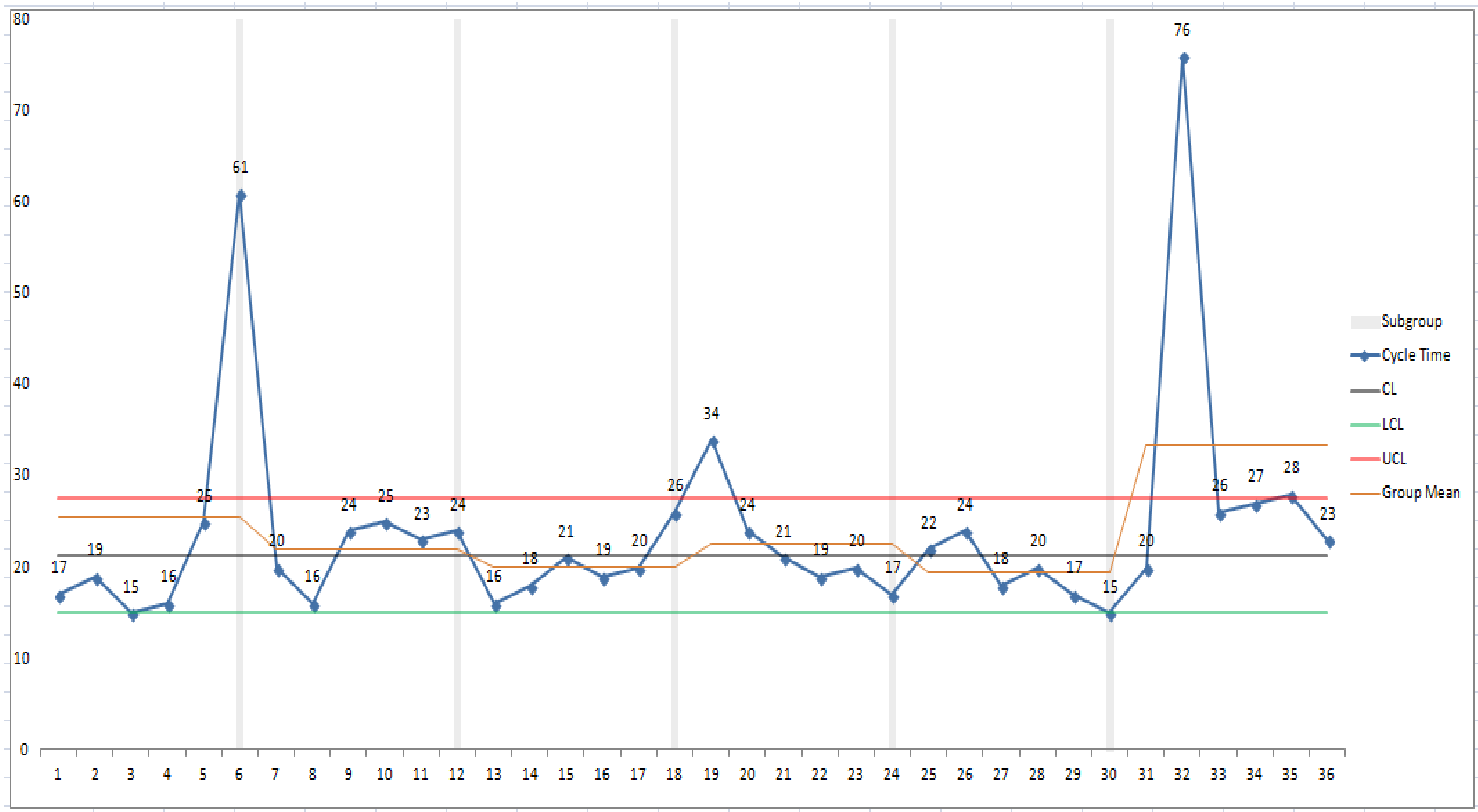

Figure 4.4. Control chart of excavator cycle times for site one.

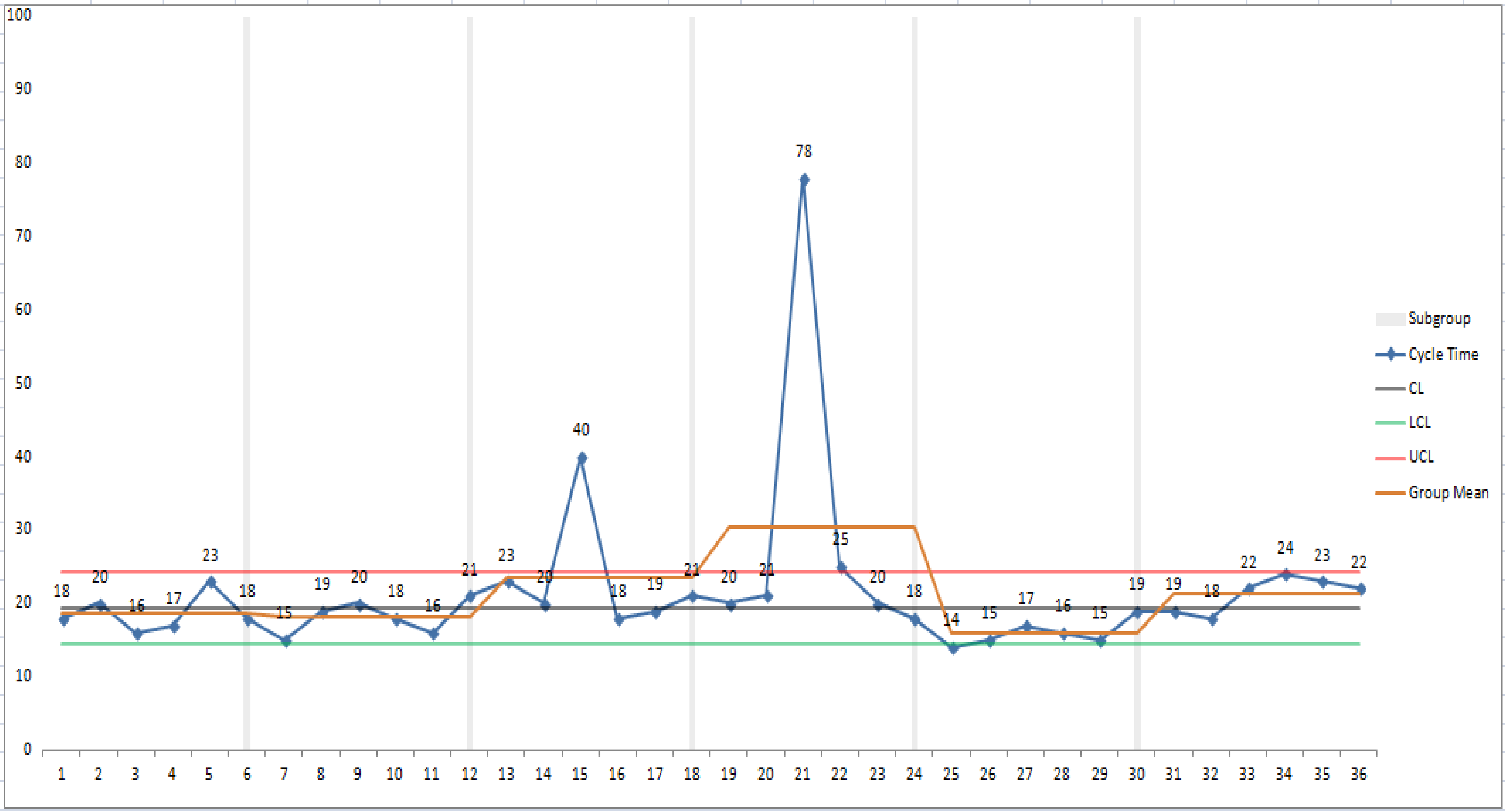

Figure 4.5. Control chart of excavator cycle times for site two.

The meeting began with a discussion of the potential root causes of the data points beyond the upper control limits which accounted for 9.7% of the total amount of observations. The total time to complete the cycles above the upper control limit amounted to 342 seconds. The total time added per cycle was calculated by subtracting the median from each of the out of control observations, totaling the remaining time, and then dividing by the total number of observations. The estimated total added time per cycle due to the points above the upper control limit equaled 2.8 seconds.

With these numbers in mind, the manger was focused on improvements that could reduce the process variability stemming from observations above the upper control limit. The operator indicated several potential causes of these interruptions including: re-positioning and leveling the excavator, removing rocks from the spoil, waiting on the trucks to arrive or back into position, and checking the elevation of the excavation floor.

The comment referring to checking elevations was of particular interest as a 360 degree laser receiver was supposed to be used on any job involving footings and trenches. The receiver is mounted to the stick of the excavator where the signal emanating from a rotating grade laser is used to give the operator a reference elevation. A LED read out on the receiver conveys elevation information to the operator. A laser receiver of this nature is supposed to reduce the use of a grade rod to check the depth of the excavation. Even with a helper using a grade rod, the excavator has to stop working for safety while the helper moves into the operating radius of the machine.

Removing rocks from the spoil and positioning the excavator was viewed as a necessary part of the job, and no process adjustments were devised for these delays. Waiting for trucks to arrive and position was a matter of concern though. Two single axle dump trucks with an approximate capacity of five cubic yards each were assigned to the projects to remove most of the excess soil not needed for backfill. These smaller trucks were used to reduce the amount of damage inflicted upon the access routes coming from the street and around the building perimeter. The dump site was located only about eight miles from the jobsites. While no calculations were done in the planning stage to determine the optimum number of haul units, the manager remarked that this arrangement had worked well in the past for keeping the excavator operator working.

