COST IMPLICATION FOR DEVELOPING PROCESS CAPABILITY DATA FOR THE CONSTRUCTION INDUSTRY USING WEB-BASED AUTOMATED DATA COLLECTION AND ANALYSIS TOOLS

A Thesis
Presented to the
Faculty of
San Diego State University

In Partial Fulfillment
of the Requirements for the Degree
Master
of
Business Administration

by
Arpit Ashok Jain
Summer 2010
SAN DIEGO STATE UNIVERSITY

The Undersigned Faculty Committee Approves the

Thesis of Arpit Ashok Jain:

Cost Implication for Developing Process Capability Data for the Construction Industry Using Web-Based Automated Data Collection and Analysis Tools

[Signatures]

Theophilus B. A. Addo, Chair
Department of Information and Decision Systems

Murray Jennex
Department of Information and Decision Systems

Colin T. Milberg
Department of Civil and Environmental Engineering

5/22/2010
Approval Date
Copyright © 2010

by

Arpit Ashok Jain

All Rights Reserved
DEDICATION

This thesis is dedicated to my parents and my lovely sister.
We should give meaning to life, not wait for life to give us meaning.

-Unknown
ABSTRACT OF THE THESIS

Cost Implication for Developing Process Capability Data for the Construction Industry Using Web-Based Automated Data Collection and Analysis Tools

by

Arpit Ashok Jain
Master of Business Administration
San Diego State University, 2010

The US concrete industry is a big market with billions of dollars in revenue every year. This study performs a cost-benefit analysis on industry collected data to find out if there is monetary benefit to the concrete contractors by implementing a new approach. The proposed approach claims to be more effective and helps reduce error rates in the industry to reduce failure costs. The study also involves development of a computer application that will automate the statistical analysis which is currently manually performed and constitutes a key part of the proposed approach. The conclusion meets the expectations and the cost benefit analysis performed reveals that the approach will reduce failure costs for the construction companies.
# TABLE OF CONTENTS

PAGE

ABSTRACT............................................................................................................................. vi
LIST OF TABLES................................................................................................................... ix
LIST OF FIGURES ................................................................................................................ x
ACKNOWLEDGEMENTS ..................................................................................................... xi
CHAPTER
1 INTRODUCTION .........................................................................................................1
   1.1 Problem Statement .............................................................................................4
   1.2 Research Objective ............................................................................................4
   1.3 Research Framework .........................................................................................5
   1.4 Research Questions ............................................................................................7
   1.5 Scope ..................................................................................................................7
   1.6 Methodology ......................................................................................................7
   1.7 Statistical Analysis Automation .........................................................................8
   1.8 Cost Benefit Implication ....................................................................................9
   1.9 Thesis Structure .................................................................................................9
2 STATISTICAL ANALYSIS APPLICATION ............................................................11
   2.1 Application Overview ......................................................................................11
   2.1.1 Purpose ....................................................................................................13
   2.1.2 Scope .......................................................................................................13
   2.2 Methodology ....................................................................................................13
   2.3 Major Functions ...............................................................................................15
   2.4 Data Definition & Collection ...........................................................................18
   2.5 Application Design & Architecture .....................................................................18
   2.6 Users ................................................................................................................20
   2.7 Resources ........................................................................................................20
   2.8 Security ............................................................................................................21
3 DATA GATHERING ..................................................................................................22
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Summary Data from Interviews</td>
<td>24</td>
</tr>
<tr>
<td>4.1</td>
<td>Summarized Results of Cost-Benefit Analysis</td>
<td>29</td>
</tr>
<tr>
<td>C.1</td>
<td>List of Questions</td>
<td>56</td>
</tr>
<tr>
<td>D.1</td>
<td>Answers for Company 1</td>
<td>59</td>
</tr>
<tr>
<td>D.2</td>
<td>Answers for Company 2</td>
<td>61</td>
</tr>
<tr>
<td>D.3</td>
<td>Answers for Company 3</td>
<td>63</td>
</tr>
<tr>
<td>D.4</td>
<td>Answers for Company 4</td>
<td>66</td>
</tr>
<tr>
<td>D.5</td>
<td>Answers for Company 5</td>
<td>68</td>
</tr>
<tr>
<td>D.6</td>
<td>Answers for Company 6</td>
<td>70</td>
</tr>
<tr>
<td>F.1</td>
<td>Statistical Analysis Cost</td>
<td>76</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 2.1. System Architecture of Application ......................................................... 12
Figure 2.2. Column with as-built points ................................................................. 16
Figure 2.3. Best fit plane for Face 1 ................................................................. 16
Figure 2.4. Intersection lines of best fit planes and center point .................... 17
Figure 2.5. Three Layer Architecture ................................................................. 19
Figure A.1. Home Page ....................................................................................... 40
Figure A.2. Registration Page ............................................................................. 41
Figure A.3. Login Page ....................................................................................... 42
Figure A.4. Data Entry Page ............................................................................... 43
Figure A.5. Upload File Page ............................................................................... 44
Figure E.1. Surveying and Uploading Cost Invoice ........................................... 74
ACKNOWLEDGEMENTS

I would like to express my gratitude to the thesis committee. I would like to thank Dr. Colin Milberg for his continuous guidance and help throughout this project, Dr. Theo Addo for his patience and support, and Dr. Murray Jennex for his understanding and cooperation. I would also like to thank all the interviewed personnel for taking out the time to share their experience and knowledge and provide valuable insights during this research. I would also like to thank Pranay Jaiswal and Jayesh Patel for their help.
CHAPTER 1

INTRODUCTION

Let’s do this: Quality has become one of the most important consumer decision factors in the selection among competing products and services. The phenomenon is widespread, regardless of whether the consumer is an individual, an industrial organization, a retail store, a bank or financial institution, or a military defense program. Consequently, understanding and improving quality are key factors leading to business success, growth, and enhanced competitiveness. Successfully employing quality as an integral part of overall business strategy can yield substantial return on investment[1]. Quality is inversely proportional to variability. Excessive variability in process performance often results in waste. Since variability can only be described in statistical terms, statistical methods play a central role in quality improvement efforts. Since 1980, there has been a profound growth in the use of statistical methods for quality and overall business improvement in the United States[1].

Process Control is one of the major statistical techniques used in quality improvement. Process Control is a statistics and engineering discipline for quality control that deals with architectures, mechanisms, and algorithms for controlling the output of a specific process to ensure it meets specification. Every process has variation. Process capability is a measure of that variation and thus the ability of a process to meet specifications[2]. Statistical Process Control uses statistical tools to observe the performance of the production process in order to predict significant deviations that may later result in rejected products[3]. These measures play a very significant role in defining how successful and efficient a company will be in the long run.

The concept of quality costs is a means to quantify the total cost of quality related efforts and deficiencies[4]. These costs can be classified as follows:

a. Costs of Control
   i. Prevention Costs: Arise from efforts to keep defects occurring at all. Examples include the following:
1. Costs Associated with the Creation of the Overall Quality Plan, the inspection plan, the reliability plan, the data system, and all specialized plans and activities of the quality-assurance function.

2. Statistical Process Control: The cost of process-control techniques, such as control charts, that monitor the process in an effort to reduce variation and build quality into the product.

3. Investment in Quality Related Information Systems: The cost of running the quality data system to acquire data on product and process performance; also the cost of analyzing these data to identify problems.

4. Quality Training and Workforce: The cost of developing, preparing, implementing, operating, and maintaining formal training programs for quality.

5. Product Design Verification: Costs incurred during the design of the product or the selection of the production processes that are intended to improve the overall quality of the product.

ii. Appraisal Costs: Arise from detecting defects via inspection, test, and audit. Examples include the following:

   1. Test and Inspection of Purchased Materials: Costs associated with the inspection and testing of purchased materials to ensure conformance of the standards that have been imposed.

   2. Product Inspection and Testing: The cost of checking the conformance of the product throughout its various stages of manufacturing, including final acceptance testing, packing, and shipping checks, and any test done at the customer’s facilities prior to the turning the product over to the customer.

   3. Quality Audits: Costs incurred in conducting a periodic audit of the quality assurance system. This could also include interplant vendors.

   4. Field Testing: The cost of operating a system that keeps the measuring instruments and equipment in calibration.

b. Costs of Failure of Control

   i. Internal Failure Costs: Arise form defects caught internally and dealt with by discarding, repairing, or accommodating the defective items. Examples include the following:

      1. Scrap: The net loss of labor, material, and overhead resulting from defective product that cannot economically be repaired or used.

      2. Rework: The cost of correcting nonconforming units so that they meet specifications

4. Special/Custom Operations: The costs incurred to determine the causes of product failures.

ii. External Failure Costs: Arise from defects that actually reach customers, such as the following:

1. Complaints in Warranty: All costs involved in service to customers under warranty.

2. Product Services: All costs of investigation and adjustment of justified complaints attributable to the nonconforming product.

3. Product Liability: Costs or awards incurred from product liability litigation.

4. Product Recall: All costs associated with receipt, handling, and replacement of the nonconforming product or material that is returned from the field.

5. Loss of Reputation: This includes loss of business reputation, loss of future business, and loss of market share that inevitably results from delivering products and services that do not conform to the customer’s expectations.

Many researchers, such as Juran[5], of this topic also believe that these costs can be subjected to other categorizations as well and one of the most renowned amongst them is categorizing them into:

- Tangible Costs
- Intangible Costs

There are two ways to increase profits. Increase sales and/or reduce costs[6]. It has been demonstrated in studies by several capital goods manufacturers that sales to new customers cost as much as 20 times more than sales to existing customers[6]. World Class organizations compete in essentially five areas: Price, Delivery, Features, Quality and Customer Service[6]. It would then stand to reason that a customer, who is satisfied, better yet enthusiastic about your product, will not only continue to buy from you in the future but will recommend your product to others. Quality is the key to long term customer satisfaction, e.g. increased sales. Quality is also one of the keys to reduced cost[6].

Reduced process variation is why Statistical Process Control (SPC) is such a powerful tool to lower costs and enhance customer satisfaction. Process variation creates a ripple effect that disrupts the synchronous manufacturing flow. An example of this is the situation where a part fails and must be scrapped. The extra cost associated with this failure is a significant expense. First, the defective part must be disposed of. There is the cost of the original raw
material, the labor applied so far, and the cost of disposal[6]. Next, are the costs associated with replacing the scrapped part. A replacement order may be required, additional raw material may have to be ordered or at the very least more used from inventory. The part, now late, must be expedited through to catch up with the higher level assembly. Finally, if the part cannot be replaced fast enough there is the cost of a delayed shipment because the part was not available. When you add up all the costs, internal failure takes a large chunk out of your profit. SPC helps you reduce variation and this reduces costs[6].

1.1 PROBLEM STATEMENT

In construction, the quality of the built components, for example a beam or a column or a wall, is inspected and accepted or rejected depending on how well they meet specifications. However, application of Statistical Process Control to observe and control the process to predict deviations is not possible in the construction industry[7]. First because construction uses mostly human processes and thus variation in the process is very difficult to control. Also, variation isn’t currently measured; instead it is estimated by people and experts in the field. The experts are constructors who get a sense for consistency, flatness, alignment and other parameters by building it. Based on their experience and context they would decide upon the quality of the constructed element. In construction, with neither a clear quality standard nor process variation data as a bench mark, application of statistical process control is not possible.

In addition, another drawback for the construction industry is the enormous potential loss associated with quality failure. First, the size of many projects is massive and often schedule critical, so even a small mistake can lead to a significant loss. Using manufacturing as an analogy, construction is a production system set up to produce a single product. So interruptions in the synchronous flow of activities can impact the delivery of the entire project. And since it is not possible to predict the variation that is inherent in the process it becomes difficult to control failure and the costs associated with it.

