A PROCESS FOR
REDUCING PRELIMINARY ENGINEERING COSTS
FOR MULTI-SIDED STEEL POLES

By

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ABSTRACT:

Preliminary engineering for fabrication of multi-sided steel poles encompasses two efforts: *planning* to allocate available human and technical resources, and *engineering design* to deliver the most cost effective proposal. Steel pole companies strive to manage these efforts effectively, seeking to maximize the utilization of the available resources and workforce productivity. Managers need to be able to reduce costs associated with the preliminary design because there is no financial reward unless the company receives a contract for fabrication. The results reported here will enable engineers and managers to direct the resources where they are needed most and maximize productivity and efficiency. In the current state of practice, the entire pole must be designed in order to provide an accurate estimate of pole weight which is the primary driver of pole cost. This process usually takes in excess of an hour per pole. By streamlining this preliminary design process, engineers and managers are able to focus their time on more profitable efforts.

The objective of this research is to reduce the amount of time spent in preliminary pole design. The methodology is based on developing predictive models using regression techniques that estimate pole weight as a function of several key parameters including pole height, “x-force”, “y-force”, “z-force”, ice thickness, and wind speed. Design data were collected for over 300 multisided steel poles used in the electrical transmission industry in the United States. Results indicate that the predictive models account for approximately 87% of the variability in pole weight thus showing promise as a surrogate for the more time consuming current preliminary design process.

In order to assess the time-saving effectiveness of the predictive models, value stream mapping was used to characterize the current preliminary pole design process versus the preliminary pole design process based on the predictive models. The purpose of value stream mapping is to determine pole design productivity, both before and after the predictive models are employed. The value stream map showed that utilizing the developed models would reduce the duration of the design and estimating process by approximately 20%. The validation process of the developed models showed that the models can provide consistency as well as accuracy that are better than the traditional process.

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INTRODUCTION

1.1 Background

This research concentrates on multisided steel monopoles, specifically utilized in the transmission industry. Pelco Structural LLC, located Claremore, OK, was an integral part of this research through allowing access to their data files, databases, software, and day-to-day operations and procedures. Without Pelco's support and contribution, this research would have not been possible. Through my background as a Structural Engineer for many years in the steel pole industry, it was possible to understand and identify areas where improvement is needed and that lend themselves to research in hopes of making a contribution that would be beneficial to the steel pole industry.

The electrical utilities and transmission industry is vital to our infrastructure with major investments and revenues estimated at $26 billion annually (CE News, Feb 2011). Multisided Steel Poles (MSP) are increasingly becoming the preferred solution for electrical transmission structures. Furthermore, MSP are used for traffic signal supports, lighting, signage and many other uses. Previous research has been done to improve the preliminary design process, increase efficiency and optimize resources in various engineering fields, such as roads, railroads, and buildings. However, these efforts have typically overlooked the electrical transmission industry in general, and particularly MSP. The purpose of this research is to evaluate parameters that affect the design and cost estimating of MSP. These parameters include, but are not limited to, pole weight, pole height, line tensions, and wind and ice loads. Ultimately, it is anticipated that this research will lead to improved processes for designing and estimating MSP.

The basis of this research was data collected from Pelco Structural, a leader in design and fabrication of MSP. Design data from previous projects was compiled, and analyzed to identify variables, trends and relationships. Three models were developed using statistical tools, such as multiple linear regression, to estimate steel weight - the primary parameter for estimating cost. The models were validated and calibrated with actual data from real-world projects. These models may be used as the primary design tool, a supplementary design aid, a quality assurance and control mechanism, or any combination of the three. Furthermore, in order to assess the value of the model, a value stream map of the current state was created for the impacted process at Pelco Structural. After the model is implemented into the system, the process was mapped again. Moreover, to quantify the effect of the models, a statistical chart that measures the daily design production was created and maintained throughout this research.

1.1.1 Pelco Structural

Pelco Structural LLC was established in 2005, in Claremore, Oklahoma, as a producer of made-to-order multi-sided pole assemblies for Traffic Control, Utility, Lighting, and Communication Industries. The 192,000ft footprint of the facility was strategically selected to be close to America's furthest inland port; Port of Catoosa. This location ensures a secure continuous supply of steel, without the need to keep large inventory in house. There are decoilers in Catoosa who also supply Pelco with sheets of steel in a timely manner.

There are approximately 130 employees, 30 of which are engineering and administrative staff while the remainder is manufacturing employees. Pelco Structural is affiliated with Pelco Products in Edmond, Oklahoma, a pioneer in traffic signal hardware, utility products and decorative outdoor lighting for 28 years. The main departments in the company are, Engineering, Drafting, Sales, Purchasing, and the Plant Operations. Figure 1.1 shows a flow chart of the work procedure, while Figure 1.2 shows an organizational chart detailing the hierarchy and how the various employees relate to each other. Currently, the business is roughly 70% Utility, 29% Traffic, and about 1% Lighting. The utility part of the business is growing more rapidly. It is a business goal to get more utility jobs, since they typically involve larger structures and bigger projects – compared to traffic or lighting - which translates into more money for the company.

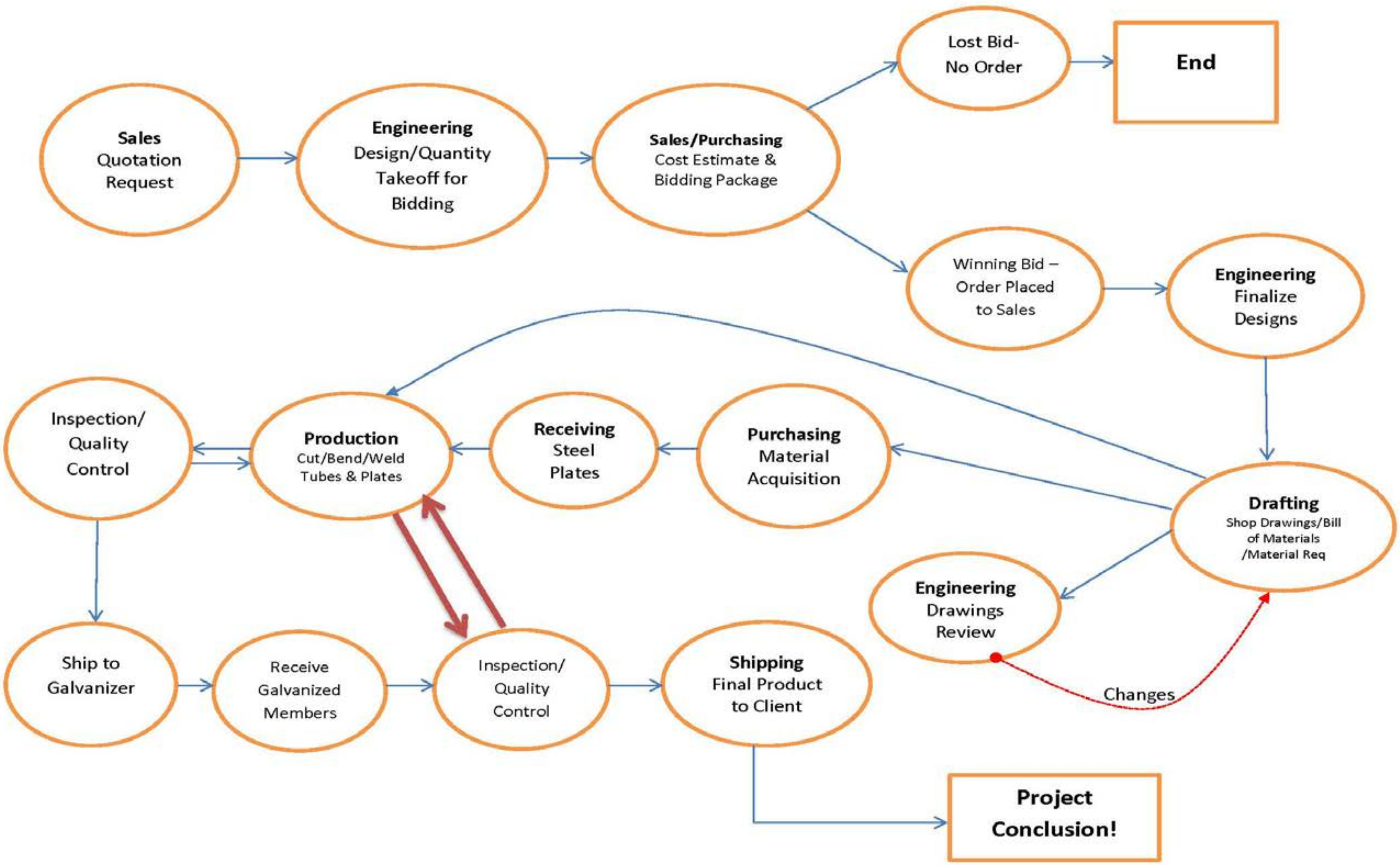

Figure 1.1. Pelco procedural flow chart

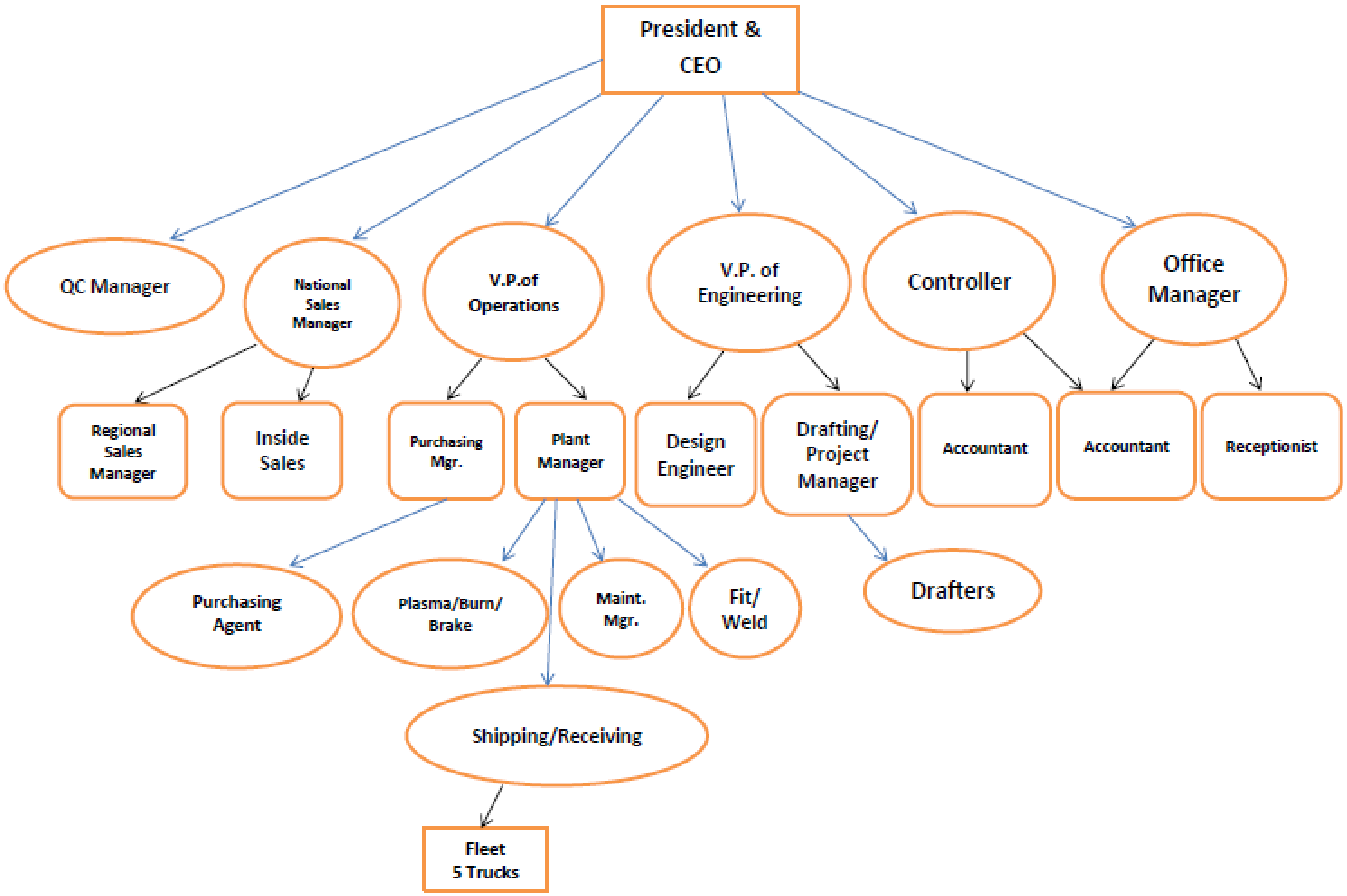

Figure 1.2. Organizational chart

1.1.2 Poles

Over the years there has always been a need for poles in various applications, most commonly traffic, lighting, sign supports, electrical substations, and transmission. Wood poles were one of the early choices due to the material availability and more importantly due to the ease of assembly. The main drawbacks were the limited capacity of the wood poles and the relatively short life spans and poor resistance to the weather. This opened the door to introduce other materials, most notably concrete poles. The concrete poles had more carrying capacity, the material was readily available, and it does not need special skills to fabricate or install. However, concrete was still unsuitable for many applications mainly due to its limited versatility. Polymers were used but never proved to be a convincing alternative due to the sophistication of the material and the limited number of fabricators, in addition to relatively limited load carrying capacity. The main challenge has always been high loads and heights. Figure 1.3. shows part of a 345 kV power line that runs between Tennessee and Missouri. The steel monopoles displayed are single circuit with side V-string connections to support the conductor cables.

Figure 1.3. Transmission line

Table 1.1 shows a detailed comparison between the different types of poles that are most commonly used. Comparison is based on the factors that matter the most when considering which type of pole to be used for a project. It is illustrated that while each type has its advantages, what usually governs the selection is the type of the project, the size and the location of the project as well as any project specific factors such as owner's preference, jurisdiction codes, and special conditions.

Table 1.1. Comparison between different types of poles

Type / Factor	Wood	Concrete	Polymer	Multisided Steel poles
Footprint	Low	Medium	Medium	Low
Load Suitability	Low	Low-Medium	Low-Medium	All Loads
Material Availability	High	Low	Low	High
Ease of Manufacturing	High	Medium	Low	Low
Ease of Construction	High	Medium	Medium	High
Cost	Low	Medium	Medium	Medium
Resistance to the Elements	Low	Low	Medium	High

The multisided steel poles have gained their popularity over other alternatives due to

- versatility
- ability to taper the sections, putting the steel only where it's needed, hence reducing the weight and saving money
- Smaller footprint
- Flexibility in design and ability to handle most loads
- Ease of assembly

Figure 1.4. shows a 12-sided monopole with the base plate attached to it, that has been loaded onto a truck after being galvanized, and is ready to be shipped to its final destination to be installed on site.

Figure 1.4. Galvanized pole about to be shipped

1.2 Problem Statement

Until recently, competition was not a serious concern among pole suppliers and fabricators. The companies in the field were limited, and with abundant work available, they were actually sharing the work available in the market rather than competing for it. This has been rapidly changing in recent years, as the number of companies entering the field has increased, leading to competition among them to acquire the work.

Accordingly, each company has been striving to increase its capacity, either by adding resources and/or increasing the productivity and efficiency of its existing ones. Companies have been scrambling to add equipment, software and staff, while streamlining existing processes to identify areas for improvement. In a situation where companies do not have enough resources to handle actual paid work, the last thing they want is to commit resources to unpaid work and activities. Unfortunately, that is not possible, since most work is awarded through a bidding process, which means plenty of work is done by many companies to compete for work, but only one company ends up with the work. For everyone else but the winning company, the cost associated with the bidding is absorbed as overhead.

Efforts have been made in various engineering fields to reduce the time involved in tasks, usually relying mainly on the experience of the designers to perform repetitive functions in shorter times as their experience progresses. A problem with that strategy is that it does not work if the designer lacks experience or is faced with an unusual task. Thus, there is a need for a tool that has the potential of reducing the time and effort involved in design and estimating activities with consistency and reliability, and more importantly, simplicity.

1.3 Significance of this Research

There were many reasons that led to recognizing the importance, potential, and necessity of this research**.**

- **Unpaid work:** Companies that bid projects do not get paid for that work unless they end up winning the bid. At Pelco structural, the winning bids comprise about 30% of the total bids. This means that 70% of the work performed at the bidding phase goes uncompensated and goes to overhead, or is loaded onto other bids that have actually been won.
- **Suffering accuracy:** Since the resources of any company has a limit, the more the bids that any company participates in, the lesser the accuracy of the work

submitted, unless there are tools implemented to increase efficiency and allow the existing resources to go farther.

- **Lost bids:** There are many reasons for losing bids. Of those, bids can be lost due to suffering accuracy (discussed above) or due to the inability to participate in the bid altogether due to prioritizing the bids and electing not to participate to free up resources for other projects.
- **Limited resources:** For any company to do more work, it can either add more employees, or it can improve the process to increase efficiency without adding more employees. In other words, to increase productivity, the choice is either to add manpower or to improve the yield of the existing manpower.
- **Move the extensive work to the back end:** The need for detailed thorough design will never go away. However, the goal is to have this detailed design occur at the back end of the process, when a bid is actually won, rather than at the front end when the bids may or may not be won. In other words, minimize the time spent on activities that are not being compensated by clients and invest that time in activities that are.

To further emphasize the importance of this research, it was necessary to examine the accuracy of the bids submitted in the past. Generally, the designs produced at the bidding phase get revised whenever a project is awarded. It was necessary to quantify the amount of change in steel weight due to that revision. To do that a spreadsheet was constructed that records the weights of the steel monopoles and their individual components that were used at the time of bidding each project. The revised weights were also tabulated and compared with the bid weights of the same structures. The results indicated differences in weight of up to 25% in many instances (see Appendix A). This only elaborates the extent of approximations and inaccuracies present in the preliminary designs used for bidding. The purpose of this research study is to increase the accuracy of the bid weights and reduce the percentage of approximations present, while saving the time and effort invested. Needless to say, this should increase the possibility of submitting successful bids in addition to increasing the productivity and profitability of the company.

1.4 Scope of the Research

This research starts by assessing the existing design and estimating process for steel monopoles in order to highlight the areas of potential improvement and to have a baseline to measure against as the research developed. Statistical models utilizing multiple regression techniques are developed to replace, or amend the existing traditional design and estimating process. Changes are introduced to the design and estimating process and the difference between the initial process and the revised process is evaluated. Multi-sided steel poles have many applications in transmission lines, sports lighting, as well as traffic structures. This research is limited to the transmission field applications. Figure 1.5. shows a flowchart of the different performed tasks and their sequence within the research. For simplicity, the flowchart shows all the tasks in sequence. In reality, some of the tasks and activities overlapped and were carried out simultaneously. All the data used in this research are actual data from real projects that took place either before or during the course of this research. Additionally, the tasks, research activities and applications were all performed within an actual work environment at an existing company.

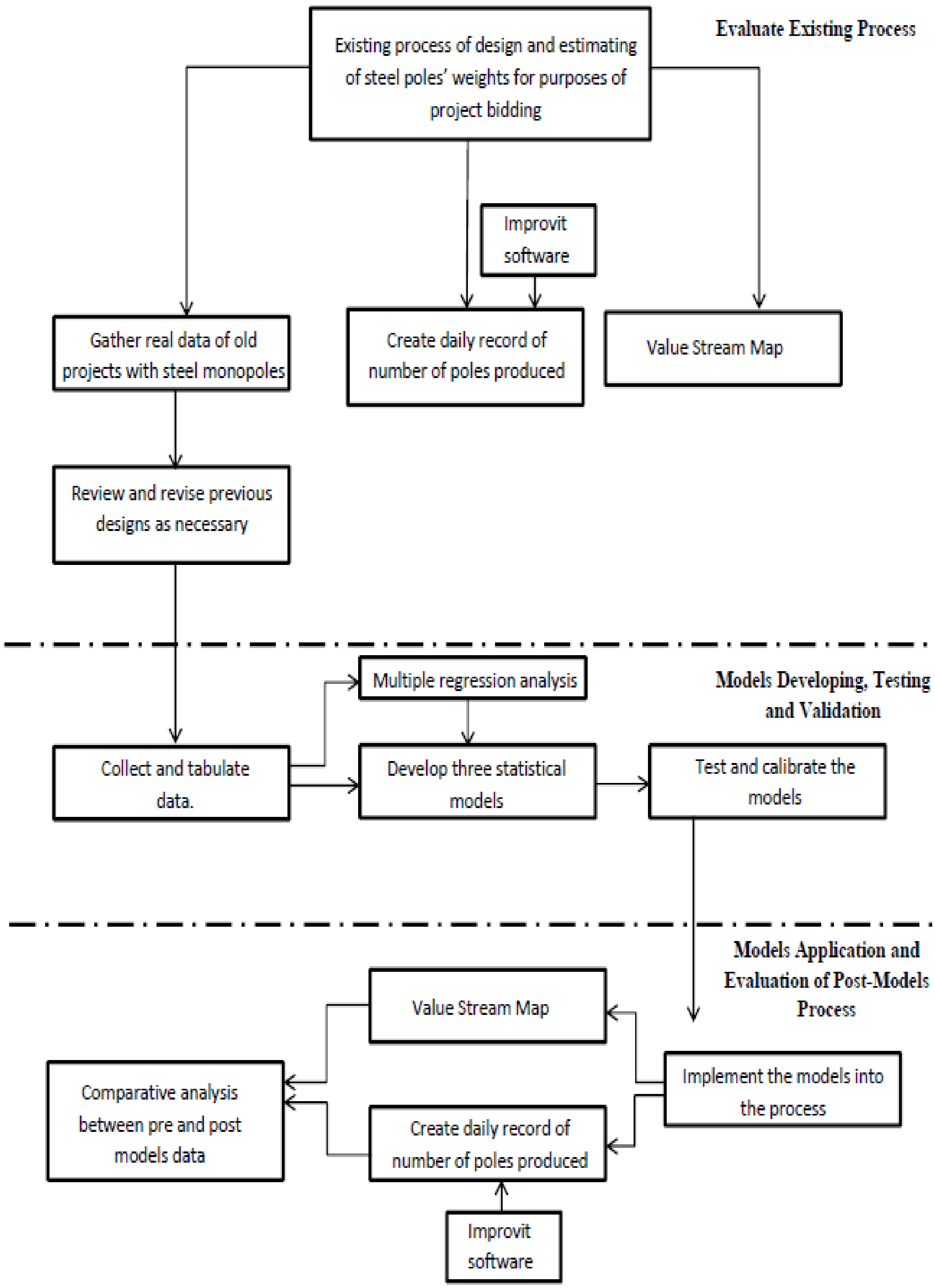

Figure 1.5. Flowchart of research tasks

1.5 Research Assumptions and Limitations

This research is based on the following assumptions and limitations:

- The software used (PLS-Pole) and other spreadsheets are accurate and reliable.
- The work produced by one engineer is comparable to that of another, i.e, the work is consistent regardless of the engineer producing it.
- The range of data available is sufficient to draw trends for other particular data that is not available.
- Other software and design packages on the market would produce comparable results to the software and design tools used in this research.
- Since real projects data is used in this research, the researcher is limited by the availability of the projects. To overcome this, a bigger range of data has been utilized. However, we do not have control over the projects that comes our way, and could only utilize what is available.
- Multi-sided steel poles can be 6-sided, 8-sided, 12-sided or 16-sided. The 12-sided is the most common for transmission monopoles, and hence, this research is limited to 12-sided poles.

CHAPTER II

REVIEW OF LITERATURE

2.1 Overview

Not much previous research on multisided steel monopoles utilized in transmission applications has been found. However, there is a lot of research done in three particular areas that relate to this research;

1- Utilization of statistical models in engineering design.

2- Identifying the parameters and constraints that make the most impact on the success of a project.

3- Budgets and cost estimates of projects.

2.2 Related Research Performed by Others

Whiteside II (2004) explored utilizing various common statistical methods to transfer technology from a "standard application" and be able to use it unconventionally. He utilized Data Regression, Running Summation, Fourier analysis, and Spectral Analysis to estimate hours required for engineering in projects. Technology transference is adapting methodologies from seemingly unrelated fields to develop a new application

(Whiteside, 2004). The data collected for these analyses are all a function of time, meaning that comparable data is collected repeatedly over time. This is the main thing that makes it different from this research, as time is not a factor in the data collected here. The paper, however, sheds light on different statistical tools, and their suitability for different engineering applications. Of particular importance to us is the engineering data collection. According to Whiteside II (2004): “If the collected data is not numeric, it is most likely the wrong type of numeric data”.

Kaldate et al (2006) realized that different parameters have different impacts on the design process and its optimization during preliminary engineering. Hence, they focused on vetting engineering parameters to extract the ones that have the most effect on design optimization. They presented a design structure matrix (DSM) that provides a visual representation of the parameters affecting the design and the dependencies between them. Different values are assigned to these parameters based on the magnitude of the impact that each parameter has. Figure 2.1 shows a DSM with initial entries, while figure 2.2. shows the matrix after being partitioned after the correlations between the various parameters have been established.