The meeting concluded without pinpointing the cause of the delay in the timely arrival of the haul units as the drivers of the trucks were needed to fully understand what was causing the problem. When the drivers were asked about the delays the following day, it was discovered that one driver had been taking a longer route to the dump site and back which was throwing off the timing of the arrival of the trucks.

This first meeting to determine the roots cause of delays yielded two adjustments to the process. The first adjustment was to add a line item on work orders specifying the type and configuration of elevation equipment assigned to each job. The second adjustment was to specify the required route for all drivers to and from the dump site by having a route plan for the day's work already in the vehicle.

4.1.3 First Excavation Intervention Results

Following the first intervention, samples were collected for site three and four in subgroups of six for a total of 72 samples. Figure 4.6 shows the frequency counts for the cycle time data for site three and four.

Frequency Counts			
		Percents	
Value	Count	Cell	Cum
14	1	1.4	1.4
15	6	8.3	9.7
16	5	6.9	16.7
17	6	8.3	25.0
18	8	11.1	36.1
19	9	12.5	48.6
20	11	15.3	63.9
21	6	8.3	72.2
22	4	5.6	77.8
23	2	2.8	80.6
24	4	5.6	86.1
25	1	1.4	87.5
26	2	2.8	90.3
29	1	1.4	91.7
30	1	1.4	93.1
31	1	1.4	94.4
33	1	1.4	95.8
34	1	1.4	97.2
38	1	1.4	98.6
43	1	1.4	100.0

Figure 4.6. Frequency counts of cycle times for sites three and four.

Figure 4.7 displays the results of the independent t-test of the null hypothesis that there would be no significant difference between the mean cycle times for the pre-intervention operations and the post-intervention operations.

T-Test Intervention 1

The TTEST Procedure

Variable: cycletime (Excavator Cycle Times)

group	N	Mean	Std Dev	Std Err	Minimum	Maximum
post	2	20.7500	0.4950	0.3500	20.4000	21.1000
pre	2	22.5500	1.7678	1.2500	21.3000	23.8000
Diff (1-2)		-1.8000	1.2981	1.2981		

group	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
post		20.7500	16.3028	25.1972	0.4950	0.2208	15.7947
pre		22.5500	6.6672	38.4328	1.7678	0.7887	56.4097
Diff (1-2)	Pooled	-1.8000	-7.3852	3.7852	1.2981	0.6759	8.1581
Diff (1-2)	Satterthwaite	-1.8000	-13.8645	10.2645			

Method	Variances	DF	t Value	Pr > |t|
Pooled	Equal	2	-1.39	0.2999
Satterthwaite	Unequal	1.1558	-1.39	0.3743

Equality of Variances				
Method	Num DF	Den DF	F Value	Pr > F
Folded F	1	1	12.76	0.3476

Figure 4.7. Independent t-test results for the first excavation intervention.

There was a failure to reject the null hypothesis with a p-value of .3743 for the first intervention. The average cycle time was reduced by 1.8 seconds which accounts for a large portion of the 2.8 seconds per cycle that cycles above the upper control limit added before the intervention. A histogram of the data still shows a lognormal distribution but with less right skew as shown in Figure 4.8. The skewness of the data fell from 3.83 pre-intervention to 1.96 post-intervention indicating that the effort to reduce variation stemming from extreme cycle time observations had some success.

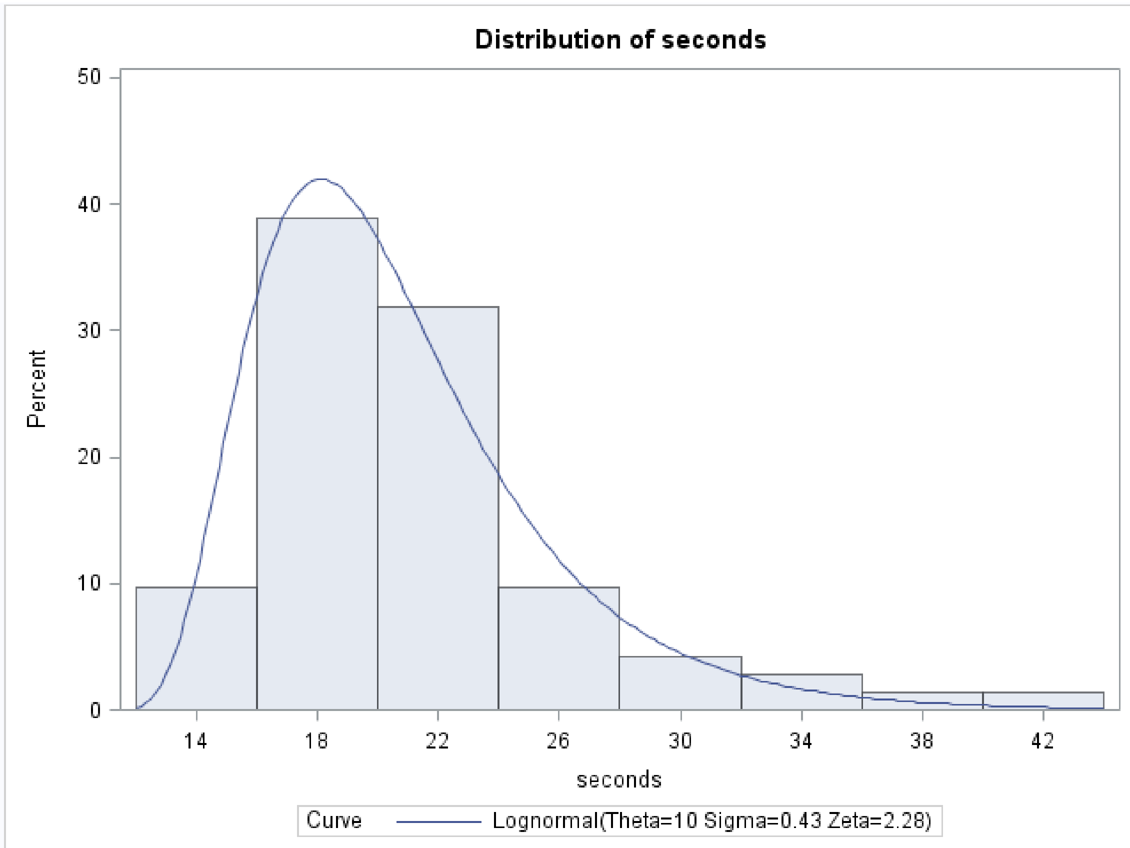

Figure 4.8. Histogram of cycle times for sites three and four.

A comparison of the basic statistical measures of the cycle times for each of the first four sites is found in Table 4.2. The dramatic decrease in the standard deviation after the intervention is due to a reduction in the magnitude, rather than the frequency, of the cycles over the upper control limit. Despite this improvement, the reduction in the average cycle time was low. The potential for improvement was limited by only focusing on the observations above the upper control limit.

Table 4.2

Comparison of basic statistical measures of sites one thru four.

	Site 1	Site 2	Site 3	Site 4
Mean	23.8	21.3	21.1	20.4
Trimmed Mean	21.3	19.4	19.8	20.0
Median	21.0	19.0	19.0	20.0
Standard Deviation	11.9	10.7	6.6	3.8
Third Quartile	24.3	21.3	22.0	22.0
First Quartile	18.0	17.8	17.0	18.0

4.1.4 Second Excavation Intervention

The data collected to test the result of first intervention was then used to construct control charts for analysis during the second intervention. The root cause analysis process began with concern over the continued presence of the outliers in the data. The operator could remember no delays from the trucks and the laser receiver was being used to check the elevation of the excavation. The charts were then more closely examined within the limits to look for patterns or out of control runs. Figure 4.9 and Figure 4.10 display the control charts of the cycle times from site three and site four.