1.2 RESEARCH OBJECTIVE

A solution to the problems described above has been proposed by Milberg[8], for the construction industry, to prevent quality failures. This solution proposes that, the variation in the process can be quantified by gathering data and performing relevant statistical analysis,
such as finding the deviation from a best fit plane, expected location, and distances between opposite faces. Once the variation is quantified changes can be made to the current processes or more robust designs can be created to accommodate the inherent variation and hopefully eliminate failures. The objective of this thesis is to investigate the cost benefits associated with the solution proposed by Milberg.

To implement the proposed approach by Milberg a two-fold limitation is encountered which gives the base for our problem statement. First, the solution to large failure costs on the construction sites proposed by Milberg requires process capability data. The aim is to have separate utilities that will facilitate the collection of that data and automating the statistical analysis and storing the results in a database. Currently, there are utilities to perform the statistical analysis but a lot of manual effort is required to get the results. The application that is developed will reduce the amount of manual effort required drastically.

Next, the cost benefits of the proposed approach needs to be quantified to figure out whether or not implementing the new approach will bring any monetary benefits to the construction companies or will the companies be better off following the current process they follow. A comparison between the failure costs and the preventive costs and quantification of the comparison will be required in order to confirm whether the proposed solution is viable.

1.3 RESEARCH FRAMEWORK

Good control systems make economic sense. The importance of control systems is often given by the 1:10:100 Rule which states that: “If a defect or service error is identified and corrected at the design stage, it might cost $1 to fix. If it is first detected during the production process, it might cost $10 to fix. However, if the defect is not discovered until it reaches the customer, it might cost $100 to correct”[9].

We usually think of a high-quality product as one that exactly meets the requirements placed on it. For example, how well does the hood fit on a new car? Is it perfectly flush with the fender height, and is the gap exactly the same on all the sides? Manufactured parts that do not exactly meet the designer’s requirements can cause significant quality problems when they are used as the components of a more complex assembly. An automobile consists of several thousand parts. If each one is just slightly too big or too small, many of the components will not fit together properly, and the vehicle or its major subsystems may not
perform as the designer intended[1]. So, in addition to costs incurred in preventing the problem to occur again there are additional losses, which could be substantial, to make non-conforming parts work in the assembly.

The basic idea is that there is a cost associated with implementing preventive measures. Then there is the correction cost for products that do not meet specifications. And there is a cost associated with failure. The cost for implementing preventive measures is less than the correction cost which is less than the failure cost.

The cost-benefit analysis is a method of analyzing projects for investment purposes. The method has three steps and it proceeds as follows[10]:

1. Identify the financial value of expected project cost and benefit variables.
2. Analyze the relationship between expected costs and benefits using simple or sophisticated selection techniques
3. Make the investment decision

Cost benefit analysis is a very standard approach which is used by people in almost every field to quantify the benefits or losses associated with a project, or in making a decision. A cost benefit analysis finds, quantifies, and adds all the positive factors. These are the benefits. Then it identifies, quantifies, and subtracts all the negatives, the costs. The difference between the two indicates whether the planned action is advisable. The real trick to doing a cost benefit analysis well is making sure you include all the costs and all the benefits and properly quantify them[11].

To aid in implementing the solution and to reduce the implementation costs, a computer application will be developed that will automate relevant statistical analysis of the geometric variation data of elements within a structure; the results obtained will give an idea of the deviation in the current process. Based on the results, inherent variation in the current process can be quantified and predicted for future. So now changes can be made to the current processes and designs to accommodate the predicted variation and conform to the specifications. Therefore, following the theory that preventive costs are less than failure costs, implementing a preventive measure might be able to potentially avoid high failure costs later.

After automating the statistical analysis the next step is to see whether using the approach recommended by Milberg will bring any cost benefits to the construction companies or not. This will involve a cost benefit analysis and comparison of the preventive
cost with the risk adjusted failure cost. Only after this comparison can it be deduced whether implementing the preventive measure has a net benefit and whether it is significant enough for people to invest in collecting process capability data.

1.4 RESEARCH QUESTIONS

This thesis will answer the following questions:

1. Can the performance be improved and cost be reduced using process capability data?
2. What will be the costs associated with implementing the new approach?
3. What extra resources time and effort will the new solution require?
4. What are the current failure costs incurred?
5. Will the approach be helpful in developing more robust designs that accommodate inherent variation?
6. Will the approach be beneficial to the construction companies in the near or far future?
7. Apart from any monetary benefits will the approach improve the long term quality goals and customer satisfaction?

The thesis seeks answers to all these questions and a discussion based on the findings will try answering them and making appropriate recommendations.

1.5 SCOPE

The cost benefit analysis will be limited to data gathered on Cast-In-Place concrete elements, such as columns, walls, beams, and the installation of items interfacing with it.

1.6 METHODOLOGY

To understand the actual costs incurred in a failure and the costs to implement the proposed measures, personnel from the construction industry will be interviewed. The costs of implementing the new measure come from the costs of control discussed in the introduction and include both prevention and appraisal costs. Once the costs are identified, comparison between the cost of failure and the cost of implementing the new measure can be performed. But, it should be noted that these costs cannot be directly compared. The probabilistic cost of failure must also be considered with the failure cost to make a fair comparison. Without previous experience on costs for a particular material or activity, a variety of cost estimates may be used. The simplest method is to take each variable characterized by uncertainty in cost and determine what types of assumptions would affect
costs. Then use the different assumptions to ascertain the range of costs that are possible[12]. Since failure is always uncertain, a probability of failure costs needs to be associated to make the comparison relevant.

So for example, if the cost of a project is $C_p$ and the probability of failure is $P_r$, then the cost of failure would be $C_f = C_p * P_r$

On the other hand, the cost of implementing the proposed solution will comprise of a number of costs such as cost of gathering/surveying the data $C_s$, cost of additional equipment, if any, for surveying $C_e$, cost of uploading the data to the database $C_u$, cost of making changes to the design $C_d$. So, the total cost of implementing the proposed solution, $C_{ps}$, would be equal to the summation of all these individual costs. This implies that

$$C_{ps} = C_s + C_e + C_u + C_d$$

Once we have both the costs, cost of failure and cost of the proposed solution, we can simply subtract $C_{ps}$ from $C_f$ and if the result is significantly greater than zero we can conclude that the proposed solution will have monetary benefits for the concrete construction companies else we can say that they are better off using the current practice.

To perform the statistical analysis, there is already a web interface to upload geometric variation data of the built concrete elements such as columns, walls, beams, and slabs. An application will be developed to perform all the statistical operations on the gathered data and store the results as process capabilities back to the database. These results can further be used to deduce what changes or modifications need to be made to the current processes and designs to accommodate the inherent variation.

1.7 Statistical Analysis Automation

To perform statistical analysis, which is an integral part of the project, on the geometric variation data collected from the companies, a computer application is developed which will automate all the operations and store the results in the database. This application would require minimal maintenance and assistance.

The automation is critical as any recommendations for change and thus the costs associated with them depend on the results that are produced from the statistical analysis performed by this application. The application role and structure is fairly simple and Chapter 2 is completely dedicated to provide insights on all fronts of the application.
1.8 Cost Benefit Implication

The question still remains; can this approach reduce costs or save time for the construction companies? To answer this question a cost benefit analysis will be performed to figure out whether the proposed solution will actually be helpful or not for the parties involved. To perform this cost benefit analysis, as mentioned earlier, a comparison will be made between the current cost, probabilistic cost of failure, and the suggested cost, cost of implementing the solution. Why do we take the probabilistic cost of failure? The reason is simple. First, the cost of failure is different for different types of failure. For minor failures the cost is less and for major failures the cost is more. So, average cost of failure needs to be considered. Next, a project can have 10 or 100 or even more instances of failure such as the components not meeting the specifications, whereas another project may have much less or even zero failures. This means that failure for every new project is uncertain. But if the failure for an upcoming project needs to be predicted then the failure rate over time is considered, where the failure rate is nothing but the probability of occurrence of failure. Because of these two reasons, the risk adjusted cost of failure needs to be accounted for which would be the probability of failure times the average cost of failure. Comparing the risk adjusted cost of failure with the cost of implementing a new measure will provide a far better comparison.

In addition, this approach will help upgrade the quality standards of companies in the long run. We suspect that with the implementation of this approach will come greater awareness to variation and thus a reduction in variation. As variation is decreased and as robust designs are created, the failure rate will go down, which will in turn reduce the total construction time and will result in more satisfied customers. The reduction in construction time means more business opportunities for contractors and more productivity, and satisfied customers means lower marketing costs and again more business opportunities. Finally, anything that helps reduce variability and stabilizes the overall construction process only helps to improve productivity [13].

1.9 Thesis Structure

Chapter 2 of the thesis provides in depth information about the statistical analysis application that was developed by the author as part of the thesis. The information is mostly
from a technical standpoint. Chapter 3 discusses the methodology used in gathering the cost benefit data. It throws light on the way the data is quantified and used for analysis purposes. Chapter 4 will present the results of the analyzed data and how the results were achieved. Chapter 5 will present a conclusion to the study performed, the limitations, and areas of future research and issues that the study may have raised.
CHAPTER 2

STATISTICAL ANALYSIS APPLICATION

To reduce the time and effort required in gathering the geometrical variation data pertaining to various concrete elements such as columns, beams, walls, and floors, an online website has been developed. The website requires the user to create an account and lets them upload the data. The uploaded data is stored on a database server. The application that is developed to automate the statistical analysis uses this data, performs the analysis and stores the results back in the database. The website was already developed and the development of the application that automated the statistical analysis is part of the thesis. In this chapter, we focus on the details of the application and present details about the website.

2.1 APPLICATION OVERVIEW

The application is developed in C# on the .NET platform. It is hosted on a machine located in the laboratory of the Construction Engineering and Management Department of San Diego State University. The reason for choosing .NET platform is that there is a high possibility of using the application in an online environment and .NET will serve that purpose efficiently and without too much difficulty. The application was required to perform a lot of mathematical calculations and .NET provides built-in libraries with a vast range of functions that can be easily performed[14]. Also, the current database used to store the uploaded data is MySQL, and .NET provides built-in libraries for establishing a connection with MySQL database as well as performs other important functions. Looking at the overall scenario .NET looked the most suitable platform for the application and thus was used.

Currently, the application is used as a desktop application and there is no authorization check performed before anyone uses the application. The application is hosted on a terminal situated in the Construction Engineering and Management department of San Diego State University where only authorized personnel can enter. However, in future, if the application goes online, then additional code will need to be written to perform the
authorization. The database server is stored in the Electrical Engineering department of San Diego State University. Figure 2.1 is a pictorial view of the overall system.

![System Architecture Diagram]

**Figure 2.1. System Architecture of Application.**

As can be seen, the user will interact with the system with the help of user interface, which is the website (Refer to Figure A.1, Appendix A). The user then has to register into the system (Refer to Figure A.2, Appendix A). After registering, the user can log in to the system (Refer to Figure A.3, Appendix A) to upload the data. The data needs to be in a particular format which is pre-decided and can be directly entered through the website (Refer to Figure A.4, Appendix A) or can be uploaded through an Excel sheet (Refer to Figure A.5, Appendix A). Details about what data is uploaded and how it is collected are discussed later in the chapter. Once the data is uploaded and verified for the format it is then stored in the central database. Now, when an analyst wants to perform the statistical analysis on the stored data he accesses the statistical analysis application. After accessing the application the analyst commands the application to perform the analysis. The application retrieves the required data from the central database, performs the operations, and stores the results back to the database. And the analyst is informed if the operations were successful or not. Once the results are stored the web application can use the results to display it on the user interface if the user demands.

