



**AN INVESTIGATION IN CONSTRUCTION COST ESTIMATION USING A
MONTE CARLO SIMULATION**

THESIS

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AFIT-ENV-MS-16-M-137

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CARLO SIMULATION

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Abstract

The Air Force estimates military construction (MILCON) costs early in a project's development as a part of the funding approval process. However, many of the initial cost estimates deviate significantly more than expected from the actual project costs, hindering funding allocation efforts. There is a need for improved estimation techniques. This research examines a cost estimation model for the initial programming stages of a project when only general scope information is available.

This study develops a Monte Carlo simulation based on historical construction cost data to predict project costs based on facility type. For a given facility type, the research identified distributions and associated correlations to model major cost elements from the historical data. The Monte Carlo simulation uses these distributions and correlations to estimate the total cost of separate validation projects. The results reveal a histogram, showing the probability range of possible costs for each project. This research compares these results to the actual costs and cost estimates for the same projects along with additional estimated costs derived from standard Air Force cost estimation guides. The results highlight the level of accuracy for current estimation techniques and validate the utility of this model. The Air Force can use this model to improve initial cost estimates, better predicting expected costs in addition to revealing the uncertainty inherent in those costs.

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AN INVESTIGATION IN CONSTRUCTION COST ESTIMATION USING A MONTE CARLO SIMULATION

I. Introduction

Background

Military Construction (MILCON) project cost estimates are heavily scrutinized items within the Department of Defense with demanding requirements for detail and accuracy (U.S. Government Accountability Office, 2009). This scrutiny is no surprise given the emphasis on reducing costs and the lengthy approval process for MILCON projects (Air Force Center for Engineering and the Environment, 2007). In response, the Air Force, along with the other military branches, has turned to a set of cost estimation principles outlined in the Unified Facilities Criteria (UFC) to optimize cost estimation.

The UFC summarizes the spectrum of construction activities with specific guides for cost estimation. Using these guides, Air Force civil engineers, and United States Army Corps of Engineers (USACE) personnel create various cost estimates for construction projects to adequately predict costs for programming and planning purposes. The DoD Facilities Pricing Guide provides principles for deriving the first cost estimate used for general scoping of a project by outlining broad cost factors for categories such as facility type and location (Department of Defense, 2015). However, this is just a preliminary estimate and is expected to be accurate only to within -15% to 25% (Department of Defense, 2011a). The next phase of estimation is to develop a parametric cost estimate using system groupings and assemblies to compile a single expected value, anticipated to be within -10% to +15% of the actual cost (Department of

Defense, 2011a). Finally, by dividing the project into as small of work increments as possible, a Quantity Take Off estimate can be constructed with an expected accuracy of - 7.5% to +10% (Department of Defense, 2011a). Increasing levels of project detail are required for each phase of cost estimation, relying on increasingly detailed designs. Therefore, a basic design concept is typically needed before conducting a parametric cost estimate; and the Quantity Take Off estimate requires a 35% design effort (Department of Defense, 2011a). The military uses these cost estimation methods throughout the construction planning process in all the services, and they are derived from the Association for the Advancement of Cost Engineering's (AACE) recommended practices (Department of Defense, 2011a). Each of these methods results in a single point estimate with a contingency amount, typically 5% added on top of the cost to cover uncertainty.

However, point estimates have inherent problems. First, the point estimates are compilations of average itemized values that, when summed, tend to create estimates that underpredict the actual value by underestimating the risks in a project (Willmer, 1991, p. 1155). As stated by Savage: "plans based on *average* assumptions are wrong on *average*" (2012, p. 11). Additionally, simply adding a contingency percentage on top of average estimates does not produce optimal results. Such a practice typically underestimates the additional funds required for complex or poorly defined projects (Burroughs & Juntima, 2004). Even without an overly complex or poorly defined project, a fixed contingency percent will still be frequently inaccurate because it is simply a set estimate meant to cover a range of actual contingency values.

Problem Statement

All three primary construction cost estimation methods used by the military have critical limitations. Preliminary estimates using general cost factors are too uncertain for use throughout the planning process for a project. Parametric cost estimates rely on a sum of average values to create an expected cost, while not accounting for uncertainty within each line item. Quantity Take Off estimates require substantial resources to conduct and can miss overarching risks to a project that could dramatically impact cost. Estimators need an intermediate cost estimation method that can provide a more accurate estimate than the standard parametric cost estimates. This method should also reveal the range of uncertainty in the estimate for decision makers to evaluate risk, while not requiring the resources needed to create a Quantity Take Off estimate.

Research Objectives/Questions/Hypotheses

The researcher seeks to develop an intermediate cost estimation model that adequately addresses project risks while revealing the level of cost uncertainty within the final estimate. Historical project data includes the risks those projects encountered, and can be analyzed for trends within major categories. The trends in the categories can then be modeled as distributions along with potential correlations between them. According to the literature, combining these assembly line items in a Monte Carlo simulation could create a realistic, cost prediction model (Clark, 2001; Touran & Suphot, 1997; Wall, 1997; Yang, 2005). In doing so, this study will seek to answer the following:

1. What distributions can adequately describe cost trends in construction project assembly items?
2. How do correlations between assembly items affect overall project costs?

3. How does a Monte Carlo cost simulation model using historical cost distributions differ in performance from the current parametric cost estimation method?

Scope and Methodology

The first phase of this research encompasses data collection and analysis. The researcher will compile project cost data from Air Force projects completed since 2000, obtained from the Air Force Civil Engineer Center (AFCEC). Then, through statistical analysis of the major work sections, the researcher will assign distributions to each element using best-fit analysis techniques. The data will also be analyzed for correlations between the elements.

Once element distributions and correlations have been determined, the second phase of research will develop a Monte Carlo simulation with the distributions as inputs. A Monte Carlo simulation is ideal for this situation because of its ability to combine easily numerous distributions with varying properties. This has been done successfully for many large projects by Honeywell Performance Polymers and Chemicals and cited as an industry best practice (Clark, 2001). The Government Accountability Office further encouraged the use of Monte Carlo techniques, emphasizing that point estimates are unable to reveal program risk while the Monte Carlo method has the benefit of capturing positive and negative effects and their combination throughout the elements of a project, therefore improving analysis of the costs (2009, p. 172).

However, the Monte Carlo method is not without potential limitations. Creation of a Monte Carlo model can be a complex and time-consuming endeavor, making the process infeasible if it must be re-accomplished for each project (Sonmez, Ergin, &

Birgonul, 2007). The amount of effort employed by Honeywell Performance Polymers and Chemicals emphasizes this limitation, putting a group of up to 30 people through an effort as long as three days to produce a single project-specific model (Clark, 2001). Hollmann goes into further detail on the limitations of the Monte Carlo method, noting the typical lack of dependencies and correlations between line items and the lack of global risk drivers in the calculations, resulting in an unreliable model (Hollmann, 2007). The lack of global risk drivers in the model becomes of even greater concern when the project is complex or poorly defined (Burroughs & Juntima, 2004). Cost estimating for Air Force construction projects is particularly vulnerable to these limitations because of the often poor project scoping and limited time spent on planning, as noted in several Air Force research efforts (Dutcher, 1986; Gannon, 2011; Nielsen, 2007).

To mitigate these limitations, the Monte Carlo simulation in this study will rely on historical project cost distributions as mentioned previously. Pre-establishing cost distributions within the model eliminates the need for a group of experts to determine individual line item distributions for each project. If the cost distributions continue to be updated and refined as projects finish, the model will continually improve and be easily used by cost estimators, as was shown by Mulholland and Christian in their study to develop better construction schedule estimates (1999). Additionally, by including correlations between the cost distributions, the model can adequately address internal effects between those costs. Finally, the use of historical data removes subjective evaluation of the risks involved. Historical cost data includes all the risks those projects encountered during construction. Therefore, both line item-specific risks and global risks

are covered if the appropriate correlations are modeled accurately, addressing the limitations cited by Hollmann (2007).

Validation of the model includes generating cost estimates for a random sample of projects withheld from the data analysis phase. The researcher can then compare the results to the parametric estimates previously completed for those same projects. A difference in means statistical test will then disclose any differences in cost estimates, revealing improvements, or lack thereof, to current estimation methods.

Significance

Establishing an accurate, programmed amount for a construction project cost is an essential part of the MILCON approval process. However, there is no proven method consistently obtaining the accuracy needed to avoid issues after the project is approved and the magnitude of the estimate errors become known. Estimators establish the programmed amount during the initial project programming phase before an Architect and Engineering (A&E) firm or other agency can do a detailed line item estimate as a part of a design effort (Air Force Center for Engineering and the Environment, 2007).

However, if a design effort, later on, indicates the project will cost more than 25% above the programmed amount, the project may have to be reprogrammed, and the approval process started from the beginning (Air Force Center for Engineering and the Environment, 2007). Even if the project remains within 25% of the original estimate, the extent to which the estimate is inaccurate creates funding ripple effects of shortages or excesses that programmers must address throughout the MILCON program. The development of a cost estimation model that would provide increased accuracy but still

be feasible to use before a project's detailed design phase could significantly mitigate these risks.

II. Literature Review

Chapter Overview

Construction cost estimation includes uncertainty, and past research has developed numerous methods to address varying types of uncertainty. Typically, these uncertainties are grouped into either *systemic* or *project-specific* categories, the former representing predictable uncertainties for which plans can be made, and the later representing unpredictable uncertainties that remain unknown until construction commences (Buertey, Abeere-Inga, & Kumi, 2012). Estimators often use parametric models in a construction cost estimate to predict systemic risks, whereas they use simulation methods such as Monte Carlo for project-specific risks (Hollmann, 2007). Industry in general, and the Air Force specifically, has conducted research and published guides to further standardize and refine these methods. The Air Force typically follows industry standards in its recommendations, but the Air Force does not currently use a simulation method for construction cost analysis, creating a gap that, if filled, could provide significant insight into project costs. This literature review will first describe a cost estimation method framework. This framework will provide the lens through which to assess industry research and practices, followed by the Air Force's current methods of construction cost estimation. Finally, this review will examine how a modified Monte Carlo application taken from industry could fill the Air Force methods gap.

Cost Estimation Framework

Construction cost estimation methods typically take one of two forms: a project cost point estimate or a contingency cost estimate that captures uncertainty around a point

estimate. The types of methods available within these categories range between more stochastic methods used at earlier project definition stages and more deterministic methods used for more well defined projects depending on how well-defined the project is (Christensen & Dysert, 2011). The Association for the Advancement of Cost Engineering (AACE) International provides useful frameworks for comparing estimation methods within the *point estimate* and *contingency estimate* categories. Research and industry best practices form the foundation of AACE's frameworks, describing the current state of industry cost estimation. The Air Force follows estimation methods defined by the Unified Facilities Criteria (UFC), all of which are point estimates represented within AACE's point estimation framework.

Current State of Industry Construction Cost Estimation

Industry currently uses both point estimate and contingency estimate methods for construction projects, often in tandem. Point estimates by themselves lack pertinent information for decision makers, masking the risk of a particular project by hiding the level of uncertainty inherent in the cost estimate (Hollmann, 2008). Contingency cost estimation methods can reveal a point estimate's uncertainty as outlined below.

Cost Point Estimation

AACE developed cost estimation recommended practices based on industry best practices and standard methods. They developed a 5-class framework categorizing estimates by the degree of project definition (from 0-100%). The classes include both stochastic and deterministic methodologies of cost estimates covering the wide variety of specific methods used throughout industry. The expected accuracy range column reflects

the range from the estimate within which the actual cost should fall (Christensen & Dysert, 2011). Figure 1 shows an overview of the classes and their characteristics.

ESTIMATE CLASS	Primary Characteristic	Secondary Characteristic			
	DEGREE OF PROJECT DEFINITION Expressed as % of complete definition	END USAGE Typical purpose of estimate	METHODOLOGY Typical estimating method	EXPECTED ACCURACY RANGE Typical +/- range relative to index of 1 (i.e. Class 1 estimate) ^[a]	PREPARATION EFFORT Typical degree of effort relative to least cost index of 1 ^[b]
Class 5	0% to 2%	Screening or feasibility	Stochastic (factors and/or models) or judgment	4 to 20	1
Class 4	1% to 15%	Concept study or feasibility	Primarily stochastic	3 to 12	2 to 4
Class 3	10% to 40%	Budget authorization or control	Mixed but primarily stochastic	2 to 6	3 to 10
Class 2	30% to 70%	Control or bid/tender	Primarily deterministic	1 to 3	5 to 20
Class 1	70% to 100%	Check estimate or bid/tender	Deterministic	1	10 to 100

Notes: [a] If the range index value of "1" represents +10/-5%, then an index value of 10 represents +100/-50%.
[b] If the cost index value of "1" represents 0.005% of project costs, then an index value of 100 represents 0.5%.

Figure 1: AACE Cost Estimate Classification Matrix (Christensen & Dysert, 2011)

AACE's classification method is significant because it only relies on the degree of project definition to classify an estimate, and all estimates rely on a project with some amount of scope definition. The numerous estimation methods do not fit neatly into typical qualitative categories, hampering other classification systems that do not rely on the level of scope definition. However, AACE's class system is quite generic and therefore, AACE still provides some general guidance on the four major cost estimation types currently in industry use (Gransberg & Lopes del Puerto, 2011).

Feasibility estimates are the broadest kind of estimates, conducted at the outset of project planning and used to decide if a project will likely be profitable or able to meet the intended goals within general budget constraints. These are Class 5 estimates, used when project definition is between 0% and 2%. Conceptual estimates are more refined, requiring some level of design for estimation and often being updated repeatedly as a design progresses. They can range from Class 4 to Class 2 estimates as the design becomes more detailed, with project definition moving from 1% to 70%. Finally, detailed lump sum estimates and detailed unit price estimates are the most exact type of estimates, relying on quantitative project attributes from at least partially complete construction documents. Detailed lump sum estimates produce total construction cost estimates. Detailed unit price estimates build schedules of bid items from unit costs, summed for the total project cost. These are Class 1 estimates with project definition between 70% and 100% (Gransberg & Lopes del Puerto, 2011).

Cost Contingency Estimation

Contingency cost estimation methods have numerous classification types, but Burroughs and Juntima (2004), in partnership with AACE, described one of the most straightforward and comprehensive systems. They divide contingency estimation methods into four main categories in order of increasing accuracy: set percentage, expert judgment, risk analysis, and regression analysis (or parametric modeling) (Burroughs & Juntima, 2004). A set percentage is a fixed amount added to the estimate of a project without regard to any project-specific factors. Expert judgment is the subjective application of a contingency amount based on the experience of an estimator or planner. Because of their simplicity, estimators often use these two types of methods early in the

planning stages of a project when little information is required. However, they also tend to be the least accurate of the contingency estimation categories (Hollmann, 2008).

Therefore, research has focused on the latter two categories, producing refined methods for increasing accuracy through risk analysis and regression analysis.

Risk Analysis

Risk analysis can use simulations, such as Monte Carlo, or more deterministic calculations to produce a confidence interval for a cost estimate. This analysis has typically relied on a planning team to identify risk or cost distributions subjectively and input them as parameters in the model. A simulation or algorithm then uses the input distributions to generate an overall risk or cost distribution for the project as a whole. One of the more complex examples is the Advanced Programmatic Risk Analysis and Management (APRAM) method, further refined by in the Modified APRAM method. These methods take the difference of the expected project cost and the maximum desired project cost and allocate those funds to specific project activities to buy down risk through a nonlinear optimization algorithm, minimizing the risk of failure for the project as a whole (Imbeah & Guikema, 2009; Zeynalian, Trigunarsyah, & Ronagh, 2013). Slightly less complex is the Estimating using Risk Analysis method, which calculates a project's expected and worst-case cost estimate using average and maximum risk estimates based on expert opinion for each possible project risk (Mak, Wong, & Picken, 1998). Monte Carlo simulations are also used for risk analysis and will be described in more detail later. Risk Analysis methods typically address project-specific risks effectively because of the detailed input required for each project (Hollmann, 2008). However, they also usually require time-consuming efforts and can neglect systemic risks

and dependencies between individual distributions because of the model's complexity (Burroughs & Juntima, 2004).

Regression Analysis

Regression Analysis is typically described as the most empirical method, relying on historical cost data trends to estimate the contingency funds required for a current project (Hollmann, 2008). Using regression analysis, Cook (2006) developed a method for estimating the contingency funds required for Air Force construction projects, creating a model using ten factors to predict contingency costs. Another example of this approach is the regression model developed by Sonmez et al. (2007), which used four project factors, including the type of contract and a country risk factor derived from historical data, to estimate contingency costs. They developed this method as a quantitative model with improved accuracy over expert judgment and with simpler application compared to complex models such as Monte Carlo simulations. Regression models, once developed, are often simple to understand and use. This characteristic, combined with the ability to better address systemic risks than other methods, makes regression analysis one of the more common cost estimation techniques in use, even though it does not capture project-specific risks (Hollmann, 2008).

Summary

Across all methods, construction cost estimation theory consistently reinforces the necessity of identifying the uncertainty inherent in an estimate (Christensen & Dysert, 2011; Hollmann, 2008). The methods available towards this end are then a function of the level of project definition and the resources available to conduct the estimation.

Current State of Air Force Construction Cost Estimation

The Air Force relies on the UFC for recommended cost estimation practices. The UFC program, developed in response to the House Conference Report 105-247 (1997), created standardized criteria integrated across the Department of Defense for use in initial facility planning through construction and maintenance. The Air Force Civil Engineer Center, United States Army Corps of Engineers, and Naval Facilities Engineering Command (together called the “Tri-Services”) jointly manage the UFC program (Department of Defense Standard Practice, 2006).

Unified Facilities Criteria Cost Estimation Methods

For standardized cost estimation methods within the UFC, the tri-services developed specific techniques derived from the cost estimation categories and practices recommended by AACE. UFC 3-740-05 outlines the four primary cost estimation methods recommended for the military: project comparison estimation; square foot or square meter estimation; parametric estimation; and quantity take off estimation (Department of Defense, 2011a), which Table 1 summarizes. It is worth noting that the square foot/square meter method included parametric principles, but the UFC reserves the term “parametric” for a slightly narrower category of assembly-based estimations.

Table 1: Unified Facilities Criteria Cost Estimation Methods

UFC 3-740-05 Estimation Methods	Timeframe for Estimate Development	Expected Accuracy	AACE Estimate Class
Project Comparison	Upon project conception	-25% to +40%	Class 5
Square Foot/ Square Meter	When project areas and/or volumes are estimated	-15% to +25%	Class 4

Parametric	When design is 10-30% complete	-10% to +15%	Class 3
Quantity Take-Off	When design is over 35% complete	-7.5% to +10%	Class 2 or 1

AACE associates cost indexes with the various estimation classes (as seen in Figure 1), which the following sections compared to the UFC 3-740-05's accuracy range. An organization can match AACE's cost index of 1 to the expected accuracy range of their own final Class 1 estimate, and derive the expected accuracy of earlier class estimates for the project. The index system provides increased fidelity in the estimation process by narrowing or widening the accuracy ranges based on an organization's average accuracy in their final cost estimates. As an example, if an organization expected the actual project cost to be within 10% of the final estimate, 10% would be associated with an index of 1. An earlier class of estimate with an index of 5 would then have an expected accuracy range of within 50%. UFC 3-740-05 states a quantity take-off Class 1 estimate will have a range of -7.5% to +10% within which the actual project costs should fall (Department of Defense, 2011a). Therefore, for the purpose of this research, an index of 1 has an expected accuracy range of -7.5% to +10%.

Project Comparison Method

Project comparison cost estimation provides a rough order-of-magnitude cost during the initial stages of a project's development when the scope of the project is still ill-defined (Department of Defense, 2011a). For this method, an estimator compares the project in question to one or more similar projects accomplished in the past, preferably in similar environments. The more similar the environment and the more recent the completion of a comparison project, the more applicable the comparison. The final cost

of the comparison project is then scaled to account for differences in scope between the comparison project and the current project. This scaling is based on a primary measure of the new project's capacity such as the number of people or vehicles supported by the facility or the number of classrooms or uniform room type within the facility. UFC 3-740-05 notes that the project comparison method provides an estimate with a typical accuracy of -25% to +40% within which the actual final costs should fall, barring significant market upheavals or rare and extreme events (Department of Defense, 2011a).

This method falls under the Class 5 cost estimate category of the AACE. Class 5 estimates include expert judgment and basic stochastic methods for use when a project has 0% to 2% of the project defined (Christensen & Dysert, 2011). A Class 5 estimate has an expected cost accuracy index of 4 to 20 compared to a completely defined Class 1 estimate with an index of 1 (Christensen & Dysert, 2011). Therefore, this Class 5 project comparison cost estimate could have an accuracy ranging as narrow as -30% to +40% at an index of 4 to as broad as -100% to +200% at an index of 20. Because the project comparison method does not rely only on an estimator's judgment but also uses some historical data, the Department of Defense expects the comparison estimates to be on the optimistic side of the spectrum for Class 5 estimates (Department of Defense, 2011a).

Square Foot or Square Meter Method

The square foot/square meter cost estimate is the next step in the UFC-recommended estimation process to improve accuracy (Department of Defense, 2011a). For this method, the project scope must be defined enough to include estimated areas or volumes of the spaces within the proposed facility. Then, using historical data from a database such as RSMeans, UFC 3-701-01, or the Parametric Cost Engineering

System (PACES), a baseline cost can be estimated using per-area or per-volume average prices. UFC 3-701-01 and PACES rely on data collected in the DoD Tri-Services Automated Cost Engineering System (TRACES) Cost Book (Department of Defense, 2015). The cost book is, in turn, developed from project records entered into the Historical Analysis Generator - Second Generation (HII) program, developed by the United States Army Corps of Engineers (USACE). USACE personnel input all of their projects into the HII program with the exception of horizontal projects (such as roads) and facility sustainment, restoration and modernization (FSRM), which are optional (USACE, 2015). USACE has mandated the addition of project data into the HII program, or its software predecessor, since 1999 resulting in a relatively comprehensive database (USACE, 1999).

Once an estimator develops a baseline cost estimate, he or she can then modify that cost by adjusting for location, project size, price escalation, and other specific parameters by applying factors often available within the same resources as the historical databases. Increasing project definition allows for more project-specific adjustments, which increase the estimate's accuracy, but the overall accuracy of the square foot/square meter method typically lies within -15% to +25% (Department of Defense, 2011a).

The square foot/square meter method falls in the Class 4 cost estimate category of the AACE classification system. Class 4 estimates include stochastic methods using factors typically for the purpose of a feasibility study (Christensen & Dysert, 2011). Class 4 estimates are designed for use when a project is between 1% and 15% defined, with a resulting cost accuracy index of 3 to 12 (Christensen & Dysert, 2011). For the square foot/square meter method, the accuracy index suggests an accuracy range as

narrow as -22.5% to +30% at an index of 3 to as broad as -90% to +120% at an index of 12. As with the project comparison method, UFC 3-740-05 states the expectation the square foot/square meter method should result in estimates slightly more accurate than a typical Class 4 estimate (Department of Defense, 2011a).

Parametric Method

Parametric cost estimation, as described in UFC 3-740-05, is an intermediate estimate recommended when a design is between 10% and 30% complete (Department of Defense, 2011a). The parametric method uses historical data to estimate the cost of assemblies and systems within a facility, summing the subtotals for an overall project estimate. This method provides more accuracy than project comparison or area cost factors, but with less project definition required for a line item by line item cost estimate (Department of Defense, 2011a). Parametric cost estimates are expected to have an accuracy of -10% to +15% (Department of Defense, 2011a).

Within the Air Force, the primary means of accomplishing a parametric cost estimate is through the software program PACES (Meyer & Burns, 1999). Developed in the 1980s, PACES uses historical construction costs from the HII database mentioned earlier. PACES breaks costs down into Work Breakdown Structure line items and organizes them into the Construction Specifications Institute's (CSI) MasterFormat structure as detailed in the PACES 2005 Training Manual for the Air Force (Earth Tech, 2005). PACES includes a range of cost estimates from an initial area cost factor Class 4 estimate as mentioned in the square foot/square meter method section, to a relatively detailed Class 2 estimate. An estimator can start with default project parameters for an

initial estimate and add information to improve the estimate's accuracy as a project becomes more defined (Earth Tech, 2005).

The parametric method primarily produces Class 3 estimates. An estimator develops these estimates for projects with 10% to 40% of the design complete and can provide enough fidelity for budget projections (Christensen & Dysert, 2011). Class 3 estimates should have a cost accuracy index from 2 to 6 (Christensen & Dysert, 2011), indicating an accuracy range of -15% to +20% at an index of 2 and -45% to +90% at an index of 6 for Air Force Class 3 estimates in general. However, the Department of Defense expects the parametric method, in particular, to be more accurate than the typical Class 3 range, with the previously mentioned accuracy range of -10% to +15% (Department of Defense, 2011a).

Quantity Take-Off Method

The final and most accurate method for cost estimation recommended by UFC 3-740-05 is the quantity take-off method (Department of Defense, 2011a). Estimators using this method divide a project into as many, individually priced, specific work increments as is feasible. With their associated quantities and unit costs, these increments subtotal and sum together into an overall project cost estimate. Typically a 35% design, at a minimum, is required to supply the level of detail need for this type of estimate, and the expected accuracy is -7.5% to +10% (Department of Defense, 2011a).

The quantity take-off method can be considered either a Class 2 or Class 1 estimate depending on how well defined the project is. Class 2 estimates typically require a project to be 30% to 70% defined whereas Class 1 estimates require 70% to 100% of a project to be defined (Christensen & Dysert, 2011). A Class 1 estimate

provides the baseline for the expected accuracy range of earlier estimates with an index of 1 (Christensen & Dysert, 2011). Therefore, the quantity take-off method's expected accuracy of -7.5% to +10% was used in this paper as a baseline to compare the expected accuracies of earlier stage estimates outlined in UFC 5-740-05 with the accuracy index range expected by AACE.

Summary

None of the methods currently recommended for use in Air Force construction cost estimation include a simulation analysis method. Furthermore, Air Force research has focused primarily on factor analysis and parametric models to improve cost estimates. Several Air Force research efforts have analyzed factors impacting a project's schedule performance, overall project success, and the number of project change orders in Air Force construction (Beach, 2008; Hoff, 2015; Nielsen, 2007). Two studies developed parametric models for estimating project costs. One study predicted contingency fund requirements for Air Force MILCON projects using historical data trends (Cook, 2006) and the second used expert opinion to model impacts of several factors on Air Force project costs in general (Stark, 1986). Appendix A summarizes other similar Air Force construction cost research.

The lack of a simulation method, both in practice and as a focus of research, is of interest because simulations are recommended by the Government Accountability Office (2009) for increased accuracy in cost estimation in the Air Force (Air Force Cost Analysis Agency, 2007). Specifically, the Government Accountability Office (2009) explicitly states that using a simulation to estimate cost is better than the summation of the most likely element costs, which is usually inaccurate. Step 9 of their "Twelve Steps

of a High-Quality Cost Estimation Process” involves using simulation to conduct uncertainty analysis for a given point estimate (U.S. Government Accountability Office, 2009). The Air Force Cost Analysis Agency (2009) provides three methods of analyzing uncertainty in a cost estimate, two of which are simulation-based. The third option, the scenario-based method, is only recommended when there are not enough resources or data to support one of the simulation-based methods (Air Force Cost Analysis Agency, 2007). Therefore, a construction-specific simulation method adapted from industry research could bring significant insight into expected project costs after the initial, highly uncertain factor analysis estimates and before the parametric cost estimate developed during design. Decision makers would then have access to a more accurate cost estimate during the budget and approval process before design commencement.

The Monte Carlo Method

The Monte Carlo method was developed by Stan Ulam and John von Neumann in the 1940s to estimate the results of combining a complex set of uncertainties together when the direct calculation of the final probabilities would be intractable (Metropolis & Ulam, 1949). Initially used for modeling atomic reactions at Los Alamos in the development of thermonuclear and fission devices (Eckhardt, 1987), the technique is ideal for the combination of cost distributions, resulting in a significantly more reliable estimate than just summing the averages of each subordinate distribution (Savage, 2012). However, the method requires careful modeling to cover systemic risks and dependencies between distributions. Therefore, the following sections provide an overview of the development of the model for construction cost estimate along with a review of techniques for compensating for some of the model’s limitations.

Development for Construction Applications

Initially, available computer computational ability limited the use of Monte Carlo simulations for construction cost and schedule estimates. A study in 1991 highlighted this fact with the development of a computer program that took activity range inputs and calculated the overall cost and time for the project using a Monte Carlo simulation (Willmer, 1991). The program had to be broken up into parts and run separately because the available computers could not run the whole simulation at once. Further advancements in technology minimized the computational restrictions and more useful and realistic models were developed using Monte Carlo simulations, such as Dawood and Nashwan's Monte Carlo Network Analysis (1998) and the Judgmental Risk Analysis Process (Öztaş & Ökmen, 2005). Both of these models estimate project duration using risk probability distributions. The technique advanced in the cost arena as well, resulting in construction organizations beginning to rely on Monte Carlo analysis for detailed cost estimation (Clark, 2001).

Monte Carlo Improvements

Despite widespread use, many research studies and organizations have not applied systemic risk factors or correlations between items in their Monte Carlo estimates, including the studies previously mentioned. Ignoring systemic risk factors, such as project location, in a line-item based simulation removes potentially significant effects on the project as a whole, reducing the model's accuracy and utility (Hollmann, 2007). Instead of ignoring these systemic risk factors, parametric models can adjust the Monte Carlo simulation results for systemic risk factors.

However, parametric modeling adjustments to a Monte Carlo simulation only address whole-project risk affects, while potential inaccuracies remain within the model without appropriate correlations. For example, electrical and mechanical costs tend to rise and fall together, but if estimators fail to include this relationship, additional error is introduced into the estimate (Chau, 1995a). Chau (1995a) went on to investigate the effects of using different types of distributions to model construction cost data, concluding that triangle distributions tended to introduce unnecessary error and instead beta and lognormal distributions were preferred. Wall's (1997) research further analyzed distribution types for cost data and recommended the lognormal distribution over the beta distribution when modeling historical data. The types of distributions chosen play a key role in correlation modeling because the most common type of correlation, the Pearson's correlation, typically relies on normal distributions to correlate. Since historical cost data does not often fit a normal distribution, a transformation to normal distributions would likely be required. Alternatively, Spearman or rank correlations provide an avenue to correlate distributions of any type without transformation and were shown to be viable in Monte Carlo cost estimates (Touran & Suphot, 1997). With accurate distribution modeling, appropriate correlations, and systemic risk factors accounted for, a Monte Carlo simulation can overcome many of the otherwise inherent disadvantages.

Conclusion

Point estimates for cost do not provide insight into a project's uncertainty and the resulting risk to the organizations involved because a single point hides the range within which the cost could fluctuate. Summations of expected values often do not take into account correlations between project items, resulting in unintentionally skewed estimates

due to unaccounted internal interdependencies. However, the Air Force has focused construction cost estimation research, along with recommended estimation methods, on parametric models and general factor analysis. These models produce a point estimate after providing adjustments to a single project expected value or a summation of project element expected values. While the resulting estimates are useful, the Air Force could benefit from a method that provides additional insight into an estimate's uncertainty and can model project risks more accurately while still being executable before the design phase of a project. A Monte Carlo simulation may be able to provide those benefits, assisting decision makers at the time Air Force projects are budgeted and approved and before significant errors in an estimate cause program upheavals to correct.

III. Methodology

Chapter Overview

The purpose of this research is to develop a cost-estimating tool that can provide a more accurate estimate than current practices using a basic 15% design. This methodology chapter describes the steps used to develop the model. The model used a Monte Carlo simulation to estimate individual project costs based on historical data. The first section provides an overview of the Monte Carlo method and the specific application used in the model. The second section describes the data collection effort. The third section describes the steps used to develop representative distributions to model individual cost elements along with correlations between those cost elements. Finally, the fourth section describes the model validation.

Monte Carlo Simulation

Element distributions and correlation matrices between those elements form the foundation of the Monte Carlo simulation used in this research. In general, the simulation takes a random sample from each element distribution, correlates them according to the correlation matrix, and outputs the results as one trial. This process repeats numerous times. The Monte Carlo simulation collects data from each trial, adding them to a histogram showing the various results. After over tens of thousands of simulation trials, the histogram becomes stable, revealing the probability of specific results based on their frequency in the histogram. To build this type of Monte Carlo simulation, Iman and Conover developed a method for correlating multivariate random variables, such as those studied here, with a rank correlation matrix (1982). Their

method allows for the use of any input distribution without concern for normality, including the use of distinct types of input distributions simultaneously for different variables. Additionally, this technique preserves the integrity of the sampling method used, allowing methods such as the Latin Hypercube Sampling, described later, without distorting the intervals. Finally, their method also provided better results for producing outputs more closely following the given correlation relationships compared to other random sampling techniques (Iman & Conover, 1982). Other studies have used Iman and Conover's method to simulate correlated construction cost, further validating the method's utility for this research (Touran & Suphot, 1997). Given their method, also available in software packages for programs including the R Project for Statistical Computing, the researcher established a Monte Carlo simulation model.