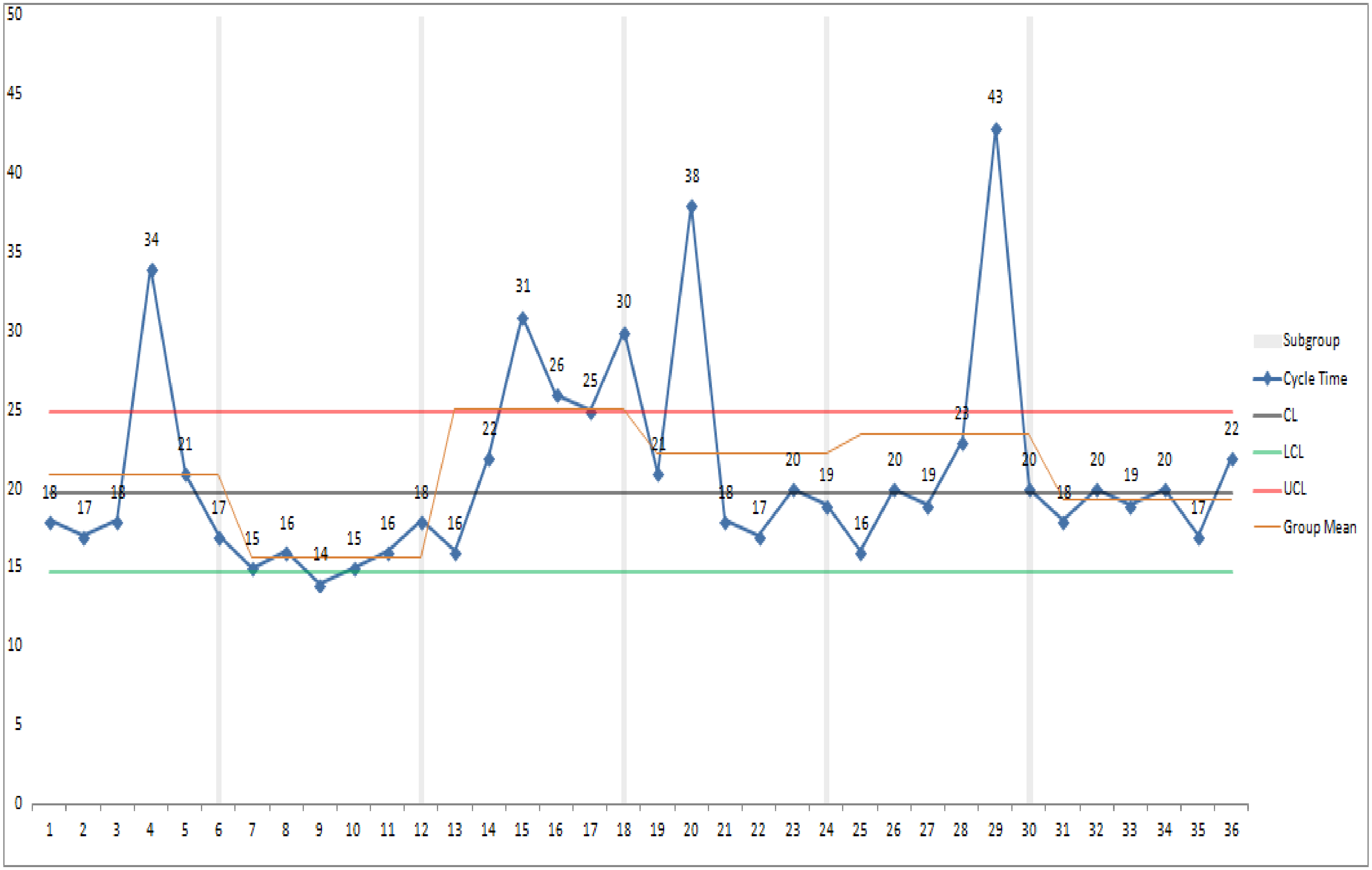

Figure 4.9. Control chart for cycle times for site three.

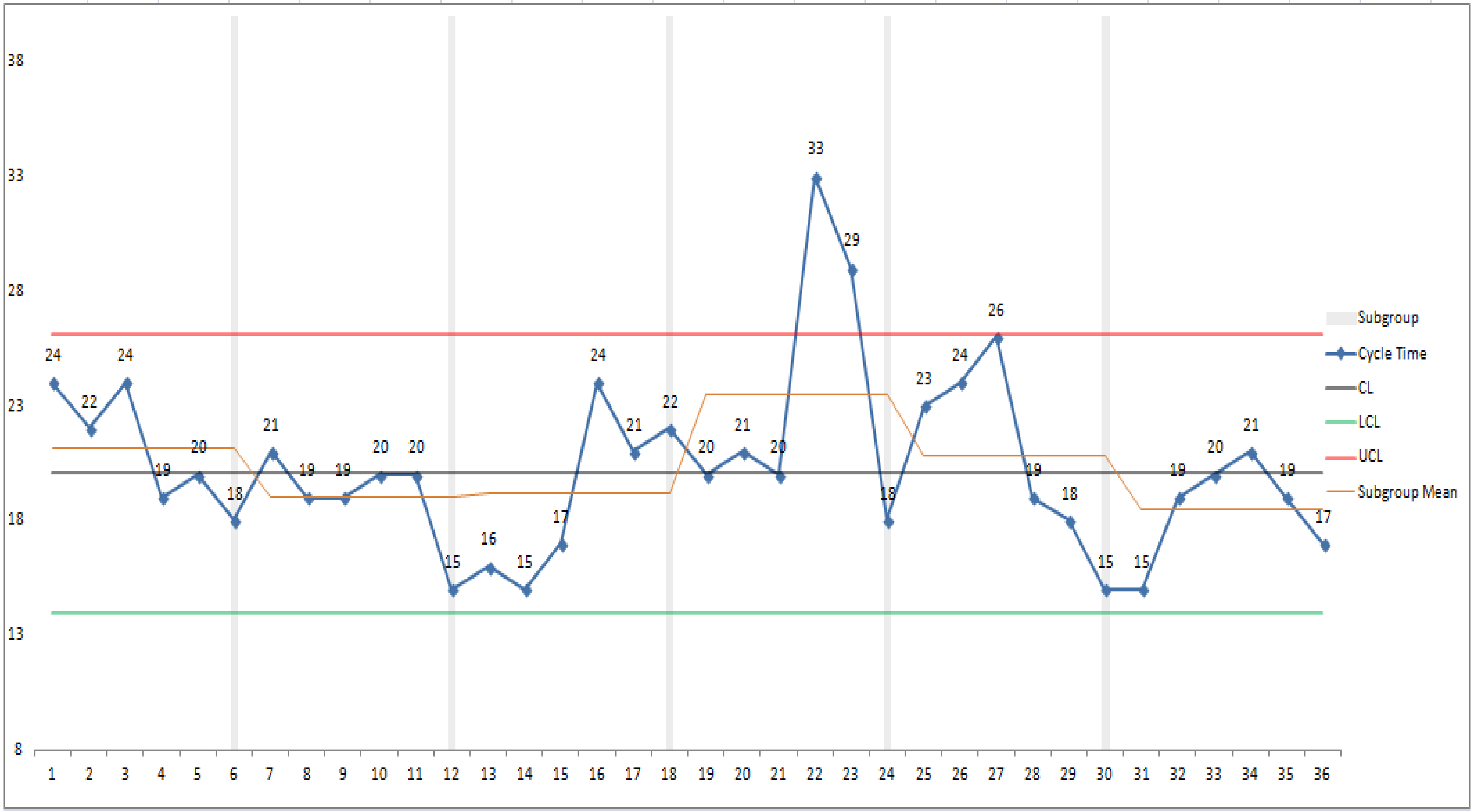

Figure 4.10. Control chart of excavator cycle time for site four.

Several clusters of cycle times well below the centerline were found in the charts. Figure 4.11 shows these groups of points.

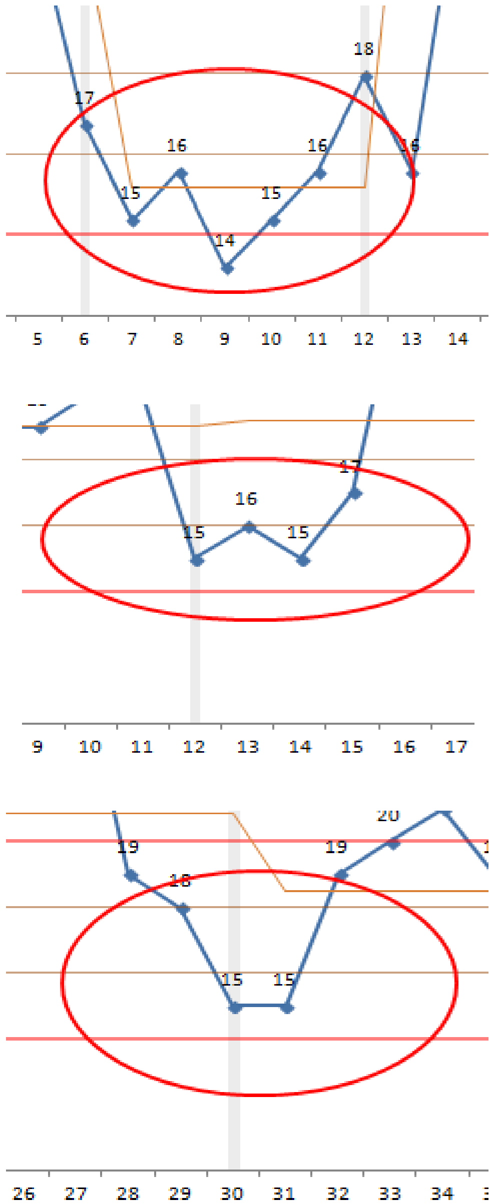

Figure 4.11. Run rule violations for site three and four control charts.

It was difficult to elicit a specific explanation from the operator regarding the potential causes for these relatively fast groups of cycles, but the performance could only be due to a shorter distance of travel between the loading point and the dumping point. The operator related how he was positioning the equipment as the excavation progressed which is displayed in Figure 4.12.

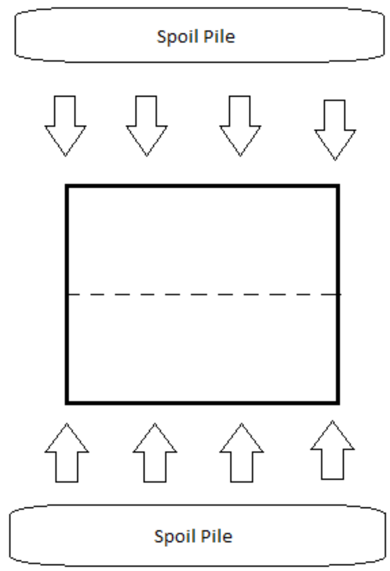

Figure 4.12. Pre-intervention excavator positioning strategy.