Design Attributes	Engineering Parameters	Material used for the vessel	Number of Vessels	Vessel geometry	Cartridges arrangement	Cartridge aspect ratios	Adsorbent type	Mass of the adsorbent per vessel	Number of cartridges	Type of adsorbate	Cycle time	Retention of adsorbate after regeneration	Inlet vapor concentration	Recycle of desorption stream	Relative humidity	Temperature	Total gas flow rate	Cartridge electrical resistance	Type of adsorbate	Cycle time	Heat transfer properties of the vessel	Purge flow rate	Recycle of desorption stream	Relative humidity	Power application algorithm	Temperature
	Components of Design Process	General			Product					Adsorption Cycle								Desorption Cycle								
	EP #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Capital Costs	Pretreatment	0.30								0.10	0.45		0.10		0.60	0.10		0.10	0.25	0.55				0.45	0.10	
	ACFC				0.55	0.30	0.95	0.45	0.30	0.85	0.95	0.75	0.80		0.15	0.25	0.50	0.10	0.35	0.15		0.10	0.85	0.10	0.10	0.90
	Vessel	0.95	0.95	0.40	0.75	0.85			0.30	0.30	0.80		0.50	0.60	0.55	0.45	0.75		0.50	0.20	0.55		0.70	0.45	0.85	0.80
	Control & Instrument		0.80						0.30	0.10	0.30		0.25	0.75					0.10	0.55					0.95	
	Piping & valves		0.80	0.10	0.80	0.25	0.15	0.15	0.55	0.75	0.10	0.25	0.45	0.65	0.35	0.30	0.95		0.75	0.10		0.75	0.75	0.35	0.10	0.10
	Auxiliary equipment		0.10														0.95					0.25				
Operating Costs	Labor		0.20								0.75									0.75						
	Maintenance	0.65	0.35				0.85		0.15	0.25				0.25					0.25				0.65			
	Electricity	0.30	0.30	0.15	0.90	0.65	0.95	0.55	0.25	0.75	0.95	0.35	0.95	0.90	0.80	0.10		0.90	0.75	0.80	0.80	0.10	0.80	0.45	0.95	0.95
	Inert gas		0.30				0.45												0.75	0.95		0.95		0.25		0.65
	Solvent	0.35					0.95			0.95	0.20	0.85		0.80	0.35				0.95	0.40			0.15	0.35	0.95	0.95

Figure 2.1. DSM with initial entries (Kaldate et al. 2006)

Engineering Parameters	EP #	5	12	15	23	14	18	9	1	6	17	20	22	24	25	11	13	19	21	16	10	2	4	7	8	3
Cartridge aspect ratio	5	5																								
Inlet vapor concentration - Adsorption	12		12																							
Temperature - Adsorption	15			15																						
Relative humidity Desorption	23				23																					
Relative humidity - Adsorption	14			x		14																				
Type of adsorbate - Desorption	18				x		18																			
Type of adsorbate - Adsorption	9					x		9																		
Material used for the vessel	1		x	x				x	1						x											
Adsorbent type	6		x	x		x		x		6			x													
Cartridge electrical resistance	17									x	17				x											
Heat transfer properties of the vessel	20								x			20														
Recycle of desorption stream - Desorption	22						x		x			x	22	x												
Power application algorithm	24		x		x		x	x		x	x	x		24												
Temperature of cartridge - Desorption	25				x			x			x				25											
Retention of adsorbate -Adsorption	11					x	x	x		x						11										
Recycle of desorption stream - Adsorption	13								x				x				13									
Cycle time - Desorption	19								x		x	x		x	x			19								
Purge flow rate	21		x				x	x							x				21							
Total gas flowrate - Adsorption	16																		x	16						
Cycle time – Adsorption	10		x			x		x					x				x	x	x	x	10					
Number of Vessels	2	x	x					x	x	x								x	x	x	x	2	x	x		
Cartridges arrangement	4	x																	x	x			4		x	
Mass of the adsorbent per vessel	7	x	x	x		x		x		x			x				x				x	x		7	x	
Number of cartridges per vessel	8		x																	x			x	x	8	
Vessel geometry	3	x							x														x		x	3

Figure 2.2. DSM after partitioning (Kaldate et al. 2006)

Wasserman (1993) emphasized the prioritization of data based on a "technical importance rating". He presents a decision model to allocate resources to design requirements based on a technical importance rating, as well as technical importance to a cost index of design requirements. Also, Yang et al. (2003) present a method that would target the most significant engineering parameters in order to increase the customer satisfaction.

George et al (2008) investigated front-end planning, and emphasized the importance of being able to define the critical activities at the beginning of the project in order to be able to effectively plan, and efficiently allocate resources necessary to bring the project to successful completion. This front-end planning provides the project team with a greater influence over the project, as their influence decreases and the cost of interfering increases when the project enters the execution phase.

Lowe et al (2006), realized the importance of forecasting the cost of construction as early and as accurately as possible in order for the client to be able to determine the feasibility of the project. They employed multiple regression techniques to predict construction costs of proposed projects. It is understood that a perfect estimate is not possible, and that a suitable accuracy of forecasting is within the range of 13% - 20% (Ashworth and Skitmore (1983); Ogunlana and Thorpe (1987)). Bailey and Smith (2011), utilize computer aided design and geometrical models of previous cases to integrate preliminary structural and architectural design. They show how this enabled them to basically filter through the thousands of parameters and constraints involved in design, and identify the ones that matter the most. This reduces the quantity of parameters and constraints to a much lesser number, which simplifies and speeds the design process.

Sundaram (2008) investigated Design Phase Cost Management and Budget Control. He emphasized the importance of controlling the budget from early on in the project, and being able to manage the costs effectively from the design phase. This allows everyone to see the big picture, and lets the owner knows the project will be performed according to his requirements and with no budget overruns. A completed project is a good thing, but a successful project is when the completion happens within the forecasted budget.

As part of the their research of front-end planning for projects, George et al (2008) conducted a survey that covered projects from all over the United States to identify the activities that are most crucial for a the success of a project. The p-value was set to 0.05, and it was concluded that certain activities are likely to be conducted successfully and efficiently if a project is to be completed successfully. At the same time, these same activities are not likely to be conducted effectively in projects that do not succeed. Seven activities were identified and are shown in Table 2.1. These findings allow a project team to focus from early on in the project, on the tasks and activities that will have the most significant effect on the success of their project.

Shane et al. (2009) investigated the cost overruns in engineering projects. They found that approximately 50% of all transportation projects in the US exceed their initial budgets. This highlights the importance of estimating the cost of the projects as accurately as possible and as early as possible. It is possible to deliver projects within budget as long as an accurate estimate is made, and awareness of cost escalation factors is present, and project management discipline is enforced.

Table 2.1.Significant activities for front-end planning (George et al. 2008)

Activity	Criteria	p-value
Establish image and public relations	Duration	0.003
	Internal resources	0.03
Define startup requirements	External resources	0.01
Refine public relations	Internal resources	0.02
Address quality and safety issues	External resources	0.05
Develop preliminary execution plan	Duration	0.05
	Internal resources	0.04
Compile project scope	External resources	0.01
Develop utilities and offsite scope	Internal resources	0.03

Flyvbrjerg et al. (2002) also investigated the discrepancy between initial cost estimates and final project costs. They showed that schedule and cost overruns are coomon in large construction projects, and can be very significant. They sampled projects over a period of 70 years and concluded that estimating practices have not improved during that time period. Their study yielded Table 2.2. which shows the inaccuracy in initial cost estimates indifferent transportation projects. It was found that rail projects have the highest cost overruns with an average cost escalation of 44.7%, followed by bridge projects at 33.8%, and road projects at 20.4%. They also determined that cost estimate inaccuracies are a worldwide problem, and is not limited to North America.

Table 2.2. Inaccuracy of transportation cost estimates (Flyvbjerg et al. 2002)

	All projects		Europe		North America	
Project type	Number of cases	Average cost escalation (%)	Number of cases	Average cost escalation (%)	Number of cases	Average cost escalation (%)
Rail	58	44.7	23	34.2	19	40.8
Bridge	33	33.8	15	43.4	18	25.7
Road	167	20.4	143	33.4	24	8.4
All projects	258	27.6	181	28.7	61	23.6

In an effort to improve cost estimates, a thorough literature review was performed by Anderson et al. (2006) to identify the factors that affect cost estimates in transportation construction projects. They collected data from various sources, and analyzed and categorized that data by performing a triangulation. This process exposed the common factors that different sources suggest that lead to cost overruns. Shane et al. (2009) talked about internal and external factors that lead to cost escalation and the phase in the project lifetime during which these factors develop. Table 2.3. shows the findings where 11 cost escalation factors were found to be internal and seven factors to be external. Some factors can be both internal and external, such as scope changes and scope creep.

Table 2.3.Cost escalation factors by cause and development phase (Shane et al. 2009)

Source	Cost Escalation Factor
Internal	• Bias • Delivery/procurement approach • Project schedule changes • Engineering and construction complexities • Scope changes • Scope creep • Poor estimating • Inconsistent application of contingencies • Faulty execution • Ambiguous contract provisions • Contract document conflicts
External	• Local concerns and requirements • Effects of inflation • Scope changes • Scope creep • Market conditions • Unforeseen events • Unforeseen conditions

CHAPTER III

METHODOLOGY

3.1 Overview

This research effort is anchored on developing statistical models to estimate the weight of transmission steel monopoles prior to design. The reliability of the models and their impact on the process must be assessed. To achieve this, the existing system without utilizing the models had to be evaluated. The models are calibrated and tested for accuracy, and then implemented into the process. After the models are consistently utilized, the process is evaluated again and the impact is measured and compared to the pre-models process.

The evaluation of the process was done by two methods. The first method recorded the number of poles produced daily over a period of five months. The second method developed a value stream map of the process. After the models were developed, tested, calibrated, and introduced into the process, the productivity was recorded again on a daily basis over a period of five months. Additionally, another value stream map was created. A comparison was then made between the pre-models data and the after-models data to determine the effectiveness of the models, and draw conclusions accordingly. The current state map at Pelco Structural is mapped using iGrafx software. Initially, the tendency was to map the whole transactional system in the office. However, after close examination, it was determined that it would be better to micro map the specific steps that are affected by this research, rather than have an overview of the whole process. Thus, the focus is on detail mapping of the design activities. The first step involved defining all different tasks that a design engineer performs. The design engineers were asked to list within 30 seconds all the different tasks they perform. Those tasks were then mapped and the current state was recorded as a snapshot picture. The reason this exercise was limited to 30 seconds is to prevent participants from overthinking, and have them go with their natural inclinations and initial thoughts.

To develop the model, extensive data collection took place over the course of 18 months. Prior projects that Pelco designed were checked for accuracy and suitability for use in the research. Most of the structures were found to be overdesigned with many approximations and estimates in place. This data was not considered suitable for the model development. The majority of the projects had to be revised or even completely redesigned with great accuracy and attention to details in order to provide precise data that is suitable for use in developing the model.

A table was created that breaks down every aspect of every structure to be used in the model. The different steel weights of every component of the structure was identified and isolated. The design factors involved such as wire tensions, ice loading, wind loading, voltage, and height were all recorded and itemized. Design data for over 300 poles were gathered. After collecting the data, many errors were discovered, or overlooked items that would require the process to be repeated all over again. After a significant amount of data points with reliable accuracy and no known errors was collected, the models were created.

Three linear regression models were created that relate the steel weights of the structure to the variables involved. The variables are:

- Radial ice thickness (inches)
- Wind speed (mph)
- Voltage (kV)
- Height (ft)
- Longitudinal force (lbs)
- Transverse force (lbs)
- Vertical force (lbs)

One model related the weight of the core steel pole to the variables. The second model related the weight of the base plates/anchor bolts to the same variables. The third model related the total weight of the steel structure (including core pole, base plate, anchor bolts, connections, and miscellaneous items) to the variables. The next step involved testing the model using data from actual projects. To do that, actual projects were used. After the models were tested developed and tested, each project was designed the conventional way and then the models were used to estimate the steel weight. A table was created comparing results from both methods for every structure considered in order to determine the accuracy and reliability of the models. After the models were tested, implemented and regularly used, another value stream map of the process was created.

During this research, before and after the implementation of the models, the number of designs performed per day were recorded and charted in order to quantify the impact of the models.

3.2 Existing Process

The existing traditional design and estimating processes utilize intensive design and estimating tasks in order to estimate steel weights that can be used to bid projects. The design process involves labor intensive activities and utilizes commercial software and in-house developed spreadsheets to design steel poles according to customers' requirements. After the designs are produced, they are passed along to the estimating department to perform a quantity takeoff to determine the amount of steel required. The accuracy of the existing process was measured by reviewing past bids and checking the associated designs. It was found that even with the labor intensive design and estimating processes, the accuracy was low. This is mainly due to limited resources and the need to meet bidding deadlines, which results in major approximations, errors, and mistakes. This inaccuracy was quantified in a table by comparing the steel weights used for bidding to the final design weights used for production. Seventy structures were examined in detail. Table 3.1. shows a brief highlight of some of the findings, while the detailed comparison can be found as part of Appendix E.

Table 3.1. Determining accuracy of existing process

No.	Preliminary Design Weight (lbs)	Final Design Weight (lbs)	% Change
1	35758	34025	-4.8
2	34418	28229	-18.0
3	23456	19793	-15.6
4	22210	18518	-16.6
5	39716	40509	2.0
6	37331	34070	-8.7

Table 3.1.(cont.) Determining accuracy of existing process

No.	Preliminary Design Weight (lbs)	Final Design Weight (lbs)	% Change
7	14438	14075	-2.5
8	11629	11456	-1.5
9	11092	10670	-3.8
10	12982	12675	-2.4
11	11836	11783	-0.4
12	4815	4712	-2.1
13	3516	3122	-11.2
14	2079	2027	-2.5
15	2243	1683	-25.0
16	43861	40947	-6.6
17	26446	24373	-7.8
18	21088	19348	-8.2
19	49627	47220	-4.9
20	97612	87024	-10.8
21	14438	14075	-2.5
22	76832	70643	-8.1
23	71354	66754	-6.4
24	70418	68035	-3.4
25	64500	60539	-6.1
26	47984	44831	-6.6
27	41200	38938	-5.5
28	85476	83345	-2.5
29	42112	47837	13.6
30	8409	8230	-2.1
31	10014	9521	-4.9
32	25073	25015	-0.2
33	23684	23440	-1.0
34	87387	91311	4.5
35	53389	47866	-10.3
36	35940	35435	-1.4
37	44299	41765	-5.7
38	30984	29781	-3.9
39	38917	37755	-3.0
40	3929	3881	-1.2
41	4257	4224	-0.8
42	4606	4596	-0.2
43	5927	4959	-16.3
44	6726	6009	-10.7
45	7822	7584	-3.1

Table 3.1.(cont.) Determining accuracy of existing process

No.	Preliminary Design Weight (lbs)	Final Design Weight (lbs)	% Change
46	8766	8398	-4.2
47	12376	12053	-2.6
48	14984	14397	-3.9
49	11062	10965	-0.9
50	15438	15012	-2.8
51	10695	9640	-9.9
52	20839	19800	-5.0
53	11614	9473	-18.4
54	18099	17005	-6.0
55	17703	16880	-4.7
56	18970	17909	-5.6
57	24504	22934	-6.4
58	6933	6313	-8.9
59	3997	2984	-25.3
60	6454	5193	-19.5
61	5326	5246	-1.5
62	6007	4422	-26.4
63	18855	17191	-8.8
64	15031	15717	4.6
65	11469	12126	5.7
66	6983	6881	-1.5
67	7880	7790	-1.1
68	7077	5342	-24.5
69	9692	8093	-16.5
70	11784	9617	-18.4

Table 3.1 shows there is generally a tendency to overdesign and/or overestimate the steel weights. 65 out of the 70 structures reviewed were heavier than they needed to be, meaning that the bids submitted could have been lower and more competitive. This is not uncommon, as engineers tend to overdesign when the resources needed to perform an accurate design are not available. The mindset is that it is better to lose a bid than to win a bid and lose money on it. The comparison shows that the existing process produces results that are off by as little as 0.2 % and as much as 26.4%. On average the bids are off

by 7.2%. This serves to show that despite the time and effort invested, the results obtained are not reliable, inconsistent, and may not allow the company to be competitive on its bids.

3.3 Productivity and Consistency Monitoring (Improvit)

Improvit software was provided as a courtesy from Pelco Products in Edmond, Oklahoma. This is the same software that they use to continuously monitor the performance of their production teams. Not only does it identify areas of improvement, but it also red flags any problems in addition to highlighting instances where performance meets or exceeds expectations. This enables them to fix problems in a timely manner, and also identify and emphasize successful procedures. Mark Nash of Pelco products recommended this software to quantify and measure the impact of the models developed when they are introduced into the process.

This software allows continuous capture of productivity (in this case, the number of monopoles designed per day) over an extensive period of time. When the models are created and implemented into the process, the productivity is recorded over an extensive period of time, and then compared to the data collected before the implementation of the models. Higher productivity (more poles designed per day and over a certain period of time), higher consistency, lower variation, are indicators of an improved process.

Data must be compared in a meaningful way so as to not falsely realize improvements that do not exist, or credit improvements to the wrong reasons. *Understanding Variation; The key to managing Chaos by* Donald J. Wheeler provides an understanding of how to capture and compare data in meaningful ways without falling into common traps and while avoiding flaws. Variation is inevitably present, and it cn come from various sources and for different reasons. The biggest challenge when comparing data from different times, is the determination of how much of the difference in data values is due to variation in numbers, and how much, if any, is due to an actual change in the process. However, it is not possible to replicate the same day twice. Hence, comparisons between two or more days (or any period of time) should not only focus on the process considered, and its associated elements, but rather utilize a broader view that encompasses other factors that may have an influence on the collected data values.

Limited comparisons and tables of data provide a narrowly focused and difficult to comprehend comparisons. Graphs on the other hand provide an easier, more accurate means of comparing and interpreting data because they encompass current values and previous related values in an easy to view fashion. The Time-Series graphs have proven valuable in this regards, and additional tools such as histograms, averages, and ranges, provide for an even better understanding of compared data within the correct context. The Improvit software utilized in this research is basically a time-series graphical presentation that allows for comparing values before and after the development/implementation of the model over extensive periods of time. How this data is interpreted, analyzed, and utilized depends on the experience and conceptual understanding of the researcher.

Dr.Walter Shewhart's developed many principles for understanding data, the first of which is:

"*No data have meaning apart from their context*". This principle has associated rules and consequences that can be summarized as follows:

- No comparison between two values can be global;
- Management reports are full of limited comparisons;

- Graphs make data more accessible to the human mind than do tables;
- Numerical summaries of data may supplement graphs, but the can never replace them; and
- No data have meaning apart from their context.

3.4 Development of Design/Estimating Models

The model was developed over a period of 2 years. During that time, data was collected, refined, quality controlled, tested and analyzed. Since real projects are used, the main challenge was to find enough projects that are suitable to provide accurate data. Additionally, it was critical to be able to determine what data is useful and include it, and which data is not and exclude it. Many projects were either missing critical information, or were utilizing different types of structures that are not in the scope of this research.

3.4.1 Data Collection

The purpose of the models is to estimate the steel weight of monopoles through utilizing common variables such as height, voltage, and loads that are readily available on every project, in order to eliminate the need for detailed design (at least at the bidding phase). To accomplish this objective, previous projects were analyzed in order to extract, categorize, divide, and organize the data in a way that would yield meaningful relationships that can be used to create the model. The objective was to predict future projects based on old ones, through finding and identifying relationships between data.

Design data from over 300 poles were collected from actual projects at Pelco Structural over the years. The data collection process took about 2 years, in order to gather sufficient, and more importantly, accurate data points that can be used for analyses. Many problems were not obvious from the beginning and it took a lot of data collection and preliminary analyses to identify them. The main challenge was not to collect the data, but rather to collect data points that are accurate, precise and not skewed in any way. Once the problems were identified, and depending on the nature of each individual problem, the pertinent data would either be revised or would be eliminated altogether. Examples of the encountered issues while collecting the data are:

- Initially, data for poles with arms and poles without arms were lumped together. This may affect the accuracy of the results, so these data were separated into two categories – with arms and without arms.
- Multi-section poles are connected using either slip joints or flange plates. The initial inclination was to compile pole data regardless of the connection used. However, as the research progressed, it was deemed as more accurate to limit the data collected to one type of connection or the other. Since slip joints constitutes the majority of the connections made, it was decided to limit the data used in the model development to poles with slip joints. As with the previous point, the procedures and findings of this research effort could be extended to future research of poles with flange plates.
- The connections were standardized for all poles included in this research. This includes all miscellaneous items, and pertains to size and quantities of the connections, vang plates, top plates, and ground lugs.
- The size of the openings in the base plates are standardized at 70% of the total plate diameter. Initially there was a big variance in their sizes from one plate to the other, which had an impact on the weight of the base plate.

- The weights of connections, base plate/anchor bolts and the core pole were isolated from each other in order to give flexibility when performing the analyses later. Initially the entire weight of the pole including connections and base plate/anchor bolts was lumped together. This isolation of data allows performing research using individual or combined weights of the components. This, allows for determination of the particular weights that contribute to accurate analyses and the ones that do not.
- Transmission poles can be guyed or self-supporting. Both types have different characteristics, and thus, cannot be combined when collected data. This research is limited to self-supporting structures.

Details of the collected data can be found as part of Appendix H.

3.4.2 Data Processing

The collected data was separated into 2 groups. The first group was used in developing the model, while the second group was used for calibration and model verification.

Three models are created:

1- Core Pole Weight vs. Variables

2- Base Plate/Anchor Bolts Weight vs. Variables

3- Total Pole Weight vs. Variables

Breaking up and isolating the data allowed the researcher to create more than one model. The idea behind this is to identify the particular weights that can be predicted more reliably than others through the input variables. In other words, it gives more options when performing the analyses as it provides alternatives in case a particular analysis fails to yield reliable results. At the same time, this methodology would provide more than one useful model, if the results prove reliable. The input variables considered are: pole height, voltage, number of wires, wire tensions, transverse loads, vertical loads, radial ice thickness, and wind speed. These are believed to have the main impact on the weight of the steel structure; besides, they are common input variables readily available on every job.

3.5 Value Stream Mapping

The idea of value stream mapping (VSM) was first introduced by Mike Rother and John Shook (1998). According to them, "Whenever there is a product (or service) for a customer, there is a value stream. The challenge lies in seeing it". The value stream map provides the means to see it. Since that first book, numerous others have published new ideas and different ways of utilizing value stream mapping. The basic concept however remains the same. The value of VSM is that there is no rigidity, and each mapper may devise with a different way to use the same basic tool. Current state, future state, and improvement state are the three phases of concern, and VSM provides the tool to get from the first state to the second state by using the third state.

Value stream mapping can be thought of as a way to see both the process flow from start to finish, as well as the communications associated with that flow. It facilitates continuous improvement, because of its ability to gather, analyze, and present information in a very condensed time period. More importantly, VSM presents a process technique that is simple enough for anybody to visualize and comprehend, regardless of their background or their position relative to an organization. Process mapping initially was a complex tool developed and utilized by technical personnel, but with VSM, that has now changed and everyone can understand the process maps. VSM uses pictures and diagrams to present the process and the time associated with each activity in a logical manner. A value stream map consists of 3 sections:

1- Process or production flow
2- Communications or information flow
3- Timelines and travel distances

VSM involves determining work flow and communication flow, and then understanding the relationship between the two. The biggest challenge is understanding the difference between the work flow of the process and the information being communicated in support of that work flow.

The mapping of the transactional processes can be done like production processes. The mapper can map the process by physically walking through each step of the process, starting from the last step and going backwards until the first step is mapped. Alternately, the mapper can be physically stationed at one location and map the process by observing the different activities distantly. The mapping technique depends on things such as the nature of the transactional process, the service provided, the setup of the office and work stations, the physical location of employees and inventory, and the pace of the flow. It may not always be possible to map every step while it is occurring. In this case, it is crucial to engage the people involved in each step, and rely on their input to accurately represent the flow. Furthermore the mapper must have a general understanding of what is going on. The flow is still walked back to front, even if it is not captured live.

The flow between process steps could be Pushed, Pulled, or FIFO (First in, first out). The pull system is the most preferred as it means that items are moved from a process step to the next, only when the next step is ready to receive. However, in reality, a push system is the one that controls. This means that items are pushed from one step to subsequent ones without regards if the subsequent steps are ready to receive it or not. This usually creates a queue of items and indicates that each step is operating with an island mentality, that is, without regards to other process steps within the value stream. The objective when creating a future VSM is to transfer as many of the pushes found in the current VSM as possible, into pulls. FIFO is more of a compromise when pull is not possible. A FIFO lane is a controlled area created between steps where items produced by one step is placed at one end, and then pulled by the subsequent step at the other end of the lane. The control is set to allow a certain number of pieces to be in the lane, and when that number is reached, a signal is sent to the feeding step to slow down or stop producing until the receiving step catches up.

It is very important to calculate the TAKT time as early as possible. TAKT is German for 'beat', and is defined according to the following formula:

$$\text{TAKT Time} = \frac{\text{Net available time for identified time period}}{\text{Customer demand for the same time period}} \tag{2.1}$$

Calculating the TAKT time early allows a better understanding of what is expected from the system, which in turn allows for better observations during the mapping process. The "close enough" concept is based on the general rule that if the data collected for a map is 70% accurate, then that is good enough to get started. To sum up: define each process step in the value stream – identify if push or pull – calculate TAKT time – capture cycle times for each step and show it in the data box of each process step.

CHAPTER IV

RESULTS

4.1 Overview

This chapter will cover in detail the results obtained in each part of this research effort. All results are related and dependent on each other, and quite often more than one activity was performed at the same time, such as monitoring productivity while developing the models, or utilizing the models while calibrating them. For simplicity, the results will be divided here by topic, rather than by sequence. However, it will be emphasized what activity took place at which phase, in order to better understand the results obtained. The productivity monitoring before and after utilizing the models is presented, followed by the three models obtained, including the validation and calibration. Subsequently, the initial and final value stream maps are presented.

4.2 Productivity of Consistency Monitoring (Original)

It was already known to everyone involved that the productivity is very inconsistent, varying greatly from day to day, and it is overall much lower than it needs to be in order to meet customers' needs. This common knowledge had to be translated into actual quantifiable data in order to clearly see the magnitude of the problem, and how it impacts the operations of the company. It was necessary to measure how inconsistent the process is, and to quantify how far off the existing productivity is, from what it needs to be. A daily log was created, where the design engineer would record the number of steel monopoles designed every day.