Within the simulation model, the nature of the sampling method affects the results. Simple random sampling is the most basic sampling method, drawing numbers using a computerized random-sampling algorithm from within the distribution parameters. Latin Hypercube Sampling is an alternate option, dividing a given distribution into equal-probability intervals and drawing a proportional number of samples from each interval (Air Force Cost Analysis Agency, 2007). Latin Hypercube Sampling preserves the overall proportions of the distribution being sampled, reducing concerns of bias introduced randomly through the simple sampling process. Increasing the number of samples taken minimizes the likelihood of a random bias from simple random sampling, but Latin Hypercube Sampling minimizes such a bias from the outset while allowing the simulation to converge to the true mean with fewer iterations. Several government agencies also recommends Latin Hypercube Sampling for government cost

estimation (Air Force Cost Analysis Agency, 2007; U.S. Government Accountability Office, 2009). Therefore, for this study, each simulation ran 100,000 trials through a Latin Hypercube Sampling method to estimate complete and accurate distributions for the final analysis.

The simulation outputs 100,000 sample costs for each of the cost elements identified. As a result, each of the 100,000 rows, comprising of one each of the 11 cost elements correlated together, is a generic cost summary per unit for the given facility type. The summation of each row provides a cost estimate total. Taking each of these 100,000 sample cost summaries, the model developed here created a cost distribution histogram for each facility type studied. These costs, multiplied by the desired facility scope and adjusted for the desired construction date and location, produce a project-specific cost estimate. If desired, the cost elements may remain separate throughout these calculations, providing a review of the element costs within the total cost, or summed together for the overall cost estimate.

Data Collection

The Department of Defense stores Air Force historical construction project data in several different databases. The Air Force has the most comprehensive database in the Automated Civil Engineer System (ACES). Both the United States Army Corps of Engineers (USACE) and the Naval Facilities Engineering Command (NAVFAC) also have project data for military construction (MILCON) projects they execute for the Air Force. While the Air Force maintains general information on every construction project type within ACES, each engineering squadron or agency records much of the specific project details locally and not in a central repository for simple retrieval. Data quality is

also an issue, with many of the information fields in ACES for a given project remaining blank or containing errors. USACE has more detailed records in their databases, specifically in the Resident Management System (RMS), but access to the system is limited to approved individuals with RMS-specific software. Therefore, the researcher examined both ACES and RMS as possible data sources to obtain project costs. The criteria for acceptable data included completed Air Force construction projects with detailed cost line items useful in identifying the subtotal costs of the main cost elements within each project. This research also required information on the scope of each project, convertible to either square feet or square meters, along with the location, facility type, and mid-point date of construction. With these components, the rest of the analysis could commence.

Cost Element Selection

Selecting appropriate cost elements to describe the main components of a project's overall cost set the foundation for the rest of the methodology. Past research has limited the number of cost elements to analyze within a project to between 5 and 15 (Touran & Suphot, 1997; Touran & Wiser, 1992; Wall, 1997; Yang, 2005). Using every detailed cost line item would be impractical, creating significant issues defining distributions and associated correlations that accurately describe the majority of the projects in a set. Instead, Touran and Wiser suggest that the items on a cost summary sheet provide a sufficient level of detail (1992, p. 259). Humphreys' assertion supports this concept that less than 20 cost items in a given construction estimate are critical items. They contribute to a majority of the cost risk, with those 20 or fewer items being the only items significant enough to change the cost by more than 0.5% if their inherent risk is

realized (Humphreys, 2008). Therefore, defining a large number of cost elements for analysis is unnecessary if only a small portion will indeed alter the overall cost significantly. To build on these lessons, the researcher sought to define between 5 and 15 cost elements of a similar type to those used in past research and which followed the general format of the CSI MasterFormat divisions. The military relies on the CSI MasterFormat divisions as a primary means of categorizing costs during the estimation process (Earth Tech, 2005), providing an initial framework for the cost elements in this study.

Construction costs, particularly individual line item costs, can come in many forms particular to the contractor supplying them, requiring a method to transform varied estimate into summaries fitting within the cost elements chosen as described earlier. Such a method was especially necessary when using data from the RMS database managed by USACE. RMS records each cost line item billed by a construction contractor to the government. For large MILCON projects, such as is the focus of this study, those line items can number in the thousands. Additionally, the line item description consists of any phrase or code the contractor deemed useful for bookkeeping and for which the government Contracting Officer accepted. There are no enforced standard or wording criteria for what is considered a minor record of cost identifiers useful only infrequently in the administration of a contract. Furthermore, when contractors or government personnel summarize these line items, they group them either into one aggregate cost for the entire project or by major contract line item number (CLIN). CLINs describe major components of the product desired by function, not construction effort or specialties. Therefore, to categorize the many thousands of

dissimilar line items into meaningful cost elements, the researcher built a list of keywords, phrases, acronyms, and abbreviations associated with each cost element. Then, a search function could scan the line item descriptions for the keywords and categorize the costs appropriately. This search also required an order of precedence for the keywords for situations when a single line item contained multiple keywords, resulting in the correct categorization of that item. Appendix C lists the keywords, phrases, and abbreviations in the order of precedence used. The abbreviations include truncated words and intentional mis-spellings to account for the shorthand used by many contractors.

In addition to having line items categorized into cost elements that adequately and succinctly describe the overall project costs, those cost elements also needed to be standardized based on a common unit of measure and based on systemic factors (Yang, 2005, p. 279). The common unit of measure is typically square feet or square meters and is necessary to compare and correlate the elements with each other as well as to compare items between projects of different scope (Yang, 2005). Standardizing based on systemic factors removes cost differences based on location or timeframe and yields a more accurate representation of general construction costs (Yang, 2005, p. 279). In this study, the model used the UFC 3-701-01 DoD Facility Pricing Guide's area cost factors and escalations factors to standardize the cost data with a generic location index of 1 and based in October 2014 dollars (2015).

Another key systemic factor affecting project cost is the facility type. Different types of facilities drive variations in cost due to the differences in construction efforts required. Therefore, the model focuses on simulating costs based on facility type. Past

research has predominantly focused on similar office buildings as a source of uniform data to analyze (Touran & Suphot, 1997; Touran & Wiser, 1992; Wall, 1997; Yang, 2005). The Air Force builds a much wider variety of facilities to support its mission than simply office buildings. Therefore, this research focused initially on airfield and airfield-related projects, sorting projects by category code (CATCODE) into groupings similar to the UFC 3-701-01 DoD Facility Pricing Guide (2015). However, due to the limited amount of airfield-specific projects and other facility types available in the data, the researcher could only analyze dormitories, education and training facilities, and squadron operations facilities. The model then took each facility-type grouping and applied the rest of the following methodology, resulting in a cost estimate profile specific to each facility type.

Distribution Characterization

Each cost element needed a distribution describing the element's behavior for modeling. Triangular distributions have historical precedence in modeling construction costs because of their direct application to subject matter expert's estimates. However, Chau argues that either generalized beta or lognormal distributions are a better fit for historical data (1995b). Additionally, other authors have suggested that the lognormal distribution is a better fit for historical construction cost data than the generalized beta (Touran & Wiser, 1992; Wall, 1997). Table 2 shows a sampling of past research detailing the construction cost elements past authors selected and the distributions they associated with those elements. Additionally, these authors correlated the elements shown in clear cells in Table 2 with the rest in their model. Touran concedes that the unbounded positive tail of the lognormal may need to be truncated in some cases, but this

is typically not necessary due to the extremely remote probabilities represented by the parts of the tail that could produce an unreasonable cost sample (1993, p. 69).

Table 2: Cost Element Selection and Associated Distributions from Past Research

Touran & Wiser (1992)		Touran & Suphot (1997)		Yang (2005)	
<i>Elements</i>	<i>Dist</i>	<i>Elements</i>	<i>Distribution</i>	<i>Elements</i>	<i>Distribution</i>
General & Overhead	Lognormal (all elements)	Sitework	Gamma	Substructure	Lognormal
Site Work		Concrete	Lognormal	Superstructure	Lognormal
Concrete		Masonry	Gamma	Internal Finishes	Lognormal
Masonry		Metals	Beta	Fittings & Furnishings	Discrete
Metals		Carpentry	Beta/Log-normal	Services	Beta
Carpentry		Moisture Protection	Lognormal	External Works	Beta
Moisture Protection		Doors, Windows, Glass	Lognormal	Preliminaries	Lognormal
Doors, Windows, Glass		Finishes	Gamma	Contingencies	Lognormal
Finishes		Mechanical	Gamma		
Specialties		Electrical	Erlang		
Equipment					
Furnishings					
Conveying Systems					
Mechanical					
Electrical					

 Elements not correlated with the others in the specified model

To identifying distribution candidates for each cost element, the researcher plotted the cost element data sets on a Cullen and Frey graph. The Cullen and Frey graph plots the data's estimated square of skewness (x-axis) versus kurtosis (y-axis) with common distributions shown as points, lines, or shaded regions, depending on the parameters of that particular distribution (Delignette-Muller & Dutang, 2014). For example, the normal distribution has only one skewness and kurtosis location on the graph, shown as a single point. Alternatively, the graph shows lognormal and gamma distributions as a line due to their potential variation in skewness and kurtosis, whereas the beta distribution is a region because of the four parameters defining a much wider variety of possible shapes

(Delignette-Muller & Dutang, 2014). Plotting the estimated square of skewness and kurtosis of the data, overlaid on these possible distributions ranges, provides an estimate of the best-fitting distribution candidates. The dataset estimation point will lie on or near the best distribution candidates.

A nonparametric bootstrap simulation can improve this graphical estimation (Frey & Burmaster, 1999). By randomly sampling the given data set with replacement, a bootstrap sample creates a new, slightly varied data set from the original and plots these points on the Cullen and Frey graph (Frey & Burmaster, 1999). Plotting numerous bootstrap points on the same graph simulates the uncertainty within the data, revealing visually the level of significance that uncertainty has on the choice of best-fitting distribution (Delignette-Muller & Dutang, 2014). This bootstrap method assists the researcher in validating the most-likely distribution option, given that skewness and kurtosis estimates lack robustness (Delignette-Muller & Dutang, 2014).

Figure 2 shows an example of the use of this technique, plotting the mechanical cost data parameters for the squadron operations facility type. The “Observation” point designates the skewness and kurtosis estimate for the data set, with the smaller “bootstrapped values” indicating possible variations due to uncertainty in the data. While the observed point is near the uniform distribution parameters, the bootstrap values show variations well into other parts of the beta region. Additionally, past research has shown the beta distribution to be a good candidate for modeling such costs, and the uniform distribution does not have any theoretical basis for modeling the same. Therefore, because the data fits well within the beta parameters and the other viable distribution candidates do not have a theoretical foundation for their use, the beta distribution appears

to be the most likely best fit in this example. Likewise, a Cullen and Frey graph provided initial insight in distribution selection, narrowing the field of potential distributions useful for modeling each cost element for each facility type.

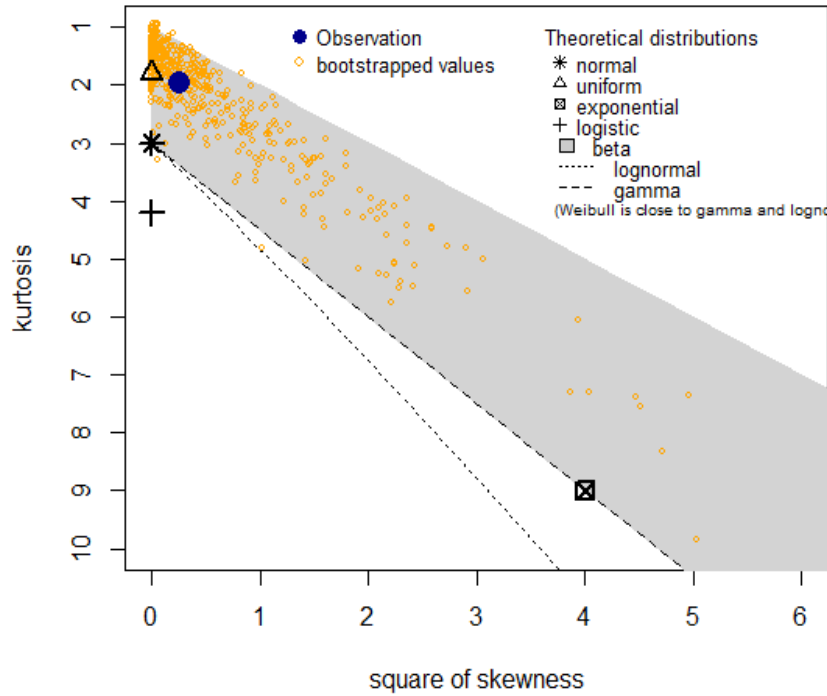


Figure 2: Cullen & Frey Graph of Mechanical Costs in Squadron Operations Facilities

Whichever distribution a researcher selects for a given cost element, that distribution should pass a goodness-of-fit test to ensure the validity of its use. Several authors recommended the Chi-Squared goodness-of-fit test for construction cost distributions (Touran & Wiser, 1992; Wall, 1997). However, the Chi-Squared test requires segregating the dataset into bins to test if the number of data points in each bin corresponds to the distribution attempting to model the data. For accurate results, this test needs an expected frequency of at least five within each bin (Field, 2007), and more than five bins overall, resulting in an overall sample size requirement of at least 30 for proper analysis (Wall, 1997). The Mann-Whitney goodness-of-fit test also requires a

sample size of at least 25, while the Kolmogorov-Smirnov goodness-of-fit test is viable despite small sample sizes (Field, 2007). Because the data available in this research consisted of small sample sizes (between 8 and 20), the Kolmogorov-Smirnov goodness-of-fit test proved the most viable method to measure the hypothesis that a given distribution could accurately model a given cost element.

Correlation Characterization

As established in Chapter II of this research, defining accurate correlations between the cost elements is a critical step in developing a complete cost model. A common measure of correlation is the Pearson's correlation, or product-moment correlation, but this measure assumes a linear relationship between normally distributed samples (Yang, 2005). The distributions of the cost elements studied here were not likely to be normally distributed; therefore requiring a different correlation measure. Kendall's tau correlation coefficient provided a non-parametric alternative but is only preferred over Spearman's correlation coefficient when the data contains a significant amount of tied ranks (Field, 2007). As this is typically not the case with continuous cost data, Spearman's correlation coefficient proved the most viable correlation method. The Spearman's correlation, or rank correlation, uses the relative ranking of the elements within a sample, and compares the order of the ranking in one variable to the next, applying a product-moment correlation to the ranks instead of the values themselves (Yang, 2005). The ranks are the relative position of each element within a variable when sorted by cost. The formula shown in Equation 1 compares the ranks of corresponding cost elements, defining a correlation coefficient between each element. A correlation matrix then combines these coefficients for use in simulations.

$$r_{xy} = 1 - \frac{6 \sum_{i=1}^n (x_i - y_i)^2}{n(n^2 - 1)} \quad (1)$$

Where r_{xy}	Spearman correlation coefficient between variables X and Y
x_i	rank of i^{th} value of variable X
y_i	rank of i^{th} value of variable Y
n	sample size

After deriving a correlation matrix as described, one more step remains before integration into the simulation. The correlation matrix must be positive definite for use in a Monte Carlo simulation (Yang, 2005). This requirement posed a potential issue because, as Yang notes, the more elements included in a model such as this, the more likely the correlation matrix will be infeasible (2005, p. 277). Higham provides an algorithmic solution, developed for a similar application of finding the nearest feasible correlation matrix from an infeasible matrix correlating stock prices (2002). This method, available within statistical software for programs such as the R Project for Statistical Computing, completes the correlation process, creating from an infeasible matrix a positive definite matrix. Viable distributions for each cost element and feasible correlation matrices are then both available for simulation.

Validation Process

Model validation required using several projects not part of the model development on which to test the model for accuracy; five projects were set aside for this purpose. The validation set included one dormitory project, two education and training projects, and two squadron operation projects. These quantities correspond to 10%

(rounded up) of the collected sample sizes for each facility type. The validation projects did not factor into the distribution modeling, correlation analysis, or Monte Carlo simulation so as not to bias the results toward the validation projects. The developed model then estimated costs for the five reserved projects. For each project, the researcher multiplied the appropriate facility type distribution developed in the simulation with the project's scope and adjusted for the project's location and midpoint construction date. The UFC 3-701-01 DoD Facility Pricing Guide (2015) provided the area cost and timeframe escalation adjustment factors. Comparing this estimate to the actual project cost revealed the accuracy of the model for each of the five projects. Additionally, comparing this estimate to the programmed amount (PA) showed the relative accuracy of this model to the estimate used in the programming phase of the project.

However, cost estimators develop and improve the initial PA during the first stages of a project's design, creating a Class 3 parametric cost estimate with a design level between 10-25% (Department of Defense, 2011a, p. 5, 2011b, p. 6). They then further refining that estimate with a design level between 35-65% (Department of Defense, 2011a, p. 11). This process results in a cost estimate more accurately described as a Class 2 estimate according to AACE, with an expected accuracy of -7.5% to +10%. The updated PA overwrites the initial PA amount recorded in project databases and therefore used by this research for comparison. The estimate developed by this research model relies on only basic scope information, resulting in a Class 4 estimate with an expected accuracy of -15% to +25%. Therefore, while noteworthy if the model performs better than the recorded PA, the comparison is not direct. Both the UFC 3-701-01 DoD Facility Pricing Guide (2015) and the AFCESA Historical Air Force Construction Cost

Handbook (2007) provide alternative Class 4 estimates for a direct comparison to evaluate the true effectiveness of the model

UFC Estimate Comparison

The UFC 3-740-05 Handbook: Construction Cost Estimating (Department of Defense, 2011a, p. 101) designates UFC 3-701-01 DoD Facility Pricing Guide (2015) as the main cost estimation tool for the development of Air Force Form 1391s, the preliminary cost and scope record for programming and approval. As such, an estimate derived from UFC 3-701-01 provides an ideal measure with which to evaluate the simulation results. UFC 3-701-01 specifies unit costs by facility type in Chapter 2. Chapter 4 provides the escalation and area cost factors to adjust those unit costs. UFC 3-701-01 then refers to the UFC 3-730-01 Programming Cost Estimate for Military Construction (Department of Defense, 2011b) for the contingency and supervision, inspection, and overhead (SIOH) factors along with facility-specific size adjustment factors to further refine the estimate. Section 4 of UFC 3-730-01 provides these factors, specifying a 5.0% cost increase for contingency and a 5.7% cost increase for SIOH for all the projects evaluated in this research. Combining the various factors together results in an estimate derived from the general formula shown in Equation 2.

$$C = F_{scope} \times UC \times S \times ACF \times CE \times DC \times SIOH \quad (2)$$

Where C	Project Cost Estimate
F_{scope}	Facility Scope in square feet or square meters
UC	Unit Cost in square feet or square meters by facility type
S	Size Adjustment Factor (only for certain facility types)
ACF	Area Cost Factor
CE	Cost Escalation Adjustment
DC	Design Contingency percent
$SIOH$	Supervision, Inspection, and Overhead percent

AFCESA Estimate Comparison

The AFCESA Cost Handbook (2007) is not as widely used in practice as it is an older cost estimation guide compared to the 2014 cost data built into UFC 3-701-01 DoD Facility Pricing Guide (2015). However, similar data collection and methodologies went into the creation of the handbook compared to UFC 3-701-01. Additionally, the AFCESA Handbook is specific to Air Force construction whereas UFC 3-701-01 creates estimates usable by the Army, Navy, and Air Force in general. While the larger scope of UFC 3-701-01 allowed it to use larger data sets for the development of its models, the AFCESA Handbook may remove some systematic errors with a more tailored estimate due to its narrower focus. Therefore, it provides a worthwhile cost estimate comparison both to measure the simulation model against, as well as to highlight any trends in the differences between a military-overall estimate from UFC 3-701-01 and an Air Force-specific estimate from the AFCESA Handbook.

Despite employing different data, the AFCESA Handbook uses similar data tables and formulas to develop a cost estimate. Section II provides historical data by facility type, standardized to October 2007 dollars and shown in cost per square feet. AFCESA removed contingency costs and SIOH from these unit costs as well. Section IV provides size adjustment tables, Section V provides escalation tables, and Section VI provides location factors. Finally, Section VIII provides the same contingency amount of 5% and SOIH amount of 5.7% as UFC 3-701-01. The validation estimates for this study did not use Section VII's supporting facility data. Taking these factors and adjustments, AFCESA uses the same general formula depicted in Equation 2 to develop a cost estimate.

Summary

The general concept of this methodology was to conduct a thorough and detailed analysis of project cost estimates for a variety of projects. Then, through careful modeling using the best practices and lessons learned from cost estimation experts, develop a simple tool for accurate cost estimation in the early stages of a given project. The facility-type cost distributions output by the Monte Carlo simulation are that tool. With a general scope, a location, and a construction timeframe, an estimator can apply the appropriate factors to a distribution, and have not only an expected cost but also an illuminating range of possible costs and their probabilities. The analysis and results chapter next assesses if this tool is indeed accurate, meeting the AACE Class 4 standards, and if it is an improvement or provides any additional insight over the current estimation methods available.

IV. Analysis and Results

Chapter Overview

The Monte Carlo cost estimation model proposed in Chapter III provided cost estimates better than, or comparable to, the programmed cost estimates in three of the five measures. Moreover, the simulation provided valuable insight despite being less accurate for the other two measures by evaluating project-specific circumstances. This finding is significant because the source data had issues in both quality and quantity. Data collection and quality assurance became significant challenges, restricting the number of facility type models this research could have otherwise created and limiting the ability to validate the models that this research did create. Such performance despite data issues indicates the potential utility of this methodology in Air Force military construction (MILCON) or sustainment, restoration, and maintenance (SRM) cost estimation.

Methodology Implementation

The following sections detail the various steps taken in implementing the proposed methodology. Microsoft Excel (2010) spreadsheets provided the platform for data collection, cost element categorization, and cost element standardization. The R Project for Statistical Computing software provided the platform for distribution modeling, correlation modeling, simulation modeling, and the final model validation steps. Appendix E displays the program code used in the R Project software for this analysis.

Data Collection

Data collection in itself proved to be a significant challenge for this research. The proposed methodology required large samples of similar-type facility projects along with a detailed line item list of final costs, a measure of scope, and a programmed cost estimate for each project. The Air Force's primary facility cost database, ACES, had substantially more projects than needed but did not track the line item costs of those projects. ACES only recorded the total cost of projects, with some cases providing costs broken out by contract line item. Contract line item costs did not provide the detail required, annotating only the primary deliverables of a project without regard to the construction specialties or methods used for those deliverables.

The USACE, as the primary MILCON execution agent for the Air Force, has their own database, namely the Resident Management System (RMS), for tracking projects given to them by the Air Force. This research focused on MILCON projects. Therefore, the researcher considered using RMS data. While ACES records primarily high-level information for MILCON project programming and approval purposes, RMS records every project and contract document from the bidding process to final close-out. With the assistance of several RMS database experts from USACE, the researcher obtained a spreadsheet of all available Air Force MILCON projects in the system. This list included 177 projects from 2001 to 2014 with an average of 370 cost line items each.

However, to use the collected data, each project needed a measure of scope and a programmed cost estimate with which to compare the final results. Because RMS primarily tracks project data starting at the bidding phase of project execution, estimates from the Air Force's programming phase are not included. Additionally, the RMS data

pull did not contain a consistent measure of scope for each project. Therefore, the researcher matched the projects from the RMS data to the associated ACES projects and removed projects out of the list that did not have the measures needed for analysis. This effort required cutting all projects earlier than 2005 because ACES did not keep project records before this date. Missing data also necessitated the removal of several other projects.

The proposed methodology required further data trimming in several other areas. The focus of this research was on Air Force construction within the U.S., necessitating the removal of all construction projects in foreign countries. Additionally, the projects had to be grouped together by facility type, and most type categories contained six or fewer projects, further limiting the sample size. The researcher kept only categories with eight projects or more. Finally, several projects had data inconsistencies or line items that combined a majority of the project costs into one single cost unsuitable for analysis. The researcher eliminated these projects as well. The final data set prepared for analysis included 43 projects: 20 of which the researcher classified as education and training facilities, 15 as squadron operation facilities, and 8 as dormitories. Each project had an average of 400 cost line items.

Cost Element Categorization

To find cost trends, the researcher had to categorize each cost line item within an overall cost category. The data fit into 11 major categories for each of the three facility types with a cost summary shown in Table 3. These categories loosely follow major CSI MasterFormat divisions as indicated, with the main exception of dividing the material specialty types of concrete, masonry, metals, and wood (CSI MasterFormat Divisions 3,

4, 5, and 6 respectively) into the functional categories of Foundations and Structural. Table 3 lists the divisions next to the category they predominantly fell under, but there was significant overlap. Also, CSI MasterFormat division 33 (Utilities) fit the Mechanical category in most cases, with some cases applied to the Electrical category. In fitting the data into these categories, the researcher used keyword searches for each project cost line item, sorting the various descriptions into the appropriate categories. The data required 648 keywords, phrases, and acronyms to capture all the costs. Appendix C lists these keyword associations.

Of note, the Structural category encompasses the largest percentage of the costs at 21.3%. Finishes comprised 13.5% of the total costs, which was greater than expected. Mechanical, Electrical, Foundations, and General Requirements all contributed a significant percent of the total as expected. The researcher included Demolition, Furnishings, and Specialties as categories despite their relatively small contribution to total cost because of their unique natures. These categories did not fit wholly into any one of the other categories, but remained distinguishable as separate activities, and individual projects could have significantly varied costs for those categories depending on the circumstances. For example, some projects required little to no demolition while some required a substantial amount. Some facilities required only basic furnishings where some (such as a satellite classroom hub and telecommunications facility) could require significantly specialized and expensive furnishing and equipment.

Table 3: Cost Categories Summary

Cost Categories	Facility Type			Division Total	Division Percent of Total Cost	Associated CSI MasterFormat Divisions*
	Dormitories	Education & Training	Squadron Operations			
General Requirements	\$23,831,221	\$16,975,839	\$20,005,494	\$60,812,554	10.6%	0 - Procurement & Contracting 1 - General Requirements 11 - Equipment 34 - Transportation
Demolition	\$3,848,474	\$2,200,429	\$2,949,394	\$8,998,297	1.6%	2 - Existing Conditions
Finishes	\$26,441,843	\$28,265,536	\$23,075,525	\$77,782,904	13.5%	8 - Openings 9 - Finishes
Foundations & Pavements	\$26,363,337	\$23,078,366	\$18,897,560	\$68,339,263	11.9%	3 - Concrete
Communications	\$6,541,712	\$9,557,069	\$14,737,169	\$30,835,950	5.4%	25 - Integrated Automation 27 - Communications 28 - Electronic Safety & Security
Earthwork	\$9,782,404	\$9,740,537	\$7,082,156	\$26,605,098	4.6%	31 - Earthwork 32 - Exterior Improvements
Furnishings	\$2,049,317	\$7,752,236	\$5,576,098	\$15,377,651	2.7%	12 - Furnishings
Electrical	\$22,484,078	\$16,631,214	\$17,198,577	\$56,313,870	9.8%	26 - Electrical 48 - Electrical Power Generation
Structural	\$50,432,533	\$37,862,819	\$34,040,122	\$122,335,474	21.3%	4 - Masonry 5 - Metals 6 - Wood, Plastics, Composites 7 - Thermal & Moisture Protection
Mechanical	\$43,042,072	\$29,819,153	\$24,399,775	\$97,261,000	16.9%	14 - Conveying Equipment 21 - Fire Suppression 22 - Plumbing 23 - HVAC 33 - Utilities 46 - Water & Wastewater Equipment
Specialties	\$3,501,161	\$3,927,717	\$3,351,987	\$10,780,864	1.9%	10 - Specialties 13 - Specialty Construction
Total Cost	\$218,318,153	\$185,810,916	\$171,313,858	\$575,442,927		

*Divisions 35 and 40-45 were not used. CSI does not have categories for divisions 15-20, 24, 29-30, 36-39, and 47.

Cost Element Standardization

After delineating categorized costs associated with each project, the researcher then standardized the data for trend analysis. The costs were divided by the square meter scope of the facility resulting in cost per square meter for each element. The costs were then multiplied by an escalation factor based on the midpoint date of construction to put each cost into October 2014 dollars. Finally, the costs were divided by the appropriate

Area Cost Factor for the project location, placing the costs at a standardized location index of 1 to adjust for differences in construction costs throughout the U.S. UFC 3-701-01 provided both the escalation rates and Area Cost Factors for these adjustments (Department of Defense, 2015). Appendix B displays the project costs and scopes along with the standardized costs. At this point, the researcher used a random number generator to select one project from the dormitories category and two projects each from the education and training category and squadron operations category and set them aside for validation of the model after creating and running the simulation. Therefore, 7 dormitory projects, 18 education and training projects, and 13 squadron operations projects were used to build the cost estimation model.

Distribution Modeling

Using the now-standardized cost data, the researcher modeled distributions and correlations for each of the three facility types. While the lognormal distribution was expected based on prior research (Touran & Wiser, 1992; Wall, 1997), the generalized beta distribution modeled all the cost distributions more closely. The analysis revealed the lognormal distribution as the next most feasible choice in most cases, but it did not pass the Kolmogorov-Smirnov Goodness of Fit test. The data did not allow for a Chi-Squared Goodness of Fit test because the test requires binning the data in such a way that the sample size multiplied by the bin probability is greater than five (Frey & Cullen, 1995). A maximum sample of 18 in the case of the education and training facility type allowed the formation of only three bins, limiting the viability of the Chi-Squared test. Therefore, the researcher turned to the Kolmogorov-Smirnov Goodness of Fit test instead.

The Kolmogorov-Smirnov test statistic indicated there was not sufficient evidence to reject the hypothesis that the data came from a generalized beta distribution for all cost categories of the dormitory, education and training and squadron operations types. The General Requirements category for dormitories had the highest Kolmogorov-Smirnov test statistic with a D of 0.437, resulting in a p-value of 0.099. Because the p-value was greater than the α of 0.05, the hypothesis that the underlying distribution was the generalized beta was not rejected. This value was the lowest p-value of the various cost elements; all others had a higher p-value, reinforcing the generalized beta as viable distribution candidate. Additionally, none of the other distributions considered had a passing test statistic, despite the lognormal distribution coming close to a passing p-value for a few elements. The gamma distribution followed the generalized beta distribution as the next closest distribution for one cost element but again did not pass the goodness of fit test. Therefore, the researcher kept the generalized beta and the associated parameters for those cost elements for the simulation modeling. This decision is supported by prior research stating the beta distribution is still a viable distribution to use when estimating construction element costs (Chau, 1995b; Touran & Suphot, 1997; Yang, 2005). Appendix B displays the test statistics and associated p-values for each cost element.

Correlation Modeling

After defining the distributions, a Spearman rank correlation function provided the basic correlation matrices between the cost elements for each facility type. The education and training correlation matrix and the squadron operations correlation matrix were both positive definite, necessitating no further changes. The dormitory correlation matrix was only semi-definite and had a negative eigenvalue, requiring modification

before it could correlate random variables. A nearest positive definite matrix function from Higham's (2002) algorithm provided the necessary modifications resulting in a feasible matrix. The new correlation matrix was similar to the initially calculated matrix but with the correlations altered an average of 2.59×10^{-8} , the largest adjustment of which was 7.20×10^{-8} . These adjustments were in both the positive and negative direction. As this maintained the overall correlation structure with minimal changes, the simulation used the revised correlation matrix. Furthermore, Spearman rank correlations of the simulation results provided an additional validation of the process. The correlations of the facility cost distribution outputs were within 0.0117 of the original input correlations on average, with a maximum difference of 0.0195. Therefore, the simulation kept the cost elements correlated as desired with only minor variations. Appendix B annotates all three correlation matrices used in the simulation.

Simulation Modeling

The researcher input the modeled distributions and feasible correlation matrices into the Monte Carlo simulation, running each simulation 100,000 times. The trials resulted in three predictive probability histograms for project construction costs of the facility types of dormitories, training and education facilities, and squadron operations facilities. The earlier cost element standardization steps aligned these probability histograms in terms of dollars per square meter, using October 2014 dollars, with a generic Area Cost Factor of 1. As described in Chapter I, the purpose of this research was to develop a model relying only on basic scope information such as square meter project area, creating an improved AACE Class 4 estimate model with an expected accuracy of -15% to +25%.