The arrows in the figure represent the position of the excavator and the direction of the front tracks in relation to the digging envelope. The operator was reaching far into the excavation near the dashed centerline from the perimeter. This orientation led to many cycles where the maximum reach of the equipment was being approached. A Caterpillar 315C with an 8'6" stick has a maximum reach along the ground of 28'8", and a reach of approximately 25' at the maximum possible depth required for each basement. These figures are calculated from the pivot point of the boom. When the distance from the pivot point of the boom to the front track is subtracted from the maximum reach, a practical reach of approximately 23' at ground level and 19' at the maximum depth can be achieved. Considering the basements are 32’ wide with a 3’ offset (17.5’ per side), many cycles were approaching the maximum practical reach of the excavator which would inevitably lead to longer cycle times.

Not only does reaching the machine far into the excavation increase cycle times, but the only mechanism for loading is to use the bucket curl rather than a combination of swing arm articulation and bucket curl. Having only the bucket curl for breakout force at this distance will decrease the fill factor of the bucket for each load and increase wear on the equipment. In addition, the operator was nearing a 180 degree swing angle to move the bucket from the digging zone to the spoil pile when stockpiling material for backfill. A new plan was formulated to reduce the distance of travel from loading and dumping points.

The plan revolved around removing a central portion of material wide enough to allow the machine to work in an optimal zone near the perimeter as seen in Figure 4.13. The excavator could deposit the material from the 10’ by 20’ central section into haul units (represented by the rectangles outside the excavation perimeter) as reaching to a spoil pile location from the center would obstruct the access roads around the building perimeter.

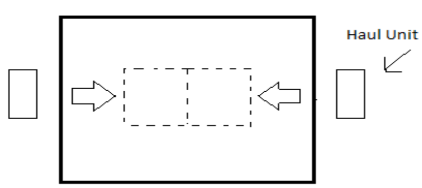

Figure 4.13. Excavation plan for the central section of soil.

Once the center of rectangle was dug to depth, the excavator then straddled the tracks over the outer perimeter of the excavation as shown in Figure 4.14. Straddling the sprayed painted perimeter line of the excavation would allow three advantages: digging straight perimeter walls would be easier with equal pressure on each of the bucket, the pivot point of the boom would be more centrally located within the excavation, and the swing angle to dump to spoil piles would not approach 180 degrees in most cases. The new plan would require more positioning than the previous approach in an effort to close the distance of travel of the bucket as much as possible. These position changes would usually only involve the operator tracking backward as indicated by the numbering sequence in the Figure 4.14.

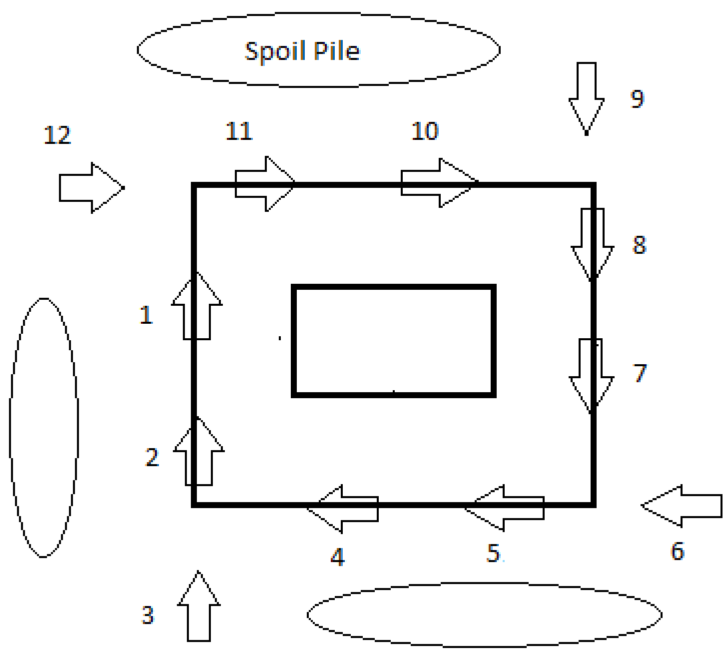

Figure 4.14. New excavator perimeter positioning and spoil pile location plan.

4.1.5 Second Excavation Intervention Results

Samples were collected, following the second intervention, for site five and six in subgroups of six for a total of 72 samples. Figure 4.15 shows the frequency counts for the cycle time data for site five and six.

Frequency Counts			
		Percents	
Value	Count	Cell	Cum
11	2	2.8	2.8
12	3	4.2	6.9
13	5	6.9	13.9
14	9	12.5	26.4
15	13	18.1	44.4
16	12	16.7	61.1
17	4	5.6	66.7
18	7	9.7	76.4
19	1	1.4	77.8
20	3	4.2	81.9
21	1	1.4	83.3
22	1	1.4	84.7
23	2	2.8	87.5
24	1	1.4	88.9
25	2	2.8	91.7
26	2	2.8	94.4
28	1	1.4	95.8
29	1	1.4	97.2
32	1	1.4	98.6
33	1	1.4	100.0

Figure 4.15. Frequency counts of cycle times for sites five and six.

Figure 4.16 displays the results of the independent t-test of the null hypothesis that there would be no significant difference between the mean cycle times for the pre-intervention operations and the post-intervention operations.

T-Test Intervention 2

The TTEST Procedure

Variable: cycletime (Excavator Cycle Times)

group	N	Mean	Std Dev	Std Err	Minimum	Maximum
post	2	17.3000	0.5657	0.4000	16.9000	17.7000
pre	2	20.7500	0.4950	0.3500	20.4000	21.1000
Diff (1-2)		-3.4500	0.5315	0.5315		

group	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
post		17.3000	12.2175	22.3825	0.5657	0.2524	18.0511
pre		20.7500	16.3028	25.1972	0.4950	0.2208	15.7947
Diff (1-2)	Pooled	-3.4500	-5.7369	-1.1631	0.5315	0.2767	3.3404
Diff (1-2)	Satterthwaite	-3.4500	-5.7759	-1.1241			

Method	Variances	DF	t Value	Pr > |t|
Pooled	Equal	2	-6.49	0.0229
Satterthwaite	Unequal	1.9654	-6.49	0.0239

Equality of Variances				
Method	Num DF	Den DF	F Value	Pr > F
Folded F	1	1	1.31	0.9152

Figure 4.16. Independent t-test results for the second excavation intervention.

For the second intervention, the null hypothesis was rejected with a p-value of 0.0239. The data provides evidence supporting the alternative hypothesis that a significant difference exists between the mean cycle times of sites three and four and the mean cycle times of sites five and six. While the t-test did provide a significant result, the statistical power of the test was only 0.17 with three degrees of freedom making the significant result of the t-test highly unreliable.

Table 4.3 gives a comparison of the basic statistical measures for sites three thru six. Unlike after the first intervention, the second intervention countermeasures made an impact on the median cycle times. The drop in the median cycle time and quartile values for site five and six shows that the process improvements of the second intervention decreased the duration of the typical cycles. The variation of the data was relatively consistent indicating that the improvements from the first intervention were still having an effect as well.

Table 4.3

Comparison of basic statistical measures for sites three thru six.

	Site 3	Site 4	Site 5	Site 6
Mean	21.1	20.4	16.9	17.7
Trimmed Mean	19.8	20.0	16.3	17.0
Median	19.0	20.0	16.0	15.5
Standard Deviation	6.6	3.8	4.2	5.2
Third Quartile	22.0	22.0	18.0	20.8
First Quartile	17.0	18.0	15.0	14.0

4.2 Foundation Forming and Reinforcing

This section will cover the forming and reinforcing processes for the foundation walls of the same speculative home projects detailed in the excavator section. For this part of the study, only four sequences were observed due to a scheduling conflict. Two forming and reinforcing sequences were observed to set the baseline level of production. An intervention was then made using the control charts to identify inefficiencies followed by the observation of two more forming and reinforcing processes for comparison to the baseline.

The process of erecting one side of the formwork, fixing the reinforcement, and closing up the interior side of the formwork took approximately three work days per job with approximately 7-14 days elapsing between each job. Both the formwork and reinforcement installation cycle times were converted into a productivity factor where the actual time to complete a cycle was divided by the estimated time to complete a cycle. This conversion allowed the data acquired from different processes to be placed on the same chart for comparison.

Job built plywood formwork was used to form the basement walls. Each of the homes was designed with 9'4" basement walls to allow for a full 8' finished ceiling height. A second lift of plywood was required to reach the full required height of the walls. The observation of the formwork operation was limited workers installing and bracing the 4' by 8' sheets of plywood for the bottom course. The forming of the garage foundation walls was also not included as part of this study.

The forming system relied upon brackets rather than wedges to secure the ties and walers. Each bracket had a rotating arm that secured the loop snap ties as well as providing a platform for the horizontal walers. The looped snap tie had a break back of 1" with a plastic cone used for spacing. The 2"x 4" horizontal walers were spaced at 12" on center with staggered joints and overlapped corners. Standard 2"x 4" strong backs were spaced at 6' on center and secured by a clamp that attached directly to the bracket securing the walers and snap ties. Another clamp was used to tie the strong backs directly to the footing plate. Scaffold brackets were attached to the strong backs to provide a working platform for the installation of the second lift of plywood and the concrete placement. Extra bracing was installed as needed on each side of the formwork.

The higher walls also required reinforcement with a maximum height of unbalanced backfill of 8 feet. Number six reinforcement bars spaced at 38" were required for vertical reinforcement. Number five horizontal reinforcement was also required at 36" on center with the top band of horizontal reinforcement at 12" from the top of the wall. The material for the reinforcement process was already cut to size at the company shop. Upon delivery, the material was placed directly into the excavation using an excavator.