From the user’s perspective, the application serves as a Decision Support System (DSS). A DSS is a class of information systems (including but not limited to computerized
A properly designed DSS is an interactive software-based system intended to help decision makers compile useful information from a combination of raw data, documents, personal knowledge, or business models to identify and solve problems and make decisions[15]. In our case, the results calculated by the application provide the users or designers with the critical information needed to make a more robust design that accommodates the inherent variation.

2.1.1 Purpose

The core purpose of the application is to automate the statistical analysis and store the results back to the database. The results can then be used to predict the inherent variation in the current process and help provide any necessary corrections.

2.1.2 Scope

The statistical analysis is performed only on geometric variation data of four faces of elements, such as columns and beams. The results are stored back into the database. No recommendations or trends based on the results are identified. However, the user will be able to query the results which will be plotted in a histogram to identify properties and trends in surface and element variations across multiple elements of a given type such as columns or beams.

2.2 METHODOLOGY

A software development methodology refers to the framework that is used to structure, plan, and control the process of developing an information system[16]. A wide variety of such frameworks have evolved over the years, each with its own recognized strengths and weaknesses. One system development methodology is not necessarily suitable for use by all projects. Each of the available methodologies is best suited to specific kinds of projects, based on various technical, organizational, project and team considerations. Some of the common methodologies are: Systems Development Life Cycle (SDLC), Rapid Application Development life cycle (RAD), and Agile development[16].

The Systems Development Life Cycle(SDLC) method for building information systems as stipulated by Widjaja[16], is the following:

- Problem Definition
• Project Initiation and Planning
• Systems Analysis
• Systems Design
• Physical Design
• Construction
• Testing
• Implementation
• Maintenance

This is a very robust and stable method. It provides a disciplined approach, and has one very important focus: it tracks requirements over the life of the system[16].

Another method suited for building an information system with heavy user interfaces but less heavy processing is Rapid Application Development life cycle[16]. This method covers the following steps:
• Requirements Planning
• Implementation with Graphical Language
• User Evaluation or Requirements Refinement
• Final Testing
• Cutover to a Final Platform
• Final Implementation

Meanwhile, Agile methods generally promote a project management process that encourages frequent inspection and adaptation, a leadership philosophy that encourages teamwork, self-organization and accountability, a set of engineering best practices that allow for rapid delivery of high-quality software, and a business approach that aligns development with customer needs and company goals[16]. This method provides the developer with opportunities to respond to the unpredictability of building the system throughout the development lifecycle. It has the ability to adapt quickly to requirements changes. Agile methodology has small development teams, and they do not emphasize written documents[16].

The proposed system in this thesis is a small project whose main user would be the statistical analyst. Currently, the author serves as the system developer, and also performs the role of the analyst. His immediate supervisor, Dr. Milberg, provided the details about how
the statistical analysis needs to be performed by the system and what steps need to be followed. The author/developer thus would have the privilege and knowledge to determine and/or change the requirements needed by the system throughout the development lifecycle, and would use very little formal process. For these reasons, Agile method was chosen for development.

2.3 MAJOR FUNCTIONS

To automate the statistical analysis the application performs a series of steps. The key major functions include the following:

a. Fetching/Retrieving Data: The application establishes a connection with the database in order to retrieve the data it needs to perform the operations. There is only a single layer of the application that interacts with the database which is known as the connection layer. The architecture of the application will be explained later in the chapter.

b. Statistical Operations: These operations and/or calculations are the core part of the application. Certain mathematical functions are performed on the input data to convert them to standard geometrical variation data definitions. The key functions are:

   i. All the points, part of the input data, undergo a transformation from the survey coordinate system typically based on northing and easting coordinates to a design coordinate system based on the column grids. This makes it easier to compare the actual surface orientation to the design. For example, Figure 2.2 shows a column. The random points on face 1 and face 2 of the column are converted from the project coordinate system to the design coordinate system in order to make the calculations easy and comparable to the design surface.

   ii. Linear regression is performed on the transformed points to find a best fit plane. This regression produces regression coefficients defining the equation of the best fit plane, the centroid of the points, and the variance of the points relative to the best fit plane. The variance of the points represents a measure of form variation in the actual surface. For example Figure 2.3 shows the best fit plane for Face 1 of the column which is found by performing linear regression of the transformed points on face 1. The residuals of the regression, the square root of the sum of squares of the perpendicular distances of the points to the best fit plane, i.e., the standard deviation of the distance of the points to the best fit plane, is the measure used for form variation.

   iii. The surface normals are calculated from the best fit plane equations. Variation in the normal from the design normal represents a measure of orientation variation in the actual surface. The vector component of the unit normal vector of the best fit plane are measures of the different directions of
orientation variation, including plumbness and plan rotation. Figure 2.3 shows the surface normal for face 1 and face 2 of the column. The two arrows show the direction of the unit normal vector for the respective faces 1 and 2 of the column.
iv. Once the best fit planes for all four faces of the column are determined, the equations are used to find the intersection of the best fit planes defining the edges of the column. These edges are used to find the centerline and center point of each plane. The centerline or center point based on best fit plane intersections is compared to the design centerline or center point of the plane representing a measure of location variation. For example, Figure 2.4 shows the intersection lines of best fit planes, the center line of the intersection lines, as well as the center point of the plane.

![Figure 2.4. Intersection lines of best fit planes and center point.](image)

v. Once we have the best fit planes we can then find the minimum and maximum distance between opposing faces with the set of points we have by simply calculating the perpendicular distance of every point on one plane to the opposing best-fit plane. These steps constitute the major statistical operations that are performed by the application.

c. Storing Results back to Database: The final function of the application is to store the results calculated from the statistical operations back to the database. Again, the connection layer performs this function and closes the connection with the database after storing the results.
2.4 DATA DEFINITION & COLLECTION

The application accepts actual multiple location data points on each surface of the element as inputs. The data is collected by the construction companies by measuring the geometric coordinates of random points on the as built surface, for example: the geometric coordinates of random points on the surface of a column. The coordinates of these points are then entered into an Excel sheet and corresponding coordinates of design points are also entered. The Excel sheet is then uploaded to a database through a website. Apart from the Excel sheet, the points can also be uploaded via a comma delimited text file, .CSV file, in a specific format explained to the users.

The data is stored in the database on the server. The application will then perform mathematical functions, including coordinate system transformation, linear regression, sum of least squares, calculation of surface normals, centroids, variance, equation of best fit plane, equation of line of intersection between two planes and distance between as built points and design points[Refer to Appendix B], on the input data as part of the analysis.

2.5 APPLICATION DESIGN & ARCHITECTURE

Object-oriented design is the process of planning a system of interacting objects for the purpose of solving a software problem[17]. It is one approach to software design. An object contains encapsulated data and procedures grouped together to represent an entity. The 'object interface', how the object can be interacted with, is also defined. An object-oriented program is described by the interaction of these objects. Object-oriented design is the discipline of defining the objects and their interactions to solve a problem that was identified and documented during object-oriented analysis[17].

From a business perspective, Object Oriented Design refers to the objects that make up that business. For example, in a certain company, a business object can consist of people, data files and database tables, artifacts, equipment, vehicles, etc. The application follows an object oriented design. Each concrete element, such as a wall, column, roof, and floor, is considered as an object and the geometric variation data as the attributes. All the statistical and mathematical operations, including coordinate transformation, linear regression, and finding equation for best fit plane, that need to be performed are scripted as the procedures for the respective objects[17].
The three layer architecture is a very common architecture in software applications and is fairly simple too. Each layer has a specific role and a change can be made to any specific layer without interfering with the other layers. The three layers are: Presentation Layer, Application Layer, and Data Layer. Figure 2.5 provides a pictorial view of the same.

![Three Layer Architecture Diagram](image)

**Figure 2.5. Three Layer Architecture.**

A persistent object is an object that continues to exist and retains its data beyond the duration of the process that creates it[18]. It is different from a business object in the sense that a business object is instantiated whenever it is required during processing. Once the processing on a business object is performed it is released by the system. A persistent object, on the other hand, will exist and will be used until the application is terminated or the user session is stopped.

**Presentation layer:** This is the topmost level of the application. The presentation layer displays information related to such services as browsing merchandise, purchasing, and
shopping cart contents. The main function of this layer is to translate tasks and results to something the user can understand.

**Application layer (Business Logic/Logic Layer/Middle layer):** The logic layer is pulled out from the presentation layer and, as its own layer, it controls an application’s functionality by processing commands, making logical decisions and evaluations, and performing calculations. It also moves and processes data between the two surrounding layers.

**Data layer:** This layer consists of Database Servers. Here information is stored and retrieved. This layer keeps data neutral and independent from application servers or business logic. Giving data its own layer also improves scalability and performance[19].

The application follows a similar architecture. The user interacts only with the presentation layer of the application. The logic for performing the operations and processing of results constitute the business layer of the application. The data layer is the part from where all the data is retrieved and stored back.

**2.6 Users**

There are two types of users who would be using the system: one type includes the construction companies, engineers, designers, architects, owners, material manufacturers and contractors who use the user interface provided by the web application. The other type includes the analysts who use the analyst interface provided by the statistical analysis application.

**2.7 Resources**

The human resources required for this project include only a single software developer who had the understanding of the tools and languages used. Software resources required included MySQL instance for the database and .NET framework for the application. Both servers were required to meet the standard Operating System need, which is Windows Server 2003. There were no other software requirements. Hardware requirements included a data server to store the data and an application server to host the application.
2.8 Security

Both the data server and application server are placed in different locations. The servers require users to log in before they can use them, which ensures that only authorized users are able to access the servers. Firewalls and antivirus software are installed and updated in a timely manner. The rooms in which the servers are placed are locked and again only authorized personnel can enter the room and access the servers.
CHAPTER 3

DATA GATHERING

To perform the cost benefit analysis, data from the concrete industry was required. The data here refers to cost numbers associated with failures and those associated with implementing the proposed approach. The data was gathered by interviewing personnel from the concrete construction industry. The personnel were selected from the following sources:

1. **American Concrete Institute (ACI)**
   “The American Concrete Institute (ACI) is a nonprofit technical and educational society organized in 1904 and is one of the world's leading authorities on concrete technology. ACI is a forum for the discussion of all matters related to concrete and the development of solutions to problems. ACI conducts this forum through conventions and meetings; the ACI Structural Journal, the ACI Materials Journal, Concrete International, and technical publications; chapter activities; and technical committee work.” [20]

2. **The BlueBook of Building and Construction**
   “Since 1913, The Blue Book of Building and Construction has been the construction industry's premier information source. The Blue Book, headquartered in Westchester County, New York, publishes regional construction directories in most major markets throughout the United States. Online, thebluebook.com provides easy access to continually updated information for each of The Blue Book's regional editions. Construction buyers and sellers also have free access to BB-Bid, The Blue Book's online bid management system, complete with a private secure online plan room and integrated takeoff and markup tools.”[21]

Using these two sources personnel were contacted directly and were asked to provide their insights on the topic. Then a list of questions (Refer to Appendix C) was sent to each person. After they filled in the answers an interview was conducted with each person. Some interviews were telephonic and some were in person. In general, the construction industry views the measures taken for dealing with tolerance incompatibility between components as part of normal work and not failure. Conducting interviews allowed the interviewer to give multiple examples to describe the proposed approach and perspective helping ensure the interviewees understood the proposed approach and answered the questions based on that understanding. Additionally, the interview gave the interviewer a chance to make sure the
answers given (Refer to Appendix D) were interpreted correctly and any doubts were addressed.

3.1 RELEVANT DATA SELECTION

For the cost benefit analysis only costs related to failure, gathering and uploading data, making changes to design, and labor are considered. Other answers from the interviews help to understand the effectiveness of the approach but are not considered in the cost benefit analysis. Those answers are discussed in Chapter 4 to further understand the usefulness of the proposed approach.