Model Validation

Validation of this model consisted of applying the simulation to estimate the costs of five reserved data samples to evaluate its predictive capability. The validation compared these five outputs to three other estimates. The first estimate was the programmed amount (PA), a Class 2 or 1 estimate, depending on the level of design accomplished before the estimation. Cost estimators can create a Class 2 estimate after designing the project to the 35% level or greater, and they can create a Class 1 estimate after designing the project to the 70% level or greater. Generally, a PA relies on a 35% to 65% design, resulting in an estimate in the Class 2 category with an expected accuracy within -7.5% to +10% of the actual project costs. Since this model is a Class 4 estimate, the PA provided the most stringent standard of measurement, as it was a higher estimate Class type with greater expected accuracy than the model.

The second and third estimates used in the validation process were Class 4 estimates based on the square meter scope of the projects. As Class 4 estimates, their expected accuracy was within -15% to +25% and was, therefore, the same Class as the model developed in this research. UFC 3-701-01 DoD Facilities Pricing Guide (2015) developed the first of these and outlines criteria for applying unit costs by facility type in Chapter 2 and adjustment factors in Chapter 4. The AFCESA Historical Air Force Construction Cost Handbook validated the other estimate and outlines similar criteria as the UFC in Sections II and IV–VI (2007).

The researcher took the three facility-type probability histograms and applied the reserved five data samples to validate the model (one sample was of the dormitory facility type, two were of the education and training type, and two were of the squadron

operations type). The scope, escalation factor, and area cost factor were applied to the appropriate model from each reserved project, producing a histogram showing probabilities of potential project costs for each reserved project. The researcher compared these costs to the actual project costs, the estimated PA, and the UFC and AFCESA-derived estimates to determine how well the model performed. The UFC 3-701-01 and the AFCESA Handbook provide data and methods for estimating both an expected cost and a cost range, modeled in this study with the normal distribution. Table 4 summarizes the results, comparing each estimate's expected value to the actual project costs, and Table 5, showing the percent difference from those estimates to the same. The rest of this chapter discusses these results in further detail.

Table 4: Cost Estimates Compared to Actual Project Costs

	Dormitory	Education & Training		Squadron Operations	
	Lackland ATC Dormitory	Whiteman CDC	Eielson Chapel	Hanscom Acquisition Facility	Kirtland AFNWC
Actual Cost	\$ 54,544,986	\$ 7,685,912	\$ 12,998,688	\$ 12,236,463	\$ 24,355,245
Simulation Estimate	\$ 50,993,620	\$ 8,456,170	\$ 22,180,870	\$ 13,817,583	\$ 15,351,992
PA Estimate	\$ 75,515,000	\$ 7,600,000	\$ 14,400,000	\$ 12,800,000	\$ 25,000,000
UFC Estimate	\$ 35,202,259	\$ 6,494,092	\$ 23,125,622	\$ 12,314,131	\$ 18,180,486
AFCESA Estimate	\$ 38,045,360	\$ 5,719,058	\$ 16,077,327	\$ 11,539,115	\$ 13,393,406

Table 5: Cost Estimate Percent Differences from Actual Project Costs

	Dormitory	Education & Training		Squadron Operations	
	Lackland ATC Dormitory	Whiteman CDC	Eielson Chapel	Hanscom Acquisition Facility	Kirtland AFNWC
Actual Cost	\$ 54,544,986	\$ 7,685,912	\$ 12,998,688	\$ 12,236,463	\$ 24,355,245
Simulation Estimate	7.0%	-9.1%	-41.4%	-11.4%	58.6%
PA Estimate	-27.8%	1.1%	-9.7%	-4.4%	-2.6%
UFC Estimate	54.9%	18.4%	-43.8%	-0.6%	34.0%
AFCESA Estimate	43.4%	34.4%	-19.1%	6.0%	81.8%

Dormitory Project Cost Estimation

The dormitory estimation results revealed the model as a better predictor of costs than the programmed estimate in the case of the one project reserved for validation. The Lackland AFB, TX Airmen Training Complex Dormitory was randomly selected as the validation project. This dormitory spanned 21,544 square meters and was built in 2009. Figure 3 shows the simulation results in the form of a histogram, with the 50th percentile marked for reference. Figure 3 also has the actual project value along with the PA estimate and estimated cost distributions from the UFC 3-701-01 DoD Facilities Pricing Guide (2015) and the AFCESA Historical Air Force Construction Cost Handbook (2007) overlaid on the histogram for comparison. The actual project cost of \$54,544,986 was located slightly above the simulated 50th percentile of \$50,993,620 and below the 75th percentile of \$58,234,100. This accuracy is significantly more accurate than the PA estimate of \$75,515,000, with the actual cost 7.0% higher than the model estimate compared to 27.8% lower than the programmed amount estimate. The model came within the Class 4 expected accuracy range of -15% to +25% whereas the PA did not even meet the Class 4 estimate expectations despite being a Class 2 estimate. However, it is also worth noting that of the seven dormitory projects used to create the underlying model, one was a companion project dormitory, identical in scope to the one estimated here and built on Lackland AFB in 2010. Having a similar project with comparable costs embedded in the model likely improved the estimate for this particular validation more than estimating for a project without such close similarities.

In comparing the simulation model results to estimates derived from UFC 3-701-1 and the AFCESA Handbook, the model produced more accurate results. The UFC 3-701-1 estimate was \$35,202,259, compared to which the actual cost was 54.9% higher and, therefore, did not come within the Class 4 expected accuracy. The AFCESA Handbook estimate was \$38,045,360, compared to which the actual cost was 43.4% higher, also outside the Class 4 accuracy range. Interestingly, both these estimates were relatively close in their values to each other but far from the PA estimate, compared to which the actual cost was 27.8% less. This discrepancy suggests that perhaps cost estimators used different information when they prepared the estimate. The project was significantly more costly than the average dormitory, suggesting the presence of cost factors for which an estimator could account, but not to the extent the PA estimated.

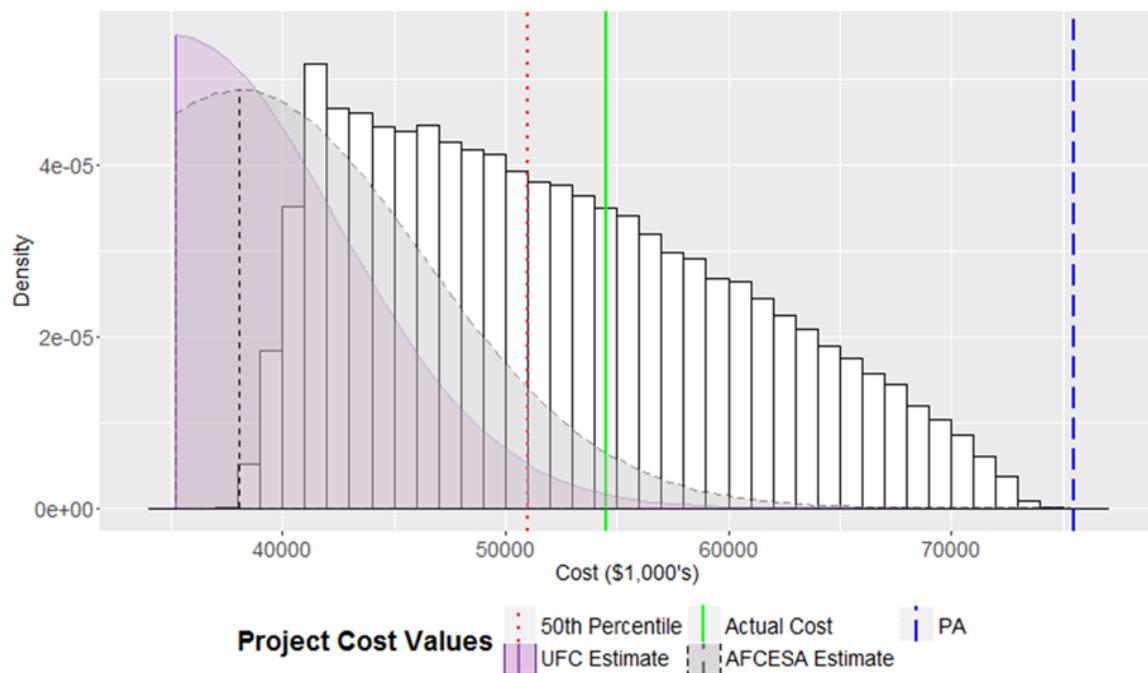


Figure 3: Lackland ATC Dormitory Simulation Results and Cost Estimate Comparison

Education and Training Project Cost Estimation

The education and training facility results showed a useful, but potentially less accurate, model. The graph in Figure 4 displays the simulation cost estimate histogram with the project's actual cost and the alternative cost estimates for the 2,540 square meter Whiteman AFB, MO Child Development Center (CDC) built in 2005. The model provided a useful prediction of the CDC costs with a 50th percentile estimate of \$8,456,170 compared to the actual cost of \$7,685,912; a -9.1% difference, which lies within the Class 4 accuracy range. The PA was a better estimate at \$7,600,000, compared to which the actual cost was only 1.1% higher, and, therefore, the PA was well within the Class 2 accuracy range or -7.5% and +10%.

Both the UFC 3-701-01 and the AFCESA Handbook estimates were less accurate than the PA and the simulation estimate. The UFC 3-701-01 estimate was \$6,494,092, just outside the Class 4 accuracy range with the actual cost 18.4% higher than estimated, and the AFCESA Handbook estimate was \$5,719,058, also outside the Class 4 range with the actual cost 34.4% higher than estimated. In summary, the simulation estimated the highest and was the only estimate higher than the actual cost, but the simulation still performed better than the UFC or AFCESA methods. The PA was the best estimate overall.

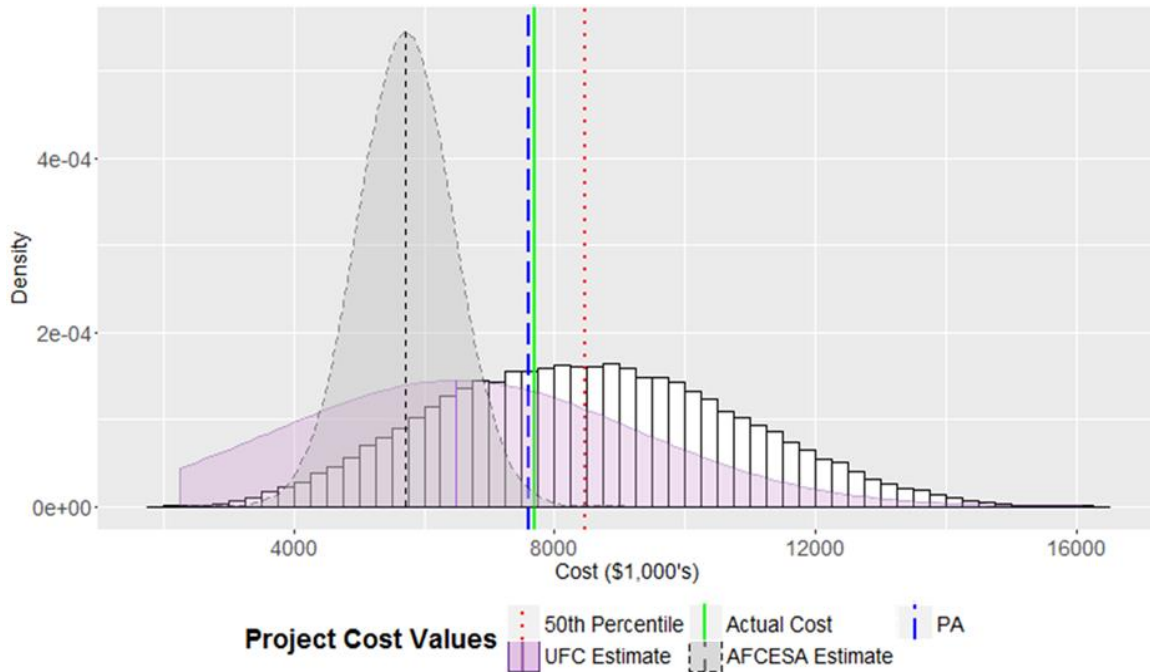


Figure 4: Whiteman CDC Simulation Results and Cost Estimate Comparisons

Figure 5 shows the simulation histogram results, actual cost, and associated cost estimates for the 2,994 square meter Eielson AFB, AK Chapel Center Replacement built in 2007. The simulation predicted a cost of \$22,180,870 at the 50th percentile versus the PA estimate of \$14,400,000. The actual cost of the project was \$12,998,688, resulting in a cost 41.4% lower than estimated and significantly outside the Class 4 expected accuracy range. The actual cost was 9.7% lower than the PA estimate; just outside the Class 2 range. The final cost was just slightly above the predicted 5th percentile value of the simulation.

The simulation produced results similar to the UFC 3-701-01 estimate but deviated from the AFCESA Handbook estimate. The UFC 3-701-01 produced an estimate of \$23,125,622, which is significantly beyond the Class 4 accuracy range with the actual cost 43.8% lower than estimated. The AFCESA Handbook produced an

estimate of \$16,077,327, which is closer to, but still outside, the Class 4 accuracy expectations with the actual cost 19.1% lower than estimated. Note Figure 5 shows no distribution for the AFCESA Handbook estimate because the handbook had only one CDC project to reference. Therefore, the handbook produced only an expected value without any standard deviation information. Figure 5 shows this as a vertical line.

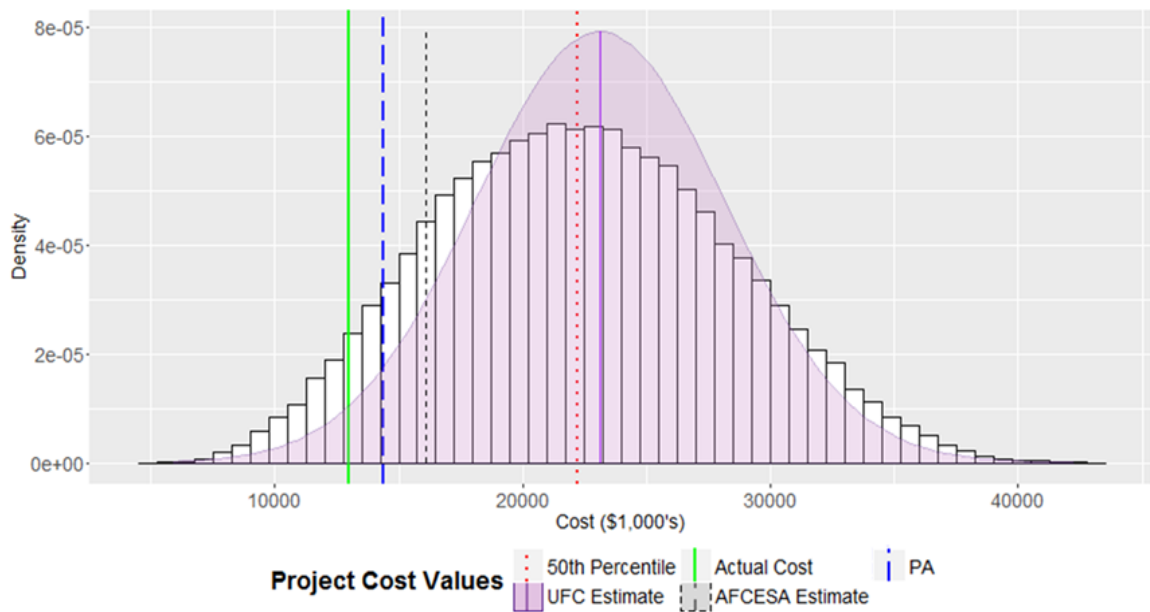


Figure 5: Eielson Chapel Simulation Results and Cost Estimate Comparisons

Squadron Operations Project Cost Estimation

The squadron operations facility results were similar to the education and training facility results. Figure 6 shows the simulation histogram for the 3,690 square meter Hanscom AFB, MA Acquisition Management Facility constructed in 2008. The actual project cost of \$12,236,463 is below the 50th percentile of \$13,817,583 predicted by the simulation, but still between the 25th and 50th percentiles. The actual cost was 11.4% lower than the simulation's predicted cost (within the Class 4 expected accuracy range)

compared to 4.4% lower than the programmed amount of \$12,800,000 (also within the Class 2 expected accuracy range).

All the cost estimation methods produced similar results for this facility, creating the tightest grouping of estimates found during this research. The UFC 3-701-01 method produced the closest estimate at \$12,314,131, with the actual cost only 0.6% lower than the UFC estimate. The AFCESA Handbook method produced an estimate of \$11,539,115, with the actual cost 6.0% higher than this AFCESA estimate. Both were within the Class 4 expected accuracy range. While the simulation estimate produced the most inaccurate results in this case, any of the methods would have been a viable tool in developing an initial cost estimate for the Hanscom Acquisitions Facility, and using multiple methods would have revealed an exceptionally accurate estimate overall.

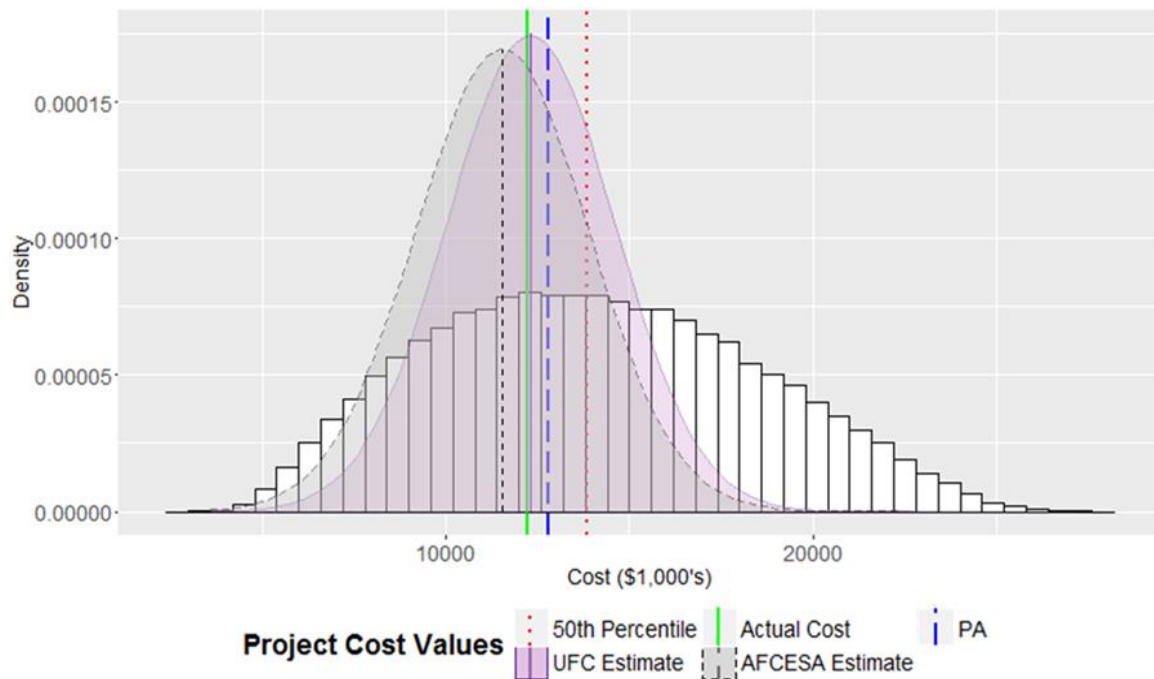


Figure 6: Hanscom Acquisition Management Facility Simulation Results and Cost Estimate Comparisons

Figure 7 shows the results of estimating the 5,310 square meter Kirtland AFB, NM Air Force Nuclear Weapons Center (AFNWC) Sustainment Center constructed in 2012. The actual cost was 58.6% higher than the simulation estimate for the AFNWC Sustainment Center with an estimated cost of \$15,351,992 versus the actual cost of \$24,355,245. This estimate was outside the Class 4 expected accuracy range. Additionally, the actual cost lay beyond the 95th percentile predicted by the model whereas the PA estimated \$25,000,000, compared to which the actual cost was only 2.6% lower and within the Class 2 accuracy range.

The UFC 3-701-01 and AFCESA methods produced results relatively similar to the simulation with values of \$18,180,486 and \$13,393,406 respectively. The actual cost was 34.0% higher than the UFC 3-70-01 estimate and 81.8% higher than the AFCESA estimate, both of which were outside the Class 4 accuracy range. The PA estimate produced the most accurate results by a significant margin, with the simulation performing better than the AFCESA method and worse than the UFC method.

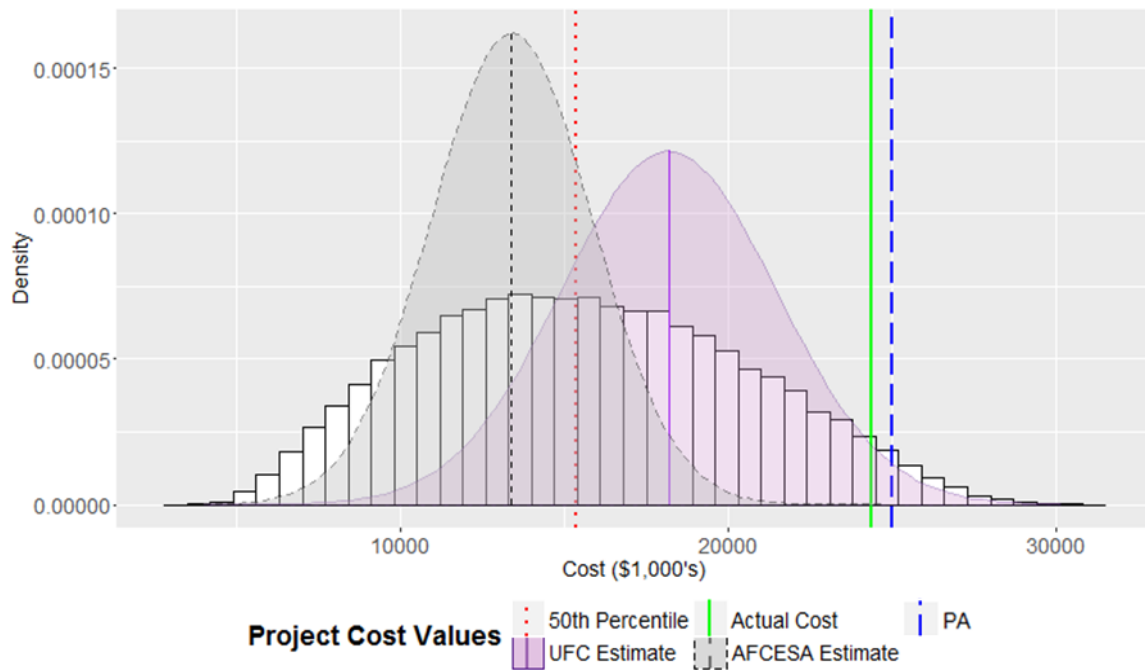


Figure 7: Kirtland AFNWC Sustainment Center Simulation Results and Cost Estimate Comparisons

In summary, the results did not produce a clear trend between the estimation methods. However, of the five facilities tested, the simulation results performed better than the UFC and AFCESA estimates twice, performed better than one of them but not the other twice, and performed worse than both once. In the one case the simulation performed worse, all the estimates formed a relatively concentrated grouping with all estimates well within the Class 4 accuracy range and the simulation estimate producing a result compared to which the actual cost was 11.4% lower. While the data available allowed only limited validation testing, the simulation performed well overall and for the dormitory estimate in particular. These results indicate the possible future utility of developing this model further for initial cost estimating. Figure 8 highlights the performance of this model, showing the accuracy of each estimate compared to the projects' actual costs and the Class 4 expected accuracy range.

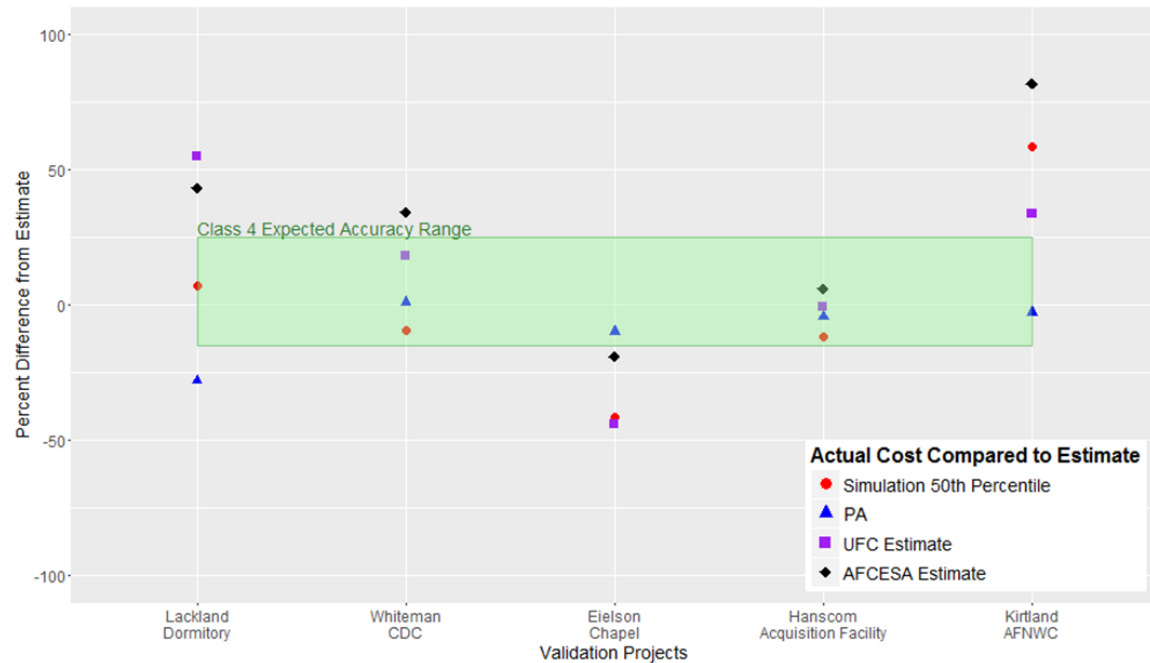


Figure 8: Accuracy Comparison between Cost Estimates

Investigative Questions Answered

This research began by trying to answer the following three questions, with the goal of providing additional insight into the behavior of Air Force construction cost elements and methods for leveraging those behaviors for improved initial cost estimates.

This is what the research found:

Question 1

What distributions can adequately describe cost trends in construction project assembly items?

While the literature predominantly supported using the lognormal distribution for construction cost elements, this study found that the generalized beta distribution better fit the data available. This result is understandable given the small sample sizes used and the greater flexibility of the generalize beta to fit a wide range of shapes over the lognormal. However, because the analysis revealed the lognormal distribution as the next

best distribution option for many of the cost elements, the researcher proposes that additional data may refine the overall cost shape, resulting in the lognormal distribution possibly becoming a better fit. Nevertheless, the predictive potential of the model as shown in the final results indicate that the generalized beta distribution may provide the resolution required for a viable model without necessitating a switch to the lognormal distribution.

Question 2

How do correlations between assembly items affect overall project costs?

The literature strongly supported the assertion that correlations between cost elements have a significant impact on final cost and should always be included if possible. This research supported that premise, with the data revealing significant correlations between the 11 cost elements modeled.

Question 3

How does a Monte Carlo cost simulation model using historical cost distributions differ in performance from the current parametric cost estimation method?

For the case of dormitory facility projections, the simulation modeled in this research performed substantially better than the programmed parametric cost estimate, the UFC 3-701-01, and AFCEA Construction Cost Handbook for the one project tested. For the education and training facility and squadron operations facility projections, the simulation did not out-perform the programmed cost estimate in any of the four tests, but still provided a useful approximation in one of the two cases tested for each facility type. Nevertheless, even in the other two cases for which the actual costs fell close to the outer

5% probability prediction values, the model showed value and still performed better than the UFC method in one case, and the AFCESA method in the other.

The model showed potential in providing a usable range of expected values for a given project type. Initial program estimates should fall within the middle 50% of the model. If they fall well below that, as was the case for the Eielson AFB Chapel, there should be reasoning behind the low estimate. The fact that the Eielson AFB Chapel had the third lowest cost per square meter of all the projects analyzed supports this reasoning, indicating some project-specific attributes contributing to a lower-than-normal cost. Indeed, the Chapel had lower-than-average costs for each of the 11 cost elements and was one of only two education and training facilities for which the researcher collected data that did not require any demolition. Taking this into consideration, a valuable future improvement to the model developed here would be to include the capability of removing or adjusting the costs of individual elements depending on project-specific conditions. Furthermore, the Chapel was one of two projects based in Alaska, both of which had cost per square meter values in the bottom 16% of all project data collected after adjusting for location factors. This fact indicates a possible systemic factor causing a reduction in relative cost.

If the initial program cost estimate falls well above the middle 50% of the model, there should be reasoning for those higher costs. For the Kirtland AFB AFNWC Sustainment Center project, the cost per square meter was third highest among the projects analyzed. Furthermore, the communication cost per square meter was over double the cost of the next highest communication cost for any of the other projects regardless of facility type. Clearly, the AFNWC Sustainment Center had a significant

communications requirement above the standard, necessitating a cost estimate higher than the average.

Summary

The results of this research provide significant insight into cost estimation. The proposed simulation produced an empirical model useful for bounding and checking initial cost estimates. Collecting enough data and applying a viable methodology to model cost element distributions and correlations were crucial to a successful simulation.

V. Conclusions and Recommendations

Chapter Overview

The Monte Carlo simulation developed in this research provided a new cost estimation tool with potential utility for preliminary Air Force construction cost estimation. This chapter outlines these results and their implications. The first section of the chapter provides a summary of the research conclusions. Next, the chapter covers limitations of the research followed by the significance of the research. Finally, the chapter discusses recommendations for both action and future research to continue and expand the work presented in this paper.

Conclusions of Research

This study provided some useful insights into Air Force construction cost estimation modeling. The generalized beta distribution proved to be a viable distribution for cost element modeling, with the lognormal distribution remaining as a possible alternative, particularly if more data become available to test its utility. Correlations between cost elements affected overall cost estimates significantly, as emphasized in past research and by the correlations found in this research. Additionally, the Monte Carlo simulation revealed a given project's range of probable costs, highlighting well the cost estimate's uncertainty and allowing for the selection of an estimate at the desired percent confidence level. These attributes provide significant benefits over the UFC or AFCESA estimation models, and even over the PACES framework used for estimates at later design phases. PACES, UFC, and AFCESA all assume normal distributions for their cost data and do not correlate internal elements. Using a more accurate distribution such as

the generalized beta and correlating major cost elements significantly improves a model's ability to simulate actual project cost effects. With a larger data set to refine the model in this research, the simulation's accuracy could improve substantially.

Specifically for the validation projects tested, this research provided an accurate cost estimation tool in three of the five cases. For the dormitory project, the model developed here performed significantly better than any other estimate tested, including the programmed amount. For one project each within the education and training projects and the squadron operations projects, this research's model performed well within the -15% to +25% accuracy range desired. For the other project in each category, this model did not fall within the desired accuracy range, but still performed better than one other measure in each case. Furthermore, the projects for which the model did not provide as accurate of predictions had possible unique factors, which may have contributed to costs deviating significantly from the model's expected value.

Limitations of Research

The key limitations of this research centered on a lack of data. The model was able to produce significant results; however, additional data could have improved the accuracy of the distribution and correlation modeling, leading to potentially more accurate results. Moreover, added data would have allowed the modeling of additional facility types, along with further testing and validation of those facility-type models. Testing the dormitory model with only one project and the education and training along with the squadron operations models with only two projects each limited the validation of this research.

Significance of Research

There are two significant ramifications from this research. First, this model provided a methodology to create a viable tool in early cost estimation efforts, highlighting not only a likely cost but also the range of expected costs and their associated uncertainty. The correlated cost element modeling and simulation developed here were overall as effective as other comparable preliminary cost estimation methods for the projects tested even with limited data, and they better reflected actual cost element characteristics. Second, this research showed the relative accuracy for currently-used estimation methods. The variation of the estimates reveals that the methods may not be consistently producing estimates within the accuracy expected of their given estimation class. Further work in cost estimation may be warranted judging by these results. The model developed here may provide a comparison estimate or an alternative means for improving preliminary cost estimation.

Recommendations for Action

The model developed in this research, if expanded, could integrate into the Air Force's primary cost estimation tool, PACES, for initial cost estimation. Instead of only creating initial estimates using historical data for average costs per square foot/square meter, the same project scope information could fuel a correlated cost-element Monte Carlo simulation, providing further insight into potential project costs. Having a probability distribution of likely costs as an additional estimate tool could give estimators greater insight into the project's inherent cost risks and provide a secondary check to other estimation methods. Then, by programming the probability cost profile into the project file to some degree, instead of only recording a point estimate, decision-makers

would have additional useful information when selecting projects for execution and allocating funds.