Workers would install the vertical bars first by overlapping and wiring the bars to the reinforcement coming out of the footing at 24" long. Once all the vertical reinforcement was installed, the workers would then attach the horizontal reinforcement to the vertical bars for final alignment. Only the installation of vertical reinforcement was observed in this study.

Four workers were assigned to the projects to complete both the formwork and reinforcement installations. Usually, the workers broke into two teams where each team would work towards each other from opposite corners whether forming or reinforcing. Once the teams would meet near the center, one team would move off and begin a new section from another corner.

The estimates used to calculate the productivity factor included one man hour per 40 square feet of contact area (SFCA) for the initial side of formwork, one man hour per 50 SFCA for the close up formwork, and 12 man hours per ton of reinforcement. The estimated time for the initial side of formwork is greater than the close up side of formwork, because workers have to install the snap ties and brackets on the initial side while on the close up side only the brackets need to be installed as the snap ties are already in place. The cycles of for each process were to be measured in seconds, so for convenience each production rate was converted to 2880 man seconds per 32 SFCA for the initial side of formwork, 2304 man seconds per 32 SFCA for the close up formwork, and 303 man seconds per 13.8 pounds of reinforcement (the weight of the vertical bars at length).

4.2.1 Formwork and Reinforcement Baseline Data Analysis

A total of 120 observations, split evenly among two jobs, were collected to establish the baseline productivity factors of 1.082 for site one and 1.045 for site two. The interpreter of these average productivity factors can gauge that the process cycles for site one took 8.2% longer than estimated and the process cycles for site two took 4.5% longer than expected. With two groups working simultaneously on similar work, control charts were created to compare the two groups and analyze the overall performance of both teams while performing different tasks. Figure 4.17 and Figure 4.18 display the charts.

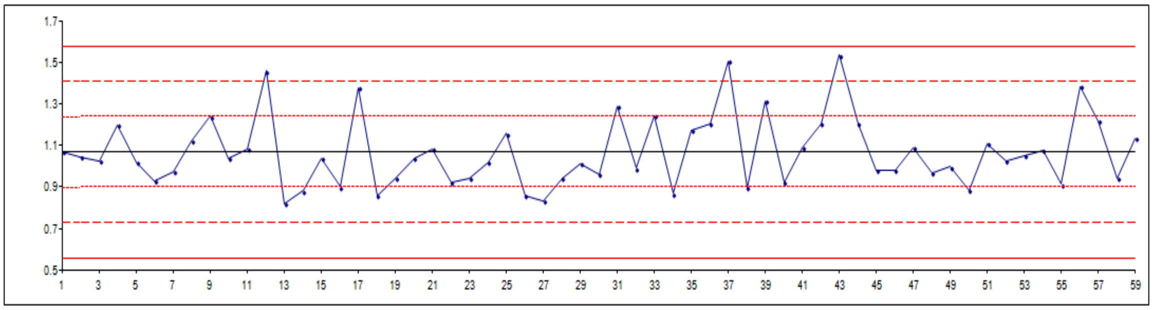

Figure 4.17. Control chart of cycle times for the forming and reinforcing of site one.

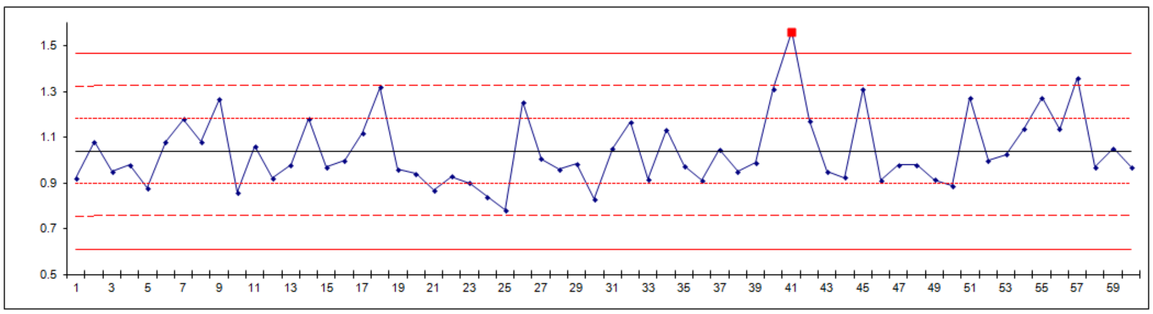

Figure 4.18. Control chart of cycle times for the forming and reinforcing of site two.

The control chart from the first process shows no out of control points above the upper control limit or run rule violations in the patterns of the data. Without any violations for discussion, the groups were compared to find if one group was more efficient than the other. One can see in Figure 4.19 that group two was better at erecting the initial side of formwork than group one.

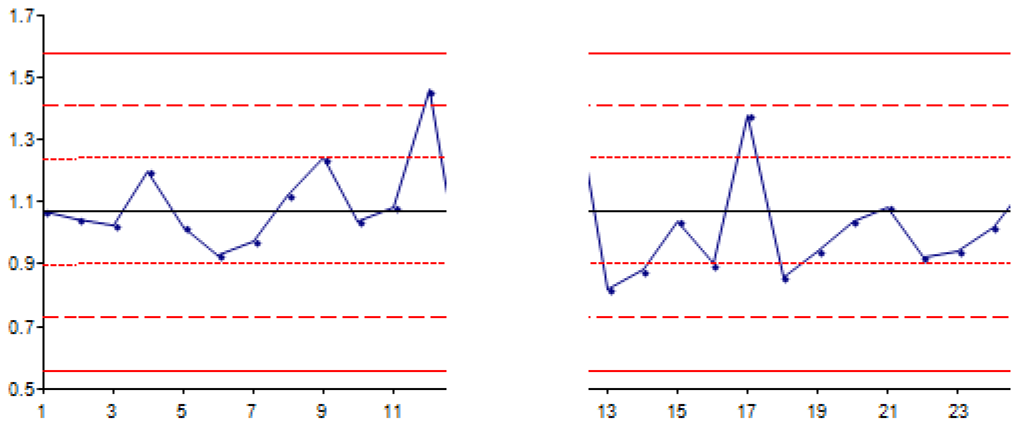

Figure 4.19. Group one and group two initial forming site one.

During the rebar installation process, group one was consistent in the time it took to install a vertical reinforcement bar, but group two had an oscillating pattern above and below the centerline for almost every observation as seen in Figure 4.20.

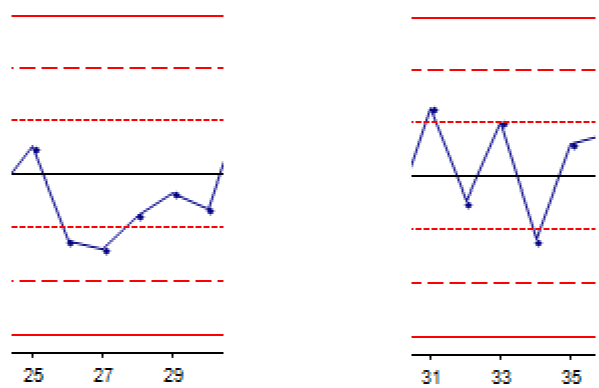

Figure 4.20. Group one and group two reinforcement site one.

On the close up of the formwork, group two was fairly consistent and performed better than group one. Group one showed another oscillating pattern, where faster cycles were followed up by much slower cycles as shown in Figure 4.21.

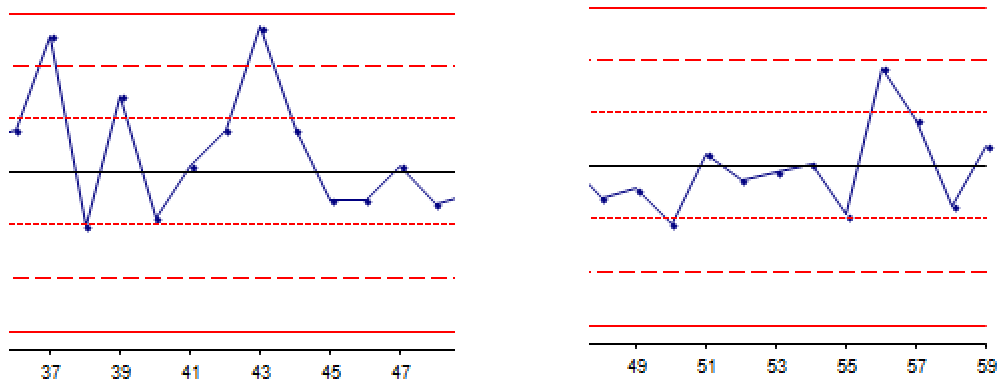

Figure 4.21. Group one and group two close-up formwork site one.

The control chart from site two shows many of the same patterns as the first control chart, but there are also two rule violations in this chart. One violation includes six consecutive points on one side of the centerline. This rule violation occurs at the tail end of group two's initial side of formwork installation. The first half of the observations in group two's installation of the initial side of formwork shows considerable variation with many cycles taking longer than estimated; then there is a shift in the process where cycles are consistently well below the expected level of performance. Figure 4.22 shows this pattern in the performance of group two.

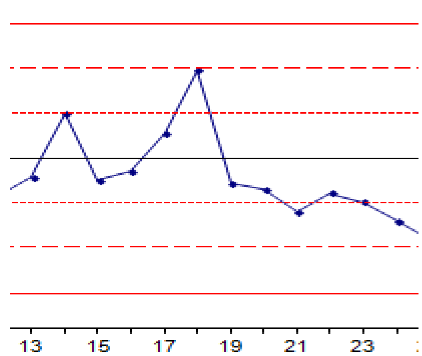

Figure 4.22. Initial side formwork installation for group two at site two.