3.2 PRESENTATION OF RAW DATA

The interviews helped to get both quantitative and qualitative information. But, for the cost benefit analysis only the quantitative data is considered. Table 3.1 summarizes the quantitative data obtained from six industry sources which are used to perform the cost benefit analysis.

It should be noted that all the costs are with respect to the average total project construction cost. The costs that were taken in percentage terms are based on the assumption that average total project cost is considered 100 percent.
### Table 3.1. Summary Data from Interviews

<table>
<thead>
<tr>
<th></th>
<th>Avg. Cost of Project</th>
<th>Failure Cost/ Failure Rate</th>
<th>Cost of Gathering Data</th>
<th>Cost of Equipment</th>
<th>Cost of Uploading Data</th>
<th>Cost of Design Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$10 M</td>
<td>$100K-$150K</td>
<td>$5K-$10K</td>
<td>NA</td>
<td>NA</td>
<td>$20K</td>
</tr>
<tr>
<td>2</td>
<td>$10 M</td>
<td>.5-1 % of total project cost</td>
<td>.4-.5% of total project cost</td>
<td>$30K</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>3</td>
<td>$50 M</td>
<td>$100K-$300K</td>
<td>$50K</td>
<td>$10K</td>
<td>$5K</td>
<td>NA</td>
</tr>
<tr>
<td>4</td>
<td>$5 M</td>
<td>.5-1% of total project cost</td>
<td>$10K-$15K</td>
<td>NA</td>
<td>$2K</td>
<td>NA</td>
</tr>
<tr>
<td>5</td>
<td>$2.5 M</td>
<td>.5-1 % of total project cost</td>
<td>$2K</td>
<td>$2K</td>
<td>$1K</td>
<td>NA</td>
</tr>
<tr>
<td>6</td>
<td>$15 M</td>
<td>1% of total project cost</td>
<td>$5K</td>
<td>$10K</td>
<td>$2K</td>
<td>NA</td>
</tr>
</tbody>
</table>
CHAPTER 4

COST BENEFIT AND EFFECTIVENESS CONSIDERATIONS

Cost- Benefit Analysis estimates and totals up the equivalent monetary value of the benefits and costs to the community of projects to establish whether they are worthwhile[22]. These projects may be dams and highways or can be training programs and health care systems. The analysis aids in making a decision whether to accept a project or not. This chapter discusses the cost benefit analysis structure, the data that will be used in the analysis, and provides insights about the data.

4.1 MODELING STRUCTURE

Cost benefit analysis refers to the evaluation of alternatives according to a comparison of both their costs and benefits when each is measured in monetary terms. Since each alternative is assessed in terms of its monetary values of its benefits, each alternative can be examined on its own merits to see if it is worthwhile[12].

In order to reach a conclusion as to the desirability of a project all aspects of the project, positive and negative, must be expressed in terms of a common unit; i.e., there must be a "bottom line." The most convenient common unit is money. This means that all benefits and costs of a project should be measured in terms of their equivalent money value. A program may provide benefits which are not directly expressed in terms of dollars but there is some amount of money the recipients of the benefits would consider just as good as the project's benefits.

Not only do the benefits and costs of a project have to be expressed in terms of equivalent money value, but they have to be expressed in terms of dollars of a particular time. This is not just due to the differences in the value of dollars at different times because of inflation. A dollar available five years from now is not as good as a dollar available now. This is because a dollar available now can be invested and earn interest for five years and would be worth more than a dollar in five years. If the interest rate is \( r \) then a dollar invested
for t years will grow to be \((1+r)^t\). Therefore the amount of money that would have to be deposited now so that it would grow to be one dollar \(t\) years in the future is \((1+r)^{-t}\). This is called the discounted value or present value of a dollar available ‘\(t\)’ years in the future.

When the dollar value of benefits at some time in the future is multiplied by the discounted value of one dollar at that time in the future the result is discounted present value of that benefit of the project. The same thing applies to costs. The net benefit of the projects is just the sum of the present value of the benefits less the present value of the costs[22].

Cost effectiveness analysis refers to the evaluation of alternatives according to both their costs and their effects with regard to producing some outcome or set of outcomes[12]. Both the cost and effectiveness aspects are important and therefore should be integrated. Just as evaluators often consider only the effects of a particular alternative or intervention, administrators sometimes consider only the costs. In both cases, the evaluation will be incomplete. Costs in combination with measures of effectiveness criterion, are the ingredients for a cost effectiveness analysis. For example, consider two software applications which perform the same task for an organization and cost the same. One application is more user friendly, has a better interface, and provides self guidance to the users about how to use the application. Even though the cost is same, clearly the application which is easier to use will be more effective as the users will not waste time in understanding how to use the application and will enjoy working with an application with a good interface. This effect cannot be quantified in dollar value but it definitely adds to the value of the process.

Similarly, the cost effectiveness analysis here tries to capture the benefits which cannot be quantified in dollar terms. It seeks additional positives such as making the process less stressful, contributing to the value of one solution over another, and trying to establish a standard.

In the following sections of this chapter, a cost benefit analysis is performed on the gathered data following the above described cost benefit analysis approach and then the effectiveness of the proposed solution based on the gathered data is discussed.

As mentioned earlier, the cost benefit analysis compares the current cost and the proposed cost. The current cost includes failure costs. Failure cost is very difficult to quantify as the number and magnitude of failures in a project are uncertain. This study assumes that failure costs are proportional to overall constructional costs. Furthermore, the study expresses
failure cost as a percentage of the total construction cost of a project to allow cross case comparison.

The different components of the proposed approach to cost-benefit analysis include:

- cost of gathering/surveying the data,
- cost of additional equipment, if any, for surveying,
- cost of uploading the data to the database,
- cost of making changes to the design.

The summation of the above individual costs is thus the total cost of implementing the proposed solution of gathering process capability data and designing systems that accommodate the construction process geometric variation. The interviewed professionals were hesitant in providing details about the cost numbers. But, one of the interviewed professional provided the actual cost numbers for surveying process capability data (Refer to Appendix E). The details show that the cost for gathering data for 25-30 columns is around $34,988.86. This cost includes surveying and uploading the data. This means that the cost of surveying and uploading data for one column is around $1,166.67. This figure can be used as an average for future research purposes.

This chapter performs the cost benefit analysis based on the modeling structure described earlier. The analysis helps in understanding whether the proposed approach is monetarily beneficial to the construction companies or not. The effectiveness of the proposed approach is also discussed to understand the overall effect.

4.2 DATA ANALYSIS

The costs described in Chapter 3 provide the following equation for the cost of the proposed solution, \( C_{ps} \):

\[
C_{ps} = C_s + C_e + C_u + C_d
\]

Where,

\( C_s \) = Cost of surveying data
\( C_e \) = Cost of additional equipment
\( C_u \) = Cost of uploading data to central database
\( C_d \) = Cost of making design changes

**For Case 1:**

\[
C_{ps} = C_s + C_e + C_u + C_d
\]
\[ C_{ps} = 10K + 0 + 0 + 20K \]
\[ C_{ps} = 30K \]

The cost of failure, \( C_{pf} \), for Case 1:
\[ C_f = 100K; \]

The difference
\[ C_f - C_{ps} = 100K - 30K = 70K \]

For Case 2:
\[ C_{ps} = C_s + C_e + C_u + C_d \]
\[ C_{ps} = 50K + 10K + 5K + 0 \]
\[ C_{ps} = 65K \]

The cost of failure, \( C_{pf} \), for Case 2:
\[ C_f = 50K \]

The difference:
\[ C_f - C_{ps} = 50K - 65K = -15K \]

For Case 3:
\[ C_{ps} = C_s + C_e + C_u + C_d \]
\[ C_{ps} = 50K + 10K + 5K + 0 \]
\[ C_{ps} = 65K \]

The cost of failure, \( C_{pf} \), for Case 3:
\[ C_f = 100K \]

The difference:
\[ C_f - C_{ps} = 100K - 65K = 35K \]

For Case 4:
\[ C_{ps} = C_s + C_e + C_u + C_d \]
\[ C_{ps} = 15K + 0 + 2K + 0 \]
\[ C_{ps} = 17K \]

The cost of failure, \( C_{pf} \), for Case 4:
\[ C_f = 25K \]

The difference:
\[ C_f - C_{ps} = 25K - 17K = 8K \]

For Case 5:
C_{ps} = C_{s} + C_{e} + C_{u} + C_{d}

C_{ps} = $2K + $2K + $2K + 0

C_{ps} = $6K

The cost of failure, C_{pf}, for Case 5:

C_{f} = $12.5K

The difference:

C_{f} - C_{ps} = $12.5K - $6K = $6.5K

For Case 6:

C_{ps} = C_{s} + C_{e} + C_{u} + C_{d}

C_{ps} = $5K + $10K + $2K + 0

C_{ps} = $17K

The cost of failure, C_{pf}, for Case 6:

C_{f} = $75K

The difference:

C_{f} - C_{ps} = $75K - $17K = $57K

Table 4.1 presents the summarized results of all the cases

<table>
<thead>
<tr>
<th>Company Number</th>
<th>Avg. Project Cost</th>
<th>C_{f} - C_{ps}</th>
<th>%age Savings with respect to avg. project cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$10 M</td>
<td>$70K</td>
<td>.70%</td>
</tr>
<tr>
<td>2</td>
<td>$10 M</td>
<td>- $15K</td>
<td>-.15%</td>
</tr>
<tr>
<td>3</td>
<td>$50 M</td>
<td>$35K</td>
<td>.05%</td>
</tr>
<tr>
<td>4</td>
<td>$5 M</td>
<td>$8K</td>
<td>.16%</td>
</tr>
<tr>
<td>5</td>
<td>$2.5 M</td>
<td>$6.5K</td>
<td>.24%</td>
</tr>
<tr>
<td>6</td>
<td>$15 M</td>
<td>$57K</td>
<td>.38%</td>
</tr>
<tr>
<td>Average</td>
<td>$15.4 M</td>
<td>$27K</td>
<td>.23%</td>
</tr>
</tbody>
</table>
4.3 RESULTS & IMPLICATIONS

From Table 4.1, it can be seen that the proposed solution has monetary benefit in five of the six cases, which indicates that the approach would be beneficial for the construction industry. However, the monetary benefit is very small, between .05 % - .70 % only. This indicates that even though the proposed solution will have monetary benefits it will not be significant. This is not surprising as only the concrete contractors were interviewed and thus only the failure costs associated with their work was considered. It is quite possible that additional failure costs are incurred by other trades who interface with the concrete structure. In addition, those interviewed only considered the internal failure costs discussed in Chapter 1 and none of the external failure costs.

After conducting the interviews, it became clear that failure cost contains two components, a fixed cost component and a variable cost component. To bid for a project, historical costs are considered. A construction company looks at the cost of a similar project that they built in the past and based on those costs they bid for a current project. The cost of failure in the previous project, which was not part of the bid cost, is now accounted for in the bid cost of the current project. This is the fixed component of failure cost. Now, if there are any additional failures, repairs or rework, that cost is the variable component of the total failure cost. It was difficult for the interviewed personnel to quantify the fixed cost component of the failure cost, but they agreed to the fact that it is indirectly and already included in the current bid cost of the project. Thus, the failure cost identified consists only of the variable part, meaning the failure cost is undervalued. Also, the interviewed personnel were not able to provide an exact amount for the failure cost. They provided a range as the severity of failure in each case is very uncertain. The calculations performed to obtain the results consider, for all the cases, the lower limit of the range for failure costs. On the other hand, the calculation considers the upper limit of any control cost where a range is provided and if the value includes part of the proposed solution cost. In addition, some of the costs, such as cost of equipment and cost of making design changes are one time fixed costs. These costs will be incurred once until the equipment goes bad or new designers are required. This makes the overall calculation process very conservative from the perspective of implementing the proposed solution. The conservative approach was chosen because it is
difficult to quantify the cost based on factual data and thus difficult to justify choosing a high failure cost or a low proposed solution cost.