Appendix A has the daily logs from the Improvit software that was used to record the number of monopoles designed each day over a period of 5 months, prior to the implementation of the software. Figure 4.1 presents a summary of the Improvit output, presented as an Excel chart for clarity. The figure shows that the number of poles designed per day is very inconsistent from day to day. The overall average is less than 2 poles per day. Another observation that is obvious is that on most days the number of poles designed is less than the peak number witnessed on a few occasions. Therefore, even when there is high productivity, it is difficult to maintain over a long period of time. This is because the increased productivity is due to increased man-hours and not due to an improved process. The increase in man-hours or overtime cannot be maintained over a long period of time, and hence, the inconsistency in the productivity.

The same process of recording the number of poles designed per day continued after the model was implemented into the process. The goal was that the number of monopoles designed per day (productivity) would increase, and the variation from day to day would decrease (higher consistency).

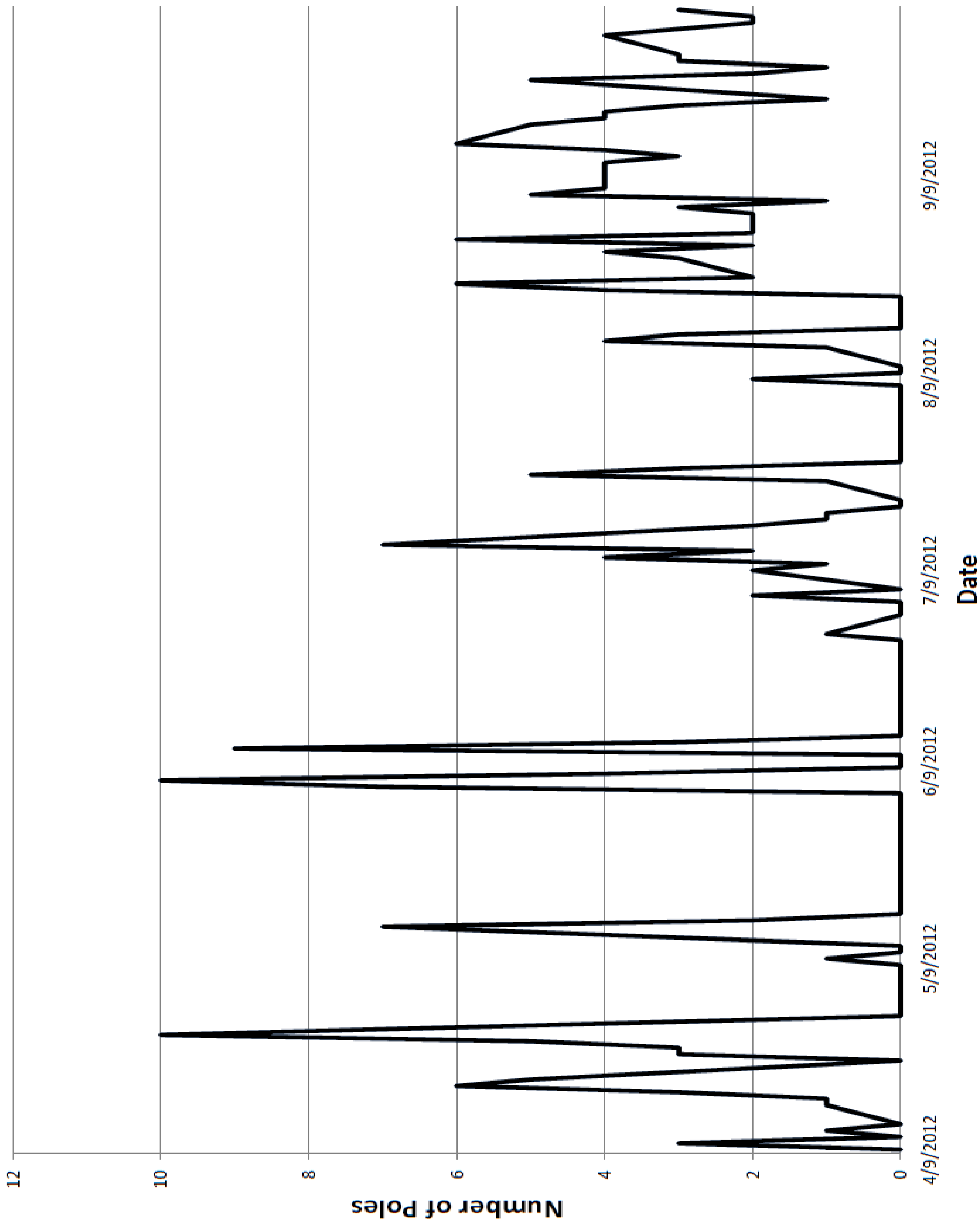

Figure 4.1. Productivity and consistency before models

4.3 Productivity and Consistency Monitoring (Revised)

The number of poles estimated utilizing the models were recorded daily in order to monitor the productivity as well as the consistency of the process once the models have been utilized. The productivity and consistency are then compared to those from the period before the models were used. The recording took place over a continuous period of 4 months. A period of 2 weeks was allowed for engineers to get used to using the models, before starting to monitor the productivity and create a daily log. Appendix B has the daily logs from the Improvit software that was used to record the number of monopoles designed each day. Figure 4.2 shows a summary of the Improvit output, presented as an Excel chart for clarity. The figure shows that the productivity has increased, and the consistency has been added to the production. There are no more spikes in the chart, and the production does not vary drastically from day to day. Additionally, the number of poles produced each day has also increased – on average – compared to production before utilizing the model. The average number of poles produced increased from under 2 poles per day to almost 7.5 poles per day.

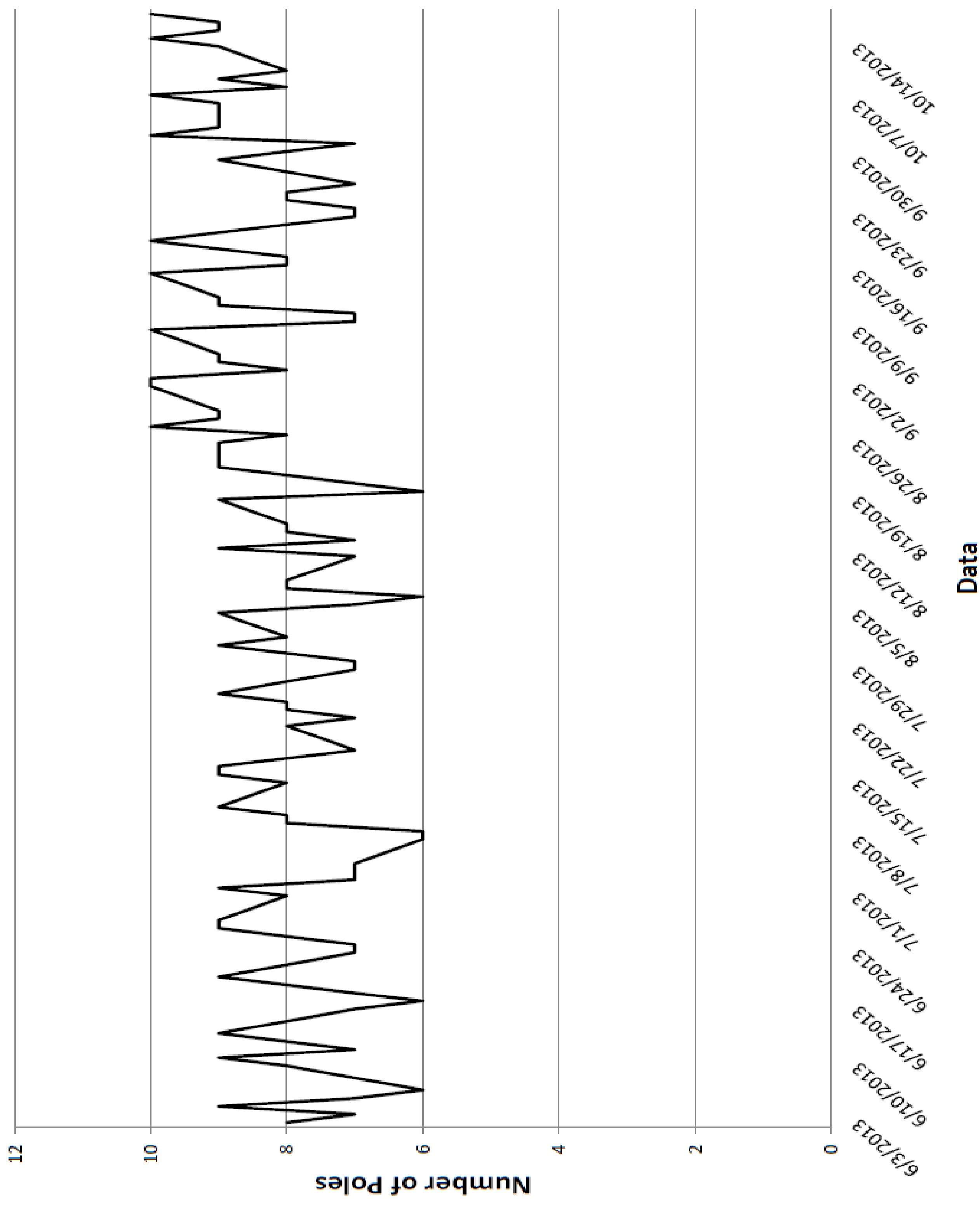

Figure 4.2. Productivity and consistency after models

4.4 Statistical Models

The three statistical models obtained as part of this research are presented in this section. The first model predicts the Total Weight of the steel pole, which includes the core pole, connections, base plate, anchor bolts, and any miscellaneous items on the pole. The second model predicts the weight of the core steel pole only, meaning no connections, base plate or anchor bolts are included in the estimated steel weight. The third and final model predicts the weight of the base plate and anchor bolts only. It was determined that the main parameters in predicting the steel weight – in all three cases – were the height, the longitudinal force (Y) , the transverse force (X), and the vertical force (Z). The voltage, radial ice thickness, and wind speed are all categorical (qualitative) variables and their impact is accounted for by the other quantitative variables utilized in the model. The voltage is accounted for in the height, transverse, longitudinal and vertical forces. The ice load is incorporated in the transverse and vertical forces. The wind speed is incorporated in the transverse force. An analysis of variance was performed and the residuals were evaluated as part of the statistical analysis. The detailed results are part of Appendix C.

To access how well the models fit and represent the data, the R^2 as well as the R^2 adjusted are calculated in all cases. The R^2 is one of the most common techniques utilized to evaluate a multiple linear regression model. It is the percentage of variability in the y-values that's explained by the model has a value between 0 and 1.0. A value closer to 0 means that the model is not successfully explaining y, while a value closer to 1 means that the model is doing a great job in explaining y. It is considered that that R^2 values higher than 0.7 are good. The difference between R^2 and R^2 adjusted is that the first doesn't change when additional variables are added to the model, even if these variables are not adding any value. The latter however, changes in value and can decrease if the additional variables are not helping the model. That means that R^2 adjusted is more useful than R^2 in evaluating the value of the variables considered while performing the analysis.

To better understand the variables considered and be able to view each variable individually, a stepwise analysis was performed. The individual p-values were calculated for each variable. The p-value evaluates the statistical significance of the variables. It is set to a certain value, commonly 0.05 or 0.01, and the idea is to have a null hypothesis that can be rejected or accepted based on the p-values of the test statistics considered. If the p-value is lower than the predetermined cutoff, then there is strong presumption against the null hypothesis. As the p-value obtained exceeds the predetermined cutoff, that presumption decreases. In other words, the p-value determines evaluates the probability of the results being reliable due to statistical significance as opposed to being obtained by chance or random error.

4.4.1 Total Weight vs. Variables

The first model developed estimates the total weight of the steel pole. Data from 136 poles was utilized in the statistical analysis to develop the model. Equation 4.1 shows the predictive equation obtained, and the detailed statistical results can be found as part of appendix C:

N = 136 R^2 = 90.19%

$$\text{Total Weight (lbs)} = -27949.2 + 0.281465 \text{ Y-Force (lbs)} + 373.402 \text{ Height (ft)} + 0.1306 \text{ X-Force (lbs)} + 0.21 \text{ Z-Force (lbs)} \quad (4.1)$$

4.4.2 Core Weight vs. Variables

The second model estimates the weight of the core of the steel pole. Data from 136 poles was utilized in the statistical analysis to develop the model. The core means the pole without the base plate, anchor bolts, connections or any miscellaneous items. Equation 4.2 shows the predictive equation obtained, and the detailed statistical results can be found as part of appendix C:

N = 136 R^2 = 91.59%

$$\text{Pole Weight (lbs)} = -23220.8 + 0.17194 \text{ Y-Force (lbs)} + 303.662 \text{ Height (ft)} + 0.1 \text{ X-Force (lbs)} + 0.14 \text{ Z-Force (lbs)} \quad (4.2)$$

4.4.3 Base Plate/Anchor Bolts Weight vs. Variables

The third model estimates the weight of the base plate and anchor bolts. Data from 136 poles was utilized in the statistical analysis to develop the model. Equation 4.3 shows the predictive equation obtained, and the detailed statistical results can be found as part of appendix C:

N=136 R^2 = 95.92%

$$\text{BP-AB (lbs)} = -1755.44 + 0.0471731 \text{ Y-Force (lbs)} + 35.8935 \text{ Height (ft)} + 0.03 \text{ X-Force (lbs)} + 0.04 \text{ Z-Force (lbs)} \quad (4.3)$$

4.5 Model Validation

The methodology utilized to validate the models was to design the poles using the usual traditional method in order to obtain the steel weights, and then estimate the pole weights using the models. Based on the results obtained, the models were calibrated to improve the accuracy. The statistical analysis showed that in all the models, the constant had by far, the largest standard error. Hence, the models were calibrated by adjusting the value of the constant. No other measures were needed to calibrate the models. A table is constructed tabulating the outputs of both methods to allow for comparison and measurement of variance between the outputs of both methods. Table 4.1 shows a sample of the results obtained. The detailed and complete table can be found as part of Appendix D.

Table 4.1. Total Weight: Design vs. Predicted

Design(lbs)	Predicted(lbs)	%Difference	Calibrated Predicted(lbs)	%Difference
10034	14213	41.66	10213	1.79
10882	16080	47.77	12080	11.01
10114	14296	41.35	10296	1.80
10585	15648	47.82	11648	10.04
9894	13781	39.28	9781	-1.15
9264	13904	50.08	9904	6.91
11619	14677	26.32	10677	-8.11
14379	19862	38.13	15862	10.32
44080	46390	5.24	42390	-3.83
52452	57722	10.05	53722	2.42
77455	82714	6.79	78714	1.62
73068	80846	10.65	76846	5.17
46275	49705	7.41	45705	-1.23
39691	44104	11.12	40104	1.04
14469	18466	27.63	14466	-0.02
20562	24565	19.47	20565	0.02
15334	18964	23.67	14964	-2.41
20784	24967	20.13	20967	0.88
25853	30824	19.23	26824	3.76
12568	16902	34.48	12902	2.65
19631	24409	24.34	20409	3.97
18602	22542	21.18	18542	-0.32
10386	14670	41.25	10575	1.83
11234	16537	47.21	12442	10.76
10466	14753	40.96	10658	1.84
10937	16105	47.24	12010	9.80
10246	14238	38.95	10143	-1.01
9616	14361	49.34	10266	6.76
11971	15134	26.42	11039	-7.78

A graph was then created utilizing the results obtained to illustrate the correlation between the design weight obtained using regular design methods, and the corresponding predicted weight obtained using the developed models. Figure 4.3. shows the plot for the total pole weight.

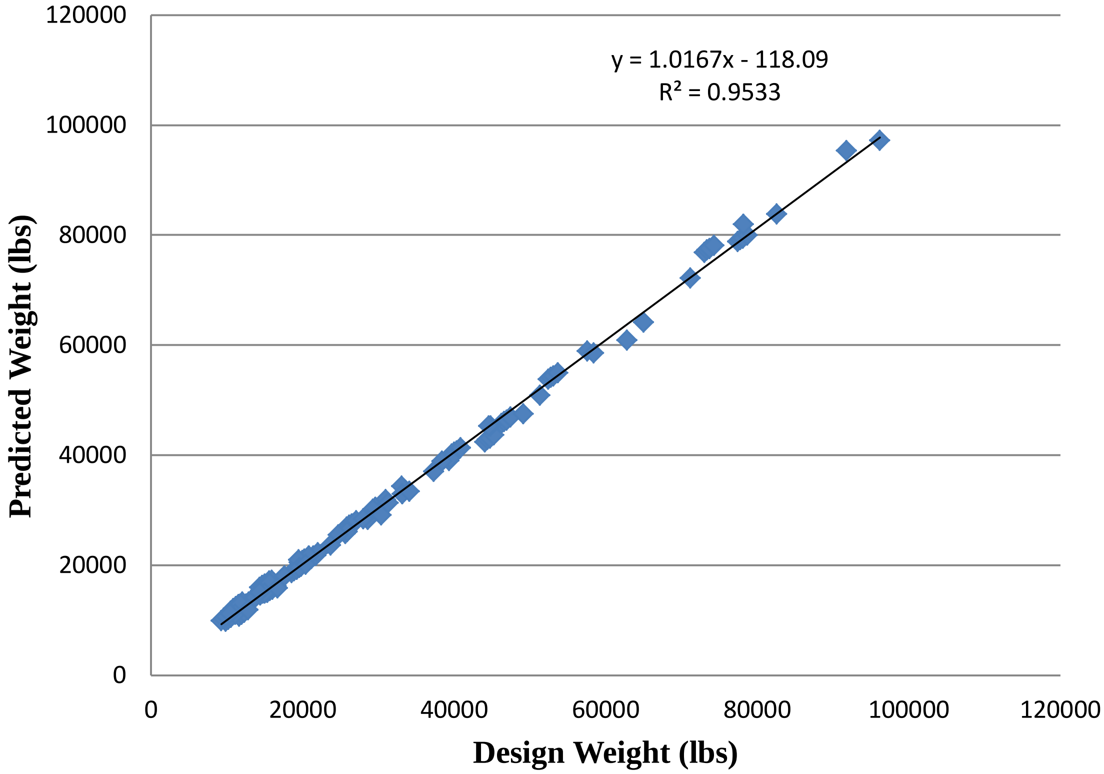

Figure 4.3. Total Weight: Design vs. Predicted

It should be noted that the model was calibrated and then retested. The calibrated model for the total weight produced results that vary from the design weight by as low as 0.018% and up to 10.035%. Figure 4.3. and the resulting equation relating the design and predicted weights, shows that both weights are highly correlated and that the model developed can in fact be used to estimate the total pole weight with results comparable to those of the detailed design process.

The same process was then repeated for the core pole weight model. Weights of the poles were calculated using the detailed design process and then using the model. Both outputs were tabulated and compared, and then a calibration was performed accordingly to further improve the output of the model. A sample of the results obtained can be seen in table 4.2., and the complete detailed results can be found as part of appendix E.

Table 4.2. Core Weight: Design vs. Predicted

Design(lbs)	Predicted(lbs)	%Variance	Calibrated Predicted(lbs)	%Variance
9097	12621	38.75	9621	5.77
8245	11103	34.67	8103	-1.72
7859	10654	35.56	7654	-2.61
7708	10393	34.84	7393	-4.08
8438	11911	41.17	8911	5.61
7229	10452	44.59	7452	3.09
33819	38744	14.56	35744	5.69
33033	32856	-0.53	29856	-9.62
34888	34657	-0.66	31657	-9.26
53069	55533	4.64	52533	-1.01
27140	28858	6.33	25858	-4.72
15247	16493	8.17	13493	-11.50
15224	19761	29.80	16761	10.10
18311	20992	14.64	17992	-1.74
16292	18267	12.13	15267	-6.29
15128	16749	10.72	13749	-9.11
12235	14560	19.00	11560	-5.52
11104	13041	17.45	10041	-9.56
9835	12209	24.14	9209	-6.36
10584	13475	27.32	10475	-1.03
9642	11957	24.01	8957	-7.10
9904	13545	36.77	10545	6.47
9769	13315	36.29	10303	5.46
8917	11797	32.29	8785	-1.49
8531	11347	33.00	8335	-2.30
8381	11087	32.29	8074	-3.65
9111	12605	38.35	9593	5.29
7902	11146	41.05	8133	2.93
34492	39437	14.34	36425	5.61

After calibrating the model, the design weights were then plotted against the predicted weights to highlight the correlation between values obtained using both methods. Figure 4.4. shows the plot obtained as well as the resulting equation and R^2 value representing it.

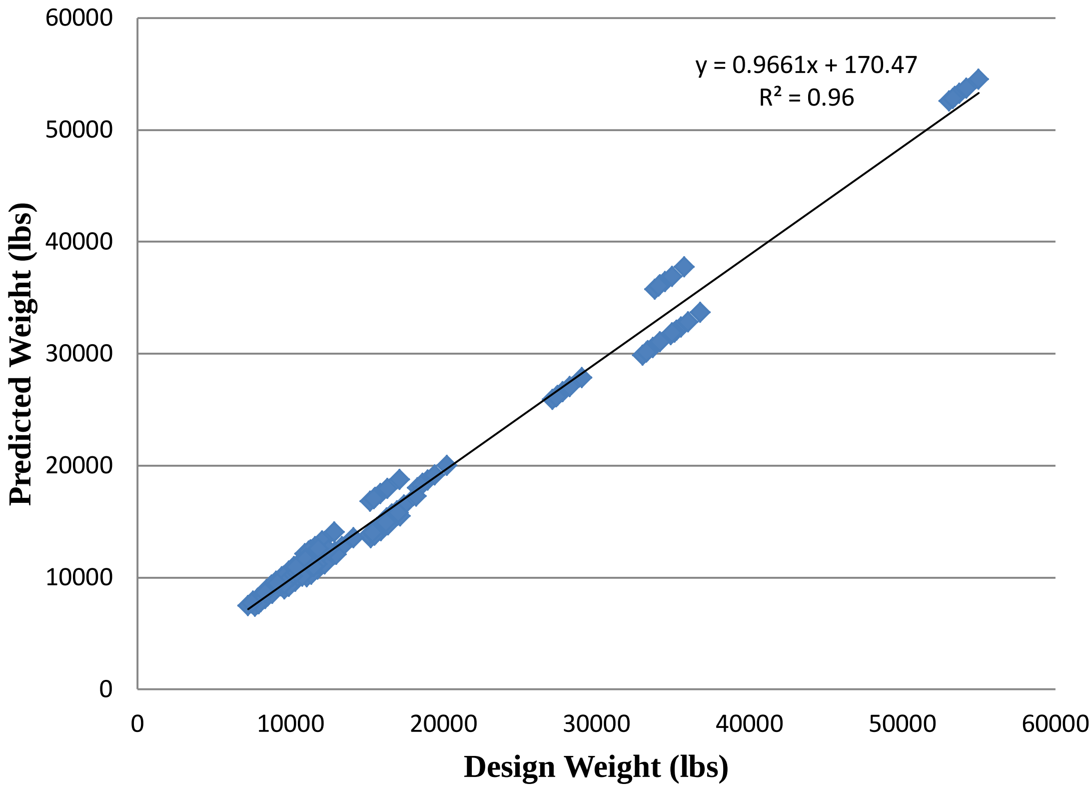

Figure 4.4. Core Weight: Design vs. Predicted

Finally, the same process was done for the Base Plate/Anchor Bolt model. A sample of the results can be seen in table 4.3., and the detailed results are part of appendix F. It can be noted that of the three models developed, the Base Plate/Anchor Bolts model produces the most accurate estimations of steel weight. This is expected, since this model is geared towards one particular item, as opposed to the other two models which are more inclusive of more items that compose the steel pole. The model was validated once against the design values for each pole design, in order to determine the necessary calibration. The model was then validated again - after calibration - against the same design values. The calibration of the model significantly improved the accuracy of the values obtained, and further calibration may improve the output even more.

Table 4.3. Base Plate/Anchor Bolts: Design vs. Predicted

Design(lbs)	Predicted(lbs)	%Difference	Calibrated Predicted(lbs)	%Difference
3429	3842	12.06	3442	0.39
3603	4022	11.63	3622	0.53
3202	3663	14.39	3263	1.90
2783	3106	11.57	2706	-2.80
2613	2926	11.98	2527	-3.32
2956	3285	11.13	2885	-2.40
2422	2774	14.51	2374	-2.00
2663	2953	10.90	2553	-4.12
2810	3214	14.35	2814	0.12
2985	3394	13.68	2994	0.28
2756	3035	10.12	2635	-4.39
278	3229	15.99	2829	1.63
2872	3408	18.69	3008	4.76
2613	3049	16.69	2649	1.39
3177	3698	16.40	3298	3.81
2995	3521	17.58	3122	4.22
3803	4328	13.81	3928	3.29
3036	3435	13.14	3035	-0.03
7554	7690	1.80	7290	-3.50
8120	8074	-0.56	7674	-5.49
9368	10408	11.10	10008	6.83
15721	15686	-0.22	15286	-2.77
15097	15507	2.72	15107	0.07
8039	8103	0.80	7703	-4.18
7337	7564	3.11	7164	-2.35
13031	13889	6.59	13489	3.52
9526	10198	7.06	9798	2.86
5552	5799	4.45	5399	-2.76
4295	4866	13.28	4466	3.97
1736	2085	20.13	1685	-2.91
4865	5252	7.95	4852	-0.27
4865	5236	7.62	4836	-0.60
4028	4444	10.32	4044	0.39
3822	4456	16.58	4056	6.12

Figure 4.5. shows the graph plotted between the design values of the Base Plate/Anchor Bolts weights and the corresponding estimated weights obtained utilizing the models. The design values are on the X-Axis while the predicted values are on the Y-axis. The equation presenting the linear correlation as well as the R^2 are also displayed in the figure and shows that the estimated value is close to the design value at any point on the plot.