Issues with such an implementation also lie in data collection, however. In this research, the dormitory model relied on the smallest sample size of eight projects total, with one reserved for validation leaving seven for model development. Such a small sample size is not ideal for developing the model, and at least that many projects per facility type would be required to expand the model to other facility categories. Due to the wide variation in Air Force facilities, this data collection effort would be substantial. However, the UFC and PACES cost estimation models require some level of data collection currently. Therefore, these collection procedures could expand to meet the parameters for data to support a method similar to this research. As enough project data became available, the model could be expanded facility type by facility type, providing utility in the order of the most-often constructed types as the Air Force completes and documents projects. Not only would such data support the model developed here, but would be useful for other cost research and analysis in the continual effort to improve the Air Force's cost estimation models.

Recommendations for Future Research

Future research could build upon this study in several ways. First, a future researcher could expand the model, validating and refining the results to include additional facility types. In particular, modeling airfield-related projects would add a crucial element to the scope of this research line as the airfield is the most critical asset of an Air Force installation. Additionally, follow-on research could compare the results to initial parametric models from PACES or RSMeans estimates for further insight. Data

for an effort such as this would likely come from the United States Army Corps of Engineer's Resident Management System, but may suffer from the same data limitations as discussed for the research in this paper. However, both the Army and Navy construct many facility types in common with the Air Force, and collecting those projects may prove useful in aggregating a larger sample size for analysis.

Second, a future researcher could modify and refine the general methodology used here for military construction projects and instead apply to facility sustainment, restoration, and modernization (FSRM) projects. The Air Force's Automated Civil Engineer System may contain the requisite data for the numerous FSRM projects documented therein. A future researcher could then build and analyze a similar model to this research for these smaller-scoped but more numerous projects constructed in the Air Force. Data quality may be a significant issue, but the utility of an application of this type would be considerable due to the large amount of FSRM projects requiring cost estimates.

Summary

This research succeeded in developing a relatively accurate Class 4 cost estimation method. The model, while not always more accurate than the standard parametric cost estimates in all cases, produced results useful for the cost estimation process with implications for improving current estimation practices. This method also revealed the range of uncertainty in the estimate for decision makers to evaluate risk, while only requiring knowledge of basic scope parameters for a given project. Additionally, the research provided insight into distribution modeling and correlation of cost elements, while validating the use of a Monte Carlo simulation to estimate costs.

Overall, these insights into Air Force construction costs and the subsequent model expand the foundation for future research and cost estimation practice development. Building on these methods, the Air Force can produce increasingly accurate estimates with a picture of the inherent risks and cost probabilities.

Appendix A: Construction Cost Research White Paper

White Paper: Report for AFCEC on Air Force Construction Cost Research

The following white paper was developed for the Air Force Civil Engineer Center (AFCEC) to provide a summary of Air Force research conducted in the realm of construction costs. The white paper focuses on Air Force Institute of Technology research and includes studies from 1986-2015. The research covers four main topics: historical cost trend analysis; parametric estimation models; contract method evaluations; and program-wide MILCON investigations. While not the primary focus of this research, contract method evaluation and program-wide MILCON investigation topics are included as an overview of the breadth of research related to construction costs. Historical cost trend analysis and parametric estimation model topics are of primary concern here as they relate to the development of specific project cost estimates prior to contracting the construction work.

AIR FORCE CONSTRUCTION COST RESEARCH SUMMARY

Developed for the Air Force Civil Engineer Center

By Captain Jeffrey D. Buchholtz

I. Overview

The Air Force Institute of Technology (AFIT) has conducted numerous research initiatives in identifying and analyzing trends, models, and methods related to construction costs. In an effort to consolidate and synthesize those efforts for the Air Force Civil Engineering Center (AFCEC), a brief summary of each research effort's scope and results are outlined and categorized into four main topics: historical cost trend analyses, parametric estimation models, contract method evaluations, and program-wide MILCON investigations. For additional references, Appendix A-1 lists the bibliographic information and abstracts from each study, sorted alphabetically by author's last name.

II. Research

1. Historical Cost Trend Analyses

Statistical analysis of trends within archived project data reveals factors that have significant impact on cost. Awareness of these critical factors allows tracking and the application of potential risk mitigation strategies to minimize negative influences or manage areas of likely cost growth. One theme throughout the studies is the quality of government personnel contract management significantly impacts overall construction performance. Recommendations include minimizing government delays, increasing communication and cooperation, and improving project definition with the user before construction begins.

1.1. *Analysis of Air Force Wartime Contracted Construction Project Performance Hoff, Ryan M. – 2015 – AFIT Thesis*

SCOPE: Captain Hoff analyzed factors for success and differing outcomes based on contract type for 25 AFCEC construction projects in Afghanistan. The projects consisted of reimbursable contracts and fixed-price contracts.

RESULTS: For general performance, government delays significantly impacted cost and schedule while project management issues also impacted schedule. Notably, weather and wartime security did not prove to be factors significantly impacting cost or schedule. For contract type, reimbursable contracts had higher cost and schedule growth, whereas fixed-price contracts did poorly in design performance and contract management. Neither contract type showed a difference in quality. As a result, Captain Hoff recommended the construction agent monitor cost and project management closely for reimbursable projects, possibly by tracking incremental progress and checking for excess labor, hours, or resources added to the project. For fixed-price contracts, construction agents could use Lean Analysis to identify sources of rework, inefficient process, and excess requirements.

1.2. *An Analysis of Cost Premiums and Losses Associated with USAF Military Construction Blomberg, Daniel L. – 2013 – AFIT Thesis*

SCOPE: Captain Blomberg conducted a case-study of two nearly identical projects constructed in 2009 on Joint Base Elmendorf-Richardson, Alaska, analyzing the differences between the contract methods and management. One project was a standard Design-Build project managed by the United States Army Corps of

Engineers (USACE) and the other project was a Design-Build pre-engineered building managed by the 673rd Civil Engineer Group (CEG) and AFCEC. These results were compared to a survey of 18 respondents comprising of construction and contract specialists from USACE, USAF and civilian contractors. Separately, Captain Blomberg conducted a geospatial analysis, validated with a multivariate analysis of the variance, to determine if the Davis-Bacon Act wage rates were higher than local area wage rates, contributing to MILCON cost premiums.

RESULTS: The CEG-managed project cost 27% less and was completed in less than half the time of the standard Design-Build project. This study validated that cost premiums do exist for MILCON and highlighted 11 major factors causing those premiums. In general, DoD actions and internal policies cause 80% of the premiums while public law and the Federal Acquisition Regulations account for 20%. Additionally, the study revealed that Davis-Bacon Act wage rates were higher than local wage rates. To mitigate some of these excess costs, Captain Blomberg recommended improving cooperation between all agencies involved by balancing risk, minimizing restrictive specifications, and encouraging innovation toward the actual end product instead of toward a specific construction or contract method.

1.3. *An Analysis of Construction Cost and Schedule*
Beach, Michael J. – 2008 – AFIT Thesis

SCOPE: Major Beach statistically analyzed 1,322 Air Force MILCON projects, completed within the years 1990 to 2005 (excluding military family housing and Non-Appropriated Funds projects) to determine if the project's Major Command

(MAJCOM), construction agent, or category code (CATCODE) predicted cost or schedule performance compared to the initial project estimates.

RESULTS: The MAJCOM and construction agent over a particular project did predict cost and schedule performance, whereas CATCODE did not. In particular, Pacific Air Forces MILCON projects managed by the USACE Alaska District were consistently completed under the projected time and budget. In contrast, this same agency did not perform favorably in Captain Blomberg's case study. Comparatively, the Air Force Center for Engineering and the Environment (AFCEE) and the USACE European District were able to minimize cost growth, but not schedule growth. Also, Air Combat Command's projects tended to perform well schedule-wise, regardless of the construction agent. While this study highlighted MAJCOM and construction agent correlations with cost and schedule, root causes were not identified.

1.4. *Characterizing Patterns of MILCON Project Contract Modification* **Nielsen, Tyler K. – 2007 – AFIT Thesis**

SCOPE: Captain Nielsen statistically analyzed 278 Air Force MILCON Projects with 3,842 change orders, completed from 2000 to 2004 and obtained from the Automated Civil Engineer System (ACES) database to reveal major causes of change orders. He used the same source data used in Captain Jason Cook's 2006 AFIT thesis.

RESULTS: Design deficiencies, followed by user change requests, were the largest contributors to contract modifications. Significantly less so but still notable were, in descending order, weather, scope deletion, and unforeseen site conditions.

Project managers could use these results to focus on the identified major contributors to change orders in an effort to reduce their occurrences or minimize their impact to cost and schedule growth.

2. Parametric Estimation Models

The following two studies developed parametric models using predictive factors to estimate a future project's cost based on past project trends or expert opinions. Of the two studies, only one is recent enough to provide relevant insight into current cost estimation issues.

2.1. *Estimating Required Contingency Funds for Construction Projects Using Multiple Linear Regression* Cook, Jason J. – 2006 – AFIT Thesis

SCOPE: Captain Cook created a model to predict contingency funds needed for a construction project, using 218 Air Force MILCON projects to build the model and reserving an additional 25 projects to validate the model once complete. The projects were pulled from the ACES database and included a wide variety of projects up to 2005.

RESULTS: Captain Cook found ten factors that combined to form a predictive model for cost estimation. Specifically, the model calculates the estimated percent the project will cost over the base estimate, thereby predicting the amount of contingency funds needed. This model had an average error of 0.3% from the 25 projects used for validation and is as follows:

$$\ln (\% \text{ Overrun}) = -2.151 - 19.285x_1 + 1.018x_2 + 0.140x_3 + 0.133x_4 - 0.216x_5 - 0.234x_6 - 1.008x_7 - 0.696x_8 - 0.958x_9 + 0.295x_{10}$$

Where

x_1 = normalized design length (design length divided by the design cost)

x_2 = estimate % of cost at award (estimate amount divided by the cost at award)

x_3 = design cost/cost at award > 10% (1 if > 10% and 0 if $\leq$ 10%)

x_4 = September award (1 if contract award in September and 0 if not)

x_5 = high competition > 9 bidders (1 if > 9 and 0 if $\leq$ 9)

x_6 = FY 2000 and later (1 if funded after October 1, 1999 and 0 if not)

x_7 = estimate % of PA (estimate amount divided by the programmed amount)

x_8 = type of work is emergency MILCON-EEIC341 (1 if so and 0 if not)

x_9 = type of work is housing - EEIC713 (1 if so and 0 if not)

x_{10} = design greater than 2 years (1 if > 2 years and 0 if $\leq$ 2 years)

2.2. *Formulation of a Construction Cost Estimating Procedure to Aid Designers in Preparing Detailed Construction Cost Estimates* **Stark, Steven R. – 1986 – AFIT Thesis**

SCOPE: Captain Stark surveyed 112 base-level Air Force civil engineers to determine factors on cost for projects and their level of impact in three price categories: less than \$200,000, between \$200,000 and \$500,000, and greater than \$500,000.

RESULTS: The result of this research was a cost estimating computer program with the goal of reducing cost estimation time but not necessarily improving accuracy. Accuracy of cost estimates at the time of this study was determined to be within 5-15% with the commonly used RS Means databases. The factors used by the model center around the type and location of the construction project along with items such as weather and the amount of competition among bidders. Because the data is outdated and most of the factors have been included in current cost estimation practices, this model is of little utility now. However, this study marks

the first Air Force research found to attempt to analyze and modify existing cost estimate practices to achieve better results.

3. Contract Method Evaluations

Several studies have examined the effect a project's contract type can have on cost performance. Of these, two found inefficiencies and issues with the standard Design-Bid-Build method, favoring more streamlined and relational methods with better cost and schedule results. The other two studies highlighted areas needing improved contract management in general, which were otherwise negatively influencing project costs.

3.1. *Firm Fixed Price and Cost Plus Fixed Fee Construction Contracts in Iraq and Afghanistan* Jaszkowiak, Lindsay M. – 2012 – AFIT Thesis

SCOPE: Captain Jaszkowiak used two methods in her research. First, she conducted a statistical analysis of 127 AFCEE projects in Iraq and Afghanistan constructed from 2006-2010. Second, she synthesized factors from a survey of 20 civil engineers and contract personnel from throughout the Air Force.

RESULTS: Overall, poor record-keeping of lessons learned contributed to internal management issues and a lack of improvement over time in all areas. Firm Fixed Price contracts appeared to have less percent cost and schedule growth compared to Cost Plus Fixed Fee, but those findings were not statistically significant. Cost Plus Fixed Fee contracts were perceived to outperform Firm Fixed Price contracts

in general, and in the area of quality in particular. However, final results indicated no substantial advantage for either type.

**3.2. *An Analysis of the Design-Build Delivery Approach in Air Force Military Construction*
Rosner, James W. – 2008 – AFIT Thesis**

SCOPE: Captain Rosner analyzed 835 projects constructed from 1996-2006, obtained through the ACES database. Of those projects, 278 were accomplished through a Design-Build method and 557 were accomplished through a Design-Bid-Build method. His goal was to determine if the Design-Build method performs better than the traditional Design-Bid-Build method.

RESULTS: Overall, the Design-Build method proved better in six of the eight performance measures, particularly with less cost growth and fewer modifications per million dollars. However, Design-Bid-Build methods seemed to be superior with less schedule growth. Captain Rosner theorized this was due instead to the timing built into the current MILCON process of fiscal year funding. Design-Build methods may prove superior with process changes to take advantage of the method's strengths.

**3.3. *Risk-Based Decision Model for Determining the Applicability of an Earned Value Management System in Construction*
Workman, Mark D. – 2006 – AFIT Thesis**

SCOPE: Major Workman gathered a series of in-depth survey data from three subject matter experts to identify risk factors that significantly impacted a construction project's cost growth and their estimated probability of occurrence. Major Workman then created a decision model for determining if Earned Value

Management practices should be applied to MILCON projects under \$20 million in response to a new policy requiring such an evaluation.

RESULTS: The study concluded if the model predicts cost growth of over 5%, the use of earned value management is recommended. However, due to the resources required for Earned Value Management, Maj Workman recommended its use only on projects over \$5 million and for which the risk of a cost growth over 5% was substantial enough to warrant additional investment.

3.4. *Cost Analysis between SABER and Design-Bid-Build Contracting Methods* ***Henry, Elwood – 2000 – AFIT Thesis***

SCOPE: Captain Elwood analyzed data from 46 projects between Wright-Patterson AFB and Holloman AFB consisting of 31 Simplified Acquisition of Base Engineering Requirements (SABER) projects and 15 Design-Bid-Build projects. The projects were accomplished between 1990 and 1999.

RESULTS: Both methods had a wide range of costs, but Design-Bid-Build projects tended to cost more. Also, SABER projects at Wright-Patterson AFB had less schedule growth than Design-Bid-Build. All other comparisons did not produce statistically significant differences. Because of the small sample size of comparable projects between only two bases, further studies would be required to generalize the findings to the Air Force overall.

4. Program-Wide MILCON Investigations

The following studies have taken a boarder look at Air Force construction, analyzing risks and inefficiencies with the MILCON system as a whole. These studies provide insights in themes and areas of concern instead of specific cost drivers.

**4.1. *Risks Associated with Federal Construction Projects*
Surajbally, Krishna R. – 2011 – AFIT Thesis**

SCOPE: Captain Surajbally conducted a risk analysis of implementing Building Information Modeling. He evaluated the risks in the areas of critical infrastructure, information technology, contracting, and cost. The study focused on Design-Build MILCON projects with the USACE as the construction agent, using a literature review as the foundation for the analysis.

RESULTS: Captain Surajbally concluded that the most significant risks in implementing Building Information Modeling are information technology related, but management teams should balance the cost of accepting the risk versus implementing mitigation measures.

**4.2. *A Proposed Military Construction Facility Investment Model*
Dempsey, Andre R. – 2003 – AFIT Thesis**

SCOPE: Major Dempsey used system dynamics and Value-Focused Thinking analysis methods to evaluate the MILCON investment model and to recommend improvements.

RESULTS: Major Dempsey created a MILCON investment model that was rated 92.02% effective at targeting C-3 and C-4 requirements for funding, compared to the existing model rated at 71.68%. The existing model allocated funds based on each MAJCOM's plant replacement value, average project costs, and number of projects for which funds were requested. Instead, the proposed model allocated funds directly based on C-3 and C-4 requirements and the age of facilities, distributing funds where most needed instead of by relative portfolio size. While

this study aimed to provide a solution for the Air Force's goal of eliminating C-3 and C-4 classified facility deficiencies by 2010, the program recommendations may still be applied to improve current MILCON funding efficiency.

4.3. *An Investigation Concerning Perceptions of Military Construction Program Effectiveness*
Dutcher, Gerald B. – 1986 – AFIT Thesis

SCOPE: Captain Dutcher surveyed 770 Air Force personnel at the Air Force Region Civil Engineer agency, MAJCOMs, and various bases working with the Military Construction Program for perceptions on primary inefficiencies.

RESULTS: Key inefficiencies identified were poor scope definition, lack of delegated authority, length of time required to input project details (particularly in "Project Books"), and breakdown in communications (particularly for special projects on a short timeline).

Appendix A-1: Abstracts

Beach, Michael J., (2008). *An Analysis of Construction Cost and Schedule*. Unpublished Masters Thesis, Air Force Institute of Technology, Wright Patterson AFB OH.

ABSTRACT:

Cost and schedule performance are widely accepted in the literature and in industry as effective measures of the success of the project management effort. Earned Value Analysis (EVA) is one method to objectively measure project cost and schedule. This research evaluates the cost and schedule performance of 1,322 completed United States Air Force (AF) Military Construction (MILCON) projects, executed from 1990 to 2005. The impact of Major Command (MAJCOM), Construction Agent (CA), facility type (CATCODE), individually and in combination, on the EVA metrics of Cost Performance Index (CPI), Time Performance Index (TPI), and CPI*TPI were evaluated. The results indicate that AF MILCON projects are typically executed either on or below their respective budgets, but typically take more time than expected for construction. This outcome implies that AF MILCON projects trade time performance in an effort to control costs. When cost and performance are given equal weight, the sacrifice made in time performance is greater than the benefit gained in cost performance.

Blomberg, Daniel L., (2013). *An Analysis of Cost Premiums and Losses Associated with USAF Military Construction*. Unpublished Masters Thesis, Air Force Institute of Technology, Wright Patterson AFB OH.

ABSTRACT:

Military construction (MILCON) represents 40% of the federal government's \$30 billion construction budget. The federal budget is fixed; therefore, any cost overages likely affect project scope or requirements. This study investigated if MILCON procurement costs more than private industry construction and if so, what causes the cost premiums. A combination of in-depth literature review, expert interviews, a unique case study, expert surveys, and geospatial statistical analysis answered the research question. The case study evaluated two nearly identical projects to determine how internal factors, in addition to public laws, affect MILCON cost premiums.

This study confirmed the existence of MILCON cost premiums. Additionally, 11 major cost premium themes emerged: overly restrictive statements of requirements, failing to balance risk, stifling or not applying innovation, unique MILCON requirements, parameterization of the execution process, selection of construction specifications, schedule and submittal policies, perception of MILCON construction agents, anti-terrorism/force protection requirements, Federal Acquisition Regulations, and socioeconomic laws and policies. Additionally, in spite of the contract requirement similarities, once complete, the studied projects differed by over a year of construction time and \$7 million. Research frequently cites federal laws and policies as the primary

cost premium driver; however, this research demonstrated internal construction policies, which the military can control, also cause increased cost premiums.

Cook, Jason J., (2005). *Estimating Required Contingency Funds for Construction Projects Using Multiple Linear Regression*. Unpublished Masters Thesis, Air Force Institute of Technology, Wright Patterson AFB OH.

ABSTRACT:

Cost overruns are a critical problem for construction projects. The common practice for dealing with cost overruns is the assignment of an arbitrary flat percentage of the construction budget as a contingency fund. This research seeks to identify significant factors that may influence, or serve as indicators of, potential cost overruns. The study uses data on 243 construction projects over a full range of project types and scopes gathered from an existing United States Air Force construction database. The author uses multiple linear regression to analyze the data and compares the proposed model to the common practice of assigning contingency funds. The multiple linear regression model provides better predictions of actual cost overruns experienced. Based on the performance metric used, the model sufficiently captures 44% of actual cost overruns versus current practices capturing only 20%

The proposed model developed in this study only uses data that would be available prior to the award of a construction contract. This allows the model to serve as a planning tool throughout the concept and design phases. The model includes project characteristics, design performance metrics, and contract award process influences. This research supports prior findings of a relationship between design funding and design performance as well as the influence of the contract award process on cost overruns. While the proposed model captures 44% of actual cost overruns, its application reduces average contingency budgeting error from -11.2% to only -0.3% over the entire test sample.

Dempsey, Andre R., (2003). *A Proposed Military Construction Facility Investment Model*. Unpublished Masters Thesis, Air Force Institute of Technology, Wright Patterson AFB OH.

ABSTRACT:

The fiscal year (FY)1999 and FY2000 National Defense Authorization Acts (NDAA) amended Title 10 USC, Section 17, and directed the secretary of defense to report annually on the capability of installations and facilities to provide support to forces in the conduct of their missions. This has come to be known as the Installations' Readiness Report (IRR). The Air Force's IRR links facility sustainment, restoration, and modernization (SRM) requirements, with the impact on the installation's ability to support the mission associated with the particular facility class. The Air Force's centralized military construction (MILCON) program model used to program major facility requirements does not directly target facility investment in the "deficient" facility classes defined in the Installations' Readiness Report.

This research combined the system dynamics and value-focused thinking methodologies together to develop a proposed MILCON model that might better target funding of deficient facility class requirements. The results from a system dynamics analysis of the existing MILCON model were used to better understand the MILCON program and leverage management policies in a proposed MILCON model. The proposed MILCON model was then developed using a gold standard value-focused thinking approach. The Air Force's goals and objectives for the MILCON program were derived from a literature review of key doctrine, policies, and guidance. The proposed model was also evaluated to identify relevant favorable or unfavorable behavior trends in eliminating deficient facility class requirements. The proposed model provides a significant short and long-term improvement over the existing model in targeting and eliminating deficient facility class requirements. The model demonstrates a 20 percent improvement in targeting these facility requirements in FY2004 and a long-term trend towards completely eliminating these requirements.

Dutcher, Gerald B., (1986). *An Investigation Concerning Perceptions of Military Construction Program Effectiveness*. Unpublished Masters Thesis, Air Force Institute of Technology, Wright Patterson AFB OH.

ABSTRACT:

In this thesis the primary inefficiencies of the Military Construction Program (MCP), as commonly perceived by the Air Force Region Civil Engineer (AFRCE), the Major Command (MAJCOM), and the bases are identified. These three management levels are the primary managers of the MCP program. The MCP problems identified included inadequate definition of scope at the inception of MCP projects, and ineffective technical and functional design reviews.

Data was gathered from the AFRCE, the MAJCOM and the base through 770 questionnaires, mailed throughout the continental United States. All of the personnel involved with the MCP were surveyed at the AFRCEs and MAJCOM. The base personnel were randomly sampled.

The methodology used involved a one-way analysis of variance of the mean responses, from the AFRCE, the MAJCOM and the base, to a seven point Likert scale. Significant opinion differences were verified with the Scheffe test for all possible comparisons.

Henry, Elwood, (2000). *Cost Analysis between SABER and Design Bid Build Contracting Methods*. Unpublished Masters Thesis, Air Force Institute of Technology, Wright Patterson AFB OH.

ABSTRACT:

The majority of Air Force construction performed by two main contractual methods, Design Bid Build (DBB) and Simplified Acquisition of Base Engineering Requirements (SABER). DBB is the traditional contracting method where each project is

competitively bid. SABER uses one contractor to complete multiple projects over the duration of the contract, using unit prices established in the original contract.

The purpose of this research project was to perform a cost analysis between DBB and SABER construction. The research involved finding appropriate projects completed by the two methods that were comparable. This involved going to Wright-Patterson and Holloman Air Force Bases to gather project information. There were a total of 46 projects collected from both bases. Then a methodology was developed to compare the projects collected. Projects were divided into categories containing similar types of construction. Data from the project was then used to calculate a unit cost per dimensional characteristic for the project. Project comparability was demonstrated by showing that the group of projects constructed by each method completed a similar type and scope of work. Time and cost growth were also compared for DBB versus SABER.

The research findings showed that SABER was cheaper but not at a statistical level of significance. The comparison could only be completed in one area of construction, interior renovation, due to the limited number of comparable projects in the remaining construction categories. SABER construction also performed better in cost and time growth for most instances.

Hoff, Ryan M., (2015). *Analysis of Air Force Wartime Contracted Construction Project Performance*. Unpublished Masters Thesis, Air Force Institute of Technology, Wright Patterson AFB OH.

ABSTRACT:

US-led construction projects in Afghanistan have performed poorly on-average; indeed, it is the norm to deliver projects late to need and over budget to the customer. Using a dataset of 25 Afghan wartime projects, we address two separate, yet related questions relating to these DoD construction activities in the Afghan theater of operations. These questions are: 1) What factors affect the success of construction projects; and 2) How do project outcomes differ based on the contract type? First, with regards to critical success factors, current literature suggests that wartime projects may face the same cost and schedule factors as peacetime projects, with some notable additions. Using peacetime factors as a baseline, project factors, health and safety compliance, quality of work, technical performance, work productivity, and external environmental factors were tested with contingency tables to determine if they are predictive of schedule or cost performance. We found that external environmental factors, to include weather and wartime security, were not predictive of project performance. However, cost performance and schedule performance was found to be significantly dependent on government-issued excusable delays. Moreover, project management deficiencies were predictive of poor schedule performance but not cost performance. Second with regards to contract type, as the Afghan security condition was volatile, contracting officers dynamically used both reimbursable and fixed-price contracts in order to accomplish the mission. Using the Mann-Whitney tests, performance differences between contract types were explored. We found reimbursable contracts to have significantly greater cost and schedule growth. Additionally, fixed price projects were found to have more problems with design performance and contract management.

There was no significant difference in overall project quality. In conclusion, cost monitoring from the owner and scrutiny of project management is critical to the success of reimbursable contracts; and technical performance monitoring is necessary to ensure that fixed-price projects meet deadlines.

Jaszkowiak, Lindsay M., (2012). *Firm Fixed Price and Cost Plus Fixed Fee Construction Contracts in Iraq and Afghanistan*. Unpublished Masters Thesis, Air Force Institute of Technology, Wright Patterson AFB OH.

ABSTRACT:

Firm Fixed Price and Cost Plus Fixed Fee contract types have been utilized the most for construction in the Iraq and Afghanistan theaters. Often construction occurs in contested regions that are known to be particularly challenging, unpredictable, and unstable. The object of this study was to analyze the performance of these two contract types in this contingency environment, and to determine what internal and external influencing factors seemed to impact contract success the most.

The methodology first evaluated existing construction performance data using bivariate and analysis of variance to identify differences contract type. Next, a quantitative/qualitative questionnaire was conducted to gather expert opinions on the factors that were perceived to have the most impact on contingency contract performance. The combined synthesis of information sources was used to determine what key performance/risk measures impacted success of each contract type the most, and what measures may be beneficial for evaluating contingency construction contract success in the future.

The findings of this study indicated there was no proven advantage in cost performance for either contract type. FFP projects showed to control schedule growth significantly better than CPFF. CPFF contracts indicated a better quality product. Additional results of this study identified that understanding project performance in a contingency environment involved a balance of numerous variables that may impact projects in unique ways based on the chosen contract type.

Nielson, Tyler K., (2007). *Characterizing Patterns of MILCON Project Contract Modifications*. Unpublished Masters Thesis, Air Force Institute of Technology, Wright Patterson AFB OH.

ABSTRACT:

Change orders are used by project managers of construction projects to account for unexpected changes in construction projects after the contract has been finalized. This can include everything from weather events to last minute changes requested by the user. This effort analyzed data from the U.S. Air Force Military Construction (MILCON) program to find the major causes of change orders in the hopes that the associated costs may be minimized and that the insight gained may improve project management efforts.

The data was analyzed using means comparison testing through the nonparametric Kruskal-Wallis test; the results were then ranked using the Dunn-Bonferroni method.

The results show that pre-construction activities (unforeseen site conditions, unforeseen environmental site conditions, user changes, and design deficiencies) are the most common causes of change orders for MILCON projects, which agrees with other construction research reported in the literature. Although the information contained in the military database was insufficient to determine a conclusive statistical ranking, there is evidence that suggests Air Force Material Command may have higher median change order cost and Air Combat Command has lower median change order costs. When considering the construction agent, the Air Force seems to have higher median change order costs than both the Army Corps of Engineers and the Naval Facilities Command. However, no specific reasons can be attributed to these observations. Furthermore, given the accuracy and completeness of the data, these results remain questionable and require further research to validate.

Rosner, James W., (2008). *An Analysis of the Design-Build Delivery Approach in Air Force Military Construction*. Unpublished Masters Thesis, Air Force Institute of Technology, Wright Patterson AFB OH.

ABSTRACT:

The design-build method for construction project delivery continues to grow in both the private and public sector. Several government agencies have observed, through experience with design-build, positive results which give “anecdotal” credibility to design-build methods. The objective of this study is to compare the performance of the design-build delivery method with traditional design-bid-build approaches for Air Force (AF) military construction (MILCON).

Data related to 835 (278 design-build, 557 traditional) MILCON projects were gathered from the Automated Civil Engineer System – Project Management Module (ACES-PM) for Fiscal Years 1996-2006. The design-build method had better performance for six of eight metrics with highly significant results for cost growth and number of modifications per million dollars. The traditional method experienced a highly significant advantage for the metrics of construction timeline and total project time. The historical analysis revealed that design-build MILCON has improved significantly for cost growth, modifications per million dollars, construction timeline, and total project time. The traditional method also improved for the cost growth and modifications per million dollars metrics. Finally, the facility type analysis revealed that the design-build method was best suited for seven of the nine facility types. This study provides empirical evidence of where the design-build delivery method provides an advantage to the traditional method for AF MILCON execution.

Stark, Steven R., (1986). *Formulation of a Construction Cost Estimating Procedure to Aid Designers in Preparing Detailed Construction Cost Estimates*. Unpublished Masters Thesis, Air Force Institute of Technology, Wright Patterson AFB OH.

ABSTRACT:

This thesis examined several existing cost estimating data bases. In addition to examining these data bases a survey was taken among Air Force Civil Engineering design personnel to determine which estimating system is currently in use and what factors affect the final costs on construction projects. Based on the results of the surveys an estimating program was developed to enable the designer to input local cost data and store the data for future use. With the data base in place the designer is able to create accurate cost estimates in less time for each particular project and have the project data stored under the particular project name/code. The computer programs developed for this thesis were written in BASIC language and compatible with the WANG VS 100 system.

Surajbally, Krishna R., (2011). *Risks Associated with Federal Construction Projects*. Unpublished Masters Thesis, Air Force Institute of Technology, Wright Patterson AFB OH.

ABSTRACT:

The rise in terrorism, corporate espionage, cyber-attacks, and federal fiscal constraints play an important role in the federal construction process. The risks associated with these occurrences are studied to aid in the risk management of the military construction process. This paper presents the status of research into these areas to identify how methods, policies, applications, and information obtained from case studies can be used by stakeholders to manage risk in the United States Air Force construction process.

The author reviewed research on risk associated with four essential components of the military construction process – Critical Infrastructure, Information Technology, Contracts, and Cost in the construction and related industry. This study focused on the methodology, management policy, areas of application, and case studies research of the construction and related industry.

Workman, Mark D., (2006). *Risk-Based Decision Model for Determining the Applicability of an Earned Value Management System in Construction*. Unpublished Masters Thesis, Air Force Institute of Technology, Wright Patterson AFB OH.

ABSTRACT:

New policy mandated by the Undersecretary of Defense for Acquisition, Technology and Logistics has lowered the dollar thresholds of contracts requiring earned value management (EVM). This policy directed that a “risk-based decision” be made to determine if EVM should be used on firm-fixed price contracts under \$20 million. Although not previously applicable to Military Construction (MILCON) building projects or other Air Force Civil Engineer (CE) managed contracts, the new threshold requires that CE projects be evaluated for risk.

Therefore, the focus of this research was to analyze the risk factors associated with construction contracts in an attempt to build a decision model to determine if EVM is warranted on the project. Due to the cost of implementing EVM, this model should

probably be used only on Air Force construction projects with cost estimates over \$5 million. If the cost growth predicted by the model is greater than 5%, the use of EVM is recommended to monitor the risk factors. However, this recommendation should be tempered with the overall risk associated with a given project. In other words, if the calculated cost growth is high but the probability of occurrence is low, the decision-maker may want to forego the use of EVM and the associated costs.