Even after following a conservative approach, the results still show a monetary benefit in most of the cases. If the costs can be correctly quantified then the probability is high for obtaining a significant monetary benefit for the construction companies by implementing the proposed approach by Milberg. Also, even though the percentage savings with respect to total project cost is low, project costs can be large making even a small percentage saving a significant monetary benefit.

4.4 Cost Effectiveness

The cost benefit analysis reveals a monetary benefit for the construction companies in implementing Milberg’s approach. After conducting the interviews with personnel from the construction industry it was understood that apart from the monetary benefit, the approach is effective in additional ways. Some points mentioned by the interviewed personnel included that the approach might help establish some standards that can be followed throughout the industry, if the approach can detect flatness and levelness at an early stage then that would reduce a lot of effort for rectification, and the approach aims to make the process easy to follow and reduces probability of error. All these answers imply that the approach would help to reduce costs and raise the quality of work and provide a new dimension to the construction industry. Unfortunately, these points regarding the effectiveness of the approach cannot be quantified. Some of the interviewed personnel also said that they can’t say anything about the effectiveness of the approach unless it is implemented. Since the approach is not currently followed it is difficult to justify what intangible benefits it can provide.

4.5 Statistical Analysis Cost

Another important part of this thesis project was to develop a computer application that will automate the statistical analysis which was previously manually done. The application was developed to reduce the manual effort required in the analysis so that it is less error prone and to reduce the costs associated with the analysis. The manual analysis was performed by research assistants who worked under the supervision of Dr. Milberg. The cost of the analysis performed by them was $13,724 (Refer to Appendix F). This was over a period of around 10 months with the research assistants working 10 hours/week. The number
of columns analyzed during this period was 170. This amounts up to $80 as analysis cost for 1 column. Currently, the author, who serves as the developer of the computer application was able to automate 75% of the functions in a time period of around 10 months working 10 hours/week. The total cost incurred so far for the development of the application is around $1400, which is significantly less than that incurred in performing the analysis manually. This is a huge benefit considering that the application development cost is a one time cost while the manual analysis cost is a continuous cost per unit. In addition to that, the application saves a lot or even eliminates analysis time and since everything will be stored on the central database all the results are just a few clicks away.

Currently, grants from Charles Pankow foundation, American Society of Concrete Contractors, and in kind donations from companies providing data, compensate for the analysis cost. Although, the analysis is a cost of the proposed solution it is not used in the calculation of control costs for the construction companies. First, this cost is not incurred by the construction companies; The construction companies are just required to gather and upload the data and it is up to the analyst to perform the analysis. In addition, this cost represents analysis of data from the equivalent of over 10 projects worth of data. Thus, the distributed cost per project is small, at approximately $1,300, and would not impact the conclusions of the cost benefit analysis. Furthermore, the analysis application developed eliminates the analysis cost in the future and is the key component of the approach proposed by Milberg.
CHAPTER 5

CONCLUSION

This Chapter presents the overall findings and conclusions from this thesis project. It discusses how the findings were analyzed to answer the research questions and what the outcome was.

5.1 SUMMARY

Concrete powers a US $35-billion industry which employs more than two million workers in the United States alone[23]. The primary goal of this thesis project was to understand if there is any monetary benefit to the concrete construction companies by implementing the approach stated by Milberg[9]. After conducting the interviews with personnel from the industry valuable data about the costs was gathered. Chapter 4 performed the analysis on the data gathered and presented the results. Based on the results it was observed that the approach stated by Milberg will certainly be of monetary benefits to the concrete construction companies if they do implement it. The analysis was performed on projects costing in the range of $2-$50 million dollars. The results showed that the approach would save around .05-.70% of total project costs. In addition to that, the approach will also be helpful in building more robust designs, and may also play an important role in establishment of some standards. It also aims at making the overall process more efficient and less error prone. Though, in some cases, the approach may require the use of additional extra resources and labor with specific skills, it will still be very helpful in reducing costs over the long run and achieving a quality standard. This will prove very valuable for the companies as this step aims at streamlining the current process and strives for continuous improvement which is a very essential factor for the long term success of any company. Considering the potential of both the tangible and intangible benefits the proposed approach can provide, it would be a very effective solution for the construction companies to implement. Apart from bringing the monetary benefits the approach makes the overall process more effective and smooth which adds value to the current process. This in turn will
make the process less error prone, will provide a guideline which can be easily followed, and help detect errors at an early stage. Thus reducing the overall failure costs and improving the process continuously.

The answers to the research questions stated in Chapter 1 were found by conducting interviews and data analysis on the data gathered during the interviews. The cost benefit analysis results show a high likelihood of reducing costs and improving performance by using process capability data and implementing the proposed approach.

To understand what extra resources, time and effort would be required to implement the proposed solution interviews were conducted with industry professionals. It was found out that in some cases additional equipment, and in some cases, labor with specific skills to make necessary design changes will be required. The surveying process can be planned in such a way that it does not interfere with the ongoing construction process. So there will be no added costs except the cost of surveying.

Figuring out the current failure costs was difficult as the companies use historical costs for project bids thus embedding money for failure costs into future pricing and not tracking it separately. Some of the common problems faced include balcony slopes, misplaced embeds, layout problems, offsets at joints, columns in and out of plane, slab floor flatness, and deflection. The costs associated with such problems are categorized as failure costs.

One of the research questions was if the proposed approach is helpful to construction companies in a long term implementation, will it address quality issues and help develop standards or benchmarks, and will it help to make design changes that accommodate inherent variation. In answer, the interviewed personnel all felt the proposed approach was providing potential intangible benefits such as developing a quality standard, continuous quality improvement approach, and possible establishment of benchmarks. Also, the cost benefit analysis showed monetary benefits.

The thesis project also involved the development of a computer application to automate the statistical analysis. This application is designed to significantly reduce the amount of human effort required to perform the statistical analysis and thus the control costs associated with implementing the approach. The application currently performs analysis on common concrete elements such as columns, walls, beams. It can be customized to analyze
more complex structures in order to cover the variety of elements constructed. The current functions performed by the application include coordinate transformation, linear regression, calculation of surface normals and centroids, and transforming points back to original coordinate system. The application is designed to fetch data from a central database, perform the functions and store the results back to the database.

Lastly, if the construction companies could implement the proposed approach it should prove beneficial in both a tangible and an intangible manner. The computer application, once completely developed, will require minimum supervision and maintenance to carry out the required operations.

5.2 DIRECTIONS FOR FUTURE RESEARCH

For future research, the investigator recommends that a study be conducted to understand, list, and quantify the possible additional failure costs that may be incurred by other trades who interface with the concrete structure. The other jobs could include fixing doors and windows, fitting tiles, fitting wooden structures into the developed concrete structures. All these jobs may face failure costs if the concrete structures developed vary even minutely from the specified dimensions. If these costs can be quantified then the failure costs can be more specifically and correctly quantified. This will add to the effectiveness of the proposed approach by identifying when effort in redesign is warranted.

Another topic where some research can be done is the statistical analysis. A study can be conducted to define what amount of geometrical variation data can be considered sufficient and what specific data would be necessary to perform the relevant statistical analysis in order to achieve effective results. This would help to streamline the surveying process for the construction companies and may help to reduce their surveying costs.

Another subject for future research should be analyzing the scale of the projects for which the proposed approach is most beneficial. This study performed analysis for projects ranging from $2 M - $50 M in project cost. The recommended study would entail categorizing projects separately based on their total costs and then analyzing the effect on each category. This will help to provide a better picture about the category of projects in which the approach is most beneficial and consequently similar projects in which the approach can be implemented. The method and the results of this study could be used as a
benchmark or a starting point for other projects in order to generate results that can be tracked over time in a more consistent manner.
REFERENCES


http://www.slac.stanford.edu/BFROOT/www/Public/Computing/  
Databases/experts/glossary.shtml.


[20] American Concrete Institute, “General Information.” American Concrete Institute.  
http://www.concrete.org/MEMBERS/MEM_INFO.HTM

http://www.thebluebook.com/about_bluebook.shtml


APPENDIX A

WEB UTILITY SCREENSHOTS
Figure A.1. Home Page.
Figure A.2. Registration Page.
Figure A.3. Login Page.
Figure A.4. Data Entry Page.
Figure A.5. Upload File Page.
APPENDIX B

SOURCE CODE

STATISTICAL AND MATHEMATICAL FUNCTIONS
using System;
using System.Collections.Generic;
using System.Linq;
using System.Web;
using list_of_classes;
using System.Data;
using System.Data.SqlClient;
/// <summary>
/// Summary description for Calculation
/// </summary>
///

namespace calculation
{
    public class Calculation
    {
        public Calculation()
        {
            //
            // TODO: Add constructor logic here
            //
        }
    }
    public class matrix
    {
        int no_of_rows, no_of_cols;
        public double[,] _matrix = new double[4, 4];
        public double[,] rotation_matrix_PtoD = new double[4, 4];
        public double[,] rotation_matrix_DtoP = new double[4, 4];
        public double[,] translation_matrix_PtoD = new double[4, 4];
        public double[,] translation_matrix_DtoP = new double[4, 4];

        // Code for Transformation Matrix Calculation

        public void find_transformation_matrix(point corner1, point corner2, point corner4)
{  
double[] vector_Xd = new double[3];  
double[] vector_Xp = new double[3];

    for (int i = 0; i < 3; i++)  
        vector_Xd[i] = corner2.coordinate[i] -  
        corner1.coordinate[i];  
    for (int i = 0; i < 3; i++)  
        vector_Xd[i] = vector_Xd[i] / (Math.Sqrt((vector_Xd[0] *  
        vector_Xd[0]) + (vector_Xd[1] * vector_Xd[1]) + vector_Xd[2] *  
        vector_Xd[2]));  

    vector_Xp[0] = -1;  
    vector_Xp[1] = 0;  
    vector_Xp[2] = 0;  

    double cos_theta = ((vector_Xp[0] * vector_Xd[0]) +  
    double theta = Math.Acos(cos_theta);  
    double sin_theta = Math.Sin(theta);  

    rotation_matrix_PtoD[0, 0] = rotation_matrix_PtoD[1, 1] =  
    rotation_matrix_DtoP[0, 0] = rotation_matrix_DtoP[1, 1] = cos_theta;  

    rotation_matrix_PtoD[0, 1] = rotation_matrix_DtoP[1, 0] =  
    sin_theta;  
    rotation_matrix_PtoD[1, 0] = rotation_matrix_DtoP[0, 1] = -  
    sin_theta;  

    rotation_matrix_PtoD[0, 2] = rotation_matrix_PtoD[0, 3] =  
    rotation_matrix_PtoD[1, 2] = rotation_matrix_PtoD[1, 3] =  
    rotation_matrix_PtoD[2, 0] = rotation_matrix_PtoD[2, 1] =  
    rotation_matrix_PtoD[2, 3] = rotation_matrix_PtoD[3, 0] =  
    rotation_matrix_PtoD[3, 1] = rotation_matrix_PtoD[3, 2] =  
    rotation_matrix_DtoP[0, 2] = rotation_matrix_DtoP[0, 3] =  
    rotation_matrix_DtoP[1, 2] = rotation_matrix_DtoP[1, 3] =  
    rotation_matrix_DtoP[2, 0] = rotation_matrix_DtoP[2, 1] =
rotation_matrix_DtoP[2, 3] = rotation_matrix_DtoP[3, 0] =
rotation_matrix_DtoP[3, 1] = rotation_matrix_DtoP[3, 2] = 0;
rotation_matrix_PtoD[2, 2] = rotation_matrix_PtoD[3, 3] =
rotation_matrix_DtoP[2, 2] = rotation_matrix_DtoP[3, 3] = 1;

for (int i = 0; i < 4; i++)
for (int j = 0; j < 4; j++)
if (i == j)
  translation_matrix_PtoD[i, j] =
translation_matrix_DtoP[i, j] = 1;
else
  translation_matrix_PtoD[i, j] =
translation_matrix_DtoP[i, j] = 0;

for (int i = 0; i < 3; i++)
{
  translation_matrix_PtoD[i, 3] = -corner1.coordinate[i];
  translation_matrix_DtoP[i, 3] = corner1.coordinate[i];
}