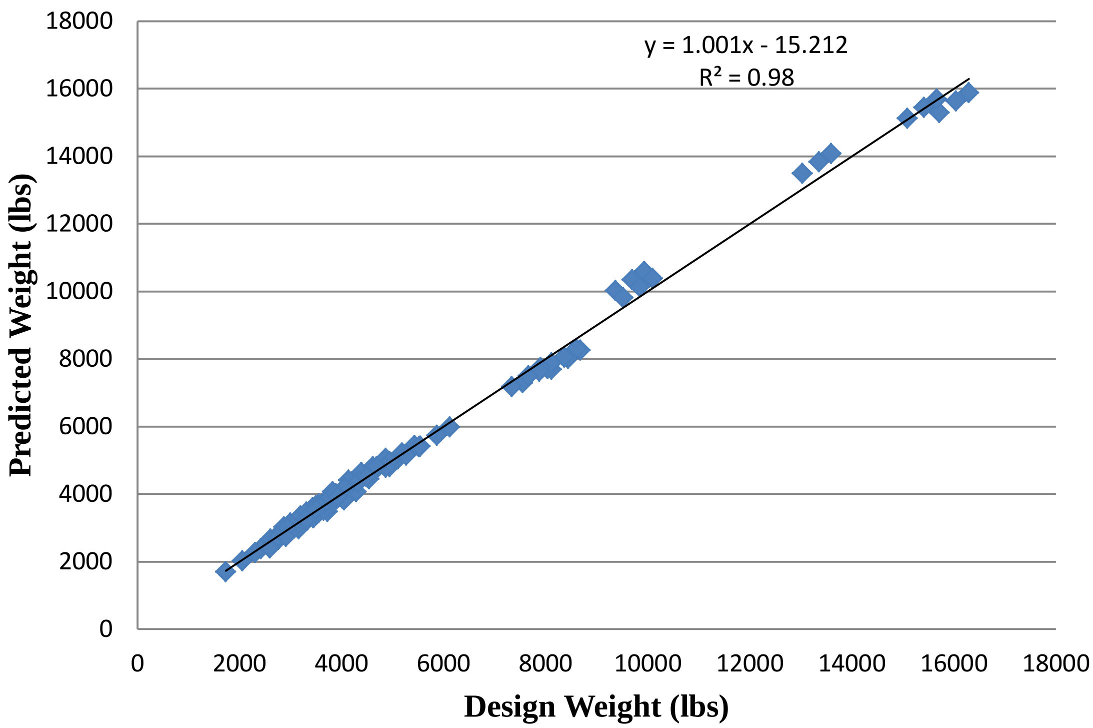

Figure 4.5. BP/AB Weight: Design vs. Predicted

It can be seen that the values of the base plate/anchor bolts weights vary in magnitude from a few hundred pounds to the order of a few thousands. This is mainly related to the size of the pole being supported. However, the ability of the model to predict the Base Plate/Anchor Bolt weights does not change regardless of the magnitude of the value. The model provides the same accuracy, as seen from table 5 and figure 12, over the entire range of weight values considered. The results shown in this section show that the three models developed can be reliably used in lieu of the traditional design process to estimate the steel weight of the entire pole, the core pole, or just the base plates and anchor bolts.

4.6 Baseline Value Stream Map

Appendix I shows the current state value stream map for the entire process at Pelco Structural. Figure 4.6. zooms in on the tasks in the map that are directly related to this research. The map specifically focuses on design/bid requests from the time they are requested by the customer, till the time a design and price is delivered to the customer fulfilling their request. This map is the basis against which any improvement in the process will be measured against. This snapshot was captured on Tuesday February 5th 2013 at 10 am. A regular workday was selected where all the employees involved were present in the office. Only the tasks and activities directly related to this research were included in the map. It took about 2 hours to map the process by physically walking through it. No prior notification was given to any of the employees, so that the activities mapped would be as regular as possible without anyone altering any work habits, or trying to influence the mapping process in any way. Many of the personnel including in the map didn’t even know that the mapping was taking place. The idea was that we want to capture what is really happening, rather than try to misrepresent the real process.

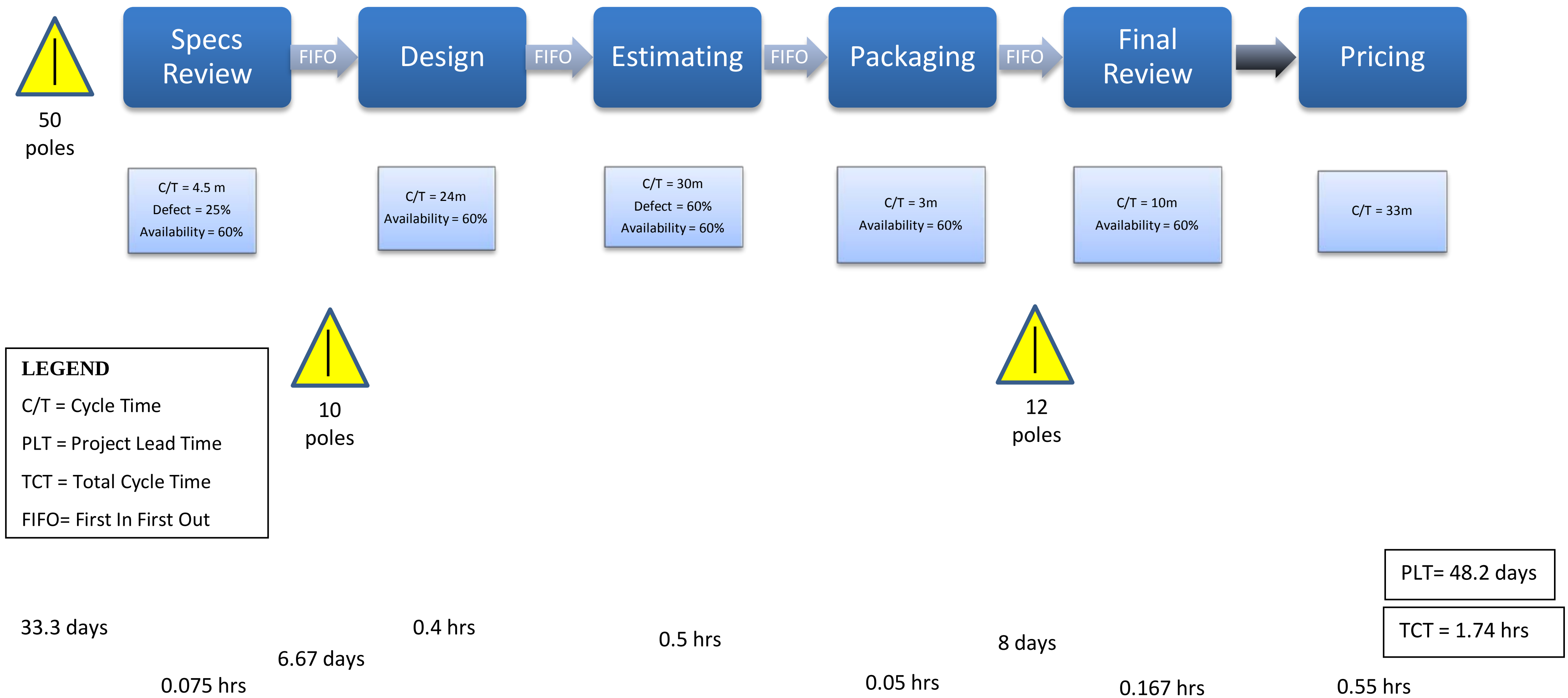

Figure 4.6. Baseline value stream map

The main players in this map are the Customer, Sales Personnel and Engineers. Having only 2 Engineers at Pelco, Engineering has always been the bottleneck and the controlling factor on *what* projects get are completed, and more importantly, *how* the projects are completed. The system was mapped on one of the busiest days in order to capture the process when it is really challenged by high work volume and be able to identify the problems. Needless to say, when the workload is low, most business practices would deliver regardless of their efficiency. It is the high work load that really tests the system and highlights any problems or deficiencies, and hence, presents an opportunity to make changes to improve the process.

The highlights of the VSM are that the customer demand is 30 poles per month, while the system in its current state has a PLT (process lead time) of 48.2 days and TCT (total cycle time) of 1.74 hours. These numbers are basically disastrous, since it means that a single pole needs 48.2 days to make it start to finish through the system, which theoretically means that the customer demand of 30 poles per month (or 1.5 poles per day based on 20 work days per month) is far from being met. The obvious question then is "how does Pelco Structural manage to stay in business?". There are many answers to this question, a few of them are:

- Overworking the staff and having the engineers and drafters work overtime.
- Make numerous approximations and estimates while performing various activities, in order to reduce the time spent on each activity. This means, that due diligence is not given to the work performed, thus, increasing the risk of errors, and reducing the possibility of winning bids.

- There are many slow days where the work load is low. These days help to counter the busy days where the work load is high.
- Prioritizing the bids and work to participate in, and in many cases electing to "no-bid" in many projects in order to free up resources for other projects that seem to have a better potential for the company.
- Sub-contracting and outsourcing some of the work to outside companies/personnel.
- Simply not meeting deadlines on many projects. This dictates asking for time extensions from customers, and go through a whole procedure of explaining and requesting more time to deliver. This is the one thing that the company tries to avoid the most, as it reflects very poorly on its image.

The power of the Value Stream Map is that it captures a snapshot of the process that highlights what is actually going on, and what problems (if any) are present. In this case, there appears to be a big back log at the front end (50 poles), meaning that the process is not moving fast enough to reduce this queue of projects to a reasonable number. As the process moves quicker downstream, this backlog and any subsequent backlogs will be reduced. The model developed in this research effort should provide a mean in moving the process smoother and quicker, thus, reducing the backlogs, and eventually reducing the PLT and TCT at the end of the cycle.

4.7 Revised Value Stream Map

The process was streamed again after implementing the model into the system in order to measure the impact that the models have made. Figure 4.7. highlights the tasks directly related to this research, while the complete map can be found as part of Appendix I.

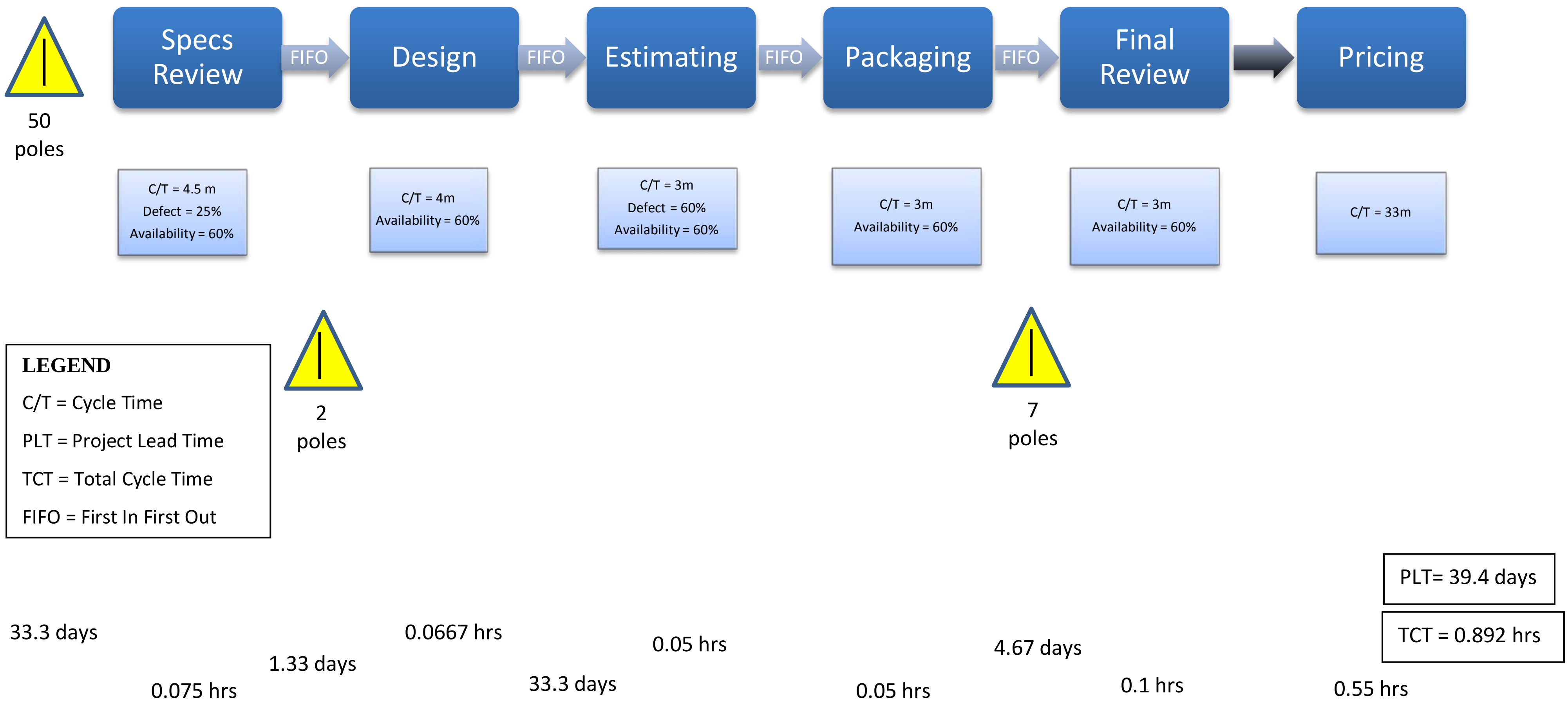

Figure 4.7.Revised value stream map

The model was implemented into the process and used for 2 weeks before the mapping took place. This is to ensure that the model is in full effect and the personnel are comfortable using it effectively before the impact is determined. As the diagram shows, by utilizing the model rather than the traditional process, the bottlenecks at the many locations were reduced, and the cycle times at the design and estimating phases have dramatically decreased. This translated into an overall lower project lead time, as well as a lower total cycle time, bringing the process closer to the goal of meeting the needs of the customers in a timely fashion, and bridging the gap between the customers demand and the process productivity. The project lead time went down from 48.2 days to 39.4 days, meaning that the utilization of the model has saved the company 8.8 days. In other words, the process can now deliver the same amount of work in 39.4 days rather than 48.2 days. This major reduction in project lead time was mainly due to the reduction of the cycle times of individual activities, as well as the reduction of the backlogs of work at each step of the process.

CHAPTER V

CONCLUSIONS

5.1 Summary

This research was conducted to evaluate and improve the design and estimating activities for steel poles used in transmission line applications, at the bidding phase of projects. It was determined that the existing design and estimating process has inaccuracies and is inconsistent. Multiple linear regression was used to develop statistical models that can estimate the weight of steel, primarily for bidding purposes. The models were tested and showed comparable accuracy to the existing process, but with a much lower investment of man-hours. The utilization of the models also improved the consistency of the process, and facilitated the flow of activities, as determined by the value stream maps constructed.

5.2 Key Findings

The results obtained in this research show that the models developed can be practically used to provide improved results. While the accuracy may not be precise, it should be noted that the traditional design and estimating process did not provide accurate results either. Moreover, with the promising results obtained, there is also room for improving the accuracy by performing further research and following the guidelines outlined here to obtain better results. Additionally, the methodology outlined and utilized in this research can be extended and applied to similar areas of research. Depending on the workload at any given time, and the qualifications of the company's personnel, the model(s) developed can be utilized in various forms:

- The models can be used as a primary design tool
- It can be used as a quality control tool, to verify designs and red flag any problems.
- The models can be used for bidding projects with lower priority, or projects that otherwise wouldn't be bid.
- The models can be used as a training and support tool for new engineers/designers.

This research highlighted that the steel weight of transmission monopoles can be estimated using the height, longitudinal force, transverse force, and vertical force. Other parameters that were considered, are voltage, radial ice thickness, and wind speed. These three parameters do not show in the models, as they are categorical variables, and their effect is accounted for by the other parameters present in the models.

It was also shown that despite any reduced accuracy when utilizing the models to estimate steel weight, this is more than made up for by the savings attained in reduced labor hours, the ability to bid more jobs, and the simple fact that the detailed labor intensive design process has comparable – if not lower – accuracy than the models developed. The consistency of the productivity is a major factor emphasized in this research. The detailed design process provides no consistency which raises a lot of red flags when it comes to reliability or trying to plan long term. The models showed the ability to provide consistent production which makes it possible for the management to plan ahead and have a reliable tool to count on to meet the production demands.

The value stream mapping highlighted the problems in the traditional process, and showed where the bottle necks and the weakest links are when it comes to meeting customers' demands and deadlines. It showed that the utilization of the models has improved the process, and brought it closer to meeting the customers' demands in a more timely fashion. At the same time, the value stream map showed that there are other areas along the process line that need to be addressed as well in order to further improve the process. Resolving the design and estimating issues alone does not resolve every problem in the process, as there are issues in other activities that need to be addressed both separately and in conjunction with other tasks and activities. The three models developed produced varying accuracy. The most accurate model is the Base Plate/Anchor Bolts model, followed by the Core Pole model, while the Total Pole weight model is the least accurate.

The productivity of any company can be improved by either adding resources, or by improving the existing process. The models developed in this research are one way of doing the latter. No additional resources or personnel are needed, yet the production and the consistency have improved drastically, as shown in this research. The improved process is about 9 days shorter than the original process for every cycle. This translates into roughly 90 days of saved work time per year. The traditional design process produced 2 poles per day on average with very high inconsistency in production. The revised process – utilizing the models – produces an average of 7.5 poles per day with very high consistency in production. This makes the new process more reliable and makes it possible for managers to better plan ahead, as they have a consistent rate of production that they can predict and plan upon accordingly.

5.3 Recommendations for Future Research

Based on the outcome of this research, it is recommended to do more research utilizing the same methodology outlined here in hopes of improving accuracy and achieving better results. More data points can be utilized and diversification of data sources can be considered. Furthermore, the same research can be applied to other types of structures in the transmission field, such as H-Frames or A-Frames, or even to a different field, such as buildings or oil and gas pipelines. It is recommended to stabilize as many factors as possible when performing any further research in this area, in order to ensure that any variation is due to the parameters considered and not due to factors which are not. It is recommended to set standards for everyone involved in data collection, if more than one person is collecting data, in order to avoid variation resulting from different collector's methods or standards. It is recommended for companies to review the value stream maps carefully, in order to identify issues in other steps of the process that are not addressed as part of this research, so the process may be further improved. It would be beneficial to test the models developed as part of this research in different companies – or work environments – in order to be able to make the models - and methodology in general - applicable to any company or work environment and not be specific only to the one considered in this research.

It is recommended that once the models are implemented at any company, that the customers and sales personnel are made aware of the main parameters that it utilizes in order for them to highlight these parameters to the model operator(s) which will facilitate the process. This will allow everyone to focus on the parameters that matter, and save them the time invested in gathering or collecting those that do not. At the same time, it helps all the parties involved have an understanding of the methodology implemented, in order to cater to it and make it successful. It is recommended that if the models are utilized, that they be calibrated at regular intervals in order to accommodate any changes in standards or design parameters that may take place. It is also highly recommended, that if the models are utilized for bidding purposes, that the traditional detailed design would still be performed periodically on some poles in order to constantly monitor and validate the models. Value stream mapping of the process is recommended at least twice a year, in order to be able to regularly monitor the system and identify any problems that may ensue, and be able to address them in a timely fashion. Continuing to create a daily log of the poles that are produced – as was done as part of this research - is very beneficial. It would allow the impact of the models to be constantly monitored, and hence, allow for timely intervention to make any necessary adjustments that may be needed to continue to use the models effectively.

If the models are not utilized, it is still highly recommended to highlight to the managers the pitfalls of the traditional design process as portrayed in this research, and the risks associated with that. The designs produced, despite the labor intensive process, do not produce accurate results, and have low consistency in both productivity and accuracy. The main consequences are a lower success rate in winning bids if the bids are high, or losses to the company if the bids are too low. The managers should be aware of that, in order to either accept the risks, or make changes in the process to eliminate them. The general tendency is to trust the exiting process, mainly because many problems go unknown and even when they are known, there is no simple alternative. Unless problems and their associated impacts are highlighted, as done in this research, companies are very hesitant to make any changes. However, when problems become known, and solutions are offered, managers are much more willing to implement changes in a process.

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APPENDICES

The appendices provides supporting results, data, calculations, or spreadsheets which are used for developing evaluating traditional design processes, developing and validating statistical models, and evaluating post-models process. The appendices are broken down as follows:

Appendix A	Pre-models results of the daily productivity monitoring using Improvit
Appendix B	Post-models results of the daily productivity monitoring using Improvit.
Appendix C	Results of multiple linear regression (MLR) analysis for the three developed models
Appendix D	Validation of model for predicting total weight of pole
Appendix E	Validation of model for predicting pole weight of pole
Appendix F	Validation of model for predicting base plate/anchor bolts weight of pole
Appendix G	Determining accuracy of existing process
Appendix H	Data collection for development of models
Appendix I	Value stream maps