Appendix B: Supplemental Data and Analysis Results

Project Data Set with Total and Unit Cost Element Amounts

Note: Shaded rows indicate projects reserved for model validation

Project Details					
ID	Project Name	Project Type	Fiscal Year	Construction Mid-Point	Location
D1	FY-11 Design/Build 96 Person Dormitory	Dormitory	2011	4/23/2013	Cannon AFB
D2	FY-12 Design/Build 96 Person Dormitory	Dormitory	2012	5/6/2013	Cannon AFB
D3	AIT 600 PN Barracks, PH II	Dormitory	2012	3/1/2013	Fort Sam Houston, Texas
D4	ARRA 200 Rm Dorm PN: ACE JCGU093002	Dormitory	2009	7/16/2010	Goodfellow Air Force Base, Texas
D5	100 Room Dorm, ACE JCGU073000	Dormitory	2010	10/3/2011	Goodfellow Air Force Base, Texas
D6	Airmen Training Complex Dormitory #1	Dormitory	2009	4/25/2011	Lackland AFB, Texas
D7	Airmen Training Complex Dormitory #2	Dormitory	2010	10/15/2011	Lackland AFB, Texas
D8	Joint Base MDL - FY11-120 Person Dorm	Dormitory	2011	9/26/2012	McGuire AFB, New Jersey
ET1	Add/Alter Child Development Center	Education & Training	2009	2/28/2011	Cannon AFB
ET2	ARRA D/B Child Development Center	Education & Training	2009	1/18/2011	Cannon AFB
ET3	Design/Build FY12 CDC	Education & Training	2012	9/14/2013	Holloman AFB, NM
ET4	Recovery Add Child Development Center	Education & Training	2009	4/15/2011	Lackland AFB
ET5	Child Development Center	Education & Training	2005	1/28/2007	Whiteman Air Force Base, Missouri
ET6	EIE214, Replace Chapel Center	Education & Training	2007	5/19/2008	Eielson AFB, Alaska
ET7	D/B Chapel Center	Education & Training	2004	9/10/2008	Goodfellow Air Force Base, Texas
ET8	Consolidated Learning Center, JCGU043002	Education & Training	2010	1/26/2012	Goodfellow Air Force Base, Texas
ET9	F-16 Academic Facility & SEAD Facility	Education & Training	2012	5/8/2013	Holloman AFB, NM
ET10	ATC DCF #1 Satellite Classrooms + DCF #1 Telecommunications Duct Bank	Education & Training	2010	1/7/2011	Lackland AFB, Texas
ET11	FY10 Warfighter & Family Support Center	Education & Training	2010	8/16/2011	McGuire AFB, New Jersey
ET12	WAFB Education Center	Education & Training	2004	9/13/2006	Whiteman Air Force Base, Missouri
ET13	MC-130 Flight Simulator Facility	Education & Training	2008	12/8/2009	Cannon AFB
ET14	CV-22 Flight Simulator Facility	Education & Training	2009	5/29/2010	Cannon AFB
ET15	FY-11 SOF MC-130 Sim Fac (RECAP) ADAL	Education & Training	2011	7/11/2012	Cannon AFB
ET16	FNWZ103010, ADAL C130J Flight Simulator	Education & Training	2012	2/20/2013	Dyess Air Force Base, Texas
ET17	F-22 AD/AL Flight Simulator	Education & Training	2009	5/7/2010	Holloman AFB, NM
ET18	Joint Intel Tech Trng Fac. PN:JCGU053000	Education & Training	2010	3/24/2012	Goodfellow Air Force Base, Texas
ET19	Basic Exp Airman Skill Train Phase II	Education & Training	2008	1/1/2009	Lackland AFB
ET20	Evasive Conduct After Capture Training	Education & Training	2010	6/20/2011	Lackland AFB, TX
SO1	ELM308 Add/Alter Air Support Op Squadron	Squadron Operations	2011	2/29/2012	Joint Base Elmendorf-Richardson
SO2	D/B Addition to Bldg 415 RDT&E Facility	Squadron Operations	2010	6/2/2011	Kirtland Air Force Base
SO3	MXG Consolidation	Squadron Operations	2009	1/2/2011	McConnell AFB
SO4	Consolidated Communications Facility - C	Squadron Operations	2010	4/1/2012	Cannon AFB
SO5	FY-11 SOF UAS Squadron Ops, Cannon AFB	Squadron Operations	2011	3/15/2013	Cannon AFB
SO6	10th Air Support Operations Squadron	Squadron Operations	2008	5/27/2009	Fort Riley, Kansas
SO7	Acquisition Management Facility	Squadron Operations	2008	11/6/2009	Hanscom AFB
SO8	Consolidated Communications Facility - W	Squadron Operations	2009	1/14/2011	Whiteman Air Force Base, Missouri
SO9	EOD Facility	Squadron Operations	2010	11/9/2011	Whiteman Air Force Base, Missouri
SO10	Force Support Squadron (FSS) Facility	Squadron Operations	2012	6/27/2013	Whiteman Air Force Base, Missouri
SO11	Joint Air-Ground Center PN093010	Squadron Operations	2009	7/21/2010	Fort Hood, Texas
SO12	FY12 ASOC - Bldg 585	Squadron Operations	2012	11/6/2013	Fort Riley, Kansas
SO13	AFNWC Sustainment Center	Squadron Operations	2012	11/30/2013	Kirtland Air Force Base, NM
SO14	Aircraft Maintenance Operations Ctr	Squadron Operations	2006	11/17/2008	Laughlin AFB, Texas
SO15	Base Ops Command Post Facility	Squadron Operations	2011	6/25/2012	McGuire AFB, New Jersey

Project Details							
ID	Project Type	Escalation Factor	Area Cost Factor	Scope (\$M)	AF PA Cost Estimate	Revised AF PA Cost Estimate	Total Actual Cost
D1	Dormitory	1.0583	1.01	3168.00	\$ 14,000,000.00	\$ 13,972,000.00	\$13,348,830.34
D2		1.0571	1.01	3168.00	\$ 15,000,000.00	\$ 15,000,000.00	\$13,296,383.78
D3		1.0636	0.84	16287.00	\$ 46,000,000.00	\$ 39,100,000.00	\$37,921,845.00
D4		1.1174	0.86	10580.00	\$ 28,400,000.00	\$ 26,220,228.00	\$23,743,643.00
D5		1.0957	0.86	5290.00	\$ 14,000,000.00	\$ 14,000,000.00	\$14,226,979.60
D6		1.1066	0.84	21543.74	\$ 75,515,000.00	\$ 69,102,000.00	\$54,544,986.13
D7		1.0951	0.84	21543.74	\$ 77,000,000.00	\$ 59,876,098.00	\$47,330,700.65
D8		1.0786	1.22	3960.00	\$ 18,440,000.00	\$ 15,482,000.00	\$13,904,784.13
ET1	Education & Training	1.1103	1.01	2379.00	\$ 8,000,000.00	\$ 7,400,000.00	\$7,597,826.14
ET2		1.1131	1.01	2165.00	\$ 12,000,000.00	\$ 9,574,969.00	\$8,775,162.58
ET3		1.0442	0.99	2700.00	\$ 11,200,000.00	\$ 11,200,000.00	\$10,327,370.61
ET4		1.1072	0.84	2787.09	\$ 6,000,000.00	\$ 6,000,000.00	\$6,604,890.78
ET5		1.1042	1.07	2450.00	\$ 7,600,000.00	\$ 7,600,000.00	\$7,685,911.90
ET6		1.0579	2.30	2994.00	\$ 14,400,000.00	\$ 14,001,108.00	\$12,998,688.00
ET7		1.0427	0.86	1680.00	\$ 4,300,000.00	\$ 4,257,000.00	\$4,886,564.00
ET8		1.0902	0.86	2598.00	\$ 12,000,000.00	\$ 12,000,000.00	\$11,277,138.00
ET9		1.0569	0.99	2222.00	\$ 10,000,000.00	\$ 10,000,000.00	\$9,062,924.79
ET10		1.1138	0.84	8074.76	\$ 32,000,000.00	\$ 28,363,258.00	\$27,928,752.97
ET11		1.0989	1.22	1672.00	\$ 7,900,000.00	\$ 7,900,000.00	\$7,042,319.00
ET12		1.1135	1.07	7763.00	\$ 13,200,000.00	\$ 13,199,374.00	\$13,214,270.08
ET13		1.1084	1.01	2200.00	\$ 13,287,000.00	\$ 12,996,000.00	\$8,292,633.94
ET14		1.1154	1.01	2788.00	\$ 8,300,000.00	\$ 8,280,591.00	\$6,043,246.82
ET15		1.0823	1.01	2200.00	\$ 13,287,000.00	\$ 12,996,000.00	\$9,568,809.61
ET16		1.0644	0.89	876.00	\$ 4,080,000.00	\$ 4,071,000.00	\$1,127,205.00
ET17		1.1145	0.99	1022.00	\$ 3,150,000.00	\$ 3,068,000.00	\$3,565,542.23
ET18		1.0875	0.86	4645.00	\$ 18,400,000.00	\$ 12,698,364.00	\$12,749,453.95
ET19		1.0566	0.84	9870.00	\$ 14,000,000.00	\$ 13,260,000.00	\$11,509,243.70
ET20		1.1027	0.84	1487.00	\$ 4,879,000.00	\$ 4,732,630.00	\$5,552,962.00
SO1	Squadron Operations	1.0886	2.05	1140.00	\$ 4,749,000.00	\$ 4,740,000.00	\$4,202,360.00
SO2		1.1040	0.91	1097.00	\$ 5,800,000.00	\$ 4,995,734.00	\$4,476,007.00
SO3		1.1142	0.92	8088.00	\$ 13,100,000.00	\$ 12,745,000.00	\$13,104,227.36
SO4		1.0871	1.01	5574.00	\$ 15,000,000.00	\$ 18,071,236.00	\$23,522,110.25
SO5		1.0622	1.01	8233.00	\$ 39,674,000.00	\$ 39,417,000.00	\$25,220,848.23
SO6		1.0828	1.05	2980.00	\$ 12,515,000.00	\$ 12,245,000.00	\$11,197,871.31
SO7		1.1071	1.26	3690.01	\$ 12,800,000.00	\$ 12,790,000.00	\$12,236,463.16
SO8		1.1134	1.07	4274.00	\$ 11,400,000.00	\$ 11,380,000.00	\$10,524,677.00
SO9		1.0939	1.07	1505.00	\$ 7,400,000.00	\$ 7,024,212.00	\$7,155,063.58
SO10		1.0520	1.07	1109.00	\$ 5,000,000.00	\$ 6,373,000.00	\$5,969,791.00
SO11		1.1176	0.86	5434.00	\$ 10,800,000.00	\$ 10,411,000.00	\$8,671,894.13
SO12		1.0383	1.05	4000.00	\$ 7,600,000.00	\$ 7,600,000.00	\$5,791,035.00
SO13		1.0356	0.91	5310.00	\$ 25,000,000.00	\$ 23,900,000.00	\$24,355,245.36
SO14		1.0485	0.89	1869.00	\$ 7,900,000.00	\$ 7,820,846.00	\$7,972,997.77
SO15		1.0831	1.22	2200.00	\$ 8,000,000.00	\$ 7,951,000.00	\$6,913,267.00

Cost Summary							
ID	Project Type	General Requirements	Demolition	Finishes	Foundations	Communications	Pavements
D1	Dormitory	\$1,139,429.00	\$0.00	\$1,999,104.74	\$506,250.00	\$109,815.00	\$405,268.00
D2		\$937,851.47	\$0.00	\$2,176,998.23	\$506,250.00	\$109,759.00	\$395,729.00
D3		\$3,331,509.00	\$3,186,598.00	\$3,268,561.00	\$1,866,000.00	\$1,120,000.00	\$2,479,001.00
D4		\$2,478,119.00	\$0.00	\$4,666,315.00	\$2,437,406.00	\$295,929.00	\$797,620.00
D5		\$959,993.10	\$26,069.00	\$1,955,254.00	\$1,894,636.50	\$812,012.00	\$573,686.00
D6		\$7,164,159.26	\$183,948.00	\$5,492,013.00	\$4,677,628.00	\$1,575,025.00	\$1,422,127.00
D7		\$6,428,998.00	\$401,859.00	\$4,186,096.82	\$4,219,867.64	\$1,770,342.10	\$2,894,436.35
D8		\$1,391,162.30	\$50,000.00	\$2,697,500.00	\$744,716.45	\$748,830.18	\$542,715.00
ET1	Education & Training	\$1,376,135.30	\$191,555.00	\$601,715.62	\$366,445.00	\$139,067.09	\$454,865.86
ET2		\$1,589,048.58	\$115,316.00	\$1,491,087.00	\$482,620.00	\$313,381.00	\$471,187.00
ET3		\$1,568,351.46	\$87,509.24	\$1,893,177.00	\$540,000.00	\$225,000.00	\$641,175.00
ET4		\$890,767.00	\$67,057.00	\$1,482,686.00	\$172,290.00	\$308,595.00	\$268,648.00
ET5		\$650,207.00	\$403,593.90	\$1,075,066.00	\$338,373.00	\$109,020.00	\$525,211.00
ET6		\$1,664,538.00	\$0.00	\$2,451,845.00	\$1,183,778.00	\$650,614.00	\$381,730.00
ET7		\$728,899.00	\$46,462.00	\$906,243.00	\$485,000.00	\$179,500.00	\$45,000.00
ET8		\$1,085,938.60	\$347,060.00	\$1,822,148.40	\$674,380.85	\$883,506.15	\$670,609.00
ET9		\$1,063,737.10	\$145,512.00	\$1,420,631.69	\$730,359.00	\$664,586.00	\$571,148.00
ET10		\$1,496,034.91	\$85,983.09	\$2,890,037.02	\$1,904,368.35	\$1,300,143.04	\$1,258,866.98
ET11		\$733,404.00	\$216,300.00	\$1,250,747.00	\$412,550.00	\$49,000.00	\$277,650.00
ET12		\$1,108,231.48	\$92,500.00	\$2,660,497.00	\$1,223,530.00	\$69,000.00	\$290,800.00
ET13		\$372,882.91	\$74,407.00	\$1,292,351.37	\$246,021.00	\$629,716.00	\$928,440.00
ET14		\$393,665.89	\$15,000.00	\$937,808.00	\$218,642.00	\$631,384.00	\$737,098.00
ET15		\$466,567.77	\$109,458.04	\$1,257,480.86	\$579,078.20	\$786,753.53	\$264,684.28
ET16		\$91,276.00	\$18,363.00	\$177,585.00	\$121,594.00	\$42,752.00	\$61,032.00
ET17		\$287,592.30	\$46,455.72	\$807,967.08	\$168,304.45	\$229,546.75	\$82,417.11
ET18		\$121,394.08	\$82,353.00	\$2,294,947.19	\$1,874,997.33	\$541,666.27	\$737,839.00
ET19		\$733,346.00	\$55,544.00	\$1,028,825.00	\$956,658.00	\$1,245,872.00	\$1,313,332.00
ET20		\$553,822.00	\$0.00	\$522,691.00	\$331,575.00	\$557,966.00	\$86,069.00
SO1	Squadron Operations	\$732,392.00	\$121,948.25	\$187,580.74	\$13,400.74	\$168,623.03	\$164,760.74
SO2		\$492,227.00	\$78,249.00	\$732,800.00	\$77,051.00	\$544,303.00	\$301,193.00
SO3		\$1,324,824.38	\$913,981.00	\$4,737,322.00	\$345,000.00	\$139,068.00	\$291,949.00
SO4		\$2,877,016.49	\$323,413.70	\$2,041,110.71	\$891,747.62	\$3,126,154.18	\$1,556,210.00
SO5		\$1,643,407.86	\$205,000.00	\$2,674,299.12	\$2,298,478.00	\$2,269,945.15	\$1,791,400.00
SO6		\$991,417.00	\$0.00	\$1,773,599.31	\$1,161,696.00	\$317,666.00	\$726,469.00
SO7		\$2,383,825.00	\$10,000.00	\$1,887,000.00	\$0.00	\$111,200.00	\$815,000.00
SO8		\$1,198,358.50	\$323,828.00	\$954,546.00	\$1,273,802.00	\$457,332.00	\$472,901.00
SO9		\$1,456,378.58	\$253,601.00	\$1,057,152.00	\$308,000.00	\$236,179.00	\$348,048.00
SO10		\$581,937.27	\$22,329.68	\$781,990.77	\$423,382.75	\$566,448.90	\$249,807.94
SO11		\$1,644,235.66	\$17,874.16	\$1,408,956.53	\$476,313.44	\$61,764.00	\$480,995.11
SO12		\$735,511.00	\$8,957.00	\$385,065.00	\$940,000.00	\$243,500.00	\$181,000.00
SO13		\$2,819,040.00	\$144,977.00	\$1,630,000.00	\$1,271,000.00	\$5,748,879.11	\$484,681.00
SO14		\$953,682.00	\$431,235.49	\$1,111,103.00	\$198,357.00	\$122,107.00	\$725,758.28
SO15		\$171,241.00	\$94,000.00	\$1,713,000.00	\$408,759.00	\$624,000.00	\$220,399.00

Cost Summary (Continued)							
ID	Project Type	Earthwork	Furnishings	Electrical	Structural	Mechanical	Specialties
D1	Dormitory	\$965,123.15	\$519,198.45	\$2,110,080.00	\$1,891,372.00	\$3,703,190.00	\$0.00
D2		\$915,091.53	\$531,121.69	\$2,316,080.00	\$2,056,671.00	\$3,327,190.00	\$23,641.86
D3		\$1,509,753.00	\$55,000.00	\$1,802,022.00	\$14,472,872.00	\$4,271,930.00	\$558,599.00
D4		\$350,941.00	\$285,765.00	\$1,800,315.00	\$5,999,623.00	\$4,429,330.00	\$202,280.00
D5		\$695,891.00	\$211,180.00	\$1,048,132.00	\$2,551,986.91	\$3,060,564.09	\$437,575.00
D6		\$1,922,791.00	\$153,461.00	\$6,384,333.87	\$12,394,353.00	\$12,449,425.00	\$725,722.00
D7		\$3,283,278.80	\$219,791.00	\$5,967,720.01	\$7,575,655.26	\$9,317,592.87	\$1,065,062.80
D8		\$139,535.00	\$73,800.00	\$1,055,395.00	\$3,490,000.00	\$2,482,850.20	\$488,280.00
ET1	Education & Training	\$436,252.00	\$695,742.65	\$369,068.08	\$953,749.00	\$1,891,710.54	\$121,520.00
ET2		\$699,269.00	\$656,597.00	\$866,012.00	\$848,002.00	\$1,211,809.00	\$30,834.00
ET3		\$543,824.00	\$529,125.00	\$1,083,855.47	\$2,005,000.00	\$1,112,458.44	\$97,895.00
ET4		\$187,446.53	\$473,699.00	\$129,185.00	\$1,062,489.00	\$1,525,924.00	\$36,104.25
ET5		\$583,323.00	\$263,282.00	\$320,320.00	\$1,866,119.00	\$1,182,918.00	\$368,479.00
ET6		\$459,105.00	\$337,236.00	\$1,195,339.00	\$2,241,719.00	\$1,977,110.00	\$455,674.00
ET7		\$317,496.00	\$102,000.00	\$267,431.00	\$1,095,420.00	\$519,043.00	\$194,070.00
ET8		\$805,615.00	\$398,652.00	\$607,561.00	\$2,239,741.00	\$1,344,699.00	\$397,227.00
ET9		\$330,987.00	\$107,415.00	\$724,458.60	\$1,745,975.30	\$1,562,573.00	(\$4,457.90)
ET10		\$1,220,308.66	\$3,458,333.24	\$2,966,951.99	\$5,070,616.33	\$5,864,395.33	\$412,714.03
ET11		\$345,141.00	\$48,614.00	\$431,708.00	\$2,096,378.00	\$1,119,747.00	\$61,080.00
ET12		\$414,230.00	\$59,780.00	\$884,372.00	\$5,131,918.14	\$1,132,890.00	\$146,521.46
ET13		\$295,134.00	\$120,642.22	\$909,792.44	\$1,736,108.00	\$1,687,139.00	\$0.00
ET14		\$201,422.00	\$69,340.00	\$361,858.00	\$1,422,749.93	\$1,054,279.00	\$0.00
ET15		\$501,256.99	\$46,803.50	\$1,378,169.56	\$1,649,387.96	\$2,366,890.84	\$162,278.08
ET16		\$73,409.00	\$42,900.00	\$103,508.00	\$182,125.00	\$188,140.00	\$24,521.00
ET17		\$158,236.04	\$7,380.49	\$612,004.95	\$418,843.31	\$592,808.26	\$153,985.77
ET18		\$427,072.00	\$76,838.00	\$986,167.43	\$3,693,501.08	\$1,252,012.36	\$660,666.21
ET19		\$1,525,712.00	\$153,624.82	\$1,602,259.88	\$1,188,618.00	\$1,304,762.00	\$400,690.00
ET20		\$215,298.00	\$104,231.00	\$831,192.00	\$1,214,359.00	\$927,844.00	\$207,915.00
SO1	Squadron Operations	\$699,500.25	\$100,409.00	\$560,293.21	\$699,158.00	\$615,350.54	\$138,943.50
SO2		\$106,572.00	\$48,300.00	\$432,919.00	\$685,800.00	\$783,630.00	\$192,963.00
SO3		\$146,922.00	\$673,490.00	\$783,408.00	\$1,581,607.00	\$1,900,261.98	\$266,394.00
SO4		\$1,498,522.16	\$27,677.00	\$2,180,082.16	\$5,361,983.00	\$3,494,015.86	\$144,177.37
SO5		\$919,758.40	\$226,787.26	\$3,203,787.72	\$5,577,438.32	\$3,962,670.24	\$447,876.16
SO6		\$1,025,845.00	\$278,805.00	\$677,481.00	\$3,070,529.00	\$1,031,235.00	\$143,129.00
SO7		\$465,000.00	\$1,175,000.00	\$1,364,463.16	\$2,206,000.00	\$1,675,775.00	\$143,200.00
SO8		\$436,519.00	\$605,376.50	\$1,381,024.00	\$1,430,390.00	\$1,262,929.00	\$727,671.00
SO9		\$346,286.00	\$45,299.00	\$611,929.00	\$1,516,355.00	\$913,890.00	\$61,946.00
SO10		\$85,313.92	\$365,250.46	\$639,021.38	\$1,534,882.33	\$647,181.23	\$72,244.37
SO11		\$309,017.76	\$345,110.00	\$599,087.00	\$2,218,514.88	\$729,474.27	\$380,551.32
SO12		\$205,000.00	\$222,913.00	\$375,357.00	\$1,486,000.00	\$841,874.00	\$165,858.00
SO13		\$386,000.00	\$220,665.00	\$3,056,173.69	\$4,027,249.56	\$4,566,580.00	\$0.00
SO14		\$220,400.00	\$706,016.00	\$854,551.00	\$1,215,215.00	\$1,198,736.00	\$235,837.00
SO15		\$231,500.00	\$535,000.00	\$479,000.00	\$1,429,000.00	\$776,172.00	\$231,196.00

Unit Costs (\$/SM) Standardized by Location and Construction Date							
ID	Project Type	Total Unit Cost	General Requirements	Demolition	Finishes	Foundations (included Pavements)	Communications
D1	Dormitory	\$4,415.33	\$376.88	\$0.00	\$661.23	\$301.50	\$36.32
D2		\$4,392.68	\$309.83	\$0.00	\$719.21	\$297.98	\$36.26
D3		\$2,948.11	\$259.00	\$247.73	\$254.10	\$337.79	\$87.07
D4		\$2,915.78	\$304.32	\$0.00	\$573.04	\$397.27	\$36.34
D5		\$3,426.44	\$231.21	\$6.28	\$470.90	\$594.47	\$195.57
D6		\$3,335.26	\$438.07	\$11.25	\$335.82	\$372.98	\$96.31
D7		\$2,864.24	\$389.05	\$24.32	\$253.32	\$430.53	\$107.13
D8		\$3,104.38	\$310.59	\$11.16	\$602.24	\$287.43	\$167.18
ET1	Education & Training	\$3,510.91	\$635.90	\$88.52	\$278.05	\$379.52	\$64.26
ET2		\$4,467.04	\$808.91	\$58.70	\$759.04	\$485.54	\$159.53
ET3		\$4,034.43	\$612.68	\$34.19	\$739.58	\$461.43	\$87.90
ET4		\$3,123.75	\$421.28	\$31.71	\$701.23	\$208.54	\$145.95
ET5		\$3,237.45	\$273.88	\$170.00	\$452.84	\$363.76	\$45.92
ET6		\$1,996.88	\$255.71	\$0.00	\$376.66	\$240.50	\$99.95
ET7		\$3,526.61	\$526.04	\$33.53	\$654.03	\$382.50	\$129.54
ET8		\$5,502.78	\$529.89	\$169.35	\$889.13	\$656.30	\$431.12
ET9		\$4,354.23	\$511.07	\$69.91	\$682.53	\$625.30	\$319.30
ET10		\$4,586.31	\$245.67	\$14.12	\$474.59	\$519.45	\$213.50
ET11		\$3,793.76	\$395.09	\$116.52	\$673.79	\$371.82	\$26.40
ET12		\$1,771.47	\$148.57	\$12.40	\$356.66	\$203.01	\$9.25
ET13		\$4,136.60	\$186.00	\$37.12	\$644.66	\$585.85	\$314.12
ET14		\$2,393.83	\$155.94	\$5.94	\$371.48	\$378.58	\$250.10
ET15		\$4,660.70	\$227.25	\$53.31	\$612.48	\$410.97	\$383.21
ET16		\$1,538.95	\$124.62	\$25.07	\$242.45	\$249.33	\$58.37
ET17		\$3,927.53	\$316.79	\$51.17	\$889.99	\$276.18	\$252.85
ET18		\$3,470.79	\$33.05	\$22.42	\$624.76	\$711.29	\$147.46
ET19		\$1,466.70	\$93.46	\$7.08	\$131.11	\$289.28	\$158.77
ET20		\$4,902.37	\$488.94	\$0.00	\$461.45	\$368.71	\$492.59
SO1	Squadron Operations	\$1,957.54	\$341.16	\$56.81	\$87.38	\$82.99	\$78.55
SO2		\$4,950.02	\$544.35	\$86.54	\$810.40	\$418.30	\$601.95
SO3		\$1,962.22	\$198.38	\$136.86	\$709.36	\$95.38	\$20.82
SO4		\$4,542.01	\$555.54	\$62.45	\$394.13	\$472.69	\$603.65
SO5		\$3,221.76	\$209.93	\$26.19	\$341.62	\$522.45	\$289.97
SO6		\$3,875.16	\$343.09	\$0.00	\$613.78	\$653.42	\$109.93
SO7		\$2,913.62	\$567.61	\$2.38	\$449.31	\$194.06	\$26.48
SO8		\$2,562.36	\$291.75	\$78.84	\$232.40	\$425.26	\$111.34
SO9		\$4,860.49	\$989.33	\$172.27	\$718.13	\$445.66	\$160.44
SO10		\$5,292.56	\$515.92	\$19.80	\$693.28	\$596.82	\$502.19
SO11		\$2,073.80	\$393.20	\$4.27	\$336.94	\$228.93	\$14.77
SO12		\$1,431.68	\$181.84	\$2.21	\$95.20	\$277.14	\$60.20
SO13		\$5,219.72	\$604.17	\$31.07	\$349.34	\$376.27	\$1,232.08
SO14		\$5,025.39	\$601.11	\$271.81	\$700.33	\$582.47	\$76.96
SO15		\$2,789.67	\$69.10	\$37.93	\$691.24	\$253.88	\$251.80

Unit Costs (\$/SM) (Continued)							
ID	Project Type	Earthwork	Furnishings	Electrical	Structural	Mechanical	Specialties
D1	Dormitory	\$319.23	\$171.73	\$697.94	\$625.60	\$1,224.89	\$0.00
D2		\$302.32	\$175.46	\$765.16	\$679.46	\$1,099.19	\$7.81
D3		\$117.37	\$4.28	\$140.09	\$1,125.14	\$332.11	\$43.43
D4		\$43.10	\$35.09	\$221.08	\$736.77	\$543.93	\$24.84
D5		\$167.60	\$50.86	\$252.43	\$614.62	\$737.11	\$105.39
D6		\$117.57	\$9.38	\$390.38	\$757.88	\$761.24	\$44.38
D7		\$198.69	\$13.30	\$361.14	\$458.44	\$563.86	\$64.45
D8		\$31.15	\$16.48	\$235.63	\$779.18	\$554.32	\$109.01
ET1	Education & Training	\$201.59	\$321.50	\$170.54	\$440.72	\$874.15	\$56.15
ET2		\$355.97	\$334.24	\$440.85	\$431.68	\$616.88	\$15.70
ET3		\$212.45	\$206.70	\$423.41	\$783.26	\$434.59	\$38.24
ET4		\$88.65	\$224.03	\$61.10	\$502.50	\$721.68	\$17.08
ET5		\$245.71	\$110.90	\$134.92	\$786.04	\$498.27	\$155.21
ET6		\$70.53	\$51.81	\$183.63	\$344.38	\$303.73	\$70.00
ET7		\$229.14	\$73.61	\$193.00	\$790.56	\$374.59	\$140.06
ET8		\$393.11	\$194.53	\$296.47	\$1,092.90	\$656.16	\$193.83
ET9		\$159.02	\$51.61	\$348.06	\$838.84	\$750.73	(\$2.14)
ET10		\$200.39	\$567.91	\$487.22	\$832.67	\$963.02	\$67.77
ET11		\$185.93	\$26.19	\$232.56	\$1,129.34	\$603.22	\$32.90
ET12		\$55.53	\$8.01	\$118.56	\$687.97	\$151.87	\$19.64
ET13		\$147.22	\$60.18	\$453.83	\$866.02	\$841.59	\$0.00
ET14		\$79.79	\$27.47	\$143.34	\$563.58	\$417.62	\$0.00
ET15		\$244.15	\$22.80	\$671.27	\$803.37	\$1,152.85	\$79.04
ET16		\$100.22	\$58.57	\$141.32	\$248.65	\$256.86	\$33.48
ET17		\$174.30	\$8.13	\$674.14	\$461.37	\$652.99	\$169.62
ET18		\$116.26	\$20.92	\$268.47	\$1,005.48	\$340.84	\$179.85
ET19		\$194.43	\$19.58	\$204.19	\$151.47	\$166.27	\$51.06
ET20		\$190.07	\$92.02	\$733.81	\$1,072.08	\$819.14	\$183.56
SO1	Squadron Operations	\$325.84	\$46.77	\$261.00	\$325.68	\$286.64	\$64.72
SO2		\$117.86	\$53.42	\$478.77	\$758.43	\$866.62	\$213.40
SO3		\$22.00	\$100.85	\$117.31	\$236.83	\$284.54	\$39.89
SO4		\$289.36	\$5.34	\$420.96	\$1,035.37	\$674.68	\$27.84
SO5		\$117.49	\$28.97	\$409.26	\$712.47	\$506.20	\$57.21
SO6		\$355.01	\$96.48	\$234.45	\$1,062.60	\$356.87	\$49.53
SO7		\$110.72	\$279.78	\$324.89	\$525.27	\$399.02	\$34.10
SO8		\$106.28	\$147.39	\$336.23	\$348.25	\$307.47	\$177.16
SO9		\$235.23	\$30.77	\$415.69	\$1,030.07	\$620.81	\$42.08
SO10		\$75.64	\$323.82	\$566.53	\$1,360.76	\$573.76	\$64.05
SO11		\$73.90	\$82.53	\$143.27	\$530.54	\$174.45	\$91.01
SO12		\$50.68	\$55.11	\$92.80	\$367.37	\$208.13	\$41.00
SO13		\$82.73	\$47.29	\$654.99	\$863.10	\$978.69	\$0.00
SO14		\$138.92	\$445.00	\$538.62	\$765.95	\$755.57	\$148.65
SO15		\$93.42	\$215.89	\$193.29	\$576.64	\$313.20	\$93.29

Cost Element Data Characteristics and Distribution Selection

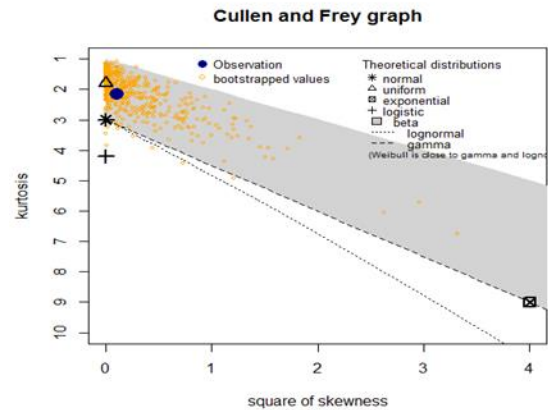
Education & Training Cost Distribution Fitting

Education & Training

General Requirements

summary statistics

min: 33.05 max: 808.91
median: 355.94
mean: 358.9528
estimated sd: 220.275
estimated skewness: 0.3187382
estimated kurtosis: 2.156634