// Code for Coordinate Transformation

class Point
{
  double coordinate[4];

  Point change_point_to_new_coordinate_system(Point pp1)
  {
    Point temp = new Point();
    for (int i = 0; i < 4; i++)
    {
      temp.coordinate[i] = 0;
      for (int j = 0; j < 4; j++)
      {
        temp.coordinate[i] += pp1.coordinate[j] *
translation_matrix_PtoD[i, j];
      }
    }
    return temp;
  }
}
for (int i = 0; i < 4; i++)
    pp1.coordinate[i] = temp.coordinate[i];

for (int i = 0; i < 4; i++)
{
    temp.coordinate[i] = 0;

    for (int j = 0; j < 4; j++)
    {
        temp.coordinate[i] += pp1.coordinate[j] * rotation_matrix_PtoD[i, j];
    }
}

for (int i = 0; i < 4; i++)
    pp1.coordinate[i] = temp.coordinate[i];

return pp1;

public point change_point_to_old_coordinate_system(point ppl)
{
    point temp = new point();

    for (int i = 0; i < 4; i++)
    {
        temp.coordinate[i] = 0;

        for (int j = 0; j < 4; j++)
        {
            temp.coordinate[i] += ppl.coordinate[j] * rotation_matrix_DtoP[i, j];
        }
    }

    return temp;
}
```java
for (int i = 0; i < 4; i++)
    ppl.coordinate[i] = temp.coordinate[i];

for (int i = 0; i < 4; i++)
{
    temp.coordinate[i] = 0;

    for (int j = 0; j < 4; j++)
    {
        temp.coordinate[i] += ppl.coordinate[j] * translation_matrix_DtoP[i, j];
    }
}

for (int i = 0; i < 4; i++)
    ppl.coordinate[i] = temp.coordinate[i];

return ppl;
}

public class regression
{
    public regression()
    {
        //
        //TODO: Add constructor logic here
        //
    }

    public double plane_var_a, plane_var_b, plane_var_c, temp,
    regression_var_a, regression_var_b, regression_var_c, d1, d2;

    public double[,] regression_matrix = new double[3, 3];

```
public double[,] data_points= new double[4, 34];

public void calculate_regression_matrix()
{
    for (int i = 0; i < 34; i++)
    {
        regression_matrix[0, 0] += (data_points[0, i] * data_points[0, i]);
        regression_matrix[0, 1] += (data_points[0, i] * data_points[2, i]);
        regression_matrix[0, 2] += data_points[0, i];
        regression_matrix[1, 0] += (data_points[0, i] * data_points[2, i]);
        regression_matrix[1, 1] += (data_points[2, i] * data_points[2, i]);
        regression_matrix[1, 2] += data_points[2, i];
        regression_matrix[2, 0] += (data_points[0, i]);
        regression_matrix[2, 1] += (data_points[2, i]);
        regression_matrix[2, 2] = 34;
        regression_var_a += (data_points[0, i] * data_points[1, i]);
        regression_var_b += (data_points[2, i] * data_points[1, i]);
        regression_var_c += data_points[1, i];
    }
    d1 = ((regression_matrix[2, 2] * regression_matrix[1, 1]) -
          (regression_matrix[1, 2] * regression_matrix[2, 1]));
    d2 = ((regression_matrix[0, 0] * regression_matrix[2, 2]) -
          (regression_matrix[0, 2] * regression_matrix[2, 0]));
    temp = (((regression_matrix[2, 2] * regression_var_b) -
             (regression_matrix[1, 2] * regression_var_c)) /
             ((regression_matrix[2, 2] * regression_matrix[1, 1]) -
             (regression_matrix[1, 2] * regression_matrix[2, 1])));
    plane_var_b = (((temp * d1 * d2) -
                    (regression_matrix[2,2]*regression_matrix[1,0]*regression_matrix[2,2])*regre
calculation of residuals and variance

```java
public void calculate_residuals(regression regression_result) {
    double standard_deviation = 0;
    double max_variation = 0, min_variation = 0;
    double[] residuals = new double[34];

    for (int i = 0; i < 34; i++) {
        residuals[i] = regression_result.data_points[1, i] -
                        ((regression_result.plane_var_a * regression_result.data_points[0, i]) +
                         (regression_result.plane_var_b * regression_result.data_points[0, i]) +
                         (regression_result.plane_var_c * regression_result.data_points[0, i]) +
                         ((regression_result.plane_var_a - plane_var_b *
                           ((regression_result.plane_var_a - plane_var_b) +
                            ((regression_result.plane_var_a - plane_var_b) +
                             ((regression_result.plane_var_a - plane_var_b) +
                              ((regression_result.plane_var_a - plane_var_b)))))) /
                         regression_result.data_points[2, i]);
```

(regression_result.plane_var_b * regression_result.data_points[2, i]) +
plane_var_c);

standard_deviation += residuals[i] * residuals[i];
}
max_variation = min_variation = residuals[0];
for (int i = 0; i < 30; i++)
{
  if (max_variation < residuals[i])
    max_variation = residuals[i];
  if (min_variation > residuals[i])
    min_variation = residuals[i];
}
standard_deviation = Math.Sqrt(standard_deviation);

//Calculation of Centroid

public void calculate_centroid(regression regression_result)
{
  double[] centroid = new double[3];
  for (int i = 0; i < 30; i++)
  {
    centroid[0] += regression_result.data_points[0, i];
    centroid[1] += regression_result.data_points[1, i];
    centroid[2] += regression_result.data_points[2, i];
  }
  centroid[0] = centroid[0] / 30;
}

//Calculation of Unit Normal Vector

public void calculate_unit_normal_vector(regression regression_result)
double[] unit_normal_vector = new double[3];

double temp_denominator;

// we have to find the cross product of (1, A, 0) \times (0, B, 1) to get the normal vector

// \( a \times b = (a_2b_3 - a_3b_2) \mathbf{i} + (a_3b_1 - a_1b_3) \mathbf{j} + (a_1b_2 - a_2b_1) \).

// we now have to find the unit vector in the normal direction

temp_denominator = Math.Sqrt((unit_normal_vector[0]*unit_normal_vector[0])+(unit_normal_vector[1]*unit_normal_vector[1])+(unit_normal_vector[2]*unit_normal_vector[2]));

unit_normal_vector[0] /= temp_denominator;
unit_normal_vector[1] /= temp_denominator;
unit_normal_vector[2] /= temp_denominator;
APPENDIX C

INTERVIEW QUESTIONS
Table C.1. List of Questions

<table>
<thead>
<tr>
<th>#</th>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>What is the average cost of a typical project for your company? Or what is the cost of the project you are currently on?</td>
</tr>
<tr>
<td>2</td>
<td>Do you have any common types of repair/rework issues you see frequently? If so what are they?</td>
</tr>
<tr>
<td>3</td>
<td>What is the rework/repair rate corresponding to non-conforming components like concrete walls, floors, slab, column, beams? Or percentage of total components built that had a problem, i.e., did not meet specification or the follow on contractor had to do additional work or make some kind of adjustment to the concrete to meet their needs.</td>
</tr>
<tr>
<td>4</td>
<td>What portion of the rework/repairs were planned or expected and what portion were unexpected?</td>
</tr>
<tr>
<td>5</td>
<td>What is the average cost of such repairs/rework as part of the total project cost, is there a way to quantify it? If yes, how do you quantify it?</td>
</tr>
<tr>
<td>6</td>
<td>How much time is spent to do the repair and make the component meet the specification?</td>
</tr>
<tr>
<td>7</td>
<td>What ways or practices are followed to avoid such situations and reduce rework/repair costs?</td>
</tr>
<tr>
<td>8</td>
<td>What would be the cost of gathering geometrical variation data of 1% of total concrete constructed elements such as walls, columns, slabs etc?</td>
</tr>
<tr>
<td>9</td>
<td>Will it require additional labor with certain expertise? If yes, what would be the cost of hiring them?</td>
</tr>
<tr>
<td>10</td>
<td>Will it require some specific equipment? If yes, what would be the cost?</td>
</tr>
<tr>
<td>11</td>
<td>What will be the time spend and labor used in the gathering of data and uploading it to the central database that we provide?</td>
</tr>
<tr>
<td>12</td>
<td>What is the average cost per hour of that labor?</td>
</tr>
<tr>
<td>13</td>
<td>Will the process of gathering the data interfere with or delay the ongoing (table continues)</td>
</tr>
<tr>
<td>#</td>
<td>Question</td>
</tr>
<tr>
<td>----</td>
<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>14</td>
<td>Could the system be designed differently so that even if the column varied to its maximum typical variation the system would still work and avoid the problem. What would be the cost of implementing that alternative design in your opinion?</td>
</tr>
<tr>
<td>15</td>
<td>What will be the cost of making more robust designs to accommodate the variation? Would it require any training costs to current designers? Would it require hiring designers with specific skills? If yes, what would be the cost of that?</td>
</tr>
<tr>
<td>16</td>
<td>Do you think that our approach has any practical limitations? If not, would you be willing to implement it?</td>
</tr>
<tr>
<td>17</td>
<td>If our approach succeeded in eliminating rework or non-standard work with interfaces so that all connections were standard, how much would that help with the schedule and cost for the project</td>
</tr>
</tbody>
</table>
APPENDIX D

INTERVIEW ANSWERS
<table>
<thead>
<tr>
<th>#</th>
<th>Answers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Answer 1)</td>
<td>Avg. cost would be $10 M</td>
</tr>
<tr>
<td>Answer 2)</td>
<td>minor issues such as patching rock pockets, form offsets</td>
</tr>
<tr>
<td>Answer 3)</td>
<td>.5-1% of total cost</td>
</tr>
<tr>
<td>Answer 4)</td>
<td>No such costs are planned, the costs in the bid are based on historical data.</td>
</tr>
<tr>
<td>Answer 5)</td>
<td>Its difficult to quantify, the historic data for costs is used to assign current costs</td>
</tr>
<tr>
<td>Answer 6)</td>
<td>Again, difficult to quantify as it is partly considered in the actual project construction time.</td>
</tr>
<tr>
<td>Answer 7)</td>
<td>Post-construction meetings, lessons-learnt, Peer review, Quality checks for flatness and levelness, focus on the process</td>
</tr>
<tr>
<td>Answer 8)</td>
<td>.5-1% of the total project cost</td>
</tr>
<tr>
<td>Answer 9)</td>
<td>No</td>
</tr>
<tr>
<td>Answer 10)</td>
<td>Total station. Cost is around 30K</td>
</tr>
<tr>
<td>#</td>
<td>Answers</td>
</tr>
<tr>
<td>------</td>
<td>-----------------------------------------------------------</td>
</tr>
<tr>
<td>Answer 11)</td>
<td>Included in Q9</td>
</tr>
<tr>
<td>Answer 12)</td>
<td>$60/hr</td>
</tr>
<tr>
<td>Answer 13)</td>
<td>We will make arrangements so that there is no intervention</td>
</tr>
<tr>
<td>Answer 14)</td>
<td>Yes, definitely</td>
</tr>
<tr>
<td>Answer 15)</td>
<td>Already answered</td>
</tr>
<tr>
<td>Answer 16)</td>
<td>It might raise certain conflicts among the employees</td>
</tr>
<tr>
<td>Answer 17)</td>
<td>It would be great and effective. It may help to set up certain system of standard which can be followed in general.</td>
</tr>
</tbody>
</table>
Table D.2. Answers for Company 2