Appendix A

Pre-models results of the daily productivity monitoring using Improvit

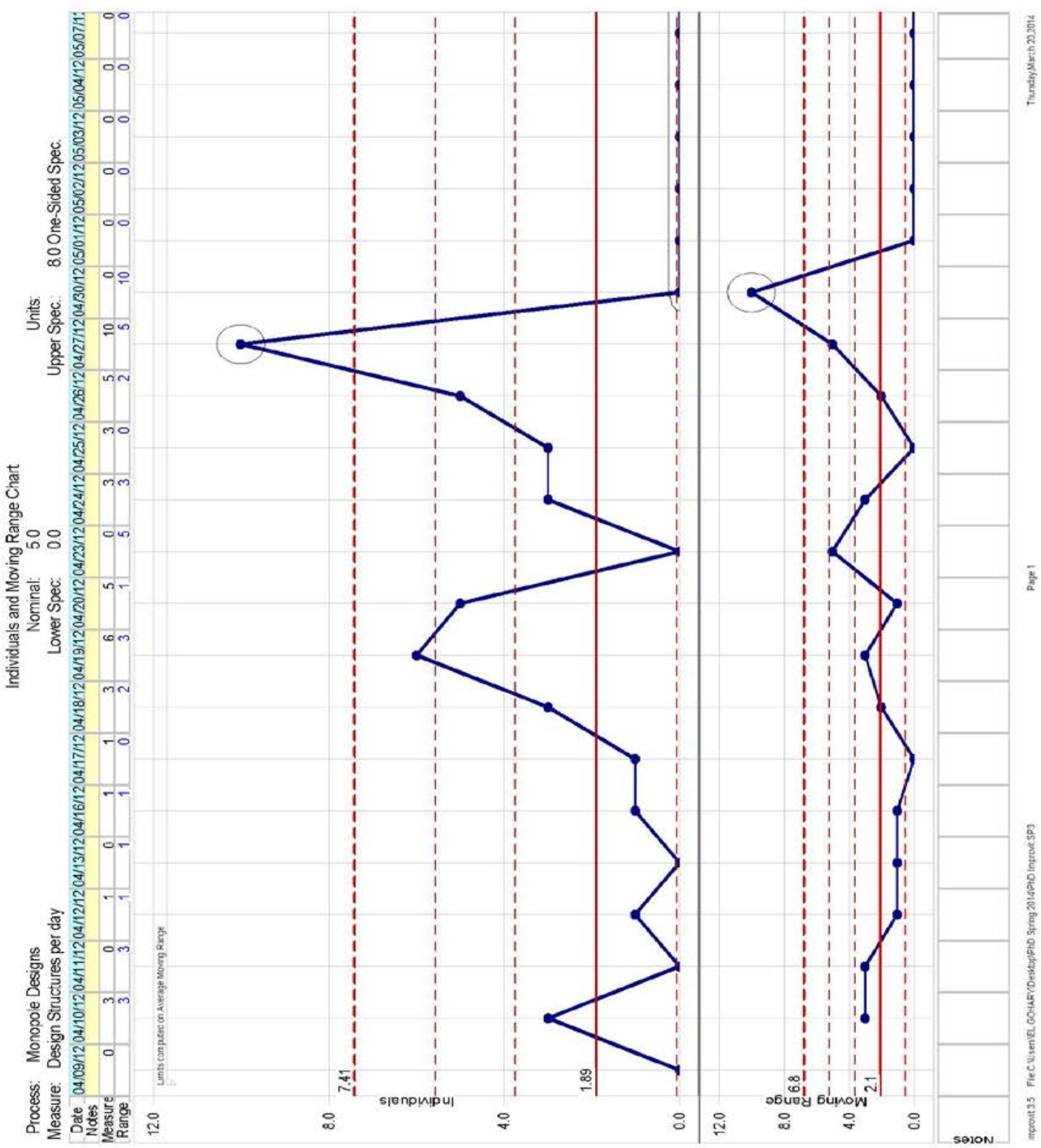

Figure A.1. Productivity Daily Log; 04/09/12 – 05/07/12

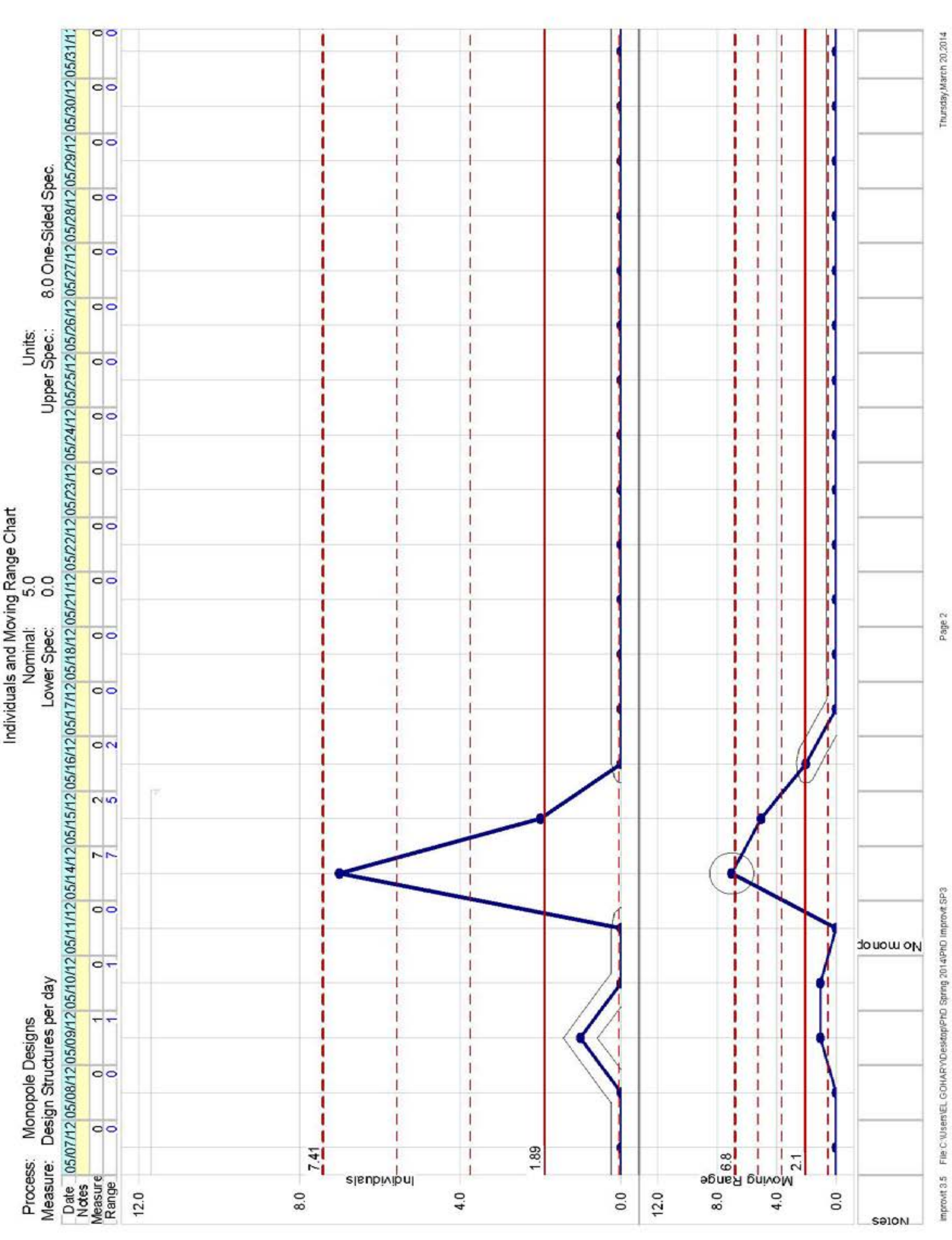

Figure A.2. Productivity Daily Log; 05/07/12 – 05/31/12

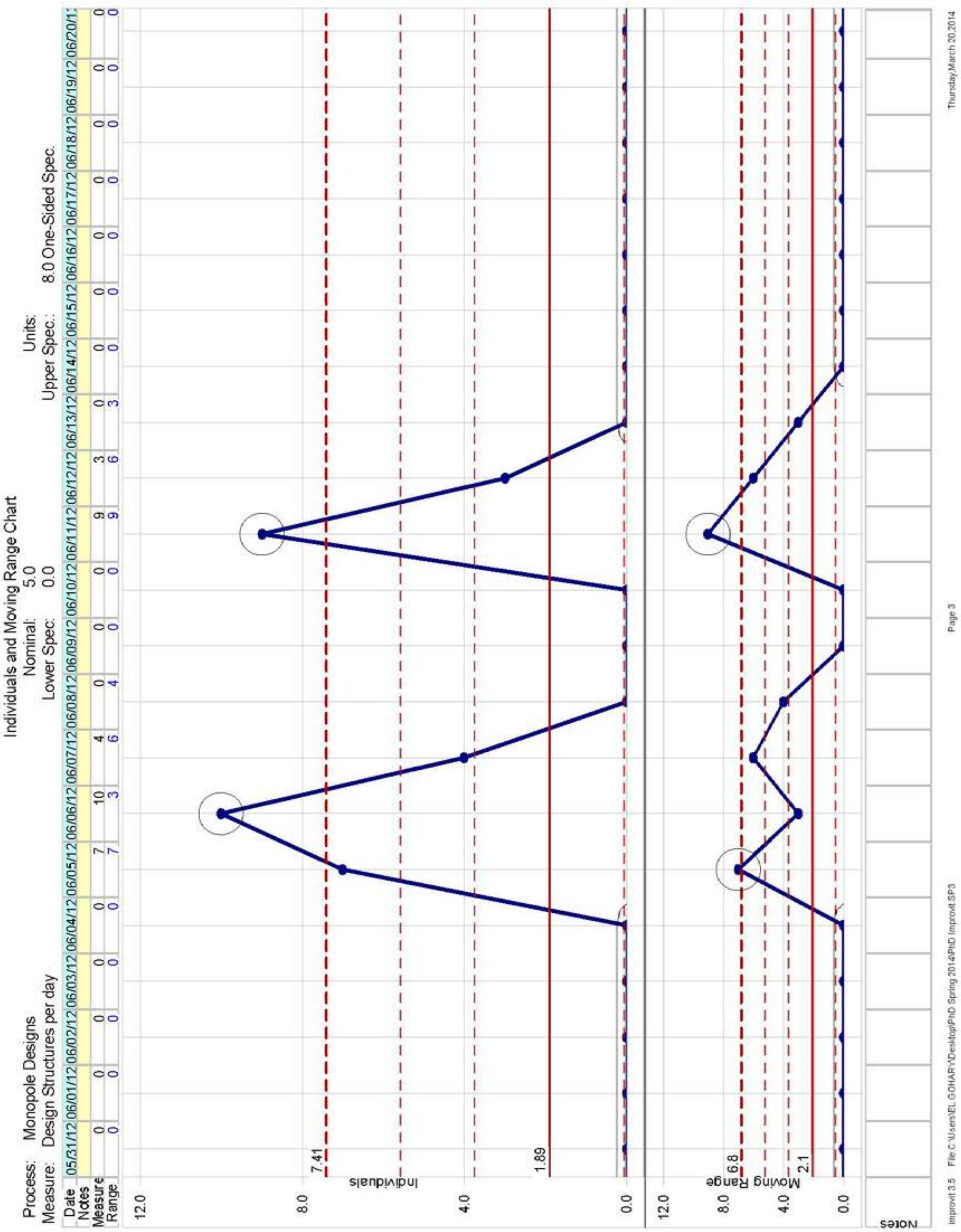

Figure A.3. Productivity Daily Log; 05/31/12 – 06/20/12

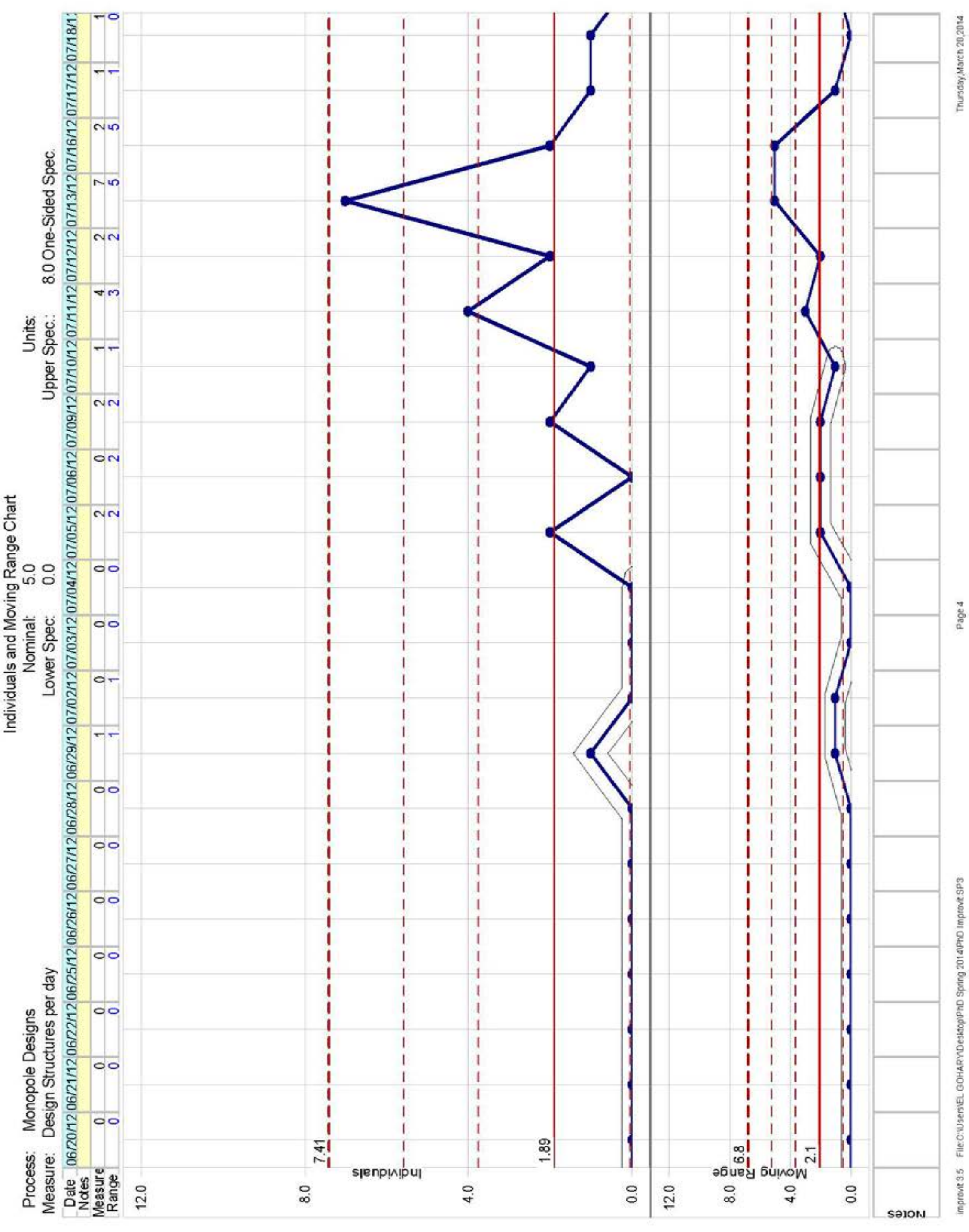

Figure A.4. Productivity Daily Log; 06/20/12 – 07/18/12

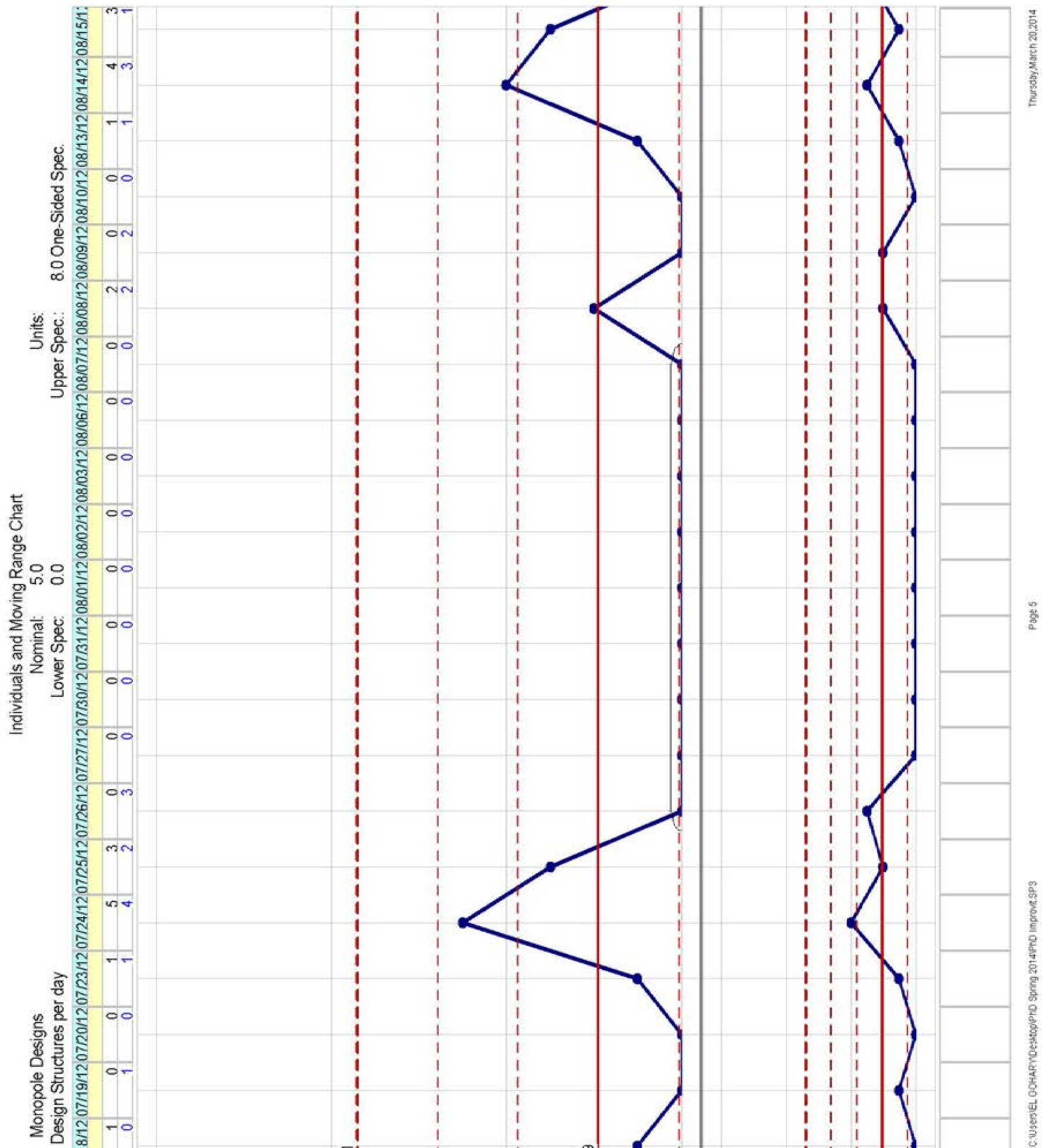

Figure A.5. Productivity Daily Log; 07/18/12 – 08/15/12

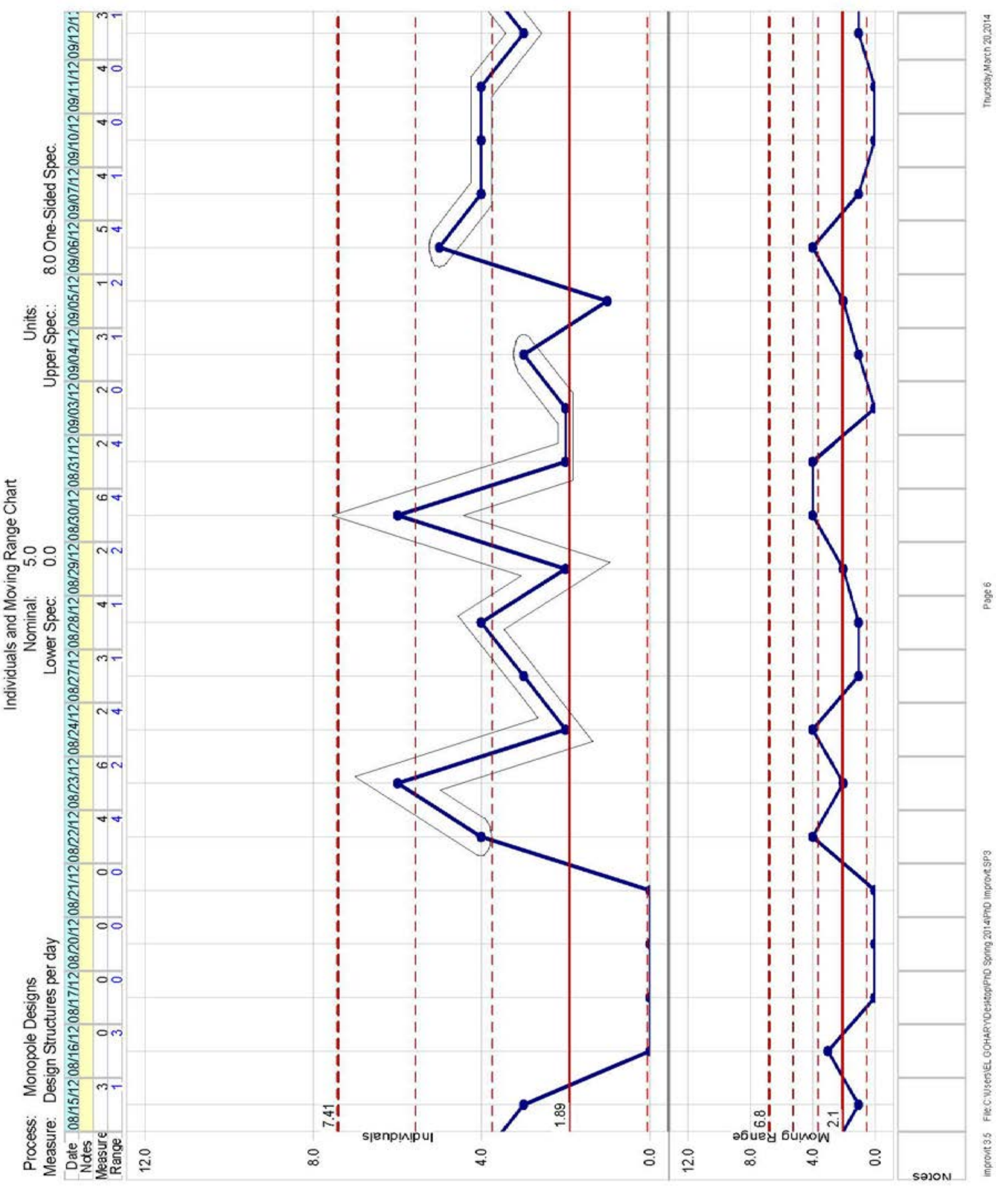

Figure A.6. Productivity Daily Log; 08/15/12 – 09/12/12

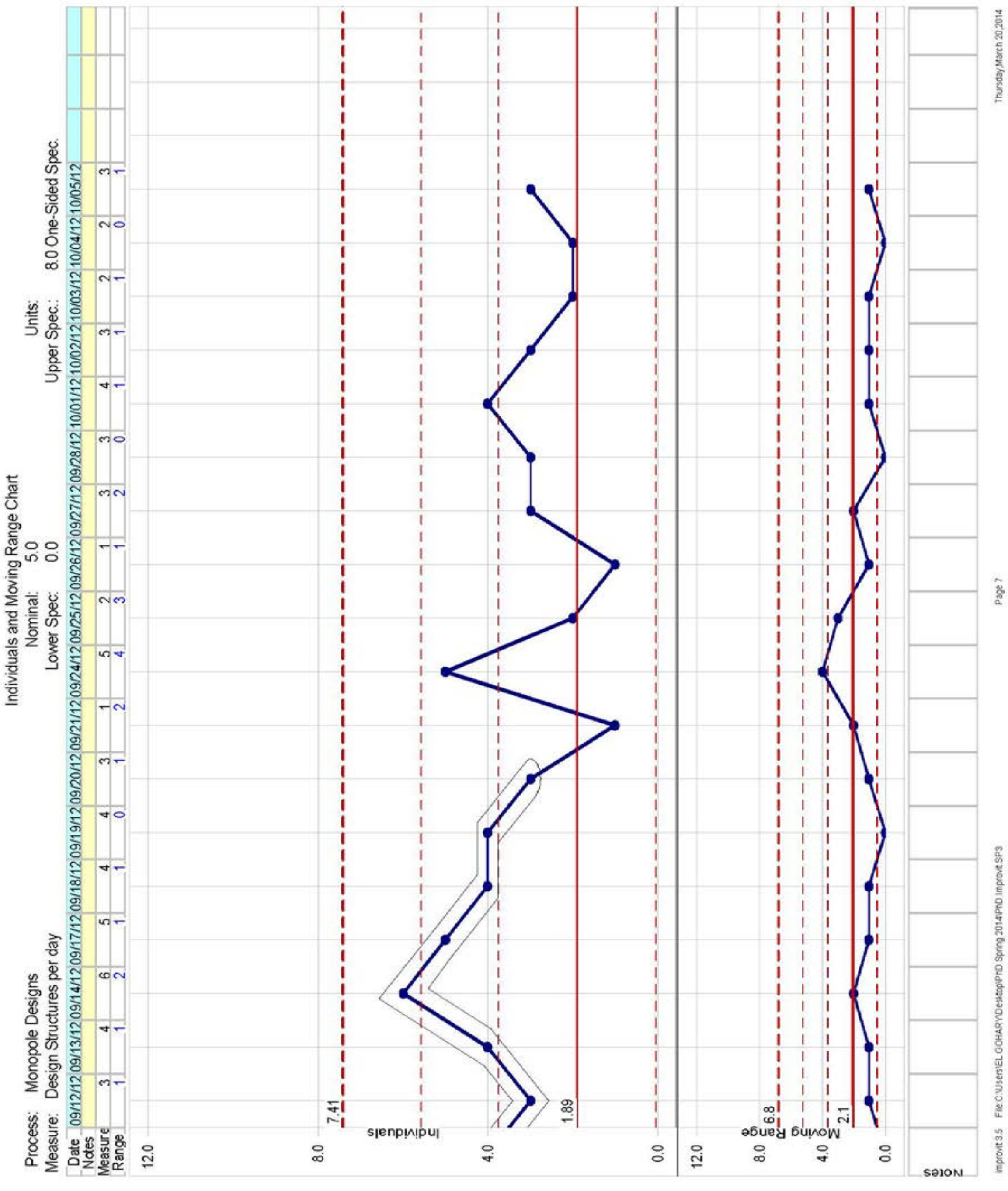

Figure A.7. Productivity Daily Log; 09/12/12 – 10/05/12

Appendix B

Post-models results of the daily productivity monitoring using Improvit.