The second out of control point is above the upper control limit. This observation occurred during group one's installation of the close-up formwork. In general group one was consistent when installing the close up formwork, but several cycles were well above the estimate indicating serious interruptions were disrupting the smooth flow of operation otherwise present. The same pattern is also found for group two's installation of the close-up formwork as seen in Figure 4.23.

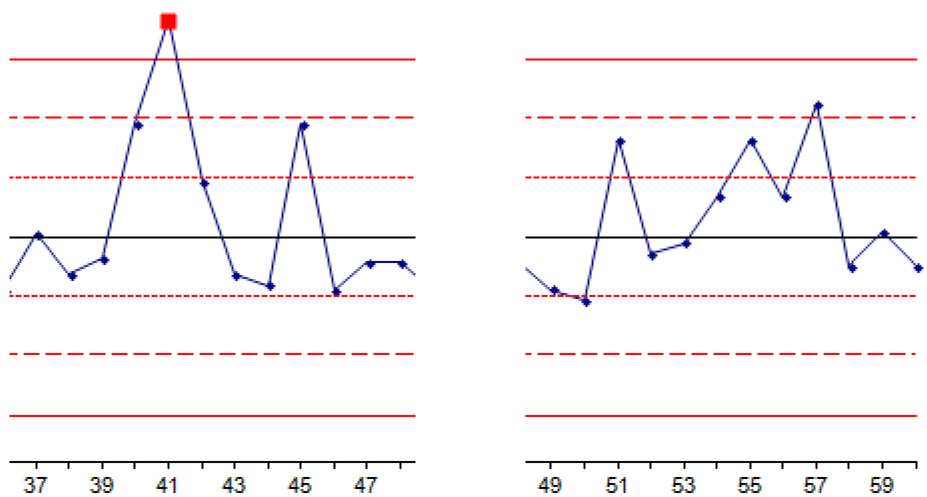

Figure 4.23. Group one and group two close-up formwork installations for site two.

4.2.2 Formwork and Reinforcement Intervention

A meeting was conducted with the four workers and the manager after the completion of site two. The discussion began with the possible differences in the method of installation of the initial side of formwork between group one and group two. Special attention was paid to the second site where group two showed a run of better than expected performance for six points in a row below the centerline.

The workers from group two quickly came up with the most likely cause of the outstanding performance during the initial side of formwork installation. The group two workers had begun to pre-load the formwork panels with the brackets and snap ties before erection. Since the snap tie could be put under tension without the walers in place, the workers would install the bracket and snap ties before tilting the panel into place.

The workers were asked how the snap ties were installed with the cones not allowing the ties to be inserted on the same side as the bracket. The workers explained that they were laying the panels horizontally on two sawhorses set-up in the excavation. The panels had two columns of pre-drilled holes for the snap ties running down the length of the plywood. One worker would insert the snap ties into the panel from the bottom and then use his other free hand to slip the loop over the rotating arm in the bracket to secure the assembly. The other worker would do the same thing on the other side. With the panels fully loaded, the workers would nail the loaded panel to the edge of the footing plate and proceed to install the walers in the brackets.

This method offered several efficiencies over the traditional method. The traditional method involves the workers nailing the panel to the footing plate first. One worker would then stand on the interior side of the panel while installing snap ties in the holes. The other worker would stand of the earth side of the panel and install the bracket on the snap tie loop. Workers would have to carry the ties and brackets over to the panel in place, usually laying them on the ground, and then stoop to pick up brackets and ties as needed.

With the alternate method, the ties and brackets stayed located near the loading area at all times. The workers could place the brackets on top of the horizontal panel first, and then only a small adjustment of the bracket was needed as they inserted the snap ties from the bottom of the panel. This technique also allowed the workers to install the brackets and ties near waist height rather than stooping and reaching during installation with the panels in place. In addition, both workers could install the assemblies by themselves on either side of the horizontal panels. This new technique of pre-loading the panels was the first adjustment to the process made for the succeeding formwork erections at site four and site five.

For the reinforcement installation, the consistency of group one compared to group two was the main focus of the discussion. This cause of the difference was not easy for the workers to pinpoint. Both teams used essentially the same technique to install the rebar with one worker holding the bar vertically while the other worker wired the bar to the reinforcement protruding from the footings. While one group may have been faster at aligning and wiring the bars, this potential difference does not explain why group two showed so much more cycle time variation than group one. The positioning of the material in the excavation was located in one central area for both sites, which should cause the observed cycle times to show an upward or downward trend as workers either worked toward or away from the stock pile location.

After some discussion, it was determined that group one was most likely more consistent and faster overall because they were staging more bars at once which required fewer trips to the small shake out area than group two. It was decided that both workers should work in tandem to carry more vertical bars at a time to the area of installation.

The close-up formwork process observations were highly varied for both groups. The discussion of the root cause of this variation barely began before there was a consensus that the drilled holes in the 4'x 8' plywood panels were not aligning easily in many cases. The workers present at the meeting were not responsible for the drilling of the holes in the plywood for the snap ties as the panels had been in storage at the yard for some time. The misalignment of the snap tie holes was due to the drill bit being out of plumb during the gang drilling of plywood. This "walking" of the drill bit can occur when workers drill large quantities of panels at once. Workers were reminded to use a drill stand when gang drilling and to only drill a maximum of five panels at a time with one panel used as the master template.

4.2.3 Formwork and Reinforcement Intervention Results

An independent t-test was used to test the effect of the intervention. Rather than test the significance of the improvements for each activity, each day's productivity factors were averaged to compare the overall performance at site one and two to the overall performance at site four and five. The results of the test can be seen in Figure 4.24.

T-Test Intervention

The TTEST Procedure

Variable: factor

group	N	Mean	Std Dev	Std Err	Minimum	Maximum
post	2	0.9615	0.00495	0.00350	0.9580	0.9650
pre	2	1.0635	0.0262	0.0185	1.0450	1.0820
Diff (1-2)		-0.1020	0.0188	0.0188		

group	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
post		0.9615	0.9170	1.0060	0.00495	0.00221	0.1579
pre		1.0635	0.8284	1.2986	0.0262	0.0117	0.8349
Diff (1-2)	Pooled	-0.1020	-0.1830	-0.0210	0.0188	0.00980	0.1183
Diff (1-2)	Satterthwaite	-0.1020	-0.3066	0.1026			

Method	Variances	DF	t Value	Pr > |t|
Pooled	Equal	2	-5.42	0.0324
Satterthwaite	Unequal	1.0715	-5.42	0.1044

Equality of Variances				
Method	Num DF	Den DF	F Value	Pr > F
Folded F	1	1	27.94	0.2381

Figure 4.24. Forming and reinforcing intervention t-test.

With a p-value of .1044, there was a failure to reject the null hypothesis that the mean productivity factors of site one and two are significantly different than the mean productivity factors of site four and five. While the results of the intervention were not statistically significant, the mean productivity factor did decrease by .1020. This drop in the mean productivity factor equates a ten percent decrease in the time to complete the forming and reinforcing operations. The forming and reinforcing operations for site one and two took 6.35% longer than estimated while the operations for site four and five took 3.85% less time than expected.

A comparison of the mean productivity factors for each activity is shown in Table 4.4. For the initial formwork erection process, both groups showed improvement from pre-loading the panels with brackets and ties. Group one improved by 12.4% while group two improved by 7.6%.

Table 4.4

Comparison of the mean productivity factors for each activity.

Activity	Group	Site 1	Site 2	Site 4	Site 5
Initial Forming	1	1.122	1.047	0.955	0.965
	2	1.035	1.007	0.944	0.945
Reinforcement	1	0.961	0.970	1.003	0.982
	2	1.113	1.026	0.930	0.994
Closing Forming	1	1.161	1.092	0.985	0.971
	2	1.058	1.083	0.942	0.957

The attempt to improve the reinforcing process was based on the staging technique used by group one which naturally lead to no improvement for that group. In fact, group one’s rate of installation for the reinforcement increased by 2.7%. Group two did show a 10.7% improvement using the method of group one.

For the close-up formwork, both groups were expected to show a dramatic decrease in the mean productivity factor as almost all new plywood was used for site four. Group one showed a 14.83% improvement while group two showed a 12.11% improvement. While this improvement was the greatest among the three activities, the problem with alignment of the formwork would most likely have been remedied whether control charts were used or not.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The primary goal of this study was to demonstrate a method of construction process improvement where hard data can be used to identify potential inefficiencies. In this regard, the researcher feels that this project was successful. The results from using control charts for process improvement is heavily dependent on the ability of management and labor to recognize and devise solutions for problems indicated by the data. Linking a pattern of inefficiency on a control chart to an actual set of events proved to be difficult as many different variables contribute to construction process variation at a given time.

Most of the root cause analysis of the data with the employees devolved into a discussion of perceived problems in general rather than making a specific link between data points and events. However, the control charts were still the major driver of the discussions. Seeing the data visually displayed where it was impossible to deny the existence of problematic performance seemed to make the workers more willing to openly discuss problems and solutions. On the other end of the spectrum, identifying and replicating the conditions that supported groups of relatively short cycles proved to be a useful technique.

One important question that needs to be addressed when considering the success of this project is the cost of the improvement processes. All the personnel participating in this study did so off company time; but the man hours required to collect the data, construct the charts, and conduct the root cause analysis meeting was tracked. The cost of this project in terms of material resources was negligible, but the man hours spent on each phase amounted to 9.5 hours for the excavation improvement process and 37.75 hours for the formwork and reinforcement improvement process. The main reason for the large expenditure of man hours to conduct this study was due to the researcher traveling to and from the jobsite and waiting for long cycles to complete.