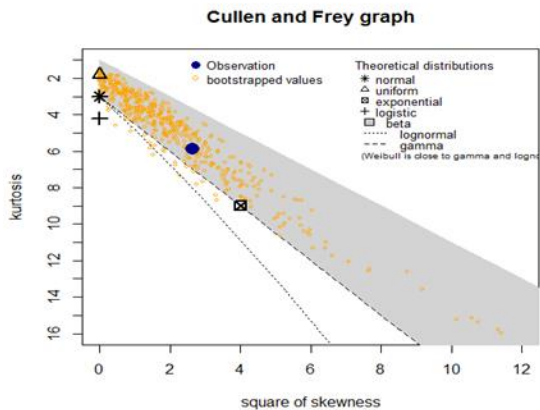


Education & Training

Demolition

summary statistics

min: 0 max: 169.35
median: 33.86
mean: 46.17
estimated sd: 43.22434
estimated skewness: 1.625792
estimated kurtosis: 5.889164

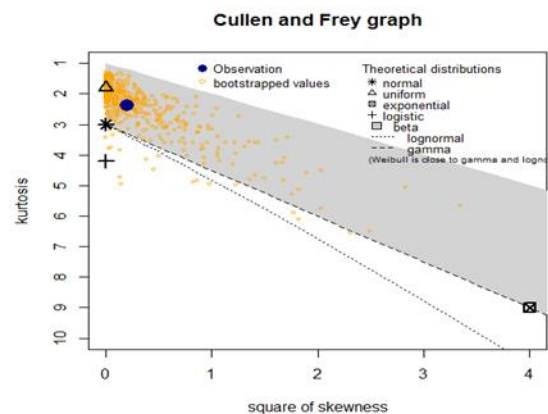


Education & Training

Finished

summary statistics

min: 131.11 max: 889.99
median: 634.71
mean: 565.945
estimated sd: 219.2888
estimated skewness: -0.4477698
estimated kurtosis: 2.364128

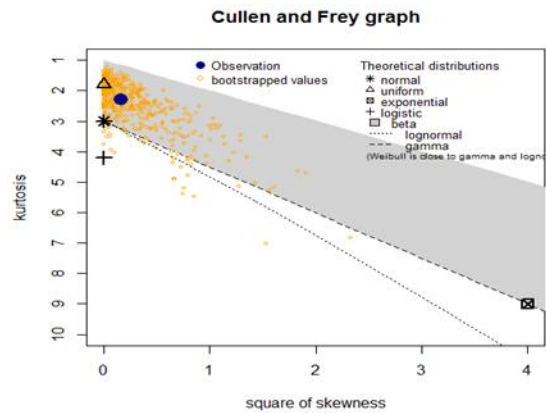


Education & Training

Foundations

summary statistics

min: 203.01 max: 711.29
median: 381.01
mean: 420.2
estimated sd: 152.3806
estimated skewness: 0.4102494
estimated kurtosis: 2.303591

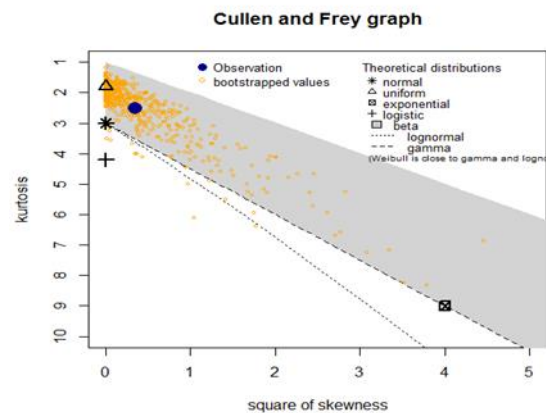


Education & Training

Communications

summary statistics

min: 9.25 max: 492.59
median: 159.15
mean: 202.4567
estimated sd: 140.7504
estimated skewness: 0.5887956
estimated kurtosis: 2.509553

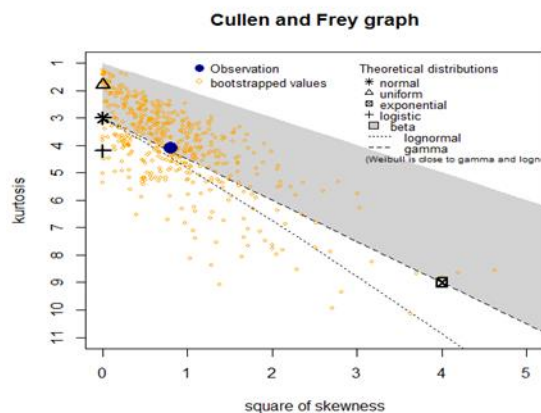


Education & Training

Earthwork

summary statistics

min: 55.53 max: 393.11
median: 188
mean: 184.9011
estimated sd: 87.65341
estimated skewness: 0.8977656
estimated kurtosis: 4.097249



Education & Training

Furnishings

summary statistics

min: 8.01 max: 567.91

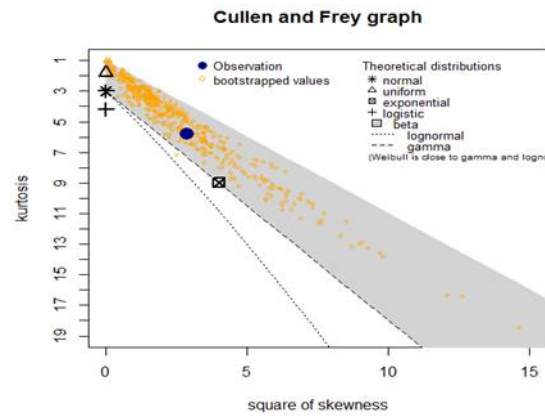
median: 59.375

mean: 128.7778

estimated sd: 152.6941

estimated skewness: 1.699039

estimated kurtosis: 5.805655



Education & Training

Electric

summary statistics

min: 61.1 max: 733.81

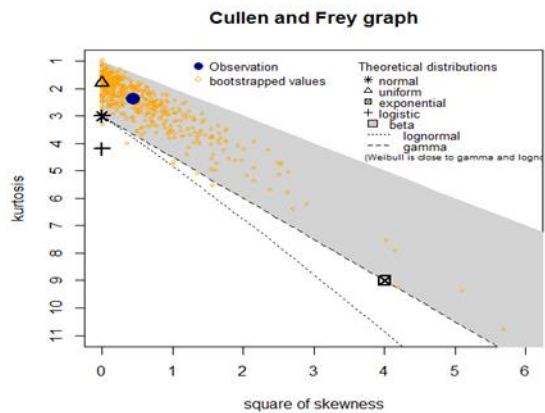
median: 282.47

mean: 336.7856

estimated sd: 205.8566

estimated skewness: 0.6654147

estimated kurtosis: 2.362561



Education & Training

Structural

summary statistics

min: 151.47 max: 1129.34

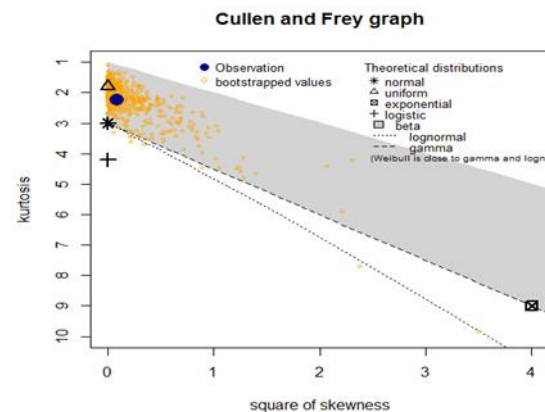
median: 786.91

mean: 705.6922

estimated sd: 288.8792

estimated skewness: -0.3018995

estimated kurtosis: 2.233272



Education & Training

Mechanical

summary statistics

min: 151.87 max: 1152.85

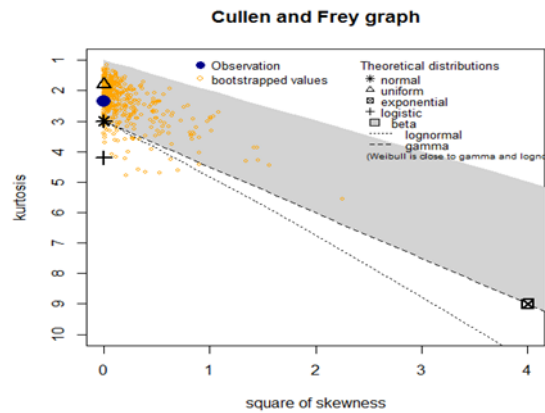
median: 634.935

mean: 599.725

estimated sd: 281.5961

estimated skewness: 0.05118367

estimated kurtosis: 2.3396



Education & Training

Specialties

summary statistics

min: -2.14 max: 193.83

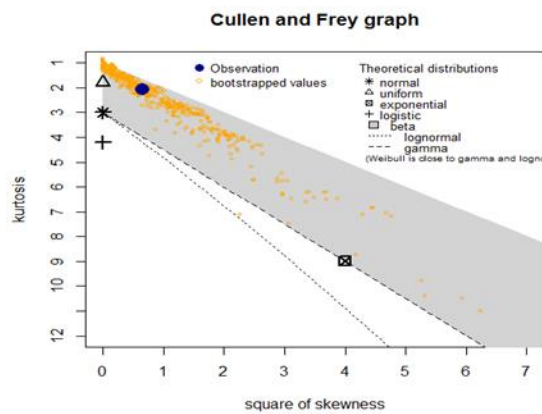
median: 44.65

mean: 70.88

estimated sd: 69.77306

estimated skewness: 0.8114085

estimated kurtosis: 2.066707



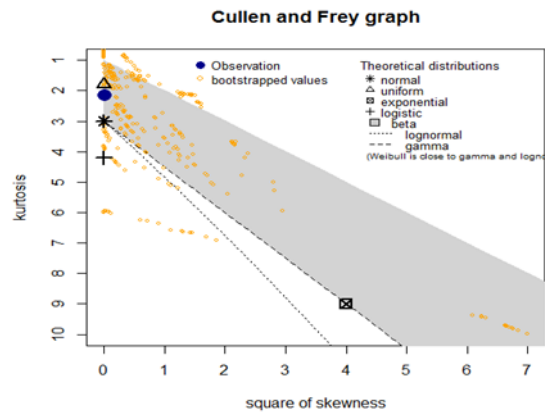
Dormitory Cost Distribution Fitting

Dormitories

General Requirements

summary statistics

min: 231.21 max: 389.05
 median: 309.83
 mean: 311.5543
 estimated sd: 57.0766
 estimated skewness: 0.1003973
 estimated kurtosis: 2.154556

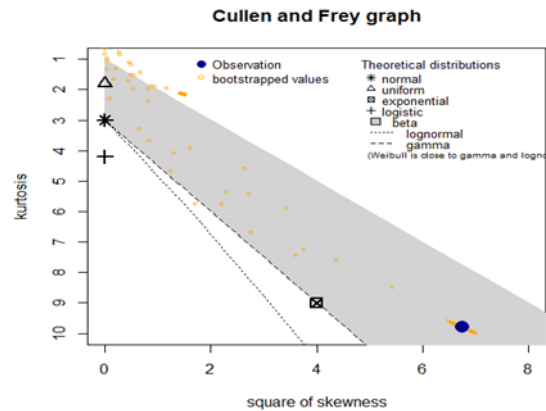


Dormitories

Demolition

summary statistics

min: 0 max: 247.73
 median: 6.28
 mean: 41.35571
 estimated sd: 91.42714
 estimated skewness: 2.595725
 estimated kurtosis: 9.789977

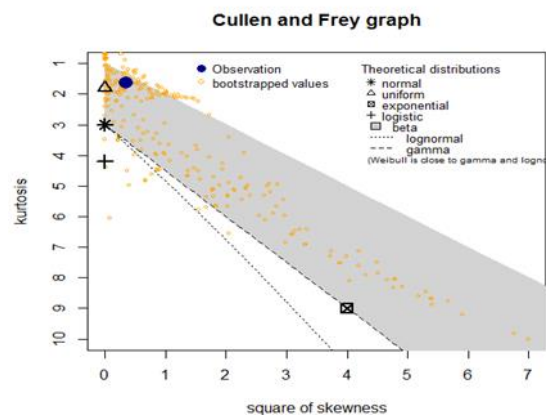


Dormitories

Finished

summary statistics

min: 253.32 max: 719.21
 median: 573.04
 mean: 504.8629
 estimated sd: 187.8985
 estimated skewness: -0.5913273
 estimated kurtosis: 1.63557



Dormitories

Foundations

summary statistics

min: 287.43 max: 594.47

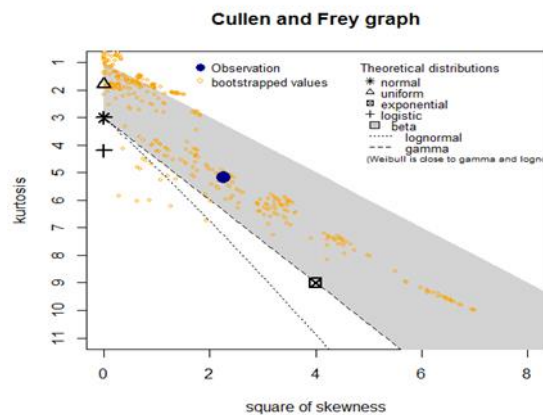
median: 337.79

mean: 378.1386

estimated sd: 109.594

estimated skewness: 1.506329

estimated kurtosis: 5.182505



Dormitories

Communications

summary statistics

min: 36.26 max: 195.57

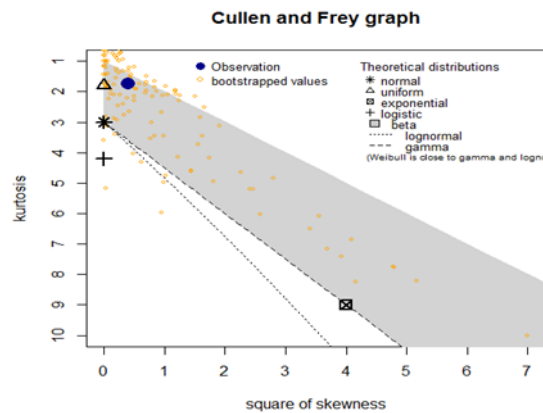
median: 87.07

mean: 95.12429

estimated sd: 65.66191

estimated skewness: 0.6414909

estimated kurtosis: 1.734263



Dormitories

Earthwork

summary statistics

min: 31.15 max: 319.23

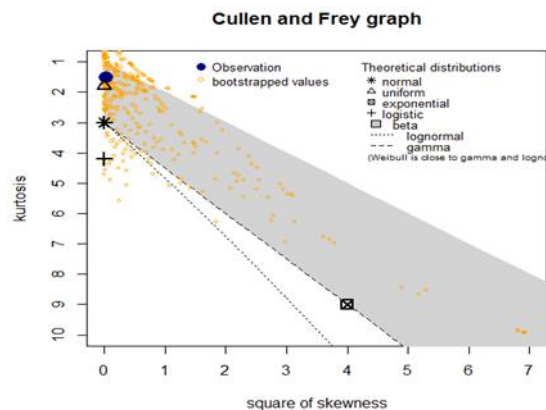
median: 167.6

mean: 168.4943

estimated sd: 114.5601

estimated skewness: 0.1789532

estimated kurtosis: 1.522481



Dormitories

Furnishings

summary statistics

min: 4.28 max: 175.46

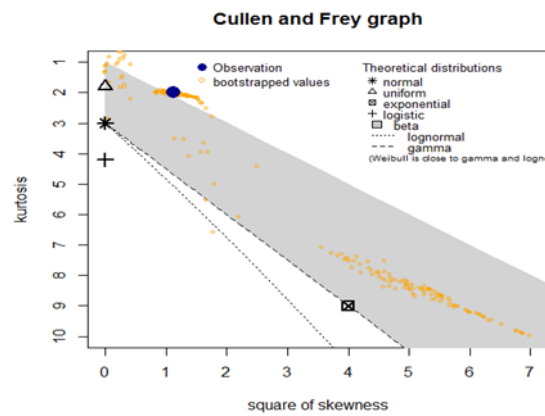
median: 35.09

mean: 66.74286

estimated sd: 74.58774

estimated skewness: 1.058897

estimated kurtosis: 2.003004



Dormitories

Electric

summary statistics

min: 140.09 max: 765.16

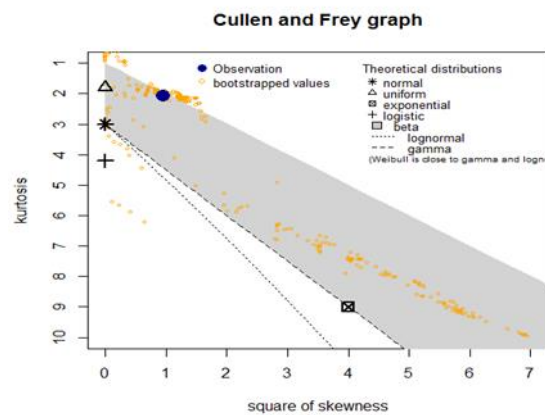
median: 252.43

mean: 381.9243

estimated sd: 248.2247

estimated skewness: 0.9798782

estimated kurtosis: 2.071009



Dormitories

Structural

summary statistics

min: 458.44 max: 1125.14

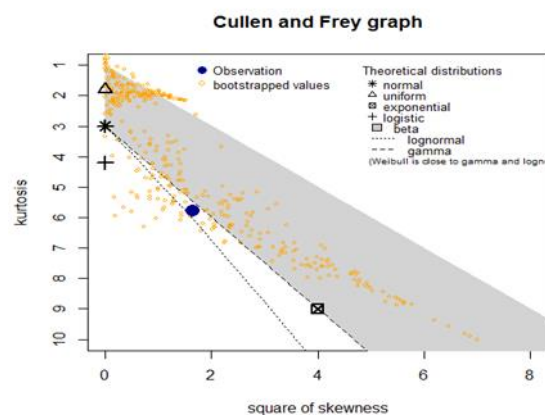
median: 679.46

mean: 717.03

estimated sd: 207.3377

estimated skewness: 1.283707

estimated kurtosis: 5.783758



Dormitories

Mechanical

summary statistics

min: 332.11 max: 1224.89

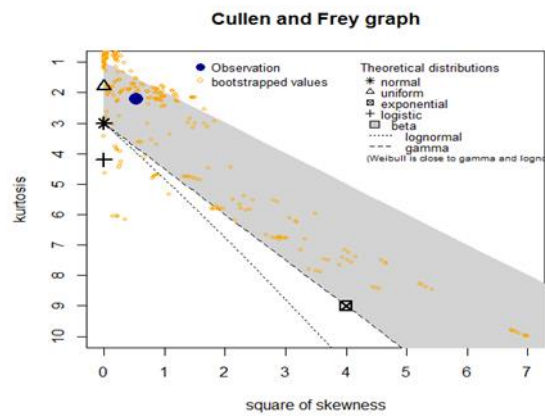
median: 563.86

mean: 722.2014

estimated sd: 324.6143

estimated skewness: 0.7290753

estimated kurtosis: 2.208028



Dormitories

Specialties

summary statistics

min: 0 max: 109.01

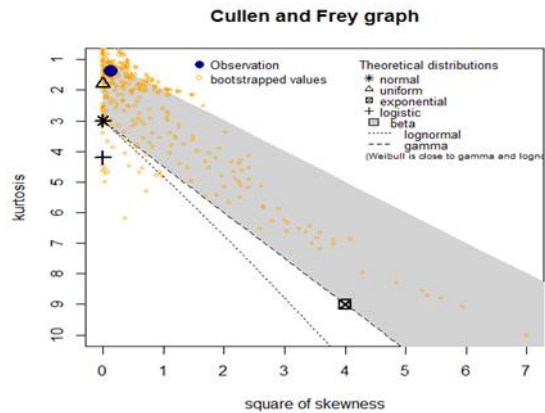
median: 43.43

mean: 50.70429

estimated sd: 44.18097

estimated skewness: 0.371712

estimated kurtosis: 1.394583



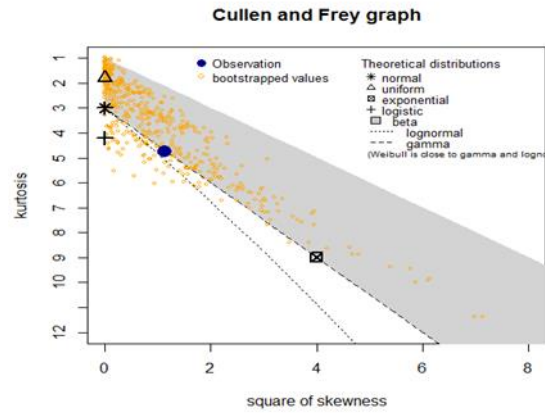
Squadron Operations Cost Fitting

Squadron Operations

General Requirements

summary statistics

min: 69.1 max: 989.33
median: 343.09
mean: 402.6692
estimated sd: 241.2572
estimated skewness: 1.067544
estimated kurtosis: 4.736978

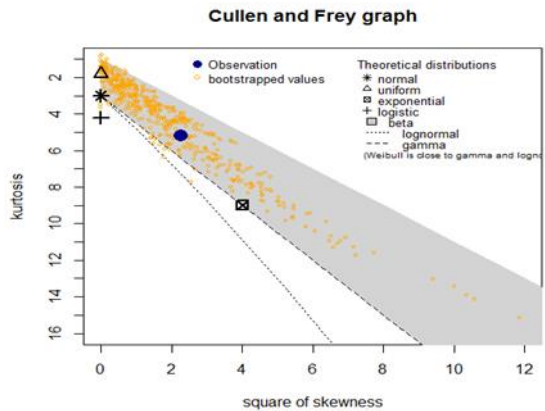


Squadron Operations

Demolition

summary statistics

min: 0 max: 271.81
median: 56.81
mean: 73.53692
estimated sd: 79.24672
estimated skewness: 1.505535
estimated kurtosis: 5.190027

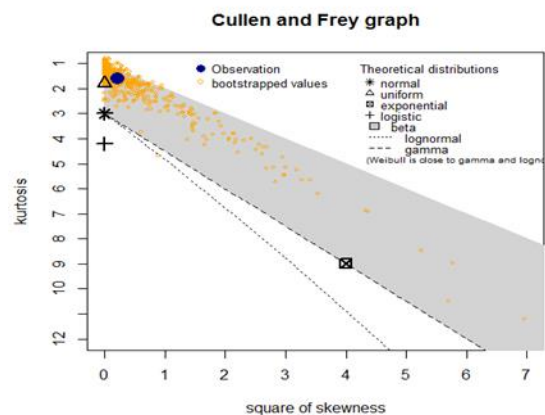


Squadron Operations

Finished

summary statistics

min: 87.38 max: 810.4
median: 613.78
mean: 494.1685
estimated sd: 255.4303
estimated skewness: -0.4630197
estimated kurtosis: 1.612724

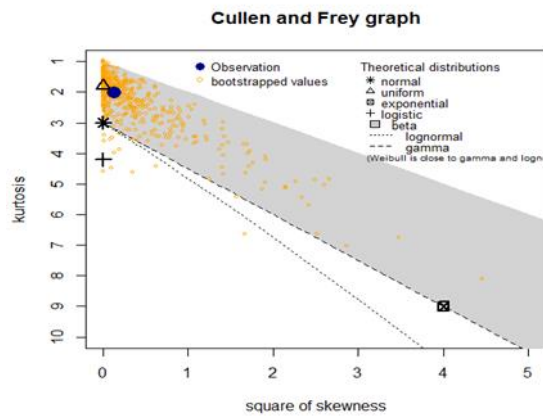


Squadron Operations

Foundations

summary statistics

min: 82.99 max: 653.42
median: 425.26
mean: 388.8762
estimated sd: 186.4094
estimated skewness: -0.3627713
estimated kurtosis: 2.0268

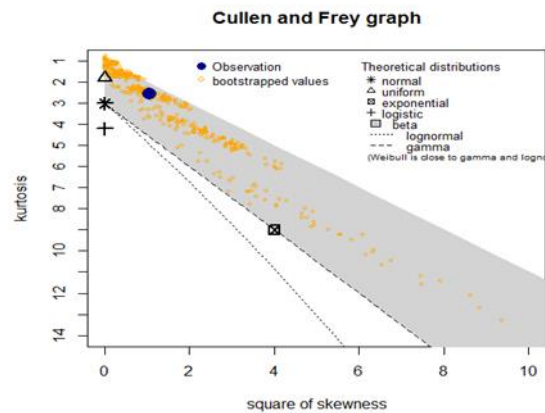


Squadron Operations

Communications

summary statistics

min: 14.77 max: 603.65
median: 111.34
mean: 221.7362
estimated sd: 214.833
estimated skewness: 1.022463
estimated kurtosis: 2.549006

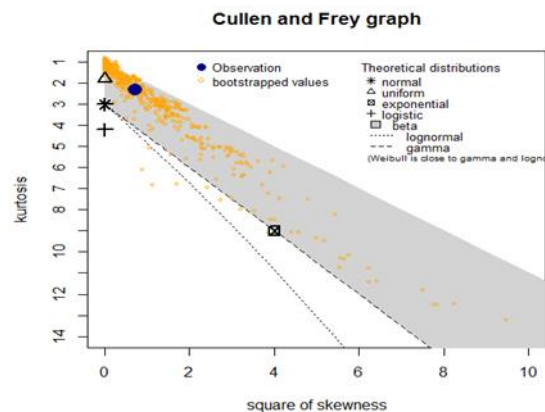


Squadron Operations

Earthwork

summary statistics

min: 22 max: 355.01
median: 117.49
mean: 153.9715
estimated sd: 109.6675
estimated skewness: 0.8509338
estimated kurtosis: 2.317123

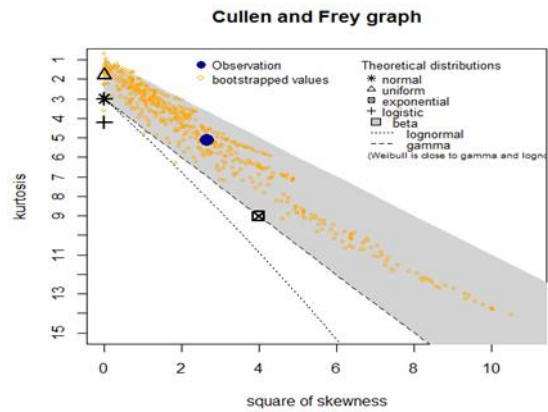


Squadron Operations

Furnishings

summary statistics

min: 5.34 max: 445
median: 82.53
mean: 125.5646
estimated sd: 129.8832
estimated skewness: 1.632063
estimated kurtosis: 5.126521

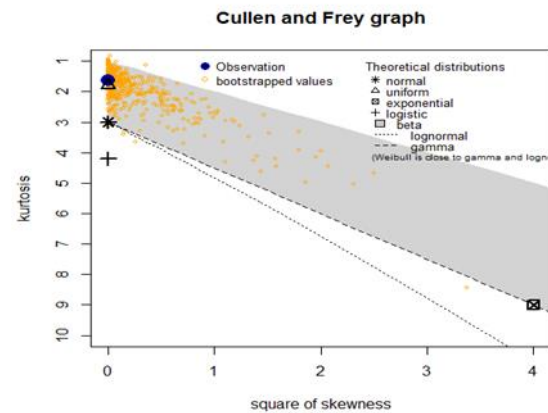


Squadron Operations

Electric

summary statistics

min: 92.8 max: 566.53
median: 336.23
mean: 323.7062
estimated sd: 161.2382
estimated skewness: 0.003404834
estimated kurtosis: 1.620349

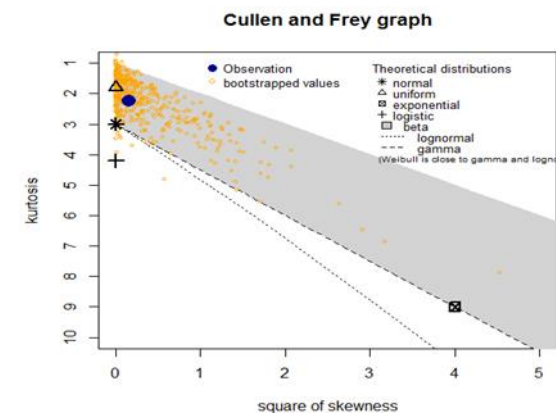


Squadron Operations

Structural

summary statistics

min: 236.83 max: 1360.76
median: 712.47
mean: 700.8431
estimated sd: 345.2485
estimated skewness: 0.4016622
estimated kurtosis: 2.237809



Squadron Operations

Mechanical

summary statistics

min: 174.45 max: 866.62

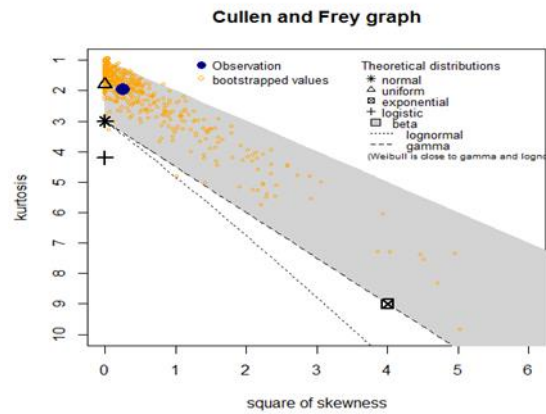
median: 356.87

mean: 456.0723

estimated sd: 223.7545

estimated skewness: 0.510536

estimated kurtosis: 1.956901



Squadron Operations

Specialties

summary statistics

min: 27.84 max: 213.4

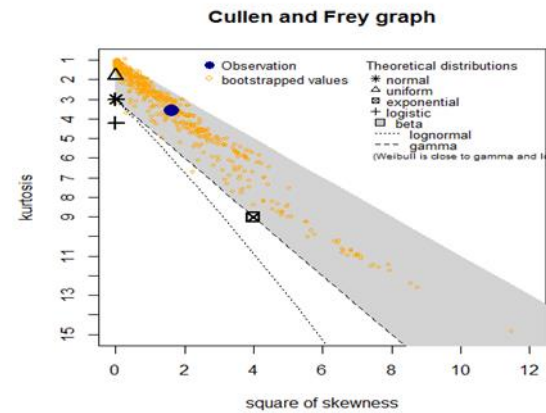
median: 64.05

mean: 85.37154

estimated sd: 58.52014

estimated skewness: 1.270841

estimated kurtosis: 3.551767



Final Cost Element Generalized Beta Distribution Parameters

Facility Type	Parameter	General Requirements	Demolition	Finishes	Foundations	Communications	Earthwork	Furnishings	Electrical	Structural	Mechanical	Specialties	Total Location	Shift
Dormitory	Alpha	1.6510	3.2439	0.4800	1.0000	0.2250	0.8398	0.4500	0.9000	8.4500	1.1000	0.8120	0.8120	
	Beta	1.5490	54.4690	0.5900	3.9900	0.7190	0.9411	0.7000	1.6500	16.6000	2.1000	0.8540	0.8540	
	Location													
	Shift	231.21	-	253.32	287.43	36.26	31.15	4.28	140.09	458.44	332.11	-	1,774.29	
	Scale	157.84	247.73	465.89	307.04	159.31	288.08	171.18	625.07	666.70	892.78	109.01		
Education & Training	Alpha	1.6356	1.3934	1.5031	1.1079	1.3066	1.7807	0.5822	1.2156	1.7597	1.4010	0.6120	0.6120	
	Beta	2.3779	4.2401	0.9878	1.5752	2.0393	2.9530	2.6876	1.6954	1.2813	1.9100	0.9870	0.9870	
	Location													
	Shift	33.05	-	131.11	203.01	9.25	55.53	8.01	61.10	151.47	151.87	(2.14)	802.26	
	Scale	775.86	169.35	758.88	508.28	483.34	337.58	559.90	672.71	977.87	1,000.98	195.97		
Squadron Operations	Alpha	2.7698	0.8528	0.9900	1.2340	0.5128	1.1615	1.2065	1.1230	1.4510	1.2188	1.0518	1.0518	
	Beta	5.4599	2.9280	0.8500	1.1578	0.7435	1.7192	3.7525	1.2065	2.2390	1.8808	2.5524	2.5524	
	Location													
	Shift	69.10	-	87.38	82.99	14.77	22.00	5.34	92.80	236.83	174.45	27.84	813.50	
	Scale	920.23	271.81	723.02	570.43	588.88	333.01	439.66	473.73	1,123.93	692.17	185.56		