<table>
<thead>
<tr>
<th>#</th>
<th>Answers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Answer 1)</td>
<td>$10 M for a warehouse, $15-20 M for an office building</td>
</tr>
<tr>
<td>Answer 2)</td>
<td>Not really, at times certain slabs, removing bad sections, deflection</td>
</tr>
<tr>
<td>Answer 3)</td>
<td>Around 25%, monetary value can be considered as $100k-150k</td>
</tr>
<tr>
<td>Answer 4)</td>
<td>No such costs are planned</td>
</tr>
<tr>
<td>Answer 5)</td>
<td>$1.5-$3 /sq.ft. Depends on the contractors who fix it</td>
</tr>
<tr>
<td>Answer 6)</td>
<td>Approximately 2 weeks in an year</td>
</tr>
<tr>
<td>Answer 7)</td>
<td>Standard processes are followed. Testing is done after regular intervals. Don’t necessarily follow the cheapest possible method</td>
</tr>
<tr>
<td>Answer 8)</td>
<td>Around $5-10k</td>
</tr>
<tr>
<td>Answer 9)</td>
<td>No.</td>
</tr>
<tr>
<td>Answer 10)</td>
<td>We already have measuring equipment</td>
</tr>
<tr>
<td>#</td>
<td>Answers</td>
</tr>
<tr>
<td>------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>11)</td>
<td>Depends on the size of the project</td>
</tr>
<tr>
<td>12)</td>
<td>$75/hr</td>
</tr>
<tr>
<td>13)</td>
<td>No</td>
</tr>
<tr>
<td>14)</td>
<td>Not sure</td>
</tr>
<tr>
<td>15)</td>
<td>The current engineer should be able to do that so we don't think there is a major cost element associated. If the work is done by a senior engineer then the salary increase would be around 15/30k per year</td>
</tr>
<tr>
<td>16)</td>
<td>It is difficult to pick up deflection in the early stage. The approach should produce accurate results.</td>
</tr>
<tr>
<td>17)</td>
<td>Yes, it seems to be effective. Especially if it could detect deflection and address flatness and levelness calculations it would be very beneficial to the industry and may also help in setting a standard.</td>
</tr>
</tbody>
</table>
### Table D.3. Answers for Company 3

<table>
<thead>
<tr>
<th>#</th>
<th>Answers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Answer 1)</td>
<td>$50 M for entire project costs</td>
</tr>
<tr>
<td>Answer 2)</td>
<td>Exterior skin water infiltration. For concrete, slab floor flatness for slabs that receive finish.</td>
</tr>
<tr>
<td>Answer 3)</td>
<td>Formed concrete inherently requires dry finish work to knock off fins and fill bug holes to meet most specifications, especially for concrete exposed to the public. Slab soffits are the more prominent elements that require dry finish work due to the amount of form-to-form edge conditions with loose laid plywood. Walls are next in the spectrum. Columns and beams are less likely to require dry finish work due to the &quot;tightness&quot; of the forms. Nearly all slabs require floor filler to be applied to the top of the slab where floor finishes, such as vinyl flooring, tile and wood floors, are applied to the slab. It would be virtually impossible (or invariably cost prohibitive) to provide a floor flatness during slab placement to meet the needs of these floor finish tolerances. Carpet is a little more forgiving and does not need as much floor filling by the flooring trade. 100-300K</td>
</tr>
<tr>
<td>Answer 4)</td>
<td>The items listed above, depending upon the specification requirements, are all planned for in Pankow's estimates. Such items as rock pockets in columns, slabs or walls and slab finishes damaged by rain are typically unexpected costs.</td>
</tr>
<tr>
<td>Answer 5)</td>
<td>Wall, column and beam dry finish costs to meet most specifications (ACI type B finish, knock down fins, patch bug holes &gt;3/8&quot; diameter) is in the $0.60-0.70/sf of contact area range. Slab soffits to meet similar specs, are in the $0.25-0.35/sf range. This does not included &quot;unexpected&quot; repairs. If you have to &quot;sack&quot; a wall or column to repair &quot;rock pockets&quot;, the costs will be .</td>
</tr>
</tbody>
</table>

(table continues)
Table D.3. (continued)

<table>
<thead>
<tr>
<th>#</th>
<th>Answers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>much higher, possibly in the $1000 per repair location range. To repair a rain damaged slab could be in the $1.50-$3.00/sf range</td>
</tr>
<tr>
<td>Answer 6)</td>
<td>To come up with the time involved, just divide the unit costs above by the hourly rate of a laborer or cement finisher. So if the cost is $0.25/sf, using $70/hour, the manhours per sf is 0.0036 or 285 sf per man-hour.</td>
</tr>
<tr>
<td>Answer 7)</td>
<td>To eliminate the expected dry finish costs, make sure the forms are as tight as possible. For soffits formed by loose laid plywood, we put a laborer on the deck to make sure the plywood edges are pushed down during the pour. To help eliminate the unexpected rock pockets, make sure you have a good vibrator man and utilize concrete that has plasticizer admixtures. To help eliminate the rain damaged slabs, have accurate weather service information.</td>
</tr>
<tr>
<td>Answer 8)</td>
<td>This could be done utilizing a Total Station system for columns and walls. This only done if we visually see an issue and know we will have a problem. If it is way out of tolerance, we typically remove the element and re-pour it. We do require Owners to survey slabs to obtain F numbers to make sure we are within specifications. Cost information could be obtained from a survey company or testing lab and would be variable depending upon the situation.</td>
</tr>
<tr>
<td>Answer 9)</td>
<td>We would probably use carpenters and our field engineers to measure this, or some testing/survey companies would utilize operating engineers. My guess is the cost would be in the $90-$120/man-hour range.</td>
</tr>
<tr>
<td>Answer 10)</td>
<td>Yes. For the vertical elements, you would use a Total Station, which will likely already be on the project. My guess is Total Stations cost about $10k. For the slab flatness measurements, this would require a machine that measures slab flatness. I do not know the costs of these, but a testing company could provide you with this cost.</td>
</tr>
<tr>
<td>#</td>
<td>Answers</td>
</tr>
<tr>
<td>-------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Answer 11)</td>
<td>In round numbers, use $100/ per man-hour</td>
</tr>
<tr>
<td>Answer 12)</td>
<td>In round numbers, use $100/ per man-hour</td>
</tr>
<tr>
<td>Answer 13)</td>
<td>As long as the data gathering is done after the pours, then it probably has no schedule implication. It would require one of our field engineers to coordinate the effort.</td>
</tr>
<tr>
<td>Answer 14)</td>
<td>Yes, it could be, but you are now adding conservatism to 99% of the elements for 1% of the elements that do not meet specifications. Design costs would not change, but construction costs would increase.</td>
</tr>
<tr>
<td>Answer 15)</td>
<td>Probably not, other than knowing the changes are incorporated in the code.</td>
</tr>
<tr>
<td>Answer 16)</td>
<td>No. The ACI code already has strength factors to accommodate variations in material and tolerances. To add more factors would just add more conservatism to the code. The old addage of &quot;build it right the first time&quot; goes a long way. If an element was not installed to specifications (not usually a high percentage of elements are installed incorrectly), then analyze the element's strength and decide if it is adequate. If it is not, then repair or remove/replace it. Do not penalize the design of 99% of elements for the 1%.</td>
</tr>
<tr>
<td>Answer 17)</td>
<td>Standardization of connections would be very good; however, cost vs. benefit analysis would need to be performed. If a designer came up with a design that required 5 different column sizes, but 1 column size would could be provided at little added material cost, then there would be a benefit.</td>
</tr>
</tbody>
</table>
Table D.4. Answers for Company 4

<table>
<thead>
<tr>
<th>#</th>
<th>Answers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Answer 1)</td>
<td>$5 M</td>
</tr>
<tr>
<td>Answer 2)</td>
<td>columns in and out of plane.</td>
</tr>
<tr>
<td>Answer 3)</td>
<td>10K - 100k, rules of thumb and average cost are dangerous. patching rubbing, .5-1%</td>
</tr>
<tr>
<td>Answer 4)</td>
<td>NA</td>
</tr>
<tr>
<td>Answer 5)</td>
<td>quantity, specific type of rework</td>
</tr>
<tr>
<td>Answer 6)</td>
<td>less than 1%</td>
</tr>
<tr>
<td>Answer 7)</td>
<td>institute a prof of pre planning and mock ups, difficult the mix is finish is pump is, have a trial</td>
</tr>
<tr>
<td>Answer 8)</td>
<td>$10K-15K</td>
</tr>
<tr>
<td>Answer 9)</td>
<td>Not really</td>
</tr>
<tr>
<td>Answer 10)</td>
<td>We currently have certain measuring equipment</td>
</tr>
</tbody>
</table>

(table continues)
Table D.4.(continued)

<table>
<thead>
<tr>
<th>#</th>
<th>Answers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Answer 11</td>
<td>20 man hours</td>
</tr>
<tr>
<td>Answer 12</td>
<td>Around $75/hr</td>
</tr>
<tr>
<td>Answer 13</td>
<td>No</td>
</tr>
<tr>
<td>Answer 14</td>
<td>Not sure</td>
</tr>
<tr>
<td>Answer 15</td>
<td>-</td>
</tr>
<tr>
<td>Answer 16</td>
<td>Can't say</td>
</tr>
<tr>
<td>Answer 17</td>
<td>Can't say without implementing it.</td>
</tr>
<tr>
<td>#</td>
<td>Answers</td>
</tr>
<tr>
<td>-----</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Answer 1</td>
<td>The cost of the building where the current office is located was built by them. The total cost was around 1.2 M USD. The cost of tilt up concrete was about $212 K and the cost of the parking lot was around $107 K. We considered cost of tilt up concrete, $212 K for our purpose.</td>
</tr>
<tr>
<td>Answer 2</td>
<td>No, not really.</td>
</tr>
<tr>
<td>Answer 3</td>
<td>At the very max it is 1%.</td>
</tr>
<tr>
<td>Answer 4</td>
<td>There was no rework/repair expected.</td>
</tr>
<tr>
<td>Answer 5</td>
<td>The average cost of repair work was considered to be 1% which gave us around $2150 as the cost of repair/ rework</td>
</tr>
<tr>
<td>Answer 6</td>
<td>This is again very low and is around 3%. We considered that it took around 35 weeks to build the structure and 1 week was spent in repair work. Also the 1% cost of repair includes this overhead cost.</td>
</tr>
<tr>
<td>Answer 7</td>
<td>Verifying dimensions by self and verifying form work before pouring concrete</td>
</tr>
<tr>
<td>Answer 8</td>
<td>The cost of gathering geometrical variation data was estimated to be around $1065. It was assumed that it would require 2 guys with a wage of $50.94/hr to work all day and might require some additional equipments such as a lift, depending on the structure whose data needs to be gathered.</td>
</tr>
</tbody>
</table>
Table D.5. (continued)