The expenditure of time spend collecting data could be greatly reduced in a real world situation where supervisors on site could collect the information quickly while doing other things in between the appointed sample times. For instance, collecting the six subgroup samples for the excavation process only took about two minutes to collect, and over the course of the day this would only amount to a supervisor spending about fifteen minutes collecting data. Even with cycles that can take twenty minutes or longer, as with formwork installation, supervisors could note the time the process was started and completed while working in between. The researcher sat idle while the panels were installed which inflated the total man hour calculations. The control charts can be completed in minutes once a template is made, and the root cause analysis meeting was conducted in twenty minutes or less with about ten minutes of preparatory analysis pre-meeting.

In the final analysis, the excavation process average cycle time dropped by over five seconds. With approximately 1100 cycles needed to complete each basement excavation, about an hour, or 15% of the total work time, was eliminated by the time the excavation of site five and six was underway. A similar reduction in total work time was gained in the forming and reinforcing processes. While one could argue that this study was practically successful, the results of the hypothesis tests failed to reject the null hypothesis in all cases but one where the significant result was highly suspect. Several modifications could improve this study which will be detailed in the following section.

5.2 Recommendations

The researcher would recommend several modifications for future research. Perhaps the most important improvement would be to add more information to the data to reduce the uncertainty as to what variables are causing a certain point or pattern in the control chart. For example, if an excavator cycle was delayed due to a rock in the spoil, this event should be noted next to the cycle. These notes would reduce the guesswork associated with linking the control chart information to particular process events. The notes could also reduce the need for the involvement of the workers in the root cause analysis process.

The notes could consist of standard labels that could be determined before the observation phase. These standard labels could be very process specific or more generalized depending on the context of the situation. Future researchers should consider a categorization system similar to James Adrian’s Method Productivity Delay Model or some of the labels used in work sampling studies.

Another important improvement could be achieved by reducing the costs associated with collecting the large amount of samples needed to adequately capture the process.

Video recordings of an activity could make the data collection much less time consuming. The person performing the data collection could review a recording of the process to sample cycle times by fast-forwarding to pre-determined points in time. This approach would allow subgroups of cycles to be collected more frequently without the need to travel to the site.

Video recording would also allow a simple random sampling method to be used instead of stratified sampling. Simple random sampling would give a more accurate representation of the overall process performance. With the method used in this study, a group of six cycles could be measured where the performance was unusually poor. The factors that lead to the string of poor performance may be just a onetime event that is not worth correcting. Simple random sampling could reduce the presence of these false alarms by collecting cycle times individually, because a rare set of events that leads to poor performance would most likely have only one observed data point unless the problem was persistent. With a more accurate overall depiction of the process, users of the control charts could more easily focus on problems having a sustained negative impact on the process.

For testing purposes, this study needs to be carried out over a longer duration to increase the statistical power of the hypothesis tests. Under the current model, only two samples were collected during each pre-intervention and post-intervention period. The 36 samples collected for each period were averaged to only count as one sample mean for use in the t-test. This required arrangement allowed only three degrees of freedom which lowered the statistical power of the tests to the point that any significant findings were highly unreliable.

A matched pairs study design where the countermeasures devised were applied to several groups doing similar work at the same time could overcome the statistical power problem. In the study presented here, the researcher only had access to a small project where one or two groups at most were working on similar activities at the same time. The statistical power of the test could be significantly increased if the countermeasures could be applied to several different groups where the pre-intervention and post-intervention cycle times could be compared for each group in a matched pairs t-test. A production home builder that constructs large residential developments may offer the opportunity to conduct an extensive matched pairs study as described above.

Looking into the future, the continued development of radio frequency identification (RFID) could lead to widespread usage of statistical analysis in construction. Material that is tagged with an RFID chip has the potential to be tracked from storage to installation. The time that it takes the material to move from a storage point to installation could be recorded to allow for widespread data collection of cycle times. This data could provide a statistical overview of the entire project where inefficiencies could be tracked and designed out of systems from project to project.

REFERENCES

REFERENCES

AACE International. (2004). *AACE International recommended practices 25R-03: Estimating lost labor productivity in construction claims*. Retrieved from website: http://www.sde-us.com/docs/emailblasts/JetBlue/LostLabor.pdf

Adrian, J., & J. Adrian. (1995). *Total productivity and quality management for construction*. Champaign, IL: Stipes Publishing, Inc.

Bureau of Economic Analysis. (2012). *Gross-Domestic-Product-(GDP)-by-Industry Data*. Industry Economic Accounts (Washington, DC: Bureau of Economic Analysis)

Chapman, R., & Burty, D. (2009). *Measuring and improving the productivity of the U.S. construction industry: issues, challenges, and opportunities.* National Institute of Standards and Technology.

Cortinas, D. (1991). *On-site construction productivity improvement through total quality managment*. (Master's thesis)Retrieved from http://www.dtic.mil/dtic/tr/fulltext/u2/a245266.pdf

Deming, W. E. (2000). *Out of the crisis*. Cambridge, Mass: MIT Press.

Dozzi, S., & AbouRizk, S. (1993). *Productivity in construction*. Informally published manuscript, Civil Engineering Department, University of Alberta, Alberta, Canada. Retrieved from http://www.nrccnrc.gc.ca/obj/irc/doc/pubs/nrcc37001.pdf

Edmund, M. (2010). Walter A. Shewhart 1891-1967. *Quality Progress*, *43*(11), 21.

FMI Productivity Report. (2012). Retrieved from http://www.fminet.com/media/pdf/report/FMIProductivitySurvey_2012.pdf

Haskell, P. (2004). *Construction industry productivity: Its history and future direction*. Informally published manuscript, Retrieved from http://www.thehaskellco.com/upload/NewsLibrary/WhitePapers/ConstructionProductivity.pdf

Jorgenson, D., Ho, M., & Stiroh, K. (2008). A retrospective look at the U.S. productivity growth resurgence. *Journal of Economic Perspectives*, *22*(1), 3-24.

Koskela, L. (1992). *Application of the new production philosophy to construction*. Informally published manuscript, Center for Integrated Facility Engineering, Stanford University, Stanford, California. Retrieved from http://www.leanconstruction.org/pdf/Koskela-TR72.pdf

Leu, S., Lin, Y., Chen, T., & Ho, Y. (2006). *Improving traditional earned value management by incorporating statistical process charts*. Informally published manuscript, National Taiwan University of Science and Technology, Taiwan, China. Retrieved from http://www.iaarc.org/publications/fulltext/isarc2006-00036_200607201532.pdf

Limpke, W. (2002). Statistical process control of project performance. *The Journal of Defense Software Engineering*, *22*(9), 15-18

Mann, D. (2010). *Creating a lean culture*. (2nd ed.). New York, NY: Productivity Press.

National Research Council, (2009). *Advancing the competitiveness and efficiency of the U.S. construction industry*. Retrieved from: http://modular.org/marketing/documents/NRC_USConstructionIndustry_Report.pdf

Shewhart, W. (1986). *Statistical method from the viewpoint of quality control*. Mineola, NY: Dover Books.

Stalk, G., & Hout, T. M. (1990). *Competing against time: How time-based competition is reshaping global markets*. New York: Free Press.

Teicholz, P. (2004, April 14). *Labor productivity declines in the construction industry: Causes and remedies*. Retrieved from http://www.aecbytes.com/viewpoint/2004/issue_4.html

Thomas, H. (2012). Benchmarking construction labor productivity. *American Society of Civil Engineers*, Retrieved from http://ascelibrary.org.ezproxy.lib.purdue.edu/doi/pdf/10.1061/(ASCE)SC.1943-5576.0000141

Tulacz, G., & Armistead, T. (2007, November 21). *Large corporations are attempting to meet the industry halfway on issues of staff shortages and risk*. Retrieved from http://enr.construction.com/features/bizLabor/archives/071121d-2.asp

APPENDICES

Appendix A Excavation Data Set

Site 1				Site 2		
Obs	Date/Time	Seconds		Obs	Date/Time	Seconds
1	6-Aug	17		1	13-Aug	18
2	8:48	19		2	8:07	20
3		15		3		16
4		16		4		17
5		25		5		23
6		61		6		18
7	9:46	20		7	9:59	15
8		16		8		19
9		24		9		20
10		25		10		18
11		23		11		16
12		24		12		21
13	10:49	16		13	10:36	23
14		18		14		20
15		21		15		40
16		19		16		18
17		20		17		19
18		26		18		21
19	11:20	34		19	11:35	20
20		24		20		21
21		21		21		78
22		19		22		25
23		20		23		20
24		17		24		18
25	1:31	22		25	1:30	14
26		24		26		15
27		18		27		17
28		20		28		16
29		17		29		15
30		15		30		19
31	2:14	20		31	2:57	19
32		76		32		18
33		26		33		22
34		27		34		24
35		28		35		23
36		23		36		22