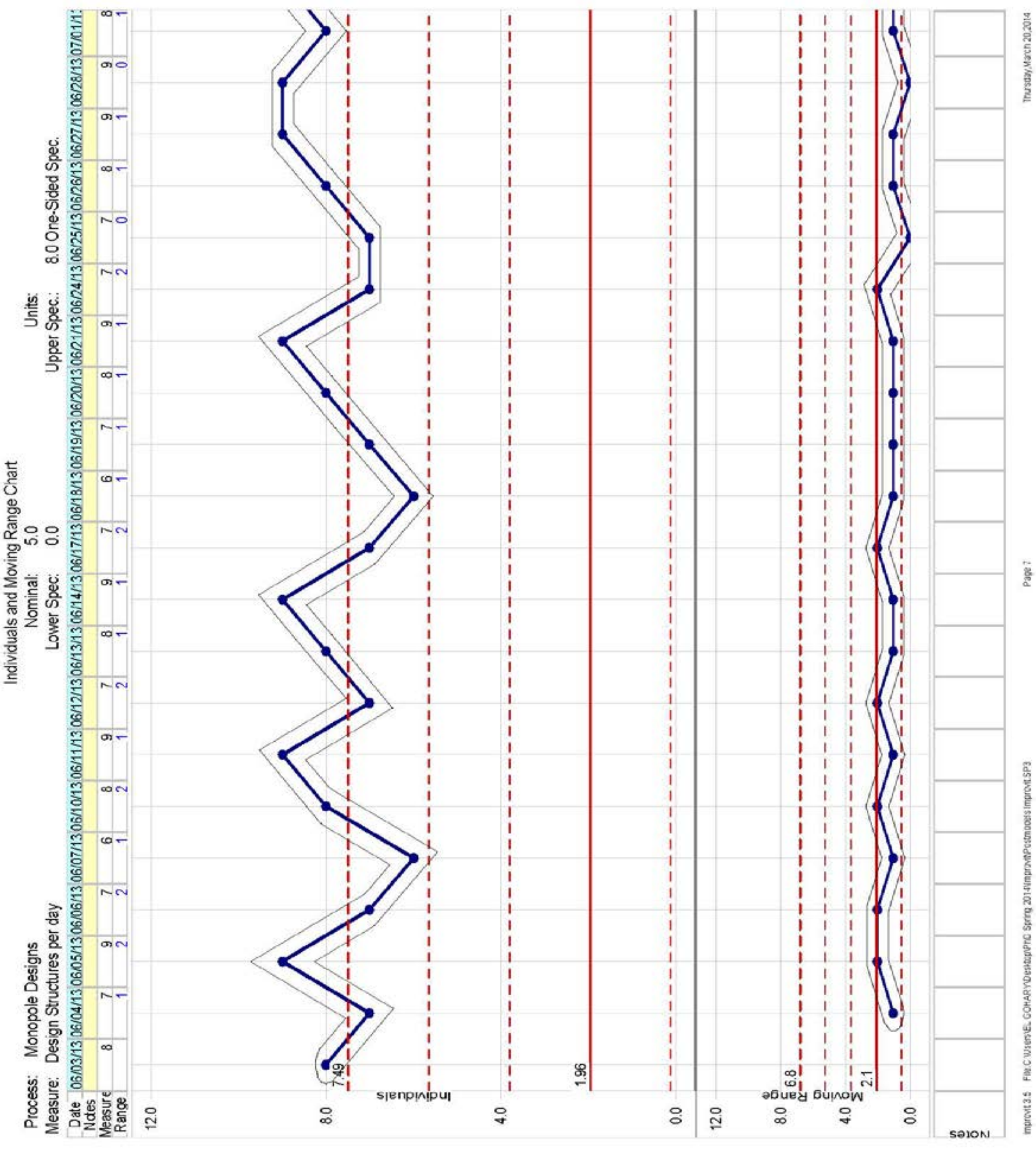

Figure B.1. Productivity Daily Log; 06/03/13 – 07/01/13

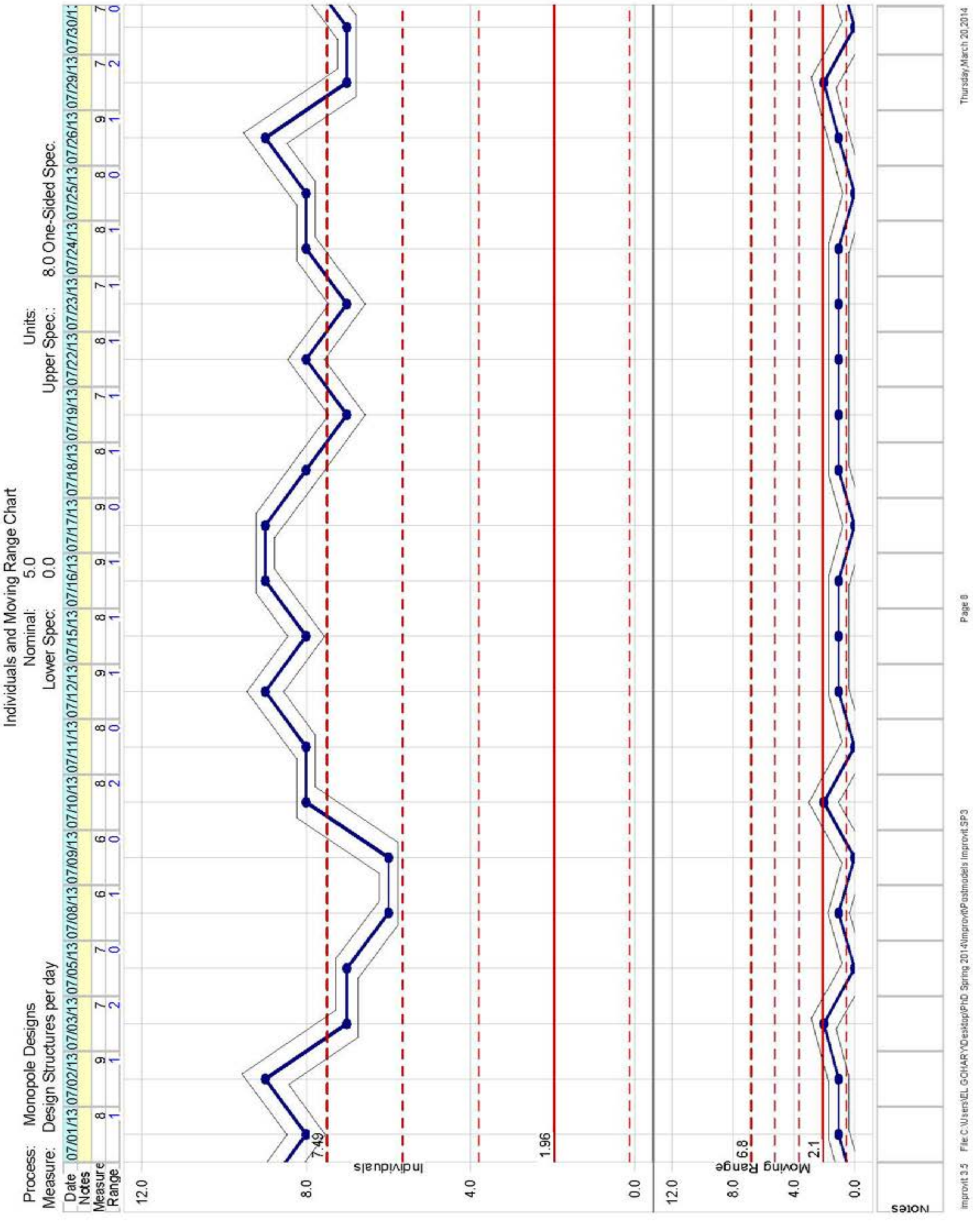

Figure B.2. Productivity Daily Log; 07/01/13 – 07/30/13

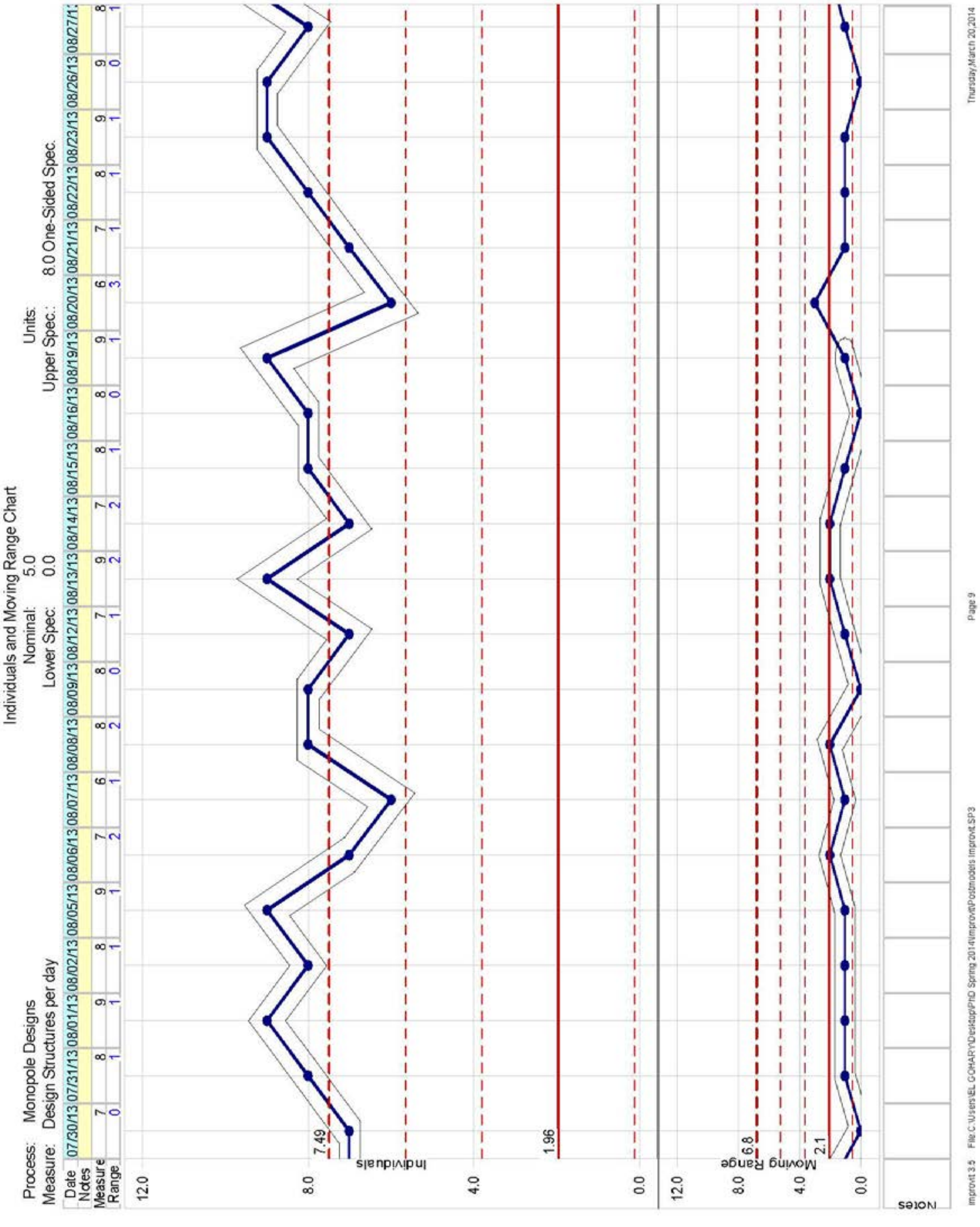

Figure B.3. Productivity Daily Log; 07/30/13 – 08/27/13

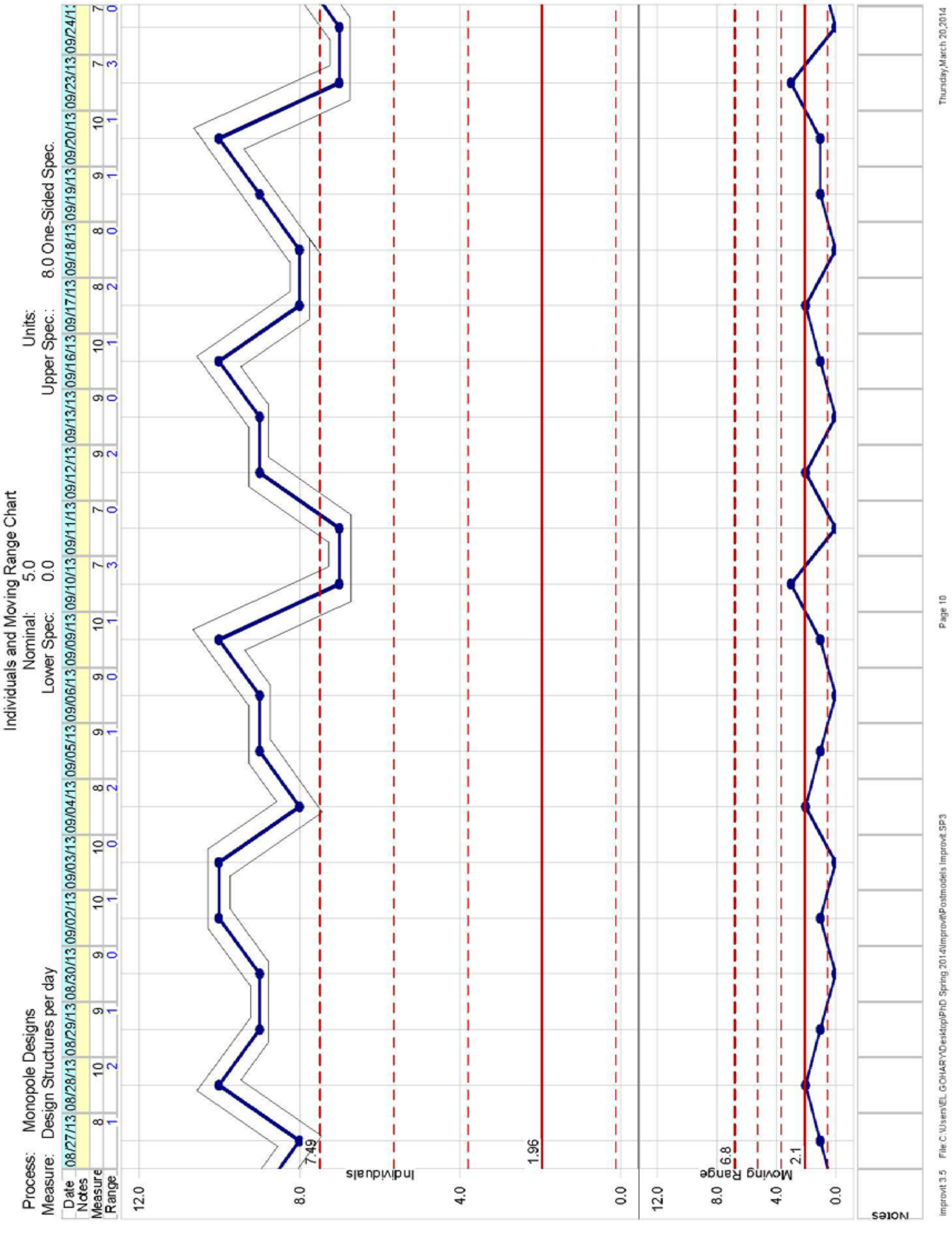

Figure B.5. Productivity Daily Log; 08/27/13 – 09//24/13

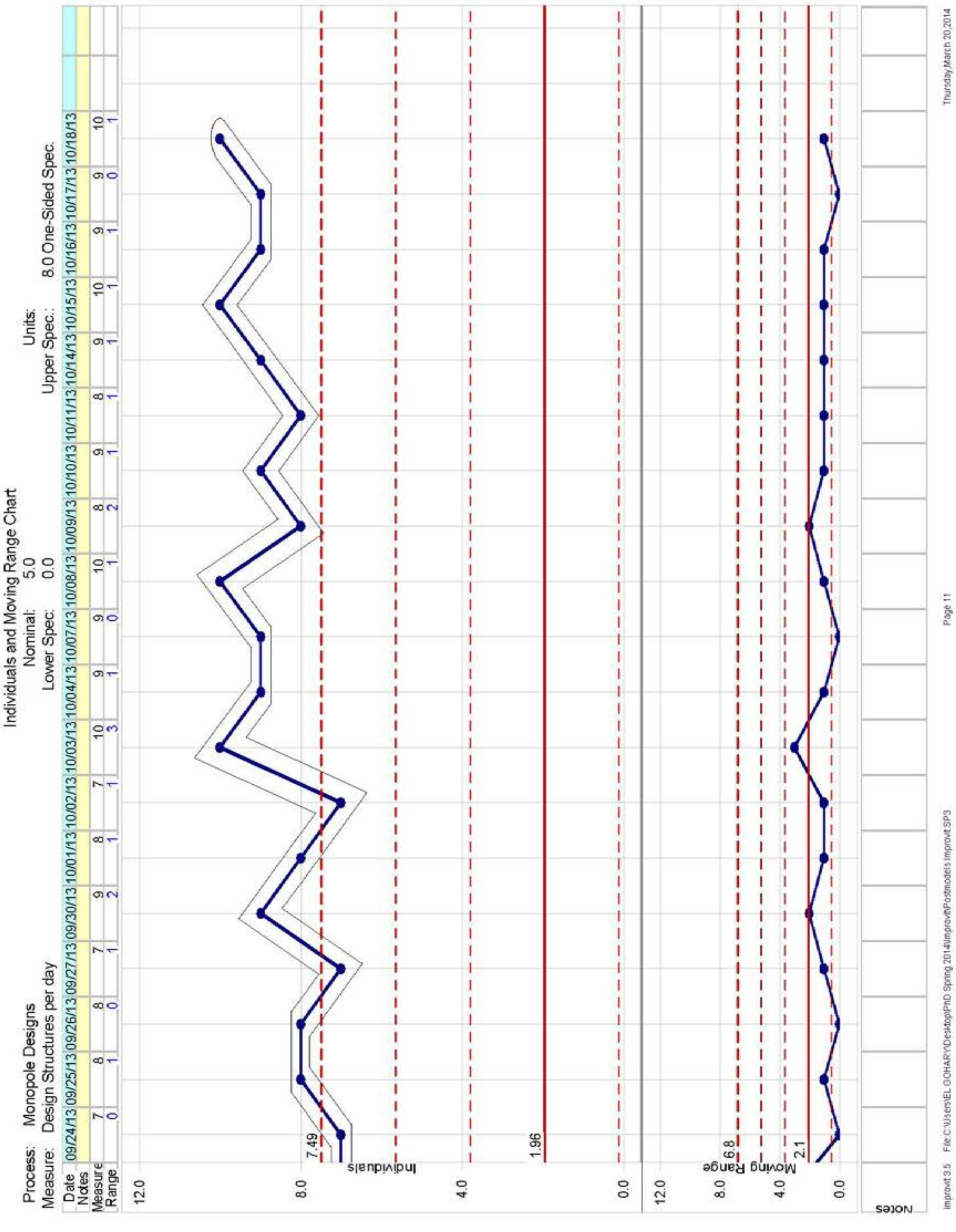

Figure B.6. Productivity Daily Log; 09/24/13 – 10/18/13

Appendix C

Results of multiple linear regression (MLR) analysis for the three developed models

Table C1.1 Analysis of Variance (ANOVA) table for Total Weight Model

Source	DF	SS	MS	p-value
Regression	3	4.03E+10	1.34E+10	0
Error	117	4.38E+9	3.74E+07	
Total	120	4.46E+10		

Table C1.2 Coefficients of Total Weight Model

Source	DF	Coef	St.Error	t-value	p-value	VIF
Constant	1	-27949.2	2583.11	-10.82	0	-
X-Force	1	0.14	0.01	19.1586	0	1.185
Y-Force	1	0.3	0.02	14.2852	0	1.409
Z-Force	1	0.18	0.01	19.2	0	1.185
Height	1	373.4	34.22	10.9104	0	1.428

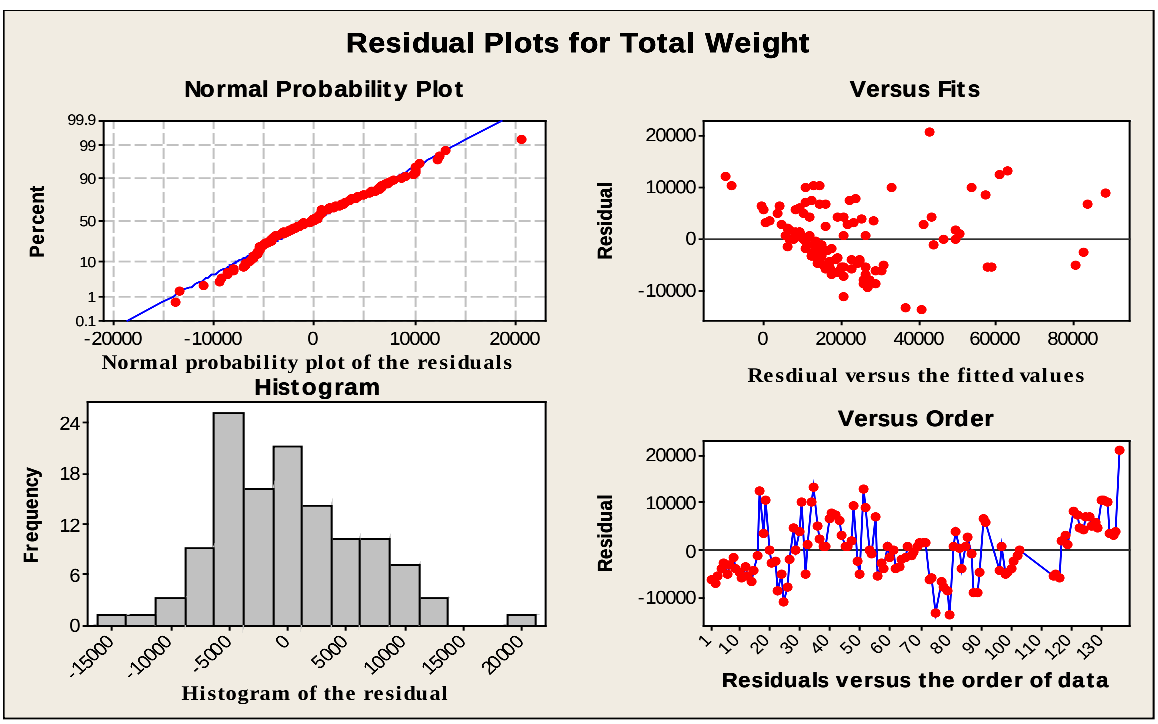

Figure C.1 The Residual plots for the Total Weight model

Table C1.3 Analysis of Variance (ANOVA) table for Core Weight Model

Source	DF	SS	MS	p-value
Regression	3	1.98E+10	6601284036	0
Error	117	1.82E+9	15546268	
Total	120	2.16E+10		

Table C1.4 Coefficients of Core Weight Model

Source	DF	Coef	St.Error	t-value	p-value	VIF
Constant	1	-23220.8	1664.3	-13.95	0	-
X-Force	1	0.1	0.02	19.1586	0	1.185
Y-Force	1	0.17	0.01	13.54	0	1.409
Z-Force	1	0.12	0.02	20.16	0	1.185
Height	1	303.7	22.05	13.77	0	1.428

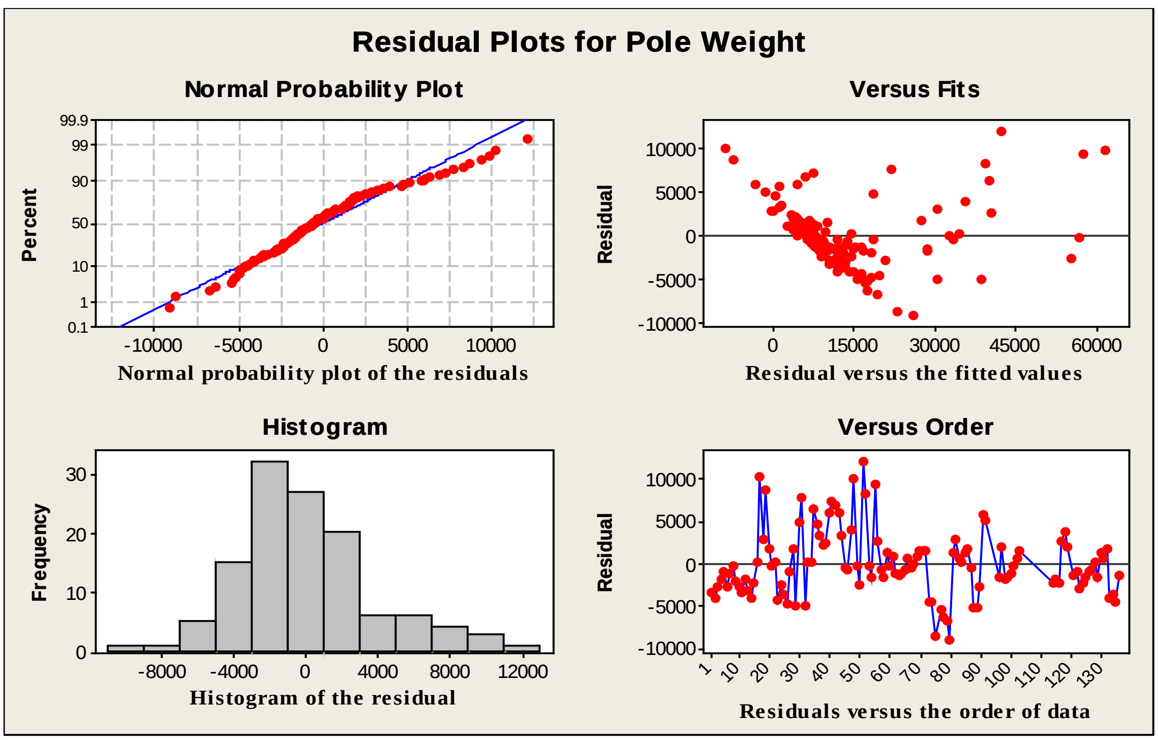

Figure C.2 Pole Weight vs. Variables

Table C1.3 Analysis of Variance (ANOVA) table for BP/AB Weight Model

Source	DF	SS	MS	p-value
Regression	3	999803421	333267807	0
Error	117	42578058	363915	
Total	120	1042381479		

Table C1.4 Coefficients of BP/AB Weight Model

Source	DF	Coef	St.Error	t-value	p-value	VIF
Constant	1	-1755.44	254.6	-6.9	0	-
X-Force	1	0.03	0.003	37.3	0	1.185
Y-Force	1	0.05	0.002	24.3	0	1.409
Z-Force	1	0.11	0.003	37.3	0	1.185
Height	1	303.7	22.05	10.6	0	1.428

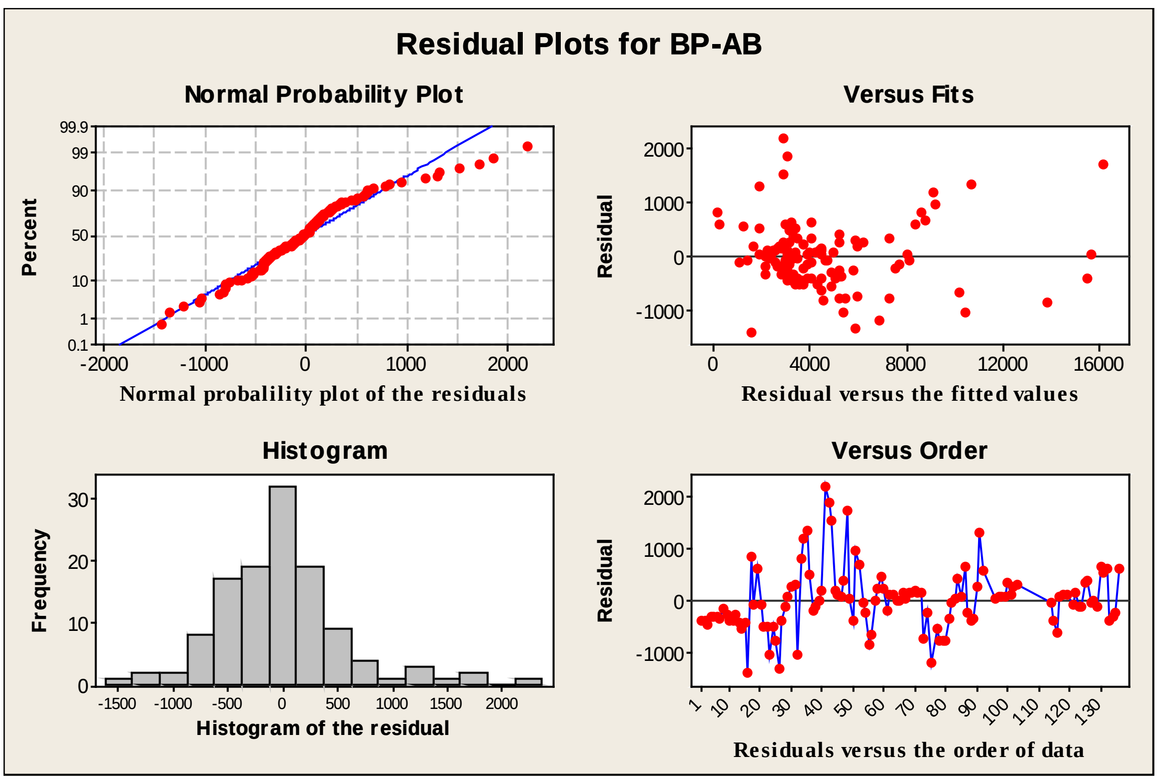

Figure C.3. Base Plate/Anchor Bolts vs. Variables

Appendix D

Validation of model for predicting total weight of pole

Table D.1. Total Weight Model Validation

Design(lbs)	Predicted(lbs)	%Difference	Calibrated Predicted(lbs)	%Difference
10034.17	14213.95	41.66	10213.95	1.79
10882.31	16080.96	47.77	12080.96	11.01
10114.25	14296.61	41.35	10296.61	1.80
10585.73	15648.09	47.82	11648.09	10.04
9894.65	13781.08	39.28	9781.08	-1.15
9264.22	13904.03	50.08	9904.03	6.91
11619.61	14677.68	26.32	10677.68	-8.11
14379.18	19862.49	38.13	15862.49	10.32
44080.10	46390.29	5.24	42390.29	-3.83
52452.91	57722.42	10.05	53722.42	2.42
77455.62	82714.00	6.79	78714.00	1.62
73068.71	80846.99	10.65	76846.99	5.17
46275.36	49705.36	7.41	45705.36	-1.23
39691.37	44104.33	11.12	40104.33	1.04
14469.20	18466.44	27.63	14466.44	-0.02
20562.00	24565.75	19.47	20565.75	0.02
15334.40	18964.72	23.67	14964.72	-2.41
20784.35	24967.43	20.13	20967.43	0.88
25853.30	30824.93	19.23	26824.93	3.76
12568.50	16902.14	34.48	12902.14	2.65
19631.23	24409.92	24.34	20409.92	3.97
18602.90	22542.91	21.18	18542.91	-0.32
10386.17	14670.95	41.25	10575.95	1.83
11234.31	16537.96	47.21	12442.96	10.76
10466.25	14753.61	40.96	10658.61	1.84
10937.73	16105.09	47.24	12010.09	9.80
10246.65	14238.08	38.95	10143.08	-1.01
9616.22	14361.03	49.34	10266.03	6.76
11971.61	15134.68	26.42	11039.68	-7.78
14731.18	20319.49	37.94	16224.49	10.14
44432.10	46847.29	5.44	42752.29	-3.78
52804.91	58179.42	10.18	54084.42	2.42