<table>
<thead>
<tr>
<th>#</th>
<th>Answers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Answer 9)</td>
<td>No such labor will be required</td>
</tr>
<tr>
<td>Answer 10)</td>
<td>This will depend on the site. It might require certain access equipments</td>
</tr>
<tr>
<td>Answer 11)</td>
<td>To gather we already mentioned that it will require 1 day. To upload, for a tilt-up should not require more than 4 hours.</td>
</tr>
<tr>
<td>Answer 12)</td>
<td>That is the same $50.94</td>
</tr>
<tr>
<td>Answer 13)</td>
<td>Arrangements can be made that there is no or very minimal interference.</td>
</tr>
<tr>
<td>Answer 14)</td>
<td>The current design include the variation to some extent.</td>
</tr>
<tr>
<td>Answer 15)</td>
<td>N/A</td>
</tr>
<tr>
<td>Answer 16)</td>
<td>It seems that something of similar sort is already in place. As the current designs are able to accommodate certain dynamic changes.</td>
</tr>
<tr>
<td>Answer 17)</td>
<td>Can't say because already the amount of error is very low.</td>
</tr>
<tr>
<td>#</td>
<td>Answers</td>
</tr>
<tr>
<td>-----</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Answer 1)</td>
<td>I work in the concrete division of our company. Our company has three basic divisions - our general contracting group or what we call Core and Shell, the Concrete Group and the Special Projects Division which does things like tenant improvement, case work, doors and hardware etc. The average contract value for each division varies. For the Concrete Group, I would guess somewhere around $15M.</td>
</tr>
<tr>
<td>Answer 2)</td>
<td>Balcony slopes are a big problem, especially on post tensioned slabs where slabs can deflect after stressing. Otherwise I think our repairs are fairly routine and can vary from job to job on what occurs most frequently, such as mis-placed embeds, or offsets at joints, layout problems, and so on</td>
</tr>
<tr>
<td>Answer 3)</td>
<td>We do not track error rates, although I have advocated for this. We perform a quality survey on a biweekly basis of every concrete job. In this survey we randomly check portions of a project to verify dimensional compliance against a self established criteria (usually more strict than ACI 117). This survey may or may not find project issues, because it is not a hunt for problems, but a survey of a randomly selected area. The Project is graded on the basis of the magnitude of errors found. This data may be available on a limited basis for you to examine. I would have to get permission.</td>
</tr>
<tr>
<td>Answer 4)</td>
<td>Our rework is not carried in a separate budget line item. Our cost history is composed, of the cost to construct various building elements. Our cost history for forming columns would carry with it the amount of rework, as any rework required due to formwork would have been charged into this cost code.</td>
</tr>
</tbody>
</table>

(table continues)
Table D.6. (continued)

<table>
<thead>
<tr>
<th>#</th>
<th>Answers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Answer 5)</td>
<td>We don't really know. See above.</td>
</tr>
<tr>
<td>Answer 6)</td>
<td>yes</td>
</tr>
<tr>
<td>Answer 7)</td>
<td>We have a set protocol which is followed and documented before each concrete placement which requires that we survey everything within a given concrete placement, whether it is a slab, wall, column, stair, deck or whatever the element is composed of. We have a list of items to be checked and signed off for as being correct.</td>
</tr>
<tr>
<td>Answer 8)</td>
<td>It depends on the extent of the data that is to be collected. I am aware of Collins current program, which I think is a much tighter survey than is needed, and has not yet, to my knowledge, covered the full range of tolerances covered in the ACI Standard, such as total plumbness of structures of various heights. It is really uninteresting to me as a contractor to plot a wall surface on a 1/2&quot; grid. There is very little information in this kind of survey that I would find usefull that I couldn't find out by a survey on, say, a 12&quot; grid.</td>
</tr>
<tr>
<td>Answer 9)</td>
<td>Yes, especially if it is done electronically. We have no budget for this on any project other than the bi-weekly quality survey we perform ourselves. These surveys, in a given area, even though they are selected randomly usually pick up all significant problems which would either need to or not need to be addressed remedially. Those surveys we do have a budget for, which amounts to one man-day twice a month.</td>
</tr>
<tr>
<td>Answer 10)</td>
<td>We have a variety of survey equipment within our company including many total stations. We do not have a scanner.</td>
</tr>
<tr>
<td>Answer 11)</td>
<td>TBD</td>
</tr>
</tbody>
</table>

(table continues)
<table>
<thead>
<tr>
<th>#</th>
<th>Answers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Answer 12</td>
<td>$65</td>
</tr>
<tr>
<td>Answer 13</td>
<td>No, other than the diversion of resources.</td>
</tr>
<tr>
<td>Answer 14</td>
<td>I don't understand this question.</td>
</tr>
<tr>
<td>Answer 15</td>
<td>It all depends on the specifics of what is trying to be accomplished.</td>
</tr>
<tr>
<td>Answer 16</td>
<td>You have not described your complete approach.</td>
</tr>
<tr>
<td>Answer 17</td>
<td>We build a variety of concrete structures. Some approaches would be</td>
</tr>
<tr>
<td></td>
<td>practical for some structures and more than needed, or inapplicable for/to others. Each project varies in design, quality level, functionality, structural performance requirements, architectural requirements, durability requirements, etc. It is a very difficult field to standardize. This said, there could be some more generally used criteria for similar elements, such as shaft sizes for elevators, or deflection anticipation for slabs above window openings or curtain walls, set-backs from property lines, framed joint details for columns and beams, beam intersections, balcony designs etc. which help avoid some of the interferences and performance problems.</td>
</tr>
</tbody>
</table>
APPENDIX E

SURVEYING AND UPLOADING COST
<table>
<thead>
<tr>
<th>Acctg</th>
<th>Cat</th>
<th>Date</th>
<th>Description</th>
<th>Invoice</th>
<th>Vendor</th>
<th>Units</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>06-011</td>
<td>BLDG. A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>01-00004</td>
<td>DECK SURVEY FF/FL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>505</td>
<td>10-26-07 VAC ACCEL 10-07</td>
<td></td>
<td></td>
<td>7.54</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>505</td>
<td>11-30-07 VAC ACCEL 11-07</td>
<td></td>
<td></td>
<td>64.07</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>505</td>
<td>12-28-07 VAC ACCEL 12-07</td>
<td></td>
<td></td>
<td>38.07</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INTERCOMPANY</td>
<td>151.13*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Cost Code Total</th>
<th>689.5000*</th>
<th>34,988.86*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extra Total</td>
<td></td>
<td></td>
<td>34,988.86*</td>
</tr>
<tr>
<td>JOB TOTAL</td>
<td></td>
<td>689.5000*</td>
<td>34,988.86*</td>
</tr>
<tr>
<td>GRAND TOTALS</td>
<td></td>
<td>689.5000*</td>
<td>34,988.86*</td>
</tr>
</tbody>
</table>

Figure E.1. Surveying and Uploading Cost Invoice.
APPENDIX F

STATISTICAL ANALYSIS COST
Table F.1. Statistical Analysis Cost

<table>
<thead>
<tr>
<th>Code</th>
<th>Date</th>
<th>Code</th>
<th>Document</th>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>6023</td>
<td>21-Feb-08</td>
<td>PAYE</td>
<td>F0050591</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>6-Mar-08</td>
<td>PAYE</td>
<td>F0050877</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>21-Mar-08</td>
<td>PAYE</td>
<td>F0051143</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>8-Apr-08</td>
<td>PAYE</td>
<td>F0051448</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>23-Apr-08</td>
<td>PAYE</td>
<td>F0051768</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>8-May-08</td>
<td>PAYE</td>
<td>F0052053</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>21-May-08</td>
<td>PAYE</td>
<td>F0052310</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>6-Jun-08</td>
<td>PAYE</td>
<td>F0052603</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>30-Jun-08</td>
<td>PAYE</td>
<td>F0053156</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>30-Jun-08</td>
<td>PAYE</td>
<td>F0053252</td>
<td>Research Asst</td>
<td>-1126.32</td>
</tr>
<tr>
<td>6023</td>
<td>23-Jul-08</td>
<td>PAYE</td>
<td>F0053596</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>7-Aug-08</td>
<td>PAYE</td>
<td>F0053848</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>21-Aug-08</td>
<td>PAYE</td>
<td>F0054082</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>8-Sep-08</td>
<td>PAYE</td>
<td>F0054376</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>9-Jan-09</td>
<td>PAYE</td>
<td>F0056457</td>
<td>Research Asst</td>
<td>-37.03</td>
</tr>
<tr>
<td>6023</td>
<td>21-Feb-08</td>
<td>PAYE</td>
<td>F0050591</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>6-Mar-08</td>
<td>PAYE</td>
<td>F0050878</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>21-Mar-08</td>
<td>PAYE</td>
<td>F0051143</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>8-Apr-08</td>
<td>PAYE</td>
<td>F0051448</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>23-Apr-08</td>
<td>PAYE</td>
<td>F0051768</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>8-May-08</td>
<td>PAYE</td>
<td>F0052053</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>21-May-08</td>
<td>PAYE</td>
<td>F0052310</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>6-Jun-08</td>
<td>PAYE</td>
<td>F0052603</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>30-Jun-08</td>
<td>PAYE</td>
<td>F0053156</td>
<td>Research Asst</td>
<td>-277.72</td>
</tr>
<tr>
<td>6023</td>
<td>30-Jun-08</td>
<td>PAYE</td>
<td>F0053252</td>
<td>Research Asst</td>
<td>-3203.07</td>
</tr>
<tr>
<td>6023</td>
<td>23-Jul-08</td>
<td>PAYE</td>
<td>F0053596</td>
<td>Research Asst</td>
<td>-277.72</td>
</tr>
<tr>
<td>6023</td>
<td>7-Aug-08</td>
<td>PAYE</td>
<td>F0053848</td>
<td>Research Asst</td>
<td>-296.24</td>
</tr>
</tbody>
</table>

(table continues)
Table F.1. (continued)

<table>
<thead>
<tr>
<th>Code</th>
<th>Date</th>
<th>Code</th>
<th>Document</th>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>6023</td>
<td>21-Aug-08</td>
<td>PAYE</td>
<td>F0054082</td>
<td>Research Asst</td>
<td>-277.72</td>
</tr>
<tr>
<td>6023</td>
<td>8-Sep-08</td>
<td>PAYE</td>
<td>F0054356</td>
<td>Research Asst</td>
<td>-296.24</td>
</tr>
<tr>
<td>6023</td>
<td>23-Sep-08</td>
<td>PAYE</td>
<td>F0054616</td>
<td>Research Asst</td>
<td>-277.72</td>
</tr>
<tr>
<td>6023</td>
<td>8-Oct-08</td>
<td>PAYE</td>
<td>F0054873</td>
<td>Research Asst</td>
<td>-277.73</td>
</tr>
<tr>
<td>6023</td>
<td>20-Oct-08</td>
<td>PAYE</td>
<td>F0055018</td>
<td>Research Asst</td>
<td>-607.13</td>
</tr>
<tr>
<td>6023</td>
<td>23-Oct-08</td>
<td>PAYE</td>
<td>F0055142</td>
<td>Research Asst</td>
<td>-281.58</td>
</tr>
<tr>
<td>6023</td>
<td>6-Nov-08</td>
<td>PAYE</td>
<td>F0055423</td>
<td>Research Asst</td>
<td>-148.12</td>
</tr>
<tr>
<td>6023</td>
<td>21-Nov-08</td>
<td>PAYE</td>
<td>F0055669</td>
<td>Research Asst</td>
<td>-138.86</td>
</tr>
<tr>
<td>6023</td>
<td>8-Dec-08</td>
<td>PAYE</td>
<td>F0055935</td>
<td>Research Asst</td>
<td>-138.86</td>
</tr>
<tr>
<td>6023</td>
<td>19-Dec-08</td>
<td>PAYE</td>
<td>F0056168</td>
<td>Research Asst</td>
<td>-138.86</td>
</tr>
<tr>
<td>6023</td>
<td>1-Jan-09</td>
<td>PAYE</td>
<td>F0056310</td>
<td>Research Asst</td>
<td>-9.26</td>
</tr>
<tr>
<td>6023</td>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>-13723.36</td>
</tr>
</tbody>
</table>