Cost Element Distribution Kolmogorov-Smirnov GoF Test Results

Kolmogorov-Smirnov Goodness-of-Fit Test			
Facility Type	Facility Type Cost Element	Test Statistic	p-value
Dormitory	General Requirements	0.4369	0.0989
	Demolition	0.2548	0.6659
	Finishes	0.2579	0.6516
	Foundations	0.2764	0.5662
	Communications	0.2268	0.7931
	Earthwork	0.2497	0.6899
	Furnishings	0.2637	0.6246
	Electrical	0.2476	0.6999
	Structural	0.2670	0.6090
Education & Training	Mechanical	0.2404	0.7331
	Specialties	0.1609	0.6817
	General Requirements	0.1058	0.9748
	Demolition	0.1412	0.8175
	Finishes	0.1438	0.8011
	Foundations	0.1357	0.8516
	Communications	0.1068	0.9724
	Earthwork	0.1461	0.7858
	Furnishings	0.1436	0.8021
	Electrical	0.1197	0.9320
	Structural	0.1719	0.6025
	Mechanical	0.1431	0.8051
	Specialties	0.2499	0.6889
Squadron Operations	General Requirements	0.2055	0.5732
	Demolition	0.1569	0.8583
	Finishes	0.2473	0.3459
	Foundations	0.1902	0.6678
	Communications	0.2062	0.5690
	Earthwork	0.2352	0.4056
	Furnishings	0.1822	0.7166
	Electrical	0.1677	0.8016
	Structural	0.2001	0.6063
	Mechanical	0.1987	0.6146
	Specialties	0.2054	0.5735

Cost Element Correlation Matrices by Facility Type

Dormitory Facilities Initial Infeasible Correlation Matrix

	General Requirements	Demolition	Finishes	Foundations	Communications	Earthwork	Furnishings	Electrical	Structural	Mechanical	Specialties
General Requirements	1	-0.037	0.107	-0.321	-0.250	0.357	0.000	0.500	-0.357	0.357	-0.179
Demolition	-0.037	1	-0.778	0.185	0.593	-0.371	-0.889	-0.519	0.185	-0.593	0.630
Finishes	0.107	-0.778	1	-0.714	-0.607	0.286	0.821	0.536	0.179	0.571	-0.500
Foundations	-0.321	0.185	-0.714	1	0.429	0.071	-0.214	-0.179	-0.571	-0.107	0.179
Communications	-0.250	0.593	-0.607	0.429	1	-0.536	-0.500	-0.429	-0.143	-0.321	0.929
Earthwork	0.357	-0.371	0.286	0.071	-0.536	1	0.571	0.821	-0.607	0.821	-0.679
Furnishings	0.000	-0.889	0.821	-0.214	-0.500	0.571	1	0.750	-0.321	0.821	-0.536
Electrical	0.500	-0.519	0.536	-0.179	-0.429	0.821	0.750	1	-0.643	0.929	-0.429
Structural	-0.357	0.185	0.179	-0.571	-0.143	-0.607	-0.321	-0.643	1	-0.643	0.036
Mechanical	0.357	-0.593	0.571	-0.107	-0.321	0.821	0.821	0.929	-0.643	1	-0.429
Specialties	-0.179	0.630	-0.500	0.179	0.929	-0.679	-0.536	-0.429	0.036	-0.429	1

Dormitory Facilities Transformed Nearest Positive Definite Matrix

	General Requirements	Demolition	Finishes	Foundations	Communications	Earthwork	Furnishings	Electrical	Structural	Mechanical	Specialties
General Requirements	1	-0.037	0.107	-0.321	-0.250	0.357	0.000	0.500	-0.357	0.357	-0.179
Demolition	-0.037	1	-0.778	0.185	0.593	-0.371	-0.889	-0.519	0.185	-0.593	0.630
Finishes	0.107	-0.778	1	-0.714	-0.607	0.286	0.821	0.536	0.179	0.571	-0.500
Foundations	-0.321	0.185	-0.714	1	0.429	0.071	-0.214	-0.179	-0.571	-0.107	0.179
Communications	-0.250	0.593	-0.607	0.429	1	-0.536	-0.500	-0.429	-0.143	-0.321	0.929
Earthwork	0.357	-0.371	0.286	0.071	-0.536	1	0.571	0.821	-0.607	0.821	-0.679
Furnishings	0.000	-0.889	0.821	-0.214	-0.500	0.571	1	0.750	-0.321	0.821	-0.536
Electrical	0.500	-0.519	0.536	-0.179	-0.429	0.821	0.750	1	-0.643	0.929	-0.429
Structural	-0.357	0.185	0.179	-0.571	-0.143	-0.607	-0.321	-0.643	1	-0.643	0.036
Mechanical	0.357	-0.593	0.571	-0.107	-0.321	0.821	0.821	0.929	-0.643	1	-0.429
Specialties	-0.179	0.630	-0.500	0.179	0.929	-0.679	-0.536	-0.429	0.036	-0.429	1

**Education & Training Facilities
Correlation Matrix**

	General Requirements	Demolition	Finishes	Foundations	Communications	Earthwork	Furnishings	Electrical	Structural	Mechanical	Specialties
General Requirements	1	0.587	0.558	0.243	0.104	0.639	0.686	0.205	0.073	0.410	0.041
Demolition	0.587	1	0.581	0.389	0.040	0.498	0.205	0.148	0.212	0.377	-0.029
Finishes	0.558	0.581	1	0.352	0.273	0.335	0.214	0.364	0.296	0.212	0.054
Foundations	0.243	0.389	0.352	1	0.441	0.451	0.304	0.432	0.523	0.352	0.112
Communications	0.104	0.040	0.273	0.441	1	0.288	0.071	0.692	0.356	0.569	0.232
Earthwork	0.639	0.498	0.335	0.451	0.288	1	0.451	0.478	0.106	0.362	0.457
Furnishings	0.686	0.205	0.214	0.304	0.071	0.451	1	0.094	0.001	0.492	-0.025
Electrical	0.205	0.148	0.364	0.432	0.692	0.478	0.094	1	0.377	0.569	0.352
Structural	0.073	0.212	0.296	0.523	0.356	0.106	0.001	0.377	1	0.321	0.264
Mechanical	0.410	0.377	0.212	0.352	0.569	0.362	0.492	0.569	0.321	1	0.083
Specialties	0.041	-0.029	0.054	0.112	0.232	0.457	-0.025	0.352	0.264	0.083	1

**Squadron Operations Facilities
Correlation Matrix**

	General Requirements	Demolition	Finishes	Foundations	Communications	Earthwork	Furnishings	Electrical	Structural	Mechanical	Specialties
General Requirements	1	0.440	0.456	0.451	0.291	0.522	-0.159	0.742	0.632	0.692	0.066
Demolition	0.440	1	0.560	-0.110	0.099	0.132	0.044	0.418	-0.121	0.489	0.187
Finishes	0.456	0.560	1	0.264	0.297	0.011	0.192	0.445	0.423	0.637	0.066
Foundations	0.451	-0.110	0.264	1	0.451	0.390	0.132	0.621	0.852	0.621	-0.055
Communications	0.291	0.099	0.297	0.451	1	0.374	-0.308	0.676	0.588	0.731	0.060
Earthwork	0.522	0.132	0.011	0.390	0.374	1	-0.374	0.434	0.451	0.533	0.027
Furnishings	-0.159	0.044	0.192	0.132	-0.308	-0.374	1	0.033	-0.005	-0.093	0.445
Electrical	0.742	0.418	0.445	0.621	0.676	0.434	0.033	1	0.670	0.879	0.297
Structural	0.632	-0.121	0.423	0.852	0.588	0.451	-0.005	0.670	1	0.703	-0.104
Mechanical	0.692	0.489	0.637	0.621	0.731	0.533	-0.093	0.879	0.703	1	0.187
Specialties	0.066	0.187	0.066	-0.055	0.060	0.027	0.445	0.297	-0.104	0.187	1

Comparison Cost Estimates from UFC and AFCESA

Project Details	Project Name	Airmen Training Complex Dormitory #1	Child Development Center	Replace Chapel Center	Acquisition Management Facility	AFNWC Sustainment Center
	Facility Type	Dormitory	Education & Training	Education & Training	Squadron Operations	Squadron Operations
	Location	Lackland AFB, Texas	Whiteman AFB, Missouri	Eielson AFB, Alaska	Hanscom AFB, Massachusetts	Kirtland AFB, New Mexico
	Fiscal Year	2009	2005	2007	2008	2012
	Construction Mid-Point	4/25/2011	1/28/2007	5/19/2008	11/6/2009	11/30/2013
	Scope (Square Meters)	21,543.74	2,450.00	2,994.00	3,690.01	5,310.00
	PA (\$)	\$75,515,000	\$7,600,000	\$14,400,000	\$12,800,000	\$25,000,000
	Actual Cost (\$)	\$54,544,986	\$7,685,912	\$12,998,688	\$12,236,463	\$24,355,245
	Actual Unit Cost (\$/SM)	\$3,335	\$3,237	\$1,997	\$2,914	\$5,220
UFC Estimation	Escalation Factor	1.1066	1.1042	1.0579	1.1071	1.0356
	Area Cost Factor	0.84	1.07	2.30	1.26	0.91
	Contingency %	1.050	1.050	1.050	1.050	1.050
	SIOH %	1.057	1.057	1.057	1.057	1.057
	Size Adj Factor (from UFC 3-730-01)	0.930	1.002	0.968	1.111	0.920
	Additional Adjustment Factor	0.950				
	Unit Cost (\$/SM)	\$2,196	\$2,459	\$3,307	\$2,378	\$3,816
	UFC Estimate (\$)	\$35,202,259	\$6,494,092	\$23,125,622	\$12,314,131	\$18,180,486
	Standard Deviation (\$/SM)	\$452	\$1,044	\$721	\$441	\$689
AFCESA Handbook Estimation	Standard Deviation (\$)	\$7,246,988	\$2,757,412	\$5,043,176	\$2,285,314	\$3,282,065
	Area Cost Factor	0.91	1.08	2.13	1.16	1.01
	Escalation Factor	1.032	0.944	0.971	1.002	1.092
	Contingency %	1.050	1.050	1.050	1.050	1.050
	SIOH %	1.057	1.057	1.057	1.057	1.057
	Size Adj Factor	0.92000	0.98000	0.98000	0.99500	0.92000
	Additional Adjustment Factor	0.950				
	Unit Cost (\$/SM)	\$1,939	\$2,105	\$2,387	\$2,436	\$2,240
	AFCESA Estimate (\$)	\$38,045,360	\$5,719,058	\$16,077,327	\$11,539,115	\$13,393,406
	Standard Deviation (\$/SM)	\$418	\$269	NA	\$548	\$454
	Standard Deviation (\$)	\$8,202,673	\$730,783	NA	\$2,353,696	\$2,460,819

Appendix C: Line Item Key Word Coding

General Requirements				Demolition	Finishes				Foundations
Bond	document	Arbitration	commission	remov	Carpet	tape	Acoust	drs	Found
Notice	pre-F	Adjustment	conference	rmx exist	Paint	trim	clng	shade	Foot
Management	LEED	settle	closeout	Abatement	Tile	prime	acou grid	blinds	Slab
Design	submitt	reimburse	punch	Asbest	VCT	interior rock	acous grid	corner guard	capillary
inspect	permit	engineering	spare parts	Lead	Finish	Gyp	AC Grid	floor mat	Vapor Barrier
insurance	general	time	plist	unforeseen	Counter	GWB	Flooring	weatherstrip	rebar
BIM	submit	project	contract close	rmv exist	Coat	dryw	wood base	hollow metal	reinf
Admin	order	subcontract	temp fac	differing site	millwork	sheetr	terrazzo	fall prot	pier
Records	meeting	dsgn	revise spec	demo	caulk	sheet rock	epoxy	snow guard	SOG
submiss	budget conf	office overhead	schedule		calking	siding	Door	install hang	cason
Test	rev of	warrant	asbuilts		soffit	hardware	Window	pape	anchor bolts
G.A	FOOH	overhead insp	100%		partition	hrdw	Gate	vinyl floor	tie-down anchors
supervis	field office	taxes			wood work	rigid sheet	store front	crystal	S.O.G
AE Service	print	delete			woodwork	fabric	Doo	FIN	methane
A&E	Crane	GC's			wood casework	entrance rough	WNDWS	int. metal	SOMD
review	scaffold	escalation			downspout	form GB	DR HDWR	flash	Fnd
CID	barricade	ARC m			covering	sealant	Glass	joint cover	set forms
CID P	trailer	dumpster			LTG	lightning	translucent	rubber base	strip shor
drawing	Clean-up	backcheck			plaster	weather pro	glaze	embedded item	dmpfng
NTP	Clean	manuals			trim	coping	storefront	lght prot boot	cure & Protect
As-Built	Mobilization	hoist			skin	T&F	DR/WDW	hard lid	
final	Mobil	start-up			glaz	Ceiling	DR & WDW	raised floor	
report	staging	checkout			horn	CLG	wood dr		
survey	Delay	QC Revis			termite	Acoustical	hm dr		
approv	Suspension	training			skylight	stripping	pr bk		

Communications		Pavements		Earthwork		Furnishings		Electrical	
Comm.	CID	Asphalt	course base	culv	trench	Furni	bleachers	Elec	ATS
Comm	panic	Sidewalk	pour	Grad	tree	Systems Fu	cabintry	Light	SD In
Commun	Telcom	side walk	prep surf	Layout	clearing	System Fu	white board	Transf	SD line
UPS	intcom	Curb	surface ap	Exca	site im	Cabinet	projection	Switch	aerial
Voice	sec. sys	Gutter	form and place	Grub	bollard	Fenc	screen	Power	HVU
Data	intercom	Park	crushed	Clear	double box	Locker	sinage	Circuit	gear pb
Control	SS device	Pave	compress j	Backfill	box bridge	desk	chain link	Feeder	trans pnl
wire	added comm	Apron	riprap	Compact	geo tech	sign	cubbies	Panel	breaker
fiber	TV supp	Road	rip rap	Fill	geotech	flag pole	coffee	Security	pole
cable	TV back	Gravel		Soil	geo-tech	seating	access floor	Grounding	corridor swit
speak	TV mount	Pad		irrig	SWPP	tub	playground	Switchboard	primary & sec
tele	additional display	base course		earth	SWP3	vanity	drink	Cathodic	recepts
computer		paving		seeding	sitework	shelv	matts	distribution p	terminate access
mass not		striping		lawn	mulch	appliance	lab. Equip	wiring	dampner circ
AV System		stripe		grass	retaining w	mirror	oven	outlet	amp j
CATV		drive		plant	hydroseed	Kitc	Laundry equip	conduit	light f
audio		taxiway		boring	reseed	vanit	overhead cran	substation	light pro
public add		conc		bore	hardscape	eyewash		kV	lightg
intrusion		saw cut		site prep	restoration	dowel		relay panel	lighted
visual display		HMAC		shoring	environmental protect	bulletin		swtbd	lighting
SCIF Sensor		troop		shore		marker		current	overhead lns
CCTV		spread f		Storm		bike		HZ	overhead trans
alarm		agg		Pond		FF&E		emergency gen	
Direct Digital		PCC		landscap		commodit		generator	
SIPR		lime		Sod		service eq		voltage	
RI/Pullbox		tunnel		erosion		FF & E		pwr lines	
RI - install		shoulder		Turf		pews		load bank	

Structural				Mechanical					Specialties	
Structur	FRP	Roof	floor plan change	Mech	DDC	MEP	wat clst	EMCS	misc change	FOD Measures
Stud	split fac	Deck		HVAC	exhaust	digester	vib. Isolat	VFI	MHS	NTE
wall	metal b	Standing Se		Duct	HRV	valve	shwr		mod	ECALS
struc revis	metal stud	SSMR		air	diff	accesso	Fire		CLIN	vacuum equip
Truss	metal deck	high mast		Diffuser	manhole	split system	Sprinkl		Option	breathing air
Steel	sheet metal	canopy		AHU	Plumbing	shower	F/A		bullet trap	
Column	metal sid	Pre-Engin		Heat	Plumb	sauna	HEF		well	
Beam	str bolt	PEMB		Chill	water	fluid	Foam		baffle	
Mason	PT	PMB		Cool	Sewer	plmb	grease		Nitrogen	
rough carpentry	draft curtain	pre-fab m		Boil	Plum	FCU	hydronic		classified for	
Stone	reb & PT	pre-fab s		Filter	Sanita	cws	VFD		disintegrator	
mezz	Strctl St	pre-fabri		grille	plbg	cwr	A/C		IOC Transition Services	
flash	purlin	P. E. Build		Condens	waste	hws	smoke		EOD	
Brick	cols	grill & diff		Fans	vent	temp contr	hot wtr press wash		FOD Protection	
CMU	pole barn	precast		Refrig	lift station	temp ctrl			system	
Fram	catwalk	pre cast		Louver	toilet	suply&retu	hydrant		blast	
stucc	temporary construct	pcast		coil	drain	geothermal	ppg		observatory	
block		tendon		VAV	bath	ARV	flush out		courts	
col def	Stair	form support		air dist	standp	hydration	hose bib		SCADA	
ice wtr shield	Rail	installstl		boxes	pipe	mop sink	FP line		SAP/SAR	
joist	joint seal	rf hatch		furnace	piping	AC unit	IWS		volleyball	
structu	Insulation	welding		air h	riser	conveyor	FP head		tennis	
casework	EIFS	rough in carp		Elevators	pump	ss line	recovery wheel		racquetball	
ICF	EFIS	SCIF Ent		Elev	brine	force main			Seismic	
Str. St	Moisture	modul		conds	fuel	MAU	FP		aqua aerobics	
Str st	Insul	exp joint		utilit	gas	VFI	FA dev		volley ball	
erect s	E.I.F.S	grating		MAU	tank	rest acc	tridium			

Appendix D: Cost Estimate Comparisons

Project Details	Project Name	Airmen Training Complex Dormitory #1	Child Development Center	Replace Chapel Center	Acquisition Management Facility	AFNWC Sustainment Center
	Facility Type	Dormitory	Education & Training	Education & Training	Squadron Operations	Squadron Operations
	Location	Lackland AFB, Texas	Whiteman AFB, Missouri	Eielson AFB, Alaska	Hanscom AFB, Massachusetts	Kirtland AFB, New Mexico
	Fiscal Year	2009	2005	2007	2008	2012
	Construction Mid-Point	4/25/2011	1/28/2007	5/19/2008	11/6/2009	11/30/2013
	Scope (Square Meters)	21,543.74	2,450.00	2,994.00	3,690.01	5,310.00
	PA (\$)	\$75,515,000	\$7,600,000	\$14,400,000	\$12,800,000	\$25,000,000
	Actual Cost (\$)	\$54,544,986	\$7,685,912	\$12,998,688	\$12,236,463	\$24,355,245
	Actual Unit Cost (\$/SM)	\$3,335	\$3,237	\$1,997	\$2,914	\$5,220
UFC Estimation	Escalation Factor	1.1066	1.1042	1.0579	1.1071	1.0356
	Area Cost Factor	0.84	1.07	2.30	1.26	0.91
	Contingency %	1.050	1.050	1.050	1.050	1.050
	SIOH %	1.057	1.057	1.057	1.057	1.057
	Size Adj Factor (from UFC 3-730-01)	0.930	1.002	0.968	1.111	0.920
	Additional Adjustment Factor	0.950				
	Unit Cost (\$/SM)	\$2,196	\$2,459	\$3,307	\$2,378	\$3,816
	UFC Estimate (\$)	\$35,202,259	\$6,494,092	\$23,125,622	\$12,314,131	\$18,180,486
	Standard Deviation (\$/SM)	\$452	\$1,044	\$721	\$441	\$689
AFCEA Handbook Estimation	Standard Deviation (\$)	\$7,246,988	\$2,757,412	\$5,043,176	\$2,285,314	\$3,282,065
	Area Cost Factor	0.91	1.08	2.13	1.16	1.01
	Escalation Factor	1.032	0.944	0.971	1.002	1.092
	Contingency %	1.050	1.050	1.050	1.050	1.050
	SIOH %	1.057	1.057	1.057	1.057	1.057
	Size Adj Factor	0.92000	0.98000	0.98000	0.99500	0.92000
	Additional Adjustment Factor	0.950				
	Unit Cost (\$/SM)	\$1,939	\$2,105	\$2,387	\$2,436	\$2,240
	AFCEA Estimate (\$)	\$38,045,360	\$5,719,058	\$16,077,327	\$11,539,115	\$13,393,406
	Standard Deviation (\$/SM)	\$418	\$269	NA	\$548	\$454
	Standard Deviation (\$)	\$8,202,673	\$730,783	NA	\$2,353,696	\$2,460,819

Appendix E: Model Code from R

```
1. #' ---
2. #' title: "Monte Carlo Simulation of Air Force Construction Costs"
3. #' author: "Jeffrey D. Buchholtz, Captain, USAF"
4. #' date: 10 February 2016"
5. #' ---
6.
7. #PURPOSE:
8. #The purpose of the code is to develop a Monte Carlo simulation using historical
9. #construction cost data from U.S. Air Force facility projects. The cost data is
10. #broken up into key cost elements and analyzed for the best-fitting distributions
11. #(the generalized beta in this case).
12. #They are also correlated using a Spearman's rank correlation matrix.
13. #The distributions and correlation matrices are then used as inputs in a
14. #correlated multivariate simulation to estimate the overall cost of a particular
15. #facility type.
16.
17. #This effort supported research in pursuit of a Master of Science in
18. #Engineering Management degree at the Air Force Institute of Technology.
19.
20.
21.
22.
23. #R Packages used for functions in the following code
24. library("ggplot2")      #for plotting
25. library("EnvStats")     #for multivariate Monte Carlo simulation
26. library("Matrix")
27. library("matrixcalc")   #for positive/definite checks on correlation matrices
28. library("mc2d")
29. library("fitdistrplus")
30. library("plyr")         #Needed for ggplot in some instances
31.
32. install.packages("rmarkdown")
33. library(rmarkdown)     #Used to print code for reports
34.
35.
36. #-----Helpful Functions-----
37. # getwd() -- prints default directory R looks in for files
38. # attributes(x) -- prints row and column names and class for an output function
39.
40.
41. #Input raw data into variable "A"
42. #Check working directory via 'getwd()'
43. #Modify file path as needed
44. #Original path: ("I:/My Documents/Thesis/Data/DataforAnalysisCSV.csv")
45. A <- read.csv("Thesis/Data/DataforAnalysisCSV.csv", header = TRUE, sep = ",")
46.
47. #Pull out facility type subsets for analysis
48. EdTrng <- subset(A, Project_Type=="Education_Training",)
49. Dorms <- subset(A, Project_Type=="Dormitory",)
50. SqdOps <- subset(A, Project_Type=="Squadron_Operations",)
51. Hangars <- subset(A, Project_Type=="Hangar",)
52. #NOTE: Hangars did not have enough samples for adequate analysis in this study
53.
54.
55. #Initial look at data
56. hist(Dorms[, "Demolition"])
57.
```

```

58. #more complete look using histograms and density functions
59. m <-
  ggplot(EdTrng, aes(x=Earthwork))          #saves data to be plotted in "m"
60. m + geom_histogram(binwidth=50)          #plots histogram with set width
61. m + geom_histogram(aes(y = ..density..),binwidth=50) + geom_density()
62. #plots histogram versus probability density (instead of count) along with curve
63.
64.
65. # compare cost CUONT between facility types
66. m <- ggplot(A, aes(x=Structural))          #get Structural data for plot
67. m <- m + geom_histogram(binwidth = 50)      #get histogram w/ width
68. m + facet_wrap( ~ Project_Type, ncol=2)    #plot by project type in 2 col
69.
70. #compare cost DENSITY between facility types
71. m <- ggplot(A, aes(x=Structural))          #get Structural data for plot
72. m <- m + geom_histogram(binwidth = 50) + aes(y = ..density..) + geom_density()
73. #get histogram w/ width by density with density curve
74. m + facet_wrap( ~ Project_Type, ncol=2) #plot by project type in 2 col
75.
76. #adding color and labels along with density together in one saved plot
77. plot_Structural = ggplot(A, aes(x=Structural, fill=Project_Type)) +
78.   geom_histogram(colour="grey30", binwidth=50) +
79.   aes(y = ..density..) +
80.   geom_density(alpha=.2) +
81.   facet_grid(Project_Type ~ .) +
82.   labs(title="Histograms")
83. plot_Structural
84.
85. #Distribution Fitting
86. SqdOps.Struc15 <- SqdOps[,15]              #pulls out Structural costs from Squad Ops
87. descdist(SqdOps.Struc15)                  # Plots observed data versus common distributions
88. descdist(SqdOps.Struc15, boot = 1000)    # same as above but also plots
89.                                           #potential variation in observed data
90.
91.
92. #Pull out each cost column as a separate variable for analysis
93. EdTrng.GenReq <- EdTrng[,14]
94. EdTrng.Demo <- EdTrng[,15]
95. EdTrng.Finish <- EdTrng[,16]
96. EdTrng.Found <- EdTrng[,17]
97. EdTrng.Comm <- EdTrng[,18]
98. EdTrng.Earth <- EdTrng[,19]
99. EdTrng.Furnish <- EdTrng[,20]
100. EdTrng.Elec <- EdTrng[,21]
101. EdTrng.Struct <- EdTrng[,22]
102. EdTrng.Mech <- EdTrng[,23]
103. EdTrng.Spec <- EdTrng[,24]
104.
105. Dorms.GenReq <- Dorms[,14]
106. Dorms.Demo <- Dorms[,15]
107. Dorms.Finish <- Dorms[,16]
108. Dorms.Found <- Dorms[,17]
109. Dorms.Comm <- Dorms[,18]
110. Dorms.Earth <- Dorms[,19]
111. Dorms.Furnish <- Dorms[,20]
112. Dorms.Elec <- Dorms[,21]
113. Dorms.Struct <- Dorms[,22]
114. Dorms.Mech <- Dorms[,23]
115. Dorms.Spec <- Dorms[,24]
116.

```

```

117. SqdOps.GenReq <- SqdOps[,14]
118. SqdOps.Demo <- SqdOps[,15]
119. SqdOps.Finish <- SqdOps[,16]
120. SqdOps.Found <- SqdOps[,17]
121. SqdOps.Comm <- SqdOps[,18]
122. SqdOps.Earth <- SqdOps[,19]
123. SqdOps.Furnish <- SqdOps[,20]
124. SqdOps.Elec <- SqdOps[,21]
125. SqdOps.Struct <- SqdOps[,22]
126. SqdOps.Mech <- SqdOps[,23]
127. SqdOps.Spec <- SqdOps[,24]
128.
129.
130. #Pull out overall costs as a matrix variable for analysis
131. EdTrng.Costs <- EdTrng[,14:24]
132. Dorms.Costs <- Dorms[,14:24]
133. SqdOps.Costs <- SqdOps[,14:24]
134.
135. #Graph each cost column to identify probable distribution matches.
136. ##Include "boot = x" to display x runs of sample from the data
137. ##with replacement to see the bootstrap variation range on the graph
138. descdist(EdTrng.GenReq, boot = 1000)
139. descdist(EdTrng.Demo, boot = 1000)
140. descdist(EdTrng.Finish, boot = 1000)
141. descdist(EdTrng.Found, boot = 1000)
142. descdist(EdTrng.Comm, boot = 1000)
143. descdist(EdTrng.Earth, boot = 1000)
144. descdist(EdTrng.Furnish, boot = 1000)
145. descdist(EdTrng.Elec, boot = 1000)
146. descdist(EdTrng.Struct, boot = 1000)
147. descdist(EdTrng.Mech, boot = 1000)
148. descdist(EdTrng.Spec, boot = 1000)
149.
150. descdist(Dorms.GenReq, boot = 1000)
151. descdist(Dorms.Demo, boot = 1000)
152. descdist(Dorms.Finish, boot = 1000)
153. descdist(Dorms.Found, boot = 1000)
154. descdist(Dorms.Comm, boot = 1000)
155. descdist(Dorms.Earth, boot = 1000)
156. descdist(Dorms.Furnish, boot = 1000)
157. descdist(Dorms.Elec, boot = 1000)
158. descdist(Dorms.Struct, boot = 1000)
159. descdist(Dorms.Mech, boot = 1000)
160. descdist(Dorms.Spec, boot = 1000)
161.
162. descdist(SqdOps.GenReq, boot = 1000)
163. descdist(SqdOps.Demo, boot = 1000)
164. descdist(SqdOps.Finish, boot = 1000)
165. descdist(SqdOps.Found, boot = 1000)
166. descdist(SqdOps.Comm, boot = 1000)
167. descdist(SqdOps.Earth, boot = 1000)
168. descdist(SqdOps.Furnish, boot = 1000)
169. descdist(SqdOps.Elec, boot = 1000)
170. descdist(SqdOps.Struct, boot = 1000)
171. descdist(SqdOps.Mech, boot = 1000)
172. descdist(SqdOps.Spec, boot = 1000)
173.
174.
175.
176. #K-S Goodness of Fit test (requires "stats" package) to get p-value

```

```

177.
178. ##Input parameters for analysis
179. Distro.Params <- read.csv("Thesis/Data/DistroParams.csv", header = TRUE, sep = ",")
180.
181. ##Save parameters based on facility type
182. EdTrng.Params <- data.matrix(Distro.Params[12:22,], rownames.force = NA)
183. Dorms.Params <- data.matrix(Distro.Params[1:11,], rownames.force = NA)
184. SqdOps.Params <- data.matrix(Distro.Params[23:33,], rownames.force = NA)
185.
186. ##Transform data to standardized beta by shifting and scaling
187. ##NOTE: if there are repeat values (such as 0),
188. ##they must be changed slightly for the KS test (no ties allowed)
189. EdTrng.GenReq.Beta <- (EdTrng.GenReq -
190.   EdTrng.Params[1,"Loc_Shift"]) / EdTrng.Params[1,"Scaler"]
191. EdTrng.Demo.Beta <- (EdTrng.Demo -
192.   EdTrng.Params[2,"Loc_Shift"]) / EdTrng.Params[2,"Scaler"]
193. EdTrng.Finish.Beta <- (EdTrng.Finish -
194.   EdTrng.Params[3,"Loc_Shift"]) / EdTrng.Params[3,"Scaler"]
195. EdTrng.Found.Beta <- (EdTrng.Found -
196.   EdTrng.Params[4,"Loc_Shift"]) / EdTrng.Params[4,"Scaler"]
197. EdTrng.Comm.Beta <- (EdTrng.Comm -
198.   EdTrng.Params[5,"Loc_Shift"]) / EdTrng.Params[5,"Scaler"]
199. EdTrng.Earth.Beta <- (EdTrng.Earth -
200.   EdTrng.Params[6,"Loc_Shift"]) / EdTrng.Params[6,"Scaler"]
201. EdTrng.Furnish.Beta <- (EdTrng.Furnish -
202.   EdTrng.Params[7,"Loc_Shift"]) / EdTrng.Params[7,"Scaler"]
203. EdTrng.Elec.Beta <- (EdTrng.Elec -
204.   EdTrng.Params[8,"Loc_Shift"]) / EdTrng.Params[8,"Scaler"]
205. EdTrng.Struct.Beta <- (EdTrng.Struct -
206.   EdTrng.Params[9,"Loc_Shift"]) / EdTrng.Params[9,"Scaler"]
207. EdTrng.Mech.Beta <- (EdTrng.Mech -
208.   EdTrng.Params[10,"Loc_Shift"]) / EdTrng.Params[10,"Scaler"]
209. EdTrng.Spec.Beta <- (EdTrng.Spec -
210.   EdTrng.Params[11,"Loc_Shift"]) / EdTrng.Params[11,"Scaler"]
211. EdTrng.Spec.Beta[12] <- EdTrng.Spec.Beta[12] + 0.00000001
212.
213. Dorms.GenReq.Beta <- (Dorms.GenReq -
214.   Dorms.Params[1,"Loc_Shift"]) / Dorms.Params[1,"Scaler"]
215. Dorms.Demo.Beta <- (Dorms.Demo -
216.   Dorms.Params[2,"Loc_Shift"]) / Dorms.Params[2,"Scaler"]
217. Dorms.Demo.Beta[2] <- Dorms.Demo.Beta[2] + 0.00000001
218. Dorms.Demo.Beta[4] <- Dorms.Demo.Beta[4] + 0.00000002
219. Dorms.Finish.Beta <- (Dorms.Finish -
220.   Dorms.Params[3,"Loc_Shift"]) / Dorms.Params[3,"Scaler"]
221. Dorms.Found.Beta <- (Dorms.Found -
222.   Dorms.Params[4,"Loc_Shift"]) / Dorms.Params[4,"Scaler"]
223. Dorms.Comm.Beta <- (Dorms.Comm -
224.   Dorms.Params[5,"Loc_Shift"]) / Dorms.Params[5,"Scaler"]
225. Dorms.Earth.Beta <- (Dorms.Earth -
226.   Dorms.Params[6,"Loc_Shift"]) / Dorms.Params[6,"Scaler"]
227. Dorms.Furnish.Beta <- (Dorms.Furnish -
228.   Dorms.Params[7,"Loc_Shift"]) / Dorms.Params[7,"Scaler"]
229. Dorms.Elec.Beta <- (Dorms.Elec -
230.   Dorms.Params[8,"Loc_Shift"]) / Dorms.Params[8,"Scaler"]
231. Dorms.Struct.Beta <- (Dorms.Struct -
232.   Dorms.Params[9,"Loc_Shift"]) / Dorms.Params[9,"Scaler"]
233. Dorms.Mech.Beta <- (Dorms.Mech -
234.   Dorms.Params[10,"Loc_Shift"]) / Dorms.Params[10,"Scaler"]
235. Dorms.Spec.Beta <- (Dorms.Spec -
236.   Dorms.Params[11,"Loc_Shift"]) / Dorms.Params[11,"Scaler"]