Table D.1.(cont.) Total Weight Model Validation

Design(lbs)	Predicted(lbs)	%Difference	Calibrated Predicted(lbs)	%Difference
77807.62	83171.00	6.89	79076.00	1.63
73420.71	81303.99	10.74	77208.99	5.16
46627.36	50162.36	7.58	46067.36	-1.20
40043.37	44561.33	11.28	40466.33	1.06
14821.20	18923.44	27.68	14828.44	0.05
20914.00	25022.75	19.65	20927.75	0.07
15686.40	19421.72	23.81	15326.72	-2.29
21136.35	25424.43	20.29	21329.43	0.91
26205.30	31281.93	19.37	27186.93	3.75
12920.50	17359.14	34.35	13264.14	2.66
19983.23	24866.92	24.44	20771.92	3.95
18954.90	22999.91	21.34	18904.91	-0.26
10712.59	14938.28	39.45	10859.84	1.37
11560.73	16805.29	45.37	12726.85	10.09
10792.67	15020.94	39.18	10942.50	1.39
11264.15	16372.42	45.35	12293.98	9.14
10573.07	14505.41	37.19	10426.97	-1.38
9942.64	14628.36	47.13	10549.92	6.11
12298.03	15402.01	25.24	11323.57	-7.92
15057.60	20586.82	36.72	16508.38	9.63
44758.52	47114.62	5.26	43036.18	-3.85
53131.33	58446.75	10.00	54368.31	2.33
78134.04	83438.33	6.79	79359.89	1.57
73747.13	81571.32	10.61	77492.88	5.08
46953.78	50429.69	7.40	46351.25	-1.28
40369.79	44828.66	11.05	40750.22	0.94
15147.62	19190.77	26.69	15112.33	-0.23
21240.42	25290.08	19.07	21211.64	-0.14
16012.82	19689.05	22.96	15610.61	-2.51
21462.77	25691.76	19.70	21613.32	0.70
26531.72	31549.26	18.91	27470.82	3.54
13246.92	17626.47	33.06	13548.03	2.27
20309.65	25134.25	23.76	21055.81	3.67
19281.32	23267.24	20.67	19188.80	-0.48
11267.64	15406.32	36.73	11424.41	1.39
12115.78	17273.33	42.57	13291.42	9.70
11347.72	15488.98	36.49	11507.07	1.40
11819.20	16840.46	42.48	12858.55	8.79
11128.12	14973.45	34.56	10991.54	-1.23

Table D1.1.(cont.) Total Weight Model Validation

Design(lbs)	Predicted(lbs)	%Difference	Calibrated Predicted(lbs)	%Difference
10497.69	15096.40	43.81	11114.49	5.88
12853.08	15870.05	23.47	11888.14	-7.51
15612.65	21054.86	34.86	17072.95	9.35
45313.57	47582.66	5.01	43600.75	-3.78
53686.38	58914.79	9.74	54932.88	2.32
78689.09	83906.37	6.63	79924.46	1.57
74302.18	82039.36	10.41	78057.45	5.05
47508.83	50897.73	7.13	46915.82	-1.25
40924.84	45296.70	10.68	41314.79	0.95
15702.67	19658.81	25.19	15676.90	-0.16
21795.47	25758.12	18.18	21776.21	-0.09
16567.87	20157.09	21.66	16175.18	-2.37
22017.82	26159.80	18.81	22177.89	0.73
27086.77	32017.30	18.20	28035.39	3.50
13801.97	18094.51	31.10	14112.60	2.25
20864.70	25602.29	22.71	21620.38	3.62
19836.37	23735.28	19.66	19753.37	-0.42
15158.04	19241.14	26.94	15311.86	1.01
16006.18	21108.15	31.87	17178.87	7.33
15238.12	19323.80	26.81	15394.52	1.03
15709.60	20675.28	31.61	16746.00	6.60
15018.52	18808.27	25.23	14878.99	-0.93
14388.09	18931.22	31.58	15001.94	4.27
16743.48	19704.87	17.69	15775.59	-5.78
19503.05	24889.68	27.62	20960.40	7.47
49203.97	51417.48	4.50	47488.20	-3.49
57576.78	62749.61	8.98	58820.33	2.16
82579.49	87741.19	6.25	83811.91	1.49
78192.58	85874.18	9.82	81944.90	4.80
51399.23	54732.55	6.49	50803.27	-1.16
44815.24	49131.52	9.63	45202.24	0.86
19593.07	23493.63	19.91	19564.35	-0.15
25685.87	29592.94	15.21	25663.66	-0.09
20458.27	23991.91	17.27	20062.63	-1.93
25908.22	29994.62	15.77	26065.34	0.61
30977.17	35852.12	15.74	31922.84	3.05
17692.37	21929.33	23.95	18000.05	1.74
24755.10	29437.11	18.91	25507.83	3.04

Table D1.1.(cont.)Total Weight Model Validation

Design(lbs)	Predicted(lbs)	%Difference	Calibrated Predicted(lbs)	%Difference
23726.77	27570.10	16.20	23640.82	-0.36
28798.82	32203.66	11.82	28637.14	-0.56
29646.96	34070.67	14.92	30504.15	2.89
28878.90	32286.32	11.80	28719.80	-0.55
29350.38	33637.80	14.61	30071.28	2.46
28659.30	31770.79	10.86	28204.27	-1.59
28028.87	31893.74	13.79	28327.22	1.06
30384.26	32667.39	7.51	29100.87	-4.22
33143.83	37852.20	14.21	34285.68	3.45
62844.75	64380.00	2.44	60813.48	-3.23
71217.56	75712.13	6.31	72145.61	1.30
96220.27	100703.71	4.66	97137.19	0.95
91833.36	98836.70	7.63	95270.18	3.74
65040.01	67695.07	4.08	64128.55	-1.40
58456.02	62094.04	6.22	58527.52	0.12
33233.85	36456.15	9.70	32889.63	-1.04
39326.65	42555.46	8.21	38988.94	-0.86
34099.05	36954.43	8.37	33387.91	-2.09
39549.00	42957.14	8.62	39390.62	-0.40
44617.95	48814.64	9.41	45248.12	1.41
31333.15	34891.85	11.36	31325.33	-0.02
38395.88	42399.63	10.43	38833.11	1.14
37367.55	40532.62	8.47	36966.10	-1.07

Appendix E

Validation of model for predicting core weight of pole

Table E1.1. Core Weight Model Validation

Design(lbs)	Predicted(lbs)	%Difference	Calibrated Predicted(lbs)	%Difference
9097.00	12621.83	38.75	9621.83	5.77
8245.00	11103.52	34.67	8103.52	-1.72
7859.00	10654.00	35.56	7654.00	-2.61
7708.00	10393.38	34.84	7393.38	-4.08
8438.00	11911.69	41.17	8911.69	5.61
7229.00	10452.36	44.59	7452.36	3.09
33819.00	38744.00	14.56	35744.00	5.69
33033.00	32856.55	-0.53	29856.55	-9.62
34888.00	34657.17	-0.66	31657.17	-9.26
53069.00	55533.41	4.64	52533.41	-1.01
27140.00	28858.20	6.33	25858.20	-4.72
15247.00	16493.22	8.17	13493.22	-11.50
15224.00	19761.06	29.80	16761.06	10.10
18311.00	20992.41	14.64	17992.41	-1.74
16292.00	18267.57	12.13	15267.57	-6.29
15128.00	16749.26	10.72	13749.26	-9.11
12235.00	14560.22	19.00	11560.22	-5.52
11104.00	13041.91	17.45	10041.91	-9.56
9835.00	12209.64	24.14	9209.64	-6.36
10584.00	13475.32	27.32	10475.32	-1.03
9642.00	11957.01	24.01	8957.01	-7.10
10976.00	15063.59	37.24	12063.59	9.91
9904.00	13545.28	36.77	10545.28	6.47
9769.98	13315.49	36.29	10303.37	5.46
8917.98	11797.18	32.29	8785.06	-1.49
8531.98	11347.66	33.00	8335.54	-2.30
8380.98	11087.04	32.29	8074.92	-3.65
9110.98	12605.35	38.35	9593.23	5.29
7901.98	11146.02	41.05	8133.90	2.93
34491.98	39437.66	14.34	36425.54	5.61
33705.98	33550.21	-0.46	30538.09	-9.40

Table E1.1.(cont.) Pole Weight Model Validation

Design(lbs)	Predicted(lbs)	%Difference	Calibrated Predicted(lbs)	%Difference
27812.98	29551.86	6.25	26539.74	-4.58
15919.98	17186.88	7.96	14174.76	-10.96
15896.98	20454.72	28.67	17442.60	9.72
18983.98	21686.07	14.23	18673.95	-1.63
16964.98	18961.23	11.77	15949.11	-5.99
15800.98	17442.92	10.39	14430.80	-8.67
12907.98	15253.88	18.17	12241.76	-5.16
11776.98	13735.57	16.63	10723.45	-8.95
10507.98	12903.30	22.80	9891.18	-5.87
11256.98	14168.98	25.87	11156.86	-0.89
10314.98	12650.67	22.64	9638.55	-6.56
11648.98	15757.25	35.27	12745.13	9.41
10576.98	14238.94	34.62	11226.82	6.14
9451.98	13034.72	37.90	10014.61	5.95
8599.98	11516.41	33.91	8496.30	-1.21
8213.98	11066.89	34.73	8046.78	-2.04
8062.98	10806.27	34.02	7786.16	-3.43
8792.98	12324.58	40.16	9304.47	5.82
7583.98	10865.25	43.27	7845.14	3.44
34173.98	39156.89	14.58	36136.78	5.74
33387.98	33269.44	-0.36	30249.33	-9.40
35242.98	35070.06	-0.49	32049.95	-9.06
53423.98	55946.30	4.72	52926.19	-0.93
27494.98	29271.09	6.46	26250.98	-4.52
15601.98	16906.11	8.36	13886.00	-11.00
15578.98	20173.95	29.49	17153.84	10.11
18665.98	21405.30	14.68	18385.19	-1.50
16646.98	18680.46	12.22	15660.35	-5.93
15482.98	17162.15	10.85	14142.04	-8.66
12589.98	14973.11	18.93	11953.00	-5.06
11458.98	13454.80	17.42	10434.69	-8.94
10189.98	12622.53	23.87	9602.42	-5.77
10938.98	13888.21	26.96	10868.10	-0.65
9996.98	12369.90	23.74	9349.79	-6.47
11330.98	15476.48	36.59	12456.37	9.93
10258.98	13958.17	36.06	10938.06	6.62
9353.20	12852.03	37.41	9861.83	5.44

Table E1.1.(cont.) Pole Weight Model Validation

Design(lbs)	Predicted(lbs)	%Difference	Calibrated Predicted(lbs)	%Difference
8501.20	11333.72	33.32	8343.52	-1.85
8115.20	10884.20	34.12	7894.00	-2.73
7964.20	10623.58	33.39	7633.38	-4.15
8694.20	12141.89	39.66	9151.69	5.26
7485.20	10682.56	42.72	7692.36	2.77
34075.20	38974.20	14.38	35984.00	5.60
33289.20	33086.75	-0.61	30096.55	-9.59
35144.20	34887.37	-0.73	31897.17	-9.24
53325.20	55763.61	4.57	52773.41	-1.03
27396.20	29088.40	6.18	26098.20	-4.74
15503.20	16723.42	7.87	13733.22	-11.42
15480.20	19991.26	29.14	17001.06	9.82
18567.20	21222.61	14.30	18232.41	-1.80
16548.20	18497.77	11.78	15507.57	-6.29
15384.20	16979.46	10.37	13989.26	-9.07
12491.20	14790.42	18.41	11800.22	-5.53
11360.20	13272.11	16.83	10281.91	-9.49
10091.20	12439.84	23.27	9449.64	-6.36
10840.20	13705.52	26.43	10715.32	-1.15
9898.20	12187.21	23.13	9197.01	-7.08
11232.20	15293.79	36.16	12303.59	9.54
10160.20	13775.48	35.58	10785.28	6.15
10230.62	13833.26	26.04	10772.17	5.29
9378.62	12314.95	23.84	9253.86	-1.33
8992.62	11865.43	24.21	8804.34	-2.09
8841.62	11604.81	23.81	8543.72	-3.37
9571.62	13123.12	27.06	10062.03	5.12
8362.62	11663.79	28.30	8602.70	2.87
34952.62	39955.43	12.52	36894.34	5.56
34166.62	34067.98	-0.29	31006.89	-9.25
36021.62	35868.60	-0.43	32807.51	-8.92
54202.62	56744.84	4.48	53683.75	-0.96
28273.62	30069.63	5.97	27008.54	-4.47
16380.62	17704.65	7.48	14643.56	-10.60
16357.62	20972.49	22.00	17911.40	9.50
19444.62	22203.84	12.43	19142.75	-1.55

Table E1.1(cont.) Pole Weight Model Validation

Design(lbs)	Predicted(lbs)	%Difference	Calibrated Predicted(lbs)	%Difference
13368.62	15771.65	15.24	12710.56	-4.92
12237.62	14253.34	14.14	11192.25	-8.54
10968.62	13421.07	18.27	10359.98	-5.55
11717.62	14686.75	20.22	11625.66	-0.78
10775.62	13168.44	18.17	10107.35	-6.20
12109.62	16275.02	25.59	13213.93	9.12
11037.62	14756.71	25.20	11695.62	5.96
11020.45	14572.06	32.23	11602.26	5.28
10168.45	13053.75	28.37	10083.95	-0.83
9782.45	12604.23	28.85	9634.43	-1.51
9631.45	12343.61	28.16	9373.81	-2.67
10361.45	13861.92	33.78	10892.12	5.12
9152.45	12402.59	35.51	9432.79	3.06
35742.45	40694.23	13.85	37724.43	5.55
34956.45	34806.78	-0.43	31836.98	-8.92
36811.45	36607.40	-0.55	33637.60	-8.62
54992.45	57483.64	4.53	54513.84	-0.87
29063.45	30808.43	6.00	27838.63	-4.21
17170.45	18443.45	7.41	15473.65	-9.88
17147.45	21711.29	26.62	18741.49	9.30
20234.45	22942.64	13.38	19972.84	-1.29
18215.45	20217.80	10.99	17248.00	-5.31
17051.45	18699.49	9.67	15729.69	-7.75
14158.45	16510.45	16.61	13540.65	-4.36
13027.45	14992.14	15.08	12022.34	-7.72
11758.45	14159.87	20.42	11190.07	-4.83
12507.45	15425.55	23.33	12455.75	-0.41
11565.45	13907.24	20.25	10937.44	-5.43
12899.45	17013.82	31.90	14044.02	8.87
11827.45	15495.51	31.01	12525.71	5.90
17425.62	19479.00	10.54	16417.91	-5.78
16261.62	17960.69	9.46	14899.60	-8.38
35560.98	35350.83	-0.59	32338.71	-9.06
53741.98	56227.07	4.62	53214.95	-0.98

Appendix F

Validation of model for predicting base plate/anchor bolts weight of pole

Table F1.1. BP/AB Model Validation

Design(lbs)	Predicted(lbs)	%Difference	Calibrated Predicted(lbs)	%Difference
3429.29	3842.78	12.06	3442.78	0.39
3603.30	4022.25	11.63	3622.25	0.53
3202.50	3663.31	14.39	3263.31	1.90
2783.96	3106.13	11.57	2706.13	-2.80
2613.46	2926.66	11.98	2526.66	-3.32
2956.50	3285.60	11.13	2885.60	-2.40
2422.64	2774.22	14.51	2374.22	-2.00
2663.46	2953.69	10.90	2553.69	-4.12
2810.96	3214.42	14.35	2814.42	0.12
2985.46	3393.89	13.68	2993.89	0.28
2755.96	3034.95	10.12	2634.95	-4.39
2783.96	3229.25	15.99	2829.25	1.63
2871.96	3408.71	18.69	3008.71	4.76
2613.46	3049.78	16.69	2649.78	1.39
3176.95	3697.97	16.40	3297.97	3.81
2995.25	3521.77	17.58	3121.77	4.22
3803.11	4328.20	13.81	3928.20	3.29
3036.20	3435.14	13.14	3035.14	-0.03
7554.50	7690.43	1.80	7290.43	-3.50
8120.00	8074.52	-0.56	7674.52	-5.49
9368.31	10408.49	11.10	10008.49	6.83
2593.50	2787.51	7.48	2387.51	-7.94
15721.78	15686.54	-0.22	15286.54	-2.77
15096.87	15507.07	2.72	15107.07	0.07
8038.89	8103.17	0.80	7703.17	-4.18
7336.90	7564.76	3.11	7164.76	-2.35
13031.16	13889.77	6.59	13489.77	3.52
9525.90	10197.95	7.06	9797.95	2.86
5552.20	5799.23	4.45	5399.23	-2.76
4295.61	4866.26	13.28	4466.26	3.97
1736.23	2085.76	20.13	1685.76	-2.91
3447.00	3681.70	6.81	3281.70	-4.80
4865.77	5252.60	7.95	4852.60	-0.27

Table F1.1.(cont.) BP/AB Model Validation

Design(lbs)	Predicted(lbs)	%Difference	Calibrated Predicted(lbs)	%Difference
4865.77	5236.74	7.62	4836.74	-0.60
4028.60	4444.33	10.32	4044.33	0.39
3822.30	4456.11	16.58	4056.11	6.12
3727.62	3874.82	3.95	3474.82	-6.78
4616.27	5024.10	8.83	4624.10	0.17
4539.61	4844.63	6.72	4444.63	-2.09
4948.94	5203.56	5.15	4803.56	-2.94
3997.18	4435.75	9.89	4023.11	0.64
4171.19	4615.22	9.62	4202.58	0.75
3770.39	4256.28	11.42	3843.64	1.91
3351.85	3699.10	9.39	3286.46	-1.99
3181.35	3519.63	9.61	3106.99	-2.39
3524.39	3878.57	9.13	3465.93	-1.69
2990.53	3367.19	11.19	2954.55	-1.22
3231.35	3546.66	8.89	3134.02	-3.11
3378.85	3807.39	11.26	3394.75	0.47
3553.35	3986.86	10.87	3574.22	0.58
3323.85	3627.92	8.38	3215.28	-3.38
3351.85	3822.22	12.31	3409.58	1.69
3439.85	4001.68	14.04	3589.04	4.16
3181.35	3642.75	12.67	3230.11	1.51
3744.84	4290.94	12.73	3878.30	3.44
3563.14	4114.74	13.41	3702.10	3.75
4371.00	4921.17	11.18	4508.53	3.05
3604.09	4028.11	10.53	3615.47	0.31
8122.39	8283.40	1.94	7870.76	-3.20
8687.89	8667.49	-0.24	8254.85	-5.25
9936.20	11001.46	9.68	10588.82	6.16
3161.39	3380.48	6.48	2967.84	-6.52
16289.67	16279.51	-0.06	15866.87	-2.66
15664.76	16100.04	2.70	15687.40	0.14
8606.78	8696.14	1.03	8283.50	-3.90
7904.79	8157.73	3.10	7745.09	-2.06
13599.05	14482.74	6.10	14070.10	3.35
10093.79	10790.92	6.46	10378.28	2.74
6120.09	6392.20	4.26	5979.56	-2.35
4863.50	5459.23	10.91	5046.59	3.63
2304.12	2678.73	13.98	2266.09	-1.68

Table F1.1.(cont.) BP/AB Model Validation

Design(lbs)	Predicted(lbs)	%Difference	Calibrated Predicted(lbs)	%Difference
4014.89	4274.67	6.08	3862.03	-3.96
5433.66	5845.57	7.05	5432.93	-0.01
5433.66	5829.71	6.79	5417.07	-0.31
4596.49	5037.30	8.75	4624.66	0.61
4390.19	5049.08	13.05	4636.44	5.31
4295.51	4467.79	3.86	4055.15	-5.93
5184.16	5617.07	7.71	5204.43	0.39
5107.50	5437.60	6.07	5024.96	-1.64
5516.83	5796.53	4.83	5383.89	-2.47
3752.71	4189.21	10.42	3778.45	0.69
3926.72	4368.68	10.12	3957.92	0.79
3525.92	4009.74	12.07	3598.98	2.07
3107.38	3452.56	10.00	3041.80	-2.11
2936.88	3273.09	10.27	2862.33	-2.54
3279.92	3632.03	9.69	3221.27	-1.79
2746.06	3120.65	12.00	2709.89	-1.32
2986.88	3300.12	9.49	2889.36	-3.27
3134.38	3560.85	11.98	3150.09	0.50
3308.88	3740.32	11.53	3329.56	0.62
3079.38	3381.38	8.93	2970.62	-3.53
3107.38	3575.68	13.10	3164.92	1.85
3195.38	3755.14	14.91	3344.38	4.66
2936.88	3396.21	13.52	2985.45	1.65
3500.37	4044.40	13.45	3633.64	3.81
3318.67	3868.20	14.21	3457.44	4.18
4126.53	4674.63	11.73	4263.87	3.33
3359.62	3781.57	11.16	3370.81	0.33
7877.92	8036.86	1.98	7626.10	-3.20
8443.42	8420.95	-0.27	8010.19	-5.13
9691.73	10754.92	9.89	10344.16	6.73
2916.92	3133.94	6.92	2723.18	-6.64
16045.20	16032.97	-0.08	15622.21	-2.64
15420.29	15853.50	2.73	15442.74	0.15
8362.31	8449.60	1.03	8038.84	-3.87
7660.32	7911.19	3.17	7500.43	-2.09
13354.58	14236.20	6.19	13825.44	3.53
9849.32	10544.38	6.59	10133.62	2.89
5875.62	6145.66	4.39	5734.90	-2.39

Table F1.1.(cont.) BP/AB Model Validation

Design(lbs)	Predicted(lbs)	%Difference	Calibrated Predicted(lbs)	%Difference
4619.03	5212.69	11.39	4801.93	3.96
2059.65	2432.19	15.32	2021.43	-1.86
3770.42	4028.13	6.40	3617.37	-4.06
5189.19	5599.03	7.32	5188.27	-0.02
5189.19	5583.17	7.06	5172.41	-0.32
4352.02	4790.76	9.16	4380.00	0.64
4145.72	4802.54	13.68	4391.78	5.94
4051.04	4221.25	4.03	3810.49	-5.94
4939.69	5370.53	8.02	4959.77	0.41
4863.03	5191.06	6.32	4780.30	-1.70
5272.36	5549.99	5.00	5139.23	-2.52
4320.41	4707.93	8.23	4319.10	-0.03
4494.42	4887.40	8.04	4498.57	0.09
4093.62	4528.46	9.60	4139.63	1.12
3675.08	3971.28	7.46	3582.45	-2.52
3504.58	3791.81	7.58	3402.98	-2.90
3847.62	4150.75	7.30	3761.92	-2.23
3313.76	3639.37	8.95	3250.54	-1.91
3554.58	3818.84	6.92	3430.01	-3.50
3702.08	4079.57	9.25	3690.74	-0.31
3876.58	4259.04	8.98	3870.21	-0.16
3647.08	3900.10	6.49	3511.27	-3.72
3675.08	4094.40	10.24	3705.57	0.83
3763.08	4273.86	11.95	3885.03	3.24
3504.58	3914.93	10.48	3526.10	0.61
4068.07	4563.12	10.85	4174.29	2.61
3886.37	4386.92	11.41	3998.09	2.87
4694.23	5193.35	9.61	4804.52	2.35
3927.32	4300.29	8.67	3911.46	-0.40