Figure A.1 Excavation observations from site one and two

Site 3				Site 4		
Obs	Date/Time	Seconds		Obs	Date/Time	Seconds
1	28-Aug	18		1	3-Sep	24
2	9:35	17		2	8:27	22
3		18		3		24
4		34		4		19
5		21		5		20
6		17		6		18
7	10:37	15		7	9:26	21
8		16		8		19
9		14		9		19
10		15		10		20
11		16		11		20
12		18		12		15
13	11:50	16		13	10:05	16
14		22		14		15
15		31		15		17
16		26		16		24
17		25		17		21
18		30		18		22
19	1:49	21		19	11:36	20
20		38		20		21
21		18		21		20
22		17		22		33
23		20		23		29
24		19		24		18
25	2:42	16		25	1:10	23
26		20		26		24
27		19		27		26
28		23		28		19
29		43		29		18
30		20		30		15
31	29-Aug	18		31	2:16	15
32	8:16	20		32		19
33		19		33		20
34		20		34		21
35		17		35		19
36		22		36		17

Figure A.2 Excavation observations from site three and four

Site 5				Site 6		
Obs	Date/Time	Seconds		Obs	Date/Time	Seconds
1	18-Sep	33		1	1-Oct	15
2	7:43	15		2	8:22	16
3		15		3		13
4		11		4		13
5		11		5		20
6		14		6		25
7	8:22	12		7	9:35	24
8		19		8		26
9		16		9		17
10		17		10		18
11		14		11		16
12		14		12		13
13	9:51	14		13	10:30	12
14		15		14		15
15		16		15		15
16		18		16		16
17		22		17		15
18		15		18		20
19	10:01	18		19	11:08	25
20		16		20		32
21		17		21		23
22		15		22		12
23		18		23		13
24		20		24		17
25	11:06	16		25	1:50	14
26		18		26		14
27		18		27		16
28		29		28		15
29		21		29		14
30		16		30		26
31	1:38	18		31	2:53	28
32		16		32		23
33		15		33		13
34		15		34		14
35		16		35		14
36		16		36		15

Figure A.3 Excavation observations from site five and six

Appendix B Forming and Reinforcing Dataset

Site 1						
	Obs	Sub #	Group 1	Group 2	PF	PF
Forming	1	1	1541.0	1253.0	1.070	0.870
	2	2	1498.0	1339.0	1.040	0.930
	3	3	1426.0	1570.0	0.990	1.090
	4	4	1323.0	1368.0	0.919	0.950
	5	5	1728.0	2059.0	1.200	1.430
	6	6	1973.0	1311.0	1.370	0.910
	7	1	2160.0	1426.0	1.500	0.990
	8	2	1685.0	1564.0	1.170	1.086
	9	3	1786.0	1628.0	1.240	1.130
	10	4	1109.0	1397.0	0.770	0.970
	11	5	1498.0	1426.0	1.040	0.990
	12	6	1656.0	1541.0	1.150	1.070
Rebar	13	1	350.0	391.0	1.156	1.289
	14	2	260.0	300.0	0.857	0.990
	15	3	253.0	377.0	0.834	1.245
	16	4	285.0	263.0	0.940	0.868
	17	5	307.0	355.0	1.012	1.173
	18	6	292.0	36.0	0.962	Error
Close	19	1	1385.0	1115.0	1.202	0.968
	20	2	1737.0	1147.0	1.508	0.996
	21	3	1033.0	1019.0	0.897	0.884
	22	4	1513.0	1275.0	1.313	1.107
	23	5	1065.0	1179.0	0.924	1.023
	24	6	1257.0	1211.0	1.091	1.051
	25	1	1385.0	1243.0	1.202	1.079
	26	2	1769.0	1051.0	1.536	0.912
	27	3	1385.0	1595.0	1.202	1.384
	28	4	1129.0	1403.0	0.980	1.218
	29	5	1129.0	1083.0	0.980	0.940
	30	6	1257.0	1307.0	1.091	1.134

Figure B.1 Forming and reinforcing observations from site one

Site 2						
	Obs	Sub #	Group 1	Group 2	PF	PF
Form	1	1	1361.0	1411.0	0.945	0.980
	2	2	1591.0	1704.0	1.105	1.183
	3	3	1404.0	1395.0	0.975	0.969
	4	4	1447.0	1665.0	1.005	1.156
	5	5	1303.0	1613.0	0.905	1.120
	6	6	1591.0	1901.0	1.105	1.320
	7	1	1735.0	1382.0	1.205	0.960
	8	2	1591.0	1354.0	1.105	0.940
	9	3	1865.0	1253.0	1.295	0.870
	10	4	1274.0	1338.0	0.885	0.929
	11	5	1562.0	1172.0	1.085	0.814
	12	6	1361.0	1210.0	0.945	0.840
Rebar	13	1	237.0	318.0	0.782	1.051
	14	2	381.0	354.0	1.256	1.167
	15	3	305.0	278.0	1.006	0.918
	16	4	292.0	344.0	0.962	1.134
	17	5	298.0	295.0	0.984	0.973
	18	6	251.0	276.0	0.829	0.912
Close	19	1	1206.0	1053.0	1.047	0.914
	20	2	1097.0	1021.0	0.952	0.887
	21	3	1140.0	1469.0	0.990	1.276
	22	4	1513.0	1149.0	1.313	0.998
	23	5	1801.0	1181.0	1.563	1.026
	24	6	1353.0	1309.0	1.174	1.137
	25	1	1097.0	1469.0	0.952	1.276
	26	2	1065.0	1309.0	0.924	1.137
	27	3	1513.0	1565.0	1.313	1.359
	28	4	1052.0	1117.0	0.913	0.970
	29	5	1127.0	1213.0	0.978	1.053
	30	6	1129.0	1117.0	0.980	0.970

Figure B.2 Forming and reinforcing observations from site two

Site 4						
	Obs	Sub #	Group 1	Group 2	PF	PF
Form	1.0	1.0	1310.0	1296.0	0.910	0.900
	2.0	2.0	1228.0	1354.0	0.853	0.940
	3.0	3.0	1165.0	1259.0	0.809	0.874
	4.0	4.0	1598.0	1392.0	1.110	0.967
	5.0	5.0	1305.0	1319.0	0.906	0.916
	6.0	6.0	1512.0	1354.0	1.050	0.940
	7.0	1.0	1685.0	1814.0	1.170	1.260
	8.0	2.0	1195.0	1323.0	0.830	0.919
	9.0	3.0	1440.0	1238.0	1.000	0.860
	10.0	4.0	1483.0	1395.0	1.030	0.969
	11.0	5.0	1267.0	1286.0	0.880	0.893
	12.0	6.0	1310.0	1282.0	0.910	0.890
Rebar	13.0	1.0	349.0	283.0	1.153	0.933
	14.0	2.0	274.0	265.0	0.903	0.875
	15.0	3.0	297.0	321.0	0.981	1.059
	16.0	4.0	321.0	232.0	1.059	0.765
	17.0	5.0	259.0	296.0	0.854	0.976
	18.0	6.0	324.0	294.0	1.070	0.969
Close	19.0	1.0	1315.0	933.0	1.141	0.810
	20.0	2.0	1033.0	741.0	0.897	0.643
	21.0	3.0	1321.0	1061.0	1.147	0.921
	22.0	4.0	1065.0	965.0	0.924	0.838
	23.0	5.0	1109.0	1413.0	0.963	1.227
	24.0	6.0	1096.0	1541.0	0.951	1.338
	25.0	1.0	1105.0	805.0	0.959	0.699
	26.0	2.0	1001.0	1189.0	0.869	1.032
	27.0	3.0	1193.0	933.0	1.036	0.810
	28.0	4.0	1257.0	1221.0	1.091	1.060
	29.0	5.0	1056.0	1061.0	0.917	0.921
	30.0	6.0	1065.0	1157.0	0.924	1.004

Figure B.3 Forming and reinforcing observations from site three

Site 5						
	Obs	Sub #	Group 1	Group 2	PF	PF
Form	1.0	1.0	1613.0	1411.0	1.120	0.980
	2.0	2.0	1354.0	1181.0	0.940	0.820
	3.0	3.0	1246.0	1395.0	0.865	0.969
	4.0	4.0	1526.0	1423.0	1.060	0.988
	5.0	5.0	1344.0	1037.0	0.933	0.720
	6.0	6.0	1555.0	1613.0	1.080	1.120
	7.0	1.0	1338.0	1498.0	0.929	1.040
	8.0	2.0	1290.0	1296.0	0.896	0.900
	9.0	3.0	1555.0	1248.0	1.080	0.867
	10.0	4.0	1302.0	1584.0	0.904	1.100
	11.0	5.0	1166.0	1296.0	0.810	0.900
	12.0	6.0	1381.0	1356.0	0.959	0.942
Rebar	13.0	1.0	258.0	275.0	0.852	0.908
	14.0	2.0	303.0	307.0	1.002	1.013
	15.0	3.0	302.0	322.0	0.997	1.063
	16.0	4.0	285.0	292.0	0.941	0.964
	17.0	5.0	327.0	268.0	1.080	0.886
	18.0	6.0	310.0	344.0	1.024	1.135
Close	19.0	1.0	1040.0	1372.0	0.903	1.191
	20.0	2.0	1117.0	924.0	0.970	0.802
	21.0	3.0	1213.0	1500.0	1.053	1.302
	22.0	4.0	1041.0	892.0	0.904	0.774
	23.0	5.0	1437.0	988.0	1.248	0.858
	24.0	6.0	1149.0	924.0	0.998	0.802
	25.0	1.0	861.0	892.0	0.748	0.774
	26.0	2.0	899.0	956.0	0.780	0.830
	27.0	3.0	1021.0	1148.0	0.887	0.997
	28.0	4.0	1076.0	1308.0	0.934	1.136
	29.0	5.0	1387.0	1276.0	1.204	1.108
	30.0	6.0	1181.0	1052.0	1.026	0.913

Figure B.4 Forming and reinforcing observations from site four