Appendix G

Determining accuracy of existing process

Table G.1 Evaluating existing process by redesigning poles bid in the past

No.	Initial Weight (lbs)	Revised Weight (lbs)	% Change	BP Thk.(in)	BP Wt. Diff.(lb)	Pole/Arms Wt. Diff. (lb)	Conn. Wt. Diff. (lb)
1	35758.8	34025.1	-4.8	2.75			
2	34418.2	28229.6	-18.0	2.8			
3	23456.6	19793.6	-15.6	2.5			
4	22210.1	18518.4	-16.6	2.5			
5	39716.4	40509.5	2.0	2.5			
6	37331.8	34070.9	-8.7	2.5			
7	25073.2	25015.3	-0.2	2.75			
8	23684.8	23440.4	-1.0	2.5			
9	87387.8	91311.7	4.5	3.5	-290.0		
10	53389.5	47866.22	-10.3	3.25	-699.0		
11	35940.2	35435.3	-1.4				
12	44299.5	41765.8	-5.7				
13	30984.6	29781.7	-3.9				
14	38917.8	37755.8	-3.0				
15	3929.1	3881.33	-1.2				
16	4257.3	4224.61	-0.8				
17	4606.2	4596.1	-0.2				
18	5927	4959.1	-16.3				
19	6726	6009.13	-10.7				
20	7822.7	7584.07	-3.1				
21	6501.3	6349.9	-2.3				
22	14438	14075	-2.5	2.5			

Table G1.1.(cont.)Evaluating existing process by redesigning poles bid in the past

No.	Initial Weight (lbs)	Revised Weight (lbs)	% Change	BP Thk.(in)	BP Wt. Diff.(lb)	Pole/Arms Wt. Diff. (lb)	Conn. Wt. Diff. (lb)
23	11629.98	11456	-1.5	2.25			
24	11092.9	10670	-3.8	1.75			
25	12982.32	12675.4	-2.4	2.25			
26	11836	11783.9	-0.4	2.00			
27	4815.7	4712.52	-2.1			95.0	
28	3516.9	3122.3	-11.2	1.5		394.6	
29	2079.3	2027.15	-2.5	1.8	0.0	57.2	
30	2243.5	1683.54	-25.0			560.0	
31	43861	40947.84	-6.6	2.75	972.0	622.6	1318.3
32	26446	24373.84	-7.8	2.75	453.0	301.3	1318.0
33	21088	19348.84	-8.2	2.75	209.0	212.0	1318.0
34	49627.64	47220.42	-4.9	3.0	1112.0	27.3	1269.0
35	97612.26	87024.85	-10.8	4.0	503.0	7799.6	2284.5
36	76832.06	70643.84	-8.1	4	-267	3876	2578.9
37	71354.34	66754.34	-6.4	4	-175	2190.5	2584.2
38	70418.14	68035.32	-3.4	3.25	941	377.5	1064.32
39	64500.04	60539.39	-6.1	3.25	817	1944.4	1199.25
40	47984.04	44831.67	-6.6	3	230	1722.38	1199.97
41	41200.14	38938.67	-5.5	3.25	-496	1567.5	1199.97
42	85476.642	83345.48	-2.5	3.5	1530	805.6	-204.5
43	42112.21	47837.58	13.6	3.25	424	-6203	53.63
44	8409.361	8230.56	-2.1	2.5	115	60	84.56
45	10014.36	9521.662	-4.9	2.5	181	297	73.7
46	8766.66	8398.9	-4.2	2.5	115	241	61.9
47	12376	12053.37	-2.6	2.5	170	-4.3	156.9
48	14984.1	14397.81	-3.9	2.75	147	126.4	312.9
49	11062.7	10965.39	-0.9	2.75	147	-55.4	5.71

Table G1.1.(cont.)Evaluating existing process by redesigning poles bid in the past

No.	Initial Weight (lbs)	Revised Weight (lbs)	% Change	BP Thk.(in)	BP Wt. Diff.(lb)	Pole/Arms Wt. Diff. (lb)	Conn. Wt. Diff. (lb)
50	15438.1	15012.4	-2.8	3	299	489	-364.31
51	10695.6	9640.3	-9.9	2.5	214	694.7	146.6
52	20839.4	19800.72	-5.0	3.25	53	778.4	207.28
53	11614.7	9473.8	-18.4	2.75	123	509	1339.9
54	18099.5	17005.22	-6.0	3	173	455.4	465.9
55	17703.4	16880.1	-4.7	3.25	253	498.6	229.7
56	18970.4	17909.1	-5.6	3.25	320	511.6	229.7
57	24504.4	22934.8	-6.4	3.25	9	1372.4	188.18
58	6933.4	6313.9	-8.9			425.3	184.3
59	3997.3	2984.6	-25.3			788.8	223.9
60	6454.6	5193.87	-19.5	2.25	409	679	608.7
61	5326.8	5246.27	-1.5			63.8	16.7
62	6007.5	4422.68	-26.4	2	94	1328.9	161.9
63	18855.9	17191.6	-8.8	3.25	574	255	
64	15031	15717.4	4.6				686.4
65	11469	12126.2	5.7				657.2
66	6983.1	6881.1	-1.5			102	
67	7880.8	7790.29	-1.1	3	-76	146	20.51
68	7077.9	5342.8	-24.5	2.25	92	1640	5.053
69	9692.9	8093.88	-16.5	2	70	1525	4.02
70	11784.9	9617.88	-18.4	2.25	241	1922	4.02

Appendix H

Data collection for development of models

Table H1.1. Data Collected from Previous Projects

Pole	Total Weight (lbs)	Pole Weight (lbs)	Conn. Weight (lbs)	BP/AB(lbs)	Arms(lbs)	Height (ft)	Voltage (kV)	Total Y-Force (lbs)	Total X-Force (lbs)	Total Z-Force (lbs)
1	12588.401	9097	62.113	3429.288		90	230	27000	27100	10450
2	13737.146	10074	59.846	3603.3		95	230	27000	27100	10214
3	11511.921	8245	64.421	3202.5		85	230	27000	27100	10638
4	10034.173	7181	69.213	2783.96		85	230	27650	12540	4541.4
5	9215.149	6530	71.687	2613.462		80	230	27650	12540	4924
6	10882.313	7859	66.813	2956.5		90	230	27650	12540	4798.5
7	9230.423	6741	66.783	2422.64		85	230	26160	6060	2258.6
8	8616.503	6124	66.783	2425.72		80	230	26160	6060	2383
9	10114.245	7384	66.783	2663.462		90	230	26160	6060	2211
10	10585.73	7708	66.77	2810.96		90	230	25910	12810	5029.7
11	11489.05	8438	65.5965	2985.458		95	230	25910	12810	4901.7
12	9894.6465	7067	71.6865	2755.96		85	230	25910	12810	4823
13	10070.613	7229	57.653	2783.96		90	230	27200	11670	4627
14	10862.473	7935	55.513	2871.96		95	230	27200	11670	4289.8
15	9264.215	6592	58.753	2613.462		85	230	27200	11670	4630.9
16	4712.52	4472	96.2	144.32		90	230	0	2180	863.7
17	2532.55	1541	65.15	926.4		45	115	4875	119	44.9
18	3685.62	2700	48.3	937.32		74	115	2062.5	1025	403.7
19	2150.068	1314	36.08	799.988		50	115	1400	2700	988.7
20	10005.02	7052	84.56	2868.46		67	115	25900	26966.9	10702.4
21	11549.614	8299	73.662	3176.952		70	115	32400	34984.5	13538

Table H1.1.(cont.) Data Collected from Previous Projects

Pole	Total Weight (lbs)	Pole Weight (lbs)	Conn.Weight (lbs)	BP/AB(lbs)	Arms(lbs)	Height (ft)	Voltage (kV)	Total Y-Force (lbs)	Total X-Force (lbs)	Total Z-Force (lbs)
25	9310.99	8906	404.99	3764.612	199.4	75	115	40900	42179.4	16563.3
26	17969.84	10670	1721.91	4531.43	1047	65	115	58900	62402.3	23257
27	11372.513	6701	987.213	3036.2	648.1	70	115	38000	21931.6	8266.6
28	47690.1	29415	8423.8	7554.5	2297	95	115	121399	7659	3011.4
29	46256.6	25641	10214.1	8120	2282	105	115	99280	34126	12612.5
30	31923.44	23316.3	3153.2	5453.94		95	115	67193	9045	3589
31	43235.3	29736.4	7295.5	6203.4		100	115	73785	14606	5690
32	52347.91	33819	9160.6	9368.31		105	115	75374	119867	43184
33	51648.6	33033	9160.6	9455		105	115	138238	2970	1177
34	63886.6	34888	15263.1	10340.5	3395	105	115	149718	1757	635
35	76144.3	46690	14034.2	12025.1	3395	105	115	183677	562	219.9
36	8308.52	5151	744.3	2413.22		60	46	31000	1200	459
37	7940.6	4606	741.1	2593.5		46	46	44100	20100	7470
38	9646.6	5953	741.1	2952.5		55	46	36300	28900	11341
39	10201.51	6358	747.8	3095.71		55	46	50200	13300	4824
40	5476.28	2908	747.8	1820.48		45	46	27700	11800	4618
41	19944	14826	33.6	5084.4		80	138	36130	1641	628.8
42	18045.2	13122	37.8	4885.4		70	138	26790	24803	9231.5
43	15104.7	10697	37.8	4369.9		65	138	25046	26641	10417
44	44243.26	33877	2503.44	6114.42	1748	150	230	36850	14000	5087.7
45	26938.84	18077	2503.44	4610	1748	110	230	36850	14000	5474.5
46	21602.12	13317	2503.44	4033.28	1748	95	230	36850	14000	5334.1
47	51614.32	39665	2548.02	7652.9	1748	150	230	71600	7300	2711
48	97375.85	71570	5101.35	17948	2757	120	230	3350	334750	130955
49	80107.12	56826	4802.84	15721.78	2757	105	230	3350	334750	121212
50	75725.71	53069	4802.84	15096.87	2757	100	230	3350	334750	130624
51	73443.22	54662	5245.12	10127.9	3408	150	230	109850	9150	3494.7

Table H1.1.(cont.) Data Collected from Previous Projects

Pole	Total Weight (lbs)	Pole Weight (lbs)	Conn.Weight (lbs)	BP/AB(lbs)	Arms(lbs)	Height (ft)	Voltage (kV)	Total Y-Force (lbs)	Total X-Force (lbs)	Total Z-Force (lbs)
52	65834.6	47819	5110.19	9497.21	3408	140	230	109850	9150	3388
53	49563.56	33007	5109.47	8038.89	3408	120	230	109850	9150	3584
54	42994.57	27140	5109.47	7336.9	3408	105	230	109850	9150	3295.3
55	90668.64	66872	7240.38	13031.16	3525	140	230	121400	121200	47295
56	53245.38	43211	508.48	9525.9		120	230	58100	121500	46902
57	11984.9	8566	58.9	3360		80	138	35150	14800	5506
58	14379.2	10432	58.9	3888.3		90	138	38550	9300	3650
59	12466	8746	104.4	3615.6		75	138	5400	48550	17868
60	15636	11612	104.4	3919.6		90	138	5400	48550	18946
61	6637.9	4644	32.2	1961.7		75	138	11350	17000	5886
62	20472	15247	193.1	5031.9		90	138	23100	58900	21916
63	15259.4	10609	152.8	4497.6		75	138	23100	58900	22987
64	14001.6	9131	883.9	3425.7	561	85	138	35000	12450	4508
65	12667.8	8077	787.3	3242.5	561	80	138	35000	12450	4863.3
66	11152.5	6881	823	2905.5	543	75	138	32050	7850	2999.4
67	12895.6	8194	855.8	3284.8	561	80	138	33900	13200	4952.7
68	12670	8068	873.8	3167.2	561	80	138	35350	6300	2458.6
69	11767.5	7321	873.8	3011.7	561	75	138	35350	6300	2280.7
70	10902	6604	873.8	2863.2	561	70	138	35350	6300	2459
71	10618.2	6439	821	2797.2	561	70	138	33900	7550	2663
72	9863	5920	773.5	2608.5	561	70	138	31500	6050	2143
73	22768.6	13728	1931.1	5187.3	1922	80	138	56000	53950	21159
74	24694.9	15224	2111.3	5552.2	1807	90	138	70100	25200	9146
75	23434.12	14313	2494.62	5707.4	919.1	85	138	107000	14000	5777
76	11079.293	6628	1055.333	2685.46	710.5	90	138		28300	10056.4
77	19483.83	11831	2438.12	4295.61	919.1	95	138	58500	11200	4201
78	19257.04	11407	2472.2	4437.94	939.9	90	138	57400	26100	10980

Table H1.1.(cont.)Data Collected from Previous Projects

Pole	Total Weight (lbs)	Pole Weight (lbs)	Conn.Weight (lbs)	BP/AB(lbs)	Arms(lbs)	Height (ft)	Voltage (kV)	Total Y-Force (lbs)	Total X-Force (lbs)	Total Z-Force (lbs)
79	20500.4	12467	2472.2	4621.3	939.9	95	138	57400	26100	8928
80	26821.73	16910	2517.72	6474.91	919.1	95	138	107000	14000	5463.7
81	6250.1	4050	217.97	1736.23	245.9	70	69	15550	14740	5631.7
82	5267.68	3176	161.08	1299	631.6	70	69	9940	3450	1283.6
83	7549.03	5524	93.8	1931.23		86		11700	350	147
84	20712.35	14842	260.6	5609.75		72	34.5	90361	2840	1023.2
85	8728.346	6141	99.88	2487.466		75	115	14595.6	19570.2	7663.8
86	18606.06	11941	1417.16	4637	610.9	74	138	4000	72400	27662
87	14154.2	8716	1358.8	3447	632.4	74	138	27800	36400	13468
88	17382.68	12480	36.91	4865.77		90.25	161	36720	50440	19671.6
89	17294.37	12392	36.6	4865.77		90.25	161	37060	49650	17874
90	25763.3	18311	977.4	6474.9		90	138	9610	106640	41589.6
91	10558.8	7132	213.6	3213.2		65	138	23270	5540	2105.2
92	5776.39	3908	104.74	1763.65		65	138	12000	1320	488.4
93	6441.227	4376	269.753	1795.474		90	138	0	11930	4652.7
94	9192.354	6991	268.88	1932.474		110	138	0	11930	4319.5
95	10887.35	8307	268.88	2311.47		125	138	0	11930	4652.7
96	12493.5	8424	201.8	3867.7		75	138	46800	17440	6735.5
97	9606.95	6457	54.25	3095.7		59.5	69	24750	37154.4	13770.4
98	20845.566	16292	94.956	4458.61		110	138	44010	3630	1415.7
99	19526.232	15128	94.956	4303.276		105	138	44010	3630	1306.8
100	18502.896	14035	94.956	4372.94		100	138	44010	3630	1441
101	12412.082	8889	97.13	3425.952		80	138	44010	3630	1379.4
102	11505.833	8077	97.13	3331.703		75	138	43970	1800	666
103	10551.335	7274	97.13	3180.205		70	138	43970	1800	716
104	18226.61	13255	107.76	4863.85		80	138	0	70460	25365.6

Table H1.1.(cont.)Data Collected from Previous Projects

Pole	Total Weight (lbs)	Pole Weight (lbs)	Conn.Weight (lbs)	BP/AB(lbs)	Arms(lbs)	Height (ft)	Voltage (kV)	Total Y-Force (lbs)	Total X-Force (lbs)	Total Z-Force (lbs)
105	16777.19	12007	107.76	4662.43		75	138	0	70460	27479.4
106	15321.95	10847	107.76	4367.19		70	138	0	70460	26774.8
107	17867.19	13057	107.76	4702.43		80	138	0	67280	25097
108	19462.02	14378	107.76	4976.26		85	138	0	67280	26239.2
109	20794.72	15563	106.8	5124.92		90	138	0	67280	24390
110	7558.65	5320	92.18	2146.47		80	138	0	18310	7140.9
111	8033.397	5872	92.18	2069.217		85	138	0	18310	6957.8
112	8927.4	6449	92.18	2386.22		90	138	0	18310	6774.7
113	16861.64	12235	66.7	4559.94		85	138	38635.2	37295.1	13504.3
114	15200.61	11104	68.01	4028.6		80	138	38635.2	37295.1	14545.1
115	13724	9835	66.7	3822.3		75	138	40506.9	39845.2	15086.6
116	8522.8	5834	248.8	2440		66	69	26000	13700	5069
117	7609.8	5079	248.8	2282		60	69	26000	13700	5461.5
118	9230.764	6336	248.8	2645.964		70	69	26000	13700	4932
119	31747.022	13543	70.022	4591		85	138	68555	3611	1379.6
120	29380.844	12328	72.244	4652.6		80	138	68555	3611	1336.1
121	25166.87	10584	59.92	3938.95		90	138	47811	8023	3129
122	23071.14	9642	59.52	3727.62		85	138	47811	8023	2888.3
123	22851.19	9525	32.19	3769		90	138	3555	44543	17506.6
124	20886.445	8619	32.445	3616		85	138	3555	44543	16926.3
125	15033.9	6358	39.43	2278.47		90	138	1236	19497	7213.9
126	13795.402	5807	39.43	2141.972		85	138	1236	19497	7644.2
127	16302.15	6938	38.68	2387.47		95	138	1236	19497	7018.9
128	22912.93	9530	48.65	3804.28		80	138	1750	48985	19104.2
129	24809.57	10442	48.29	3877.28		85	138	1750	48985	18715.4
130	20935.65	8653	49.03	3580.62		75	138	1750	48985	18124.5

Table H1.1.(cont.)Data Collected from Previous Projects

Pole	Total Weight (lbs)	Pole Weight (lbs)	Conn.Weight (lbs)	BP/AB(lbs)	Arms(lbs)	Height (ft)	Voltage (kV)	Total Y-Force (lbs)	Total X-Force (lbs)	Total Z-Force (lbs)
131	26637.802	10976	69.53	4616.272		80	138	32830	58438	22790.8
132	24417.14	9904	69.53	4539.61		75	138	32830	58438	21037.7
133	29163.09	12073	68.15	4948.94		85	138	32830	58438	22790.8
134	63572.16	27242	69.64	9018.52		90	138	0	140183	53269.5

Appendix I

Value stream maps

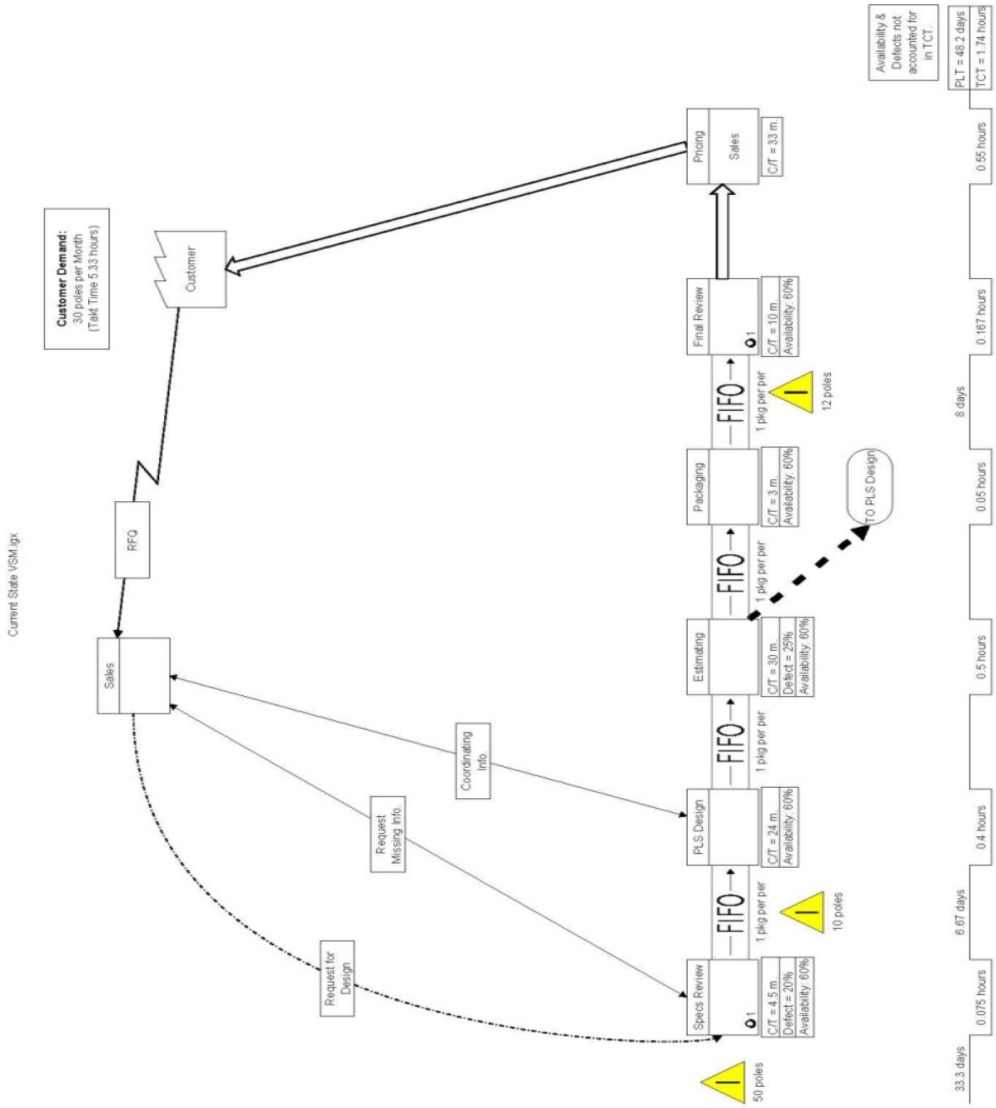

Figure I.1. Baseline Value Stream Map Generated by Improvit (Process before implementing models)

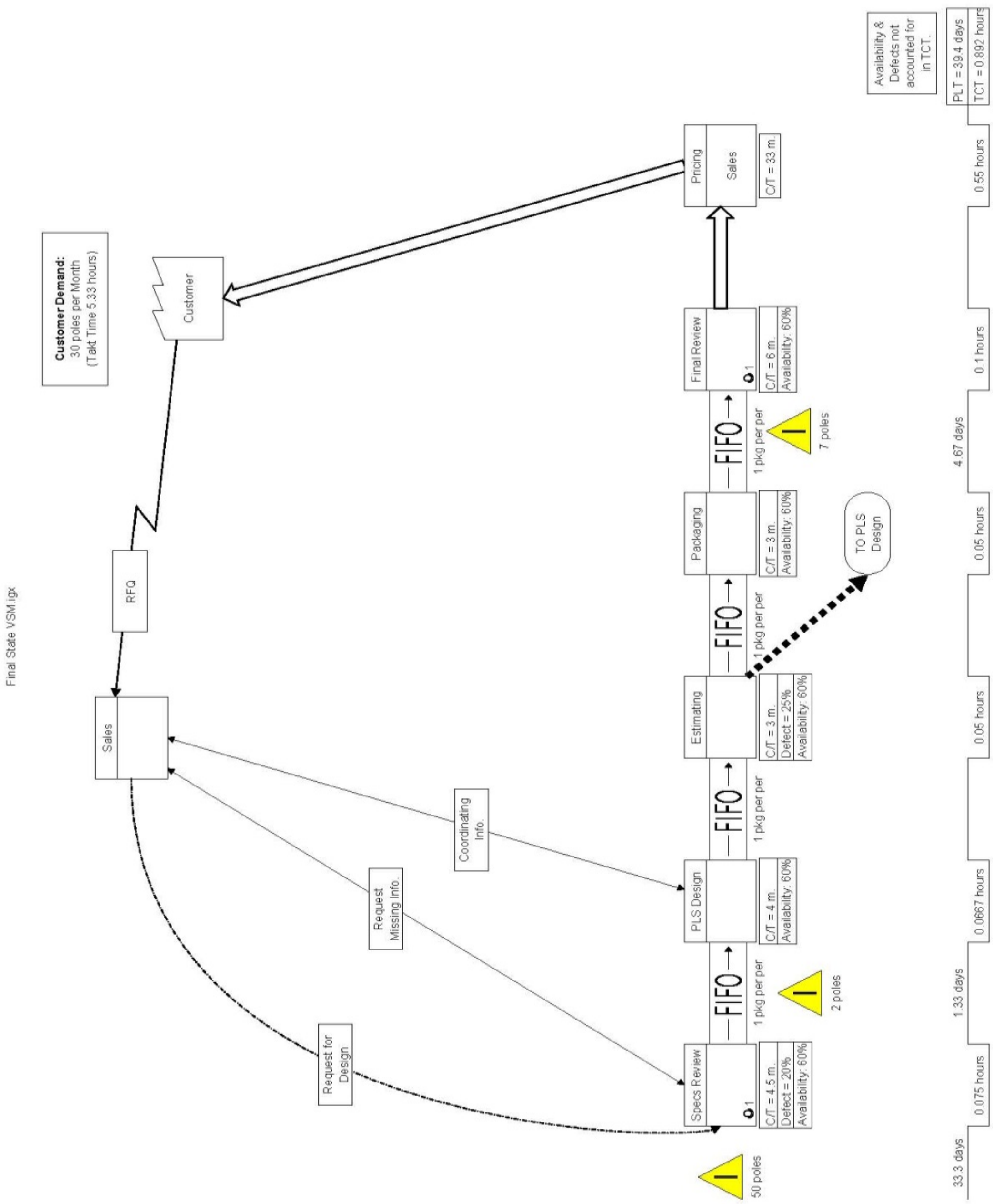

Figure I.2. Revised Value Stream Map Generated by Improvit (Process after implementing models)

VITA

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