```

```

237.
238. SqdOps.GenReq.Beta <- (SqdOps.GenReq -
239.      SqdOps.Params[1,"Loc_Shift"]) / SqdOps.Params[1,"Scaler"]
240. SqdOps.Demo.Beta <- (SqdOps.Demo -
241.      SqdOps.Params[2,"Loc_Shift"]) / SqdOps.Params[2,"Scaler"]
242. SqdOps.Finish.Beta <- (SqdOps.Finish -
243.      SqdOps.Params[3,"Loc_Shift"]) / SqdOps.Params[3,"Scaler"]
244. SqdOps.Found.Beta <- (SqdOps.Found -
245.      SqdOps.Params[4,"Loc_Shift"]) / SqdOps.Params[4,"Scaler"]
246. SqdOps.Comm.Beta <- (SqdOps.Comm -
247.      SqdOps.Params[5,"Loc_Shift"]) / SqdOps.Params[5,"Scaler"]
248. SqdOps.Earth.Beta <- (SqdOps.Earth -
249.      SqdOps.Params[6,"Loc_Shift"]) / SqdOps.Params[6,"Scaler"]
250. SqdOps.Furnish.Beta <- (SqdOps.Furnish -
251.      SqdOps.Params[7,"Loc_Shift"]) / SqdOps.Params[7,"Scaler"]
252. SqdOps.Elec.Beta <- (SqdOps.Elec -
253.      SqdOps.Params[8,"Loc_Shift"]) / SqdOps.Params[8,"Scaler"]
254. SqdOps.Struct.Beta <- (SqdOps.Struct -
255.      SqdOps.Params[9,"Loc_Shift"]) / SqdOps.Params[9,"Scaler"]
256. SqdOps.Mech.Beta <- (SqdOps.Mech -
257.      SqdOps.Params[10,"Loc_Shift"]) / SqdOps.Params[10,"Scaler"]
258. SqdOps.Spec.Beta <- (SqdOps.Spec -
259.      SqdOps.Params[11,"Loc_Shift"]) / SqdOps.Params[11,"Scaler"]
260.
261.
262. ##Perform Kolmogorov-Smirnov Goodness of Fit Test
263. #for each distribution and save results
264. EdTrng.GenReq.KS <- ks.test(EdTrng.GenReq.Beta, "pbeta",
265.      EdTrng.Params[1,"Alpha"],
266.      EdTrng.Params[1,"Beta"])
267. EdTrng.Demo.KS <- ks.test(EdTrng.Demo.Beta, "pbeta",
268.      EdTrng.Params[2,"Alpha"],
269.      EdTrng.Params[2,"Beta"])
270. EdTrng.Finish.KS <- ks.test(EdTrng.Finish.Beta, "pbeta",
271.      EdTrng.Params[3,"Alpha"],
272.      EdTrng.Params[3,"Beta"])
273. EdTrng.Found.KS <- ks.test(EdTrng.Found.Beta, "pbeta",
274.      EdTrng.Params[4,"Alpha"],
275.      EdTrng.Params[4,"Beta"])
276. EdTrng.Comm.KS <- ks.test(EdTrng.Comm.Beta, "pbeta",
277.      EdTrng.Params[5,"Alpha"],
278.      EdTrng.Params[5,"Beta"])
279. EdTrng.Earth.KS <- ks.test(EdTrng.Earth.Beta, "pbeta",
280.      EdTrng.Params[6,"Alpha"],
281.      EdTrng.Params[6,"Beta"])
282. EdTrng.Furnish.KS <- ks.test(EdTrng.Furnish.Beta, "pbeta",
283.      EdTrng.Params[7,"Alpha"],
284.      EdTrng.Params[7,"Beta"])
285. EdTrng.Elec.KS <- ks.test(EdTrng.Elec.Beta, "pbeta",
286.      EdTrng.Params[8,"Alpha"],
287.      EdTrng.Params[8,"Beta"])
288. EdTrng.Struct.KS <- ks.test(EdTrng.Struct.Beta, "pbeta",
289.      EdTrng.Params[9,"Alpha"],
290.      EdTrng.Params[9,"Beta"])
291. EdTrng.Mech.KS <- ks.test(EdTrng.Mech.Beta, "pbeta",
292.      EdTrng.Params[10,"Alpha"],
293.      EdTrng.Params[10,"Beta"])
294. EdTrng.Spec.KS <- ks.test(EdTrng.Spec.Beta, "pbeta",
295.      EdTrng.Params[11,"Alpha"],
296.      EdTrng.Params[11,"Beta"])

```

```

297.
298. Dorms.GenReq.KS <- ks.test(Dorms.GenReq.Beta, "pbeta",
299.                             Dorms.Params[1,"Alpha"],
300.                             Dorms.Params[1,"Beta"])
301. Dorms.Demo.KS <- ks.test(Dorms.Demo.Beta, "pbeta",
302.                           Dorms.Params[2,"Alpha"],
303.                           Dorms.Params[2,"Beta"])
304. Dorms.Finish.KS <- ks.test(Dorms.Finish.Beta, "pbeta",
305.                             Dorms.Params[3,"Alpha"],
306.                             Dorms.Params[3,"Beta"])
307. Dorms.Found.KS <- ks.test(Dorms.Found.Beta, "pbeta",
308.                             Dorms.Params[4,"Alpha"],
309.                             Dorms.Params[4,"Beta"])
310. Dorms.Comm.KS <- ks.test(Dorms.Comm.Beta, "pbeta",
311.                             Dorms.Params[5,"Alpha"],
312.                             Dorms.Params[5,"Beta"])
313. Dorms.Earth.KS <- ks.test(Dorms.Earth.Beta, "pbeta",
314.                             Dorms.Params[6,"Alpha"],
315.                             Dorms.Params[6,"Beta"])
316. Dorms.Furnish.KS <- ks.test(Dorms.Furnish.Beta, "pbeta",
317.                             Dorms.Params[7,"Alpha"],
318.                             Dorms.Params[7,"Beta"])
319. Dorms.Elec.KS <- ks.test(Dorms.Elec.Beta, "pbeta",
320.                             Dorms.Params[8,"Alpha"],
321.                             Dorms.Params[8,"Beta"])
322. Dorms.Struct.KS <- ks.test(Dorms.Struct.Beta, "pbeta",
323.                             Dorms.Params[9,"Alpha"],
324.                             Dorms.Params[9,"Beta"])
325. Dorms.Mech.KS <- ks.test(Dorms.Mech.Beta, "pbeta",
326.                             Dorms.Params[10,"Alpha"],
327.                             Dorms.Params[10,"Beta"])
328. Dorms.Spec.KS <- ks.test(Dorms.Spec.Beta, "pbeta",
329.                             Dorms.Params[11,"Alpha"],
330.                             Dorms.Params[11,"Beta"])
331.
332. SqdOps.GenReq.KS <- ks.test(SqdOps.GenReq.Beta, "pbeta",
333.                             SqdOps.Params[1,"Alpha"],
334.                             SqdOps.Params[1,"Beta"])
335. SqdOps.Demo.KS <- ks.test(SqdOps.Demo.Beta, "pbeta",
336.                             SqdOps.Params[2,"Alpha"],
337.                             SqdOps.Params[2,"Beta"])
338. SqdOps.Finish.KS <- ks.test(SqdOps.Finish.Beta, "pbeta",
339.                             SqdOps.Params[3,"Alpha"],
340.                             SqdOps.Params[3,"Beta"])
341. SqdOps.Found.KS <- ks.test(SqdOps.Found.Beta, "pbeta",
342.                             SqdOps.Params[4,"Alpha"],
343.                             SqdOps.Params[4,"Beta"])
344. SqdOps.Comm.KS <- ks.test(SqdOps.Comm.Beta, "pbeta",
345.                             SqdOps.Params[5,"Alpha"],
346.                             SqdOps.Params[5,"Beta"])
347. SqdOps.Earth.KS <- ks.test(SqdOps.Earth.Beta, "pbeta",
348.                             SqdOps.Params[6,"Alpha"],
349.                             SqdOps.Params[6,"Beta"])
350. SqdOps.Furnish.KS <- ks.test(SqdOps.Furnish.Beta, "pbeta",
351.                             SqdOps.Params[7,"Alpha"],
352.                             SqdOps.Params[7,"Beta"])
353. SqdOps.Elec.KS <- ks.test(SqdOps.Elec.Beta, "pbeta",
354.                             SqdOps.Params[8,"Alpha"],
355.                             SqdOps.Params[8,"Beta"])
356. SqdOps.Struct.KS <- ks.test(SqdOps.Struct.Beta, "pbeta",

```

```

357.             SqdOps.Params[9,"Alpha"],
358.             SqdOps.Params[9,"Beta"])
359. SqdOps.Mech.KS <- ks.test(SqdOps.Mech.Beta, "pbeta",
360.             SqdOps.Params[10,"Alpha"],
361.             SqdOps.Params[10,"Beta"])
362. SqdOps.Spec.KS <- ks.test(SqdOps.Spec.Beta, "pbeta",
363.             SqdOps.Params[11,"Alpha"],
364.             SqdOps.Params[11,"Beta"])
365.
366.
367. #Save KS test results into lists and combine into a dataframe
368. KS.CostElement <- as.vector(1:33)
369. KS.Statistic <- as.vector(1:33)
370. KS.Pvalue <- as.vector(1:33)
371.
372. ##Save Cost Element Names
373. KS.CostElement[1] <- c(EdTrng.GenReq.KS$data.name)
374. KS.CostElement[2] <- c(EdTrng.Demo.KS$data.name)
375. KS.CostElement[3] <- c(EdTrng.Finish.KS$data.name)
376. KS.CostElement[4] <- c(EdTrng.Found.KS$data.name)
377. KS.CostElement[5] <- c(EdTrng.Comm.KS$data.name)
378. KS.CostElement[6] <- c(EdTrng.Earth.KS$data.name)
379. KS.CostElement[7] <- c(EdTrng.Furnish.KS$data.name)
380. KS.CostElement[8] <- c(EdTrng.Elec.KS$data.name)
381. KS.CostElement[9] <- c(EdTrng.Struct.KS$data.name)
382. KS.CostElement[10] <- c(EdTrng.Mech.KS$data.name)
383. KS.CostElement[11] <- c(EdTrng.Spec.KS$data.name)
384.
385. KS.CostElement[12] <- c(Dorms.GenReq.KS$data.name)
386. KS.CostElement[13] <- c(Dorms.Demo.KS$data.name)
387. KS.CostElement[14] <- c(Dorms.Finish.KS$data.name)
388. KS.CostElement[15] <- c(Dorms.Found.KS$data.name)
389. KS.CostElement[16] <- c(Dorms.Comm.KS$data.name)
390. KS.CostElement[17] <- c(Dorms.Earth.KS$data.name)
391. KS.CostElement[18] <- c(Dorms.Furnish.KS$data.name)
392. KS.CostElement[19] <- c(Dorms.Elec.KS$data.name)
393. KS.CostElement[20] <- c(Dorms.Struct.KS$data.name)
394. KS.CostElement[21] <- c(Dorms.Mech.KS$data.name)
395. KS.CostElement[22] <- c(Dorms.Spec.KS$data.name)
396.
397. KS.CostElement[23] <- c(SqdOps.GenReq.KS$data.name)
398. KS.CostElement[24] <- c(SqdOps.Demo.KS$data.name)
399. KS.CostElement[25] <- c(SqdOps.Finish.KS$data.name)
400. KS.CostElement[26] <- c(SqdOps.Found.KS$data.name)
401. KS.CostElement[27] <- c(SqdOps.Comm.KS$data.name)
402. KS.CostElement[28] <- c(SqdOps.Earth.KS$data.name)
403. KS.CostElement[29] <- c(SqdOps.Furnish.KS$data.name)
404. KS.CostElement[30] <- c(SqdOps.Elec.KS$data.name)
405. KS.CostElement[31] <- c(SqdOps.Struct.KS$data.name)
406. KS.CostElement[32] <- c(SqdOps.Mech.KS$data.name)
407. KS.CostElement[33] <- c(SqdOps.Spec.KS$data.name)
408.
409.
410. ##Save D Statistic Value
411. KS.Statistic[1] <- c(EdTrng.GenReq.KS$statistic)
412. KS.Statistic[2] <- c(EdTrng.Demo.KS$statistic)
413. KS.Statistic[3] <- c(EdTrng.Finish.KS$statistic)
414. KS.Statistic[4] <- c(EdTrng.Found.KS$statistic)
415. KS.Statistic[5] <- c(EdTrng.Comm.KS$statistic)
416. KS.Statistic[6] <- c(EdTrng.Earth.KS$statistic)

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417. KS.Statistic[7] <- c(EdTrng.Furnish.KS$statistic)
418. KS.Statistic[8] <- c(EdTrng.Elec.KS$statistic)
419. KS.Statistic[9] <- c(EdTrng.Struct.KS$statistic)
420. KS.Statistic[10] <- c(EdTrng.Mech.KS$statistic)
421. KS.Statistic[11] <- c(EdTrng.Spec.KS$statistic)
422.
423. KS.Statistic[12] <- c(Dorms.GenReq.KS$statistic)
424. KS.Statistic[13] <- c(Dorms.Demo.KS$statistic)
425. KS.Statistic[14] <- c(Dorms.Finish.KS$statistic)
426. KS.Statistic[15] <- c(Dorms.Found.KS$statistic)
427. KS.Statistic[16] <- c(Dorms.Comm.KS$statistic)
428. KS.Statistic[17] <- c(Dorms.Earth.KS$statistic)
429. KS.Statistic[18] <- c(Dorms.Furnish.KS$statistic)
430. KS.Statistic[19] <- c(Dorms.Elec.KS$statistic)
431. KS.Statistic[20] <- c(Dorms.Struct.KS$statistic)
432. KS.Statistic[21] <- c(Dorms.Mech.KS$statistic)
433. KS.Statistic[22] <- c(Dorms.Spec.KS$statistic)
434.
435. KS.Statistic[23] <- c(SqdOps.GenReq.KS$statistic)
436. KS.Statistic[24] <- c(SqdOps.Demo.KS$statistic)
437. KS.Statistic[25] <- c(SqdOps.Finish.KS$statistic)
438. KS.Statistic[26] <- c(SqdOps.Found.KS$statistic)
439. KS.Statistic[27] <- c(SqdOps.Comm.KS$statistic)
440. KS.Statistic[28] <- c(SqdOps.Earth.KS$statistic)
441. KS.Statistic[29] <- c(SqdOps.Furnish.KS$statistic)
442. KS.Statistic[30] <- c(SqdOps.Elec.KS$statistic)
443. KS.Statistic[31] <- c(SqdOps.Struct.KS$statistic)
444. KS.Statistic[32] <- c(SqdOps.Mech.KS$statistic)
445. KS.Statistic[33] <- c(SqdOps.Spec.KS$statistic)
446.
447.
448. ##Save p-values
449. KS.Pvalue[1] <- c(EdTrng.GenReq.KS$p.value)
450. KS.Pvalue[2] <- c(EdTrng.Demo.KS$p.value)
451. KS.Pvalue[3] <- c(EdTrng.Finish.KS$p.value)
452. KS.Pvalue[4] <- c(EdTrng.Found.KS$p.value)
453. KS.Pvalue[5] <- c(EdTrng.Comm.KS$p.value)
454. KS.Pvalue[6] <- c(EdTrng.Earth.KS$p.value)
455. KS.Pvalue[7] <- c(EdTrng.Furnish.KS$p.value)
456. KS.Pvalue[8] <- c(EdTrng.Elec.KS$p.value)
457. KS.Pvalue[9] <- c(EdTrng.Struct.KS$p.value)
458. KS.Pvalue[10] <- c(EdTrng.Mech.KS$p.value)
459. KS.Pvalue[11] <- c(EdTrng.Spec.KS$p.value)
460.
461. KS.Pvalue[12] <- c(Dorms.GenReq.KS$p.value)
462. KS.Pvalue[13] <- c(Dorms.Demo.KS$p.value)
463. KS.Pvalue[14] <- c(Dorms.Finish.KS$p.value)
464. KS.Pvalue[15] <- c(Dorms.Found.KS$p.value)
465. KS.Pvalue[16] <- c(Dorms.Comm.KS$p.value)
466. KS.Pvalue[17] <- c(Dorms.Earth.KS$p.value)
467. KS.Pvalue[18] <- c(Dorms.Furnish.KS$p.value)
468. KS.Pvalue[19] <- c(Dorms.Elec.KS$p.value)
469. KS.Pvalue[20] <- c(Dorms.Struct.KS$p.value)
470. KS.Pvalue[21] <- c(Dorms.Mech.KS$p.value)
471. KS.Pvalue[22] <- c(Dorms.Spec.KS$p.value)
472.
473. KS.Pvalue[23] <- c(SqdOps.GenReq.KS$p.value)
474. KS.Pvalue[24] <- c(SqdOps.Demo.KS$p.value)
475. KS.Pvalue[25] <- c(SqdOps.Finish.KS$p.value)
476. KS.Pvalue[26] <- c(SqdOps.Found.KS$p.value)

```

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477. KS.Pvalue[27] <- c(SqdOps.Comm.KS$p.value)
478. KS.Pvalue[28] <- c(SqdOps.Earth.KS$p.value)
479. KS.Pvalue[29] <- c(SqdOps.Furnish.KS$p.value)
480. KS.Pvalue[30] <- c(SqdOps.Elec.KS$p.value)
481. KS.Pvalue[31] <- c(SqdOps.Struct.KS$p.value)
482. KS.Pvalue[32] <- c(SqdOps.Mech.KS$p.value)
483. KS.Pvalue[33] <- c(SqdOps.Spec.KS$p.value)
484.
485. ##Combine lists into one dataframe and save to file
486. KS.Test.Results <- data.frame(KS.CostElement, KS.Statistic, KS.Pvalue)
487. write.csv(KS.Test.Results, "KSTestResults.csv")
488.
489.
490. #Correlate each column of costs with a facility cost matrix
491. ##between each other foreach facility type
492. cor(EdTrng.Costs, use = "everything", method = "spearman")
493.
494. #Save correlations into a separate matrix variable
495. EdTrng.Costs.Corr <- cor(EdTrng.Costs, use = "everything", method = "spearman")
496. Dorms.Costs.Corr <- cor(Dorms.Costs, use = "everything", method = "spearman")
497. SqdOps.Costs.Corr <- cor(SqdOps.Costs, use = "everything", method = "spearman")
498.
499. #Test correlations for positive definite for use in further calculations
500. ##(requires 'matrixcalc' package)
501. is.positive.definite(EdTrng.Costs.Corr, tol=1e-8)
502. is.positive.definite(Dorms.Costs.Corr, tol=1e-8)
503. is.positive.definite(SqdOps.Costs.Corr, tol=1e-8)
504.
505. #if 'FALSE' test for positive semi-definite matrix to assess deviance
506. is.positive.semi.definite(Dorms.Costs.Corr, tol=1e-8)
507.
508. #if NOT Positive Definite (Semi-Definite does NOT work),
509. #turn to the following Higham method:
510.
511. #Convert to the nearest positive definite matrix (requires 'Matrix' package)
512. Dorms.Costs.Corr2 <- nearPD(Dorms.Costs.Corr,
513.                             corr = TRUE,
514.                             keepDiag = FALSE,
515.                             do2eigen = TRUE,
516.                             doSym = FALSE,
517.                             doDykstra = TRUE,
518.                             only.values = FALSE,
519.                             ensureSymmetry = TRUE,
520.                             eig.tol = 1e-06,
521.                             conv.tol = 1e-07,
522.                             posd.tol = 1e-08,
523.                             maxit = 100,
524.                             conv.norm.type = "I",
525.                             trace = FALSE)
526.
527. #Pull out matrix output results
528. Dorms.Costs.CorrPD <- data.matrix(Dorms.Costs.Corr2$mat, rownames.force = NA)
529.
530. #Check the new matrix for feasibility
531. is.positive.definite(Dorms.Costs.CorrPD, tol=1e-8)
532.
533.
534. #Input beta distribution scale factors for each facility type, cost type
535. #Check working directory via 'getwd()'
536. #Modify file path as needed ("I:/My Documents/Thesis/Data/DistroScalers.csv")

```

```

537. ##This pulls from the same "DistroParams.csv" file saved earlier
538. ##If needed again: Distro.Params <-
    read.csv("Thesis/Data/DistroParams.csv", header = TRUE, sep = ",")
539.
540. EdTrng.Scalers <- data.matrix(Distro.Params[12:22,3], rownames.force = NA)
541. Dorms.Scalers <- data.matrix(Distro.Params[1:11,3], rownames.force = NA)
542. SqdOps.Scalers <- data.matrix(Distro.Params[23:33,3], rownames.force = NA)
543.
544.
545.
546. #Education & Training Simulation
547. #(returns each cost column with a random beta value per row)
548.
549. #NOTES:  for 'sample.method':  SRS = Simple Random Sample
550. #                                           LHS = Latin Hypercube Sample
551. ##Set SEED = 8 for all simulations
552.
553. n <- 100000
554. sim.seed <- 8
555.
556. EdTrng.Sim <- simulateMvMatrix(n,
557.                                distributions = c(Var.1 = "beta",
558.                                                    Var.2 = "beta",
559.                                                    Var.3 = "beta",
560.                                                    Var.4 = "beta",
561.                                                    Var.5 = "beta",
562.                                                    Var.6 = "beta",
563.                                                    Var.7 = "beta",
564.                                                    Var.8 = "beta",
565.                                                    Var.9 = "beta",
566.                                                    Var.10 = "beta",
567.                                                    Var.11 = "beta"),
568.                                param.list = list(Var.1 = list(shape1 = EdTrng.Params[
569.                                1,"Alpha"],
570.                                shape2 = EdTrng.Params[
571.                                1,"Beta"], ncp = 0),
572.                                Var.2 = list(shape1 = EdTrng.Params[
573.                                2,"Alpha"],
574.                                shape2 = EdTrng.Params[
575.                                2,"Beta"], ncp = 0),
576.                                Var.3 = list(shape1 = EdTrng.Params[
577.                                3,"Alpha"],
578.                                shape2 = EdTrng.Params[
579.                                3,"Beta"], ncp = 0),
580.                                Var.4 = list(shape1 = EdTrng.Params[
581.                                4,"Alpha"],
582.                                shape2 = EdTrng.Params[
583.                                4,"Beta"], ncp = 0),
584.                                Var.5 = list(shape1 = EdTrng.Params[
585.                                5,"Alpha"],
586.                                shape2 = EdTrng.Params[
587.                                5,"Beta"], ncp = 0),
588.                                Var.6 = list(shape1 = EdTrng.Params[
589.                                6,"Alpha"],
590.                                shape2 = EdTrng.Params[
591.                                6,"Beta"], ncp = 0),
592.                                Var.7 = list(shape1 = EdTrng.Params[
593.                                7,"Alpha"],
594.                                shape2 = EdTrng.Params[
595.                                7,"Beta"], ncp = 0),
596.                                Var.8 = list(shape1 = EdTrng.Params[
597.                                8,"Alpha"],
598.                                shape2 = EdTrng.Params[
599.                                8,"Beta"], ncp = 0),
600.                                Var.9 = list(shape1 = EdTrng.Params[
601.                                9,"Alpha"],
602.                                shape2 = EdTrng.Params[
603.                                9,"Beta"], ncp = 0),
604.                                Var.10 = list(shape1 = EdTrng.Params[
605.                                10,"Alpha"],
606.                                shape2 = EdTrng.Params[
607.                                10,"Beta"], ncp = 0),
608.                                Var.11 = list(shape1 = EdTrng.Params[
609.                                11,"Alpha"],
610.                                shape2 = EdTrng.Params[
611.                                11,"Beta"], ncp = 0))

```

```

582.                                     Var.8 = list(shape1 = EdTrng.Params[
583.                                     shape2 = EdTrng.Params
584.                                     Var.9 = list(shape1 = EdTrng.Params[
585.                                     shape2 = EdTrng.Params
586.                                     Var.10 = list(shape1 = EdTrng.Params
587.                                     shape2 = EdTrng.Param
588.                                     Var.11 = list(shape1 = EdTrng.Params
589.                                     shape2 = EdTrng.Param
590.                                     cor.mat = EdTrng.Costs.Corr,
591.                                     sample.method = "LHS",
592.                                     seed = sim.seed,
593.                                     tol.1 = .Machine$double.eps,
594.                                     tol.symmetry = .Machine$double.eps,
595.                                     tol.recip.cond.num = .Machine$double.eps,
596.                                     max.iter = 10)
597.
598. #convert the beta numbers by multiplying by the scaler, adding the rows,
599. ##and adding the location shift factor,
600. #resulting in each row being a total cost estimate per square meter
601.
602. #note that because the row costs are summed before
603. #the location shift factor is applied,
604. ##a total location shift factor is added which is simply the sum
605. #of the location shift factors for each row
606. ##(i.e. each cost element beta distribution)
607.
608. EdTrng.Sim.Costs <- EdTrng.Sim %%% EdTrng.Scalers + 802.26
609.
610. #Evaluate the simulate costs
611. #Convert to a data.frame so that ggplot can be used to plot the data
612. EdTrng.Sim.Costs <- as.data.frame(EdTrng.Sim.Costs)
613.
614. #Histogram of the simulated cost values showing mean value and
615. #5%, 25%, 50%, 75%, and 95% percentiles
616. ggplot(EdTrng.Sim.Costs, aes(x=EdTrng.Sim.Costs[,1])) +
617.   geom_histogram(binwidth=100, colour="black", fill="white") +
618.   geom_vline(aes(xintercept=mean(EdTrng.Sim.Costs[,1])),
619.             color="green", linetype="solid", size=1) +
620.   geom_vline(aes(xintercept=quantile(EdTrng.Sim.Costs[,1], c(.05))),
621.             color="red", linetype="solid", size=1) +
622.   geom_vline(aes(xintercept=quantile(EdTrng.Sim.Costs[,1], c(.25))),
623.             color="red", linetype="solid", size=1) +
624.   geom_vline(aes(xintercept=quantile(EdTrng.Sim.Costs[,1], c(.75))),
625.             color="red", linetype="solid", size=1) +
626.   geom_vline(aes(xintercept=quantile(EdTrng.Sim.Costs[,1], c(.95))),
627.             color="red", linetype="solid", size=1) +
628.   geom_vline(aes(xintercept=quantile(EdTrng.Sim.Costs[,1], c(.5))),
629.             color="blue", linetype="solid", size=1) +
630.   aes(y = ..density..) +
631.   labs(title="Education & Training Simulated Costs with
632.         Mean, 5%, 25%, 50%, 75%, and 95% Percentiles") +
633.   xlab("Cost ($)") +

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634.   ylab("Density")
635.
636.   #Print the quantile values and the mean:
637.   quantile(EdTrng.Sim.Costs[,1], c(.05, .25, .5, .75, .95))
638.   mean(EdTrng.Sim.Costs[,1])
639.
640.
641.
642.   #Do the Same for Squad Ops
643.   SqdOps.Sim <- simulateMvMatrix(n,
644.                                   distributions = c(Var.1 = "beta",
645.                                                       Var.2 = "beta",
646.                                                       Var.3 = "beta",
647.                                                       Var.4 = "beta",
648.                                                       Var.5 = "beta",
649.                                                       Var.6 = "beta",
650.                                                       Var.7 = "beta",
651.                                                       Var.8 = "beta",
652.                                                       Var.9 = "beta",
653.                                                       Var.10 = "beta",
654.                                                       Var.11 = "beta"),
655.                                   param.list = list(Var.1 = list(shape1 = Dorms.Params[1
656.                                   , "Alpha"],
657.                                   shape2 = Dorms.Params[
658.                                   1, "Beta"], ncp = 0),
659.                                   Var.2 = list(shape1 = Dorms.Params[2
660.                                   , "Alpha"],
661.                                   shape2 = Dorms.Params[
662.                                   2, "Beta"], ncp = 0),
663.                                   Var.3 = list(shape1 = Dorms.Params[3
664.                                   , "Alpha"],
665.                                   shape2 = Dorms.Params[
666.                                   3, "Beta"], ncp = 0),
667.                                   Var.4 = list(shape1 = Dorms.Params[4
668.                                   , "Alpha"],
669.                                   shape2 = Dorms.Params[
670.                                   4, "Beta"], ncp = 0),
671.                                   Var.5 = list(shape1 = Dorms.Params[5
672.                                   , "Alpha"],
673.                                   shape2 = Dorms.Params[
674.                                   5, "Beta"], ncp = 0),
675.                                   Var.6 = list(shape1 = Dorms.Params[6
676.                                   , "Alpha"],
677.                                   shape2 = Dorms.Params[
678.                                   6, "Beta"], ncp = 0),
679.                                   Var.7 = list(shape1 = Dorms.Params[7
680.                                   , "Alpha"],
681.                                   shape2 = Dorms.Params[
682.                                   7, "Beta"], ncp = 0),
683.                                   Var.8 = list(shape1 = Dorms.Params[8
684.                                   , "Alpha"],
685.                                   shape2 = Dorms.Params[
686.                                   8, "Beta"], ncp = 0),
687.                                   Var.9 = list(shape1 = Dorms.Params[9
688.                                   , "Alpha"],
689.                                   shape2 = Dorms.Params[
690.                                   9, "Beta"], ncp = 0),
691.                                   Var.10 = list(shape1 = Dorms.Params[10
692.                                   , "Alpha"],
693.                                   shape2 = Dorms.Params[
694.                                   10, "Beta"], ncp = 0),
695.                                   Var.11 = list(shape1 = Dorms.Params[11
696.                                   , "Alpha"],
697.                                   shape2 = Dorms.Params[
698.                                   11, "Beta"], ncp = 0))
699.
700.

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```

674.                                     shape2 = Dorms.Params
    [10,"Beta"], ncp = 0),
675.                                     Var.11 = list(shape1 = Dorms.Params[
    11,"Alpha"],
676.                                     shape2 = Dorms.Params
    [11,"Beta"], ncp = 0)),
677.                                     cor.mat = SqdOps.Costs.Corr,
678.                                     sample.method = "LHS",
679.                                     seed = sim.seed,
680.                                     max.iter = 10)
681.
682. SqdOps.Sim.Costs <- SqdOps.Sim %*% SqdOps.Scalers + 813.5
683.
684. SqdOps.Sim.Costs <- as.data.frame(SqdOps.Sim.Costs)
685.
686. ggplot(SqdOps.Sim.Costs, aes(x= SqdOps.Sim.Costs[,1])) +
687.   geom_histogram(binwidth=100, colour="black", fill="white") +
688.   geom_vline(aes(xintercept=mean(SqdOps.Sim.Costs[,1])),
689.             color="green", linetype="solid", size=1) +
690.   geom_vline(aes(xintercept=quantile(SqdOps.Sim.Costs[,1], c(.05))),
691.             color="red", linetype="solid", size=1) +
692.   geom_vline(aes(xintercept=quantile(SqdOps.Sim.Costs[,1], c(.25))),
693.             color="red", linetype="solid", size=1) +
694.   geom_vline(aes(xintercept=quantile(SqdOps.Sim.Costs[,1], c(.75))),
695.             color="red", linetype="solid", size=1) +
696.   geom_vline(aes(xintercept=quantile(SqdOps.Sim.Costs[,1], c(.95))),
697.             color="red", linetype="solid", size=1) +
698.   geom_vline(aes(xintercept=quantile(SqdOps.Sim.Costs[,1], c(.5))),
699.             color="blue", linetype="solid", size=1) +
700.   aes(y = ..density..) +
701.   labs(title="Squadron Operations Facility Simulated Costs with
702.         Mean, 5%, 25%, 50%, 75%, and 95% Percentiles") +
703.   xlab("Cost ($)") +
704.   ylab("Density")
705.
706. quantile(SqdOps.Sim.Costs[,1], c(.05, .25, .5, .75, .95))
707. mean(SqdOps.Sim.Costs[,1])
708.
709.
710. #Do the Same for Dorms
711. Dorms.Sim <- simulateMvMatrix(n,
712.                               distributions = c(Var.1 = "beta",
713.                                                  Var.2 = "beta",
714.                                                  Var.3 = "beta",
715.                                                  Var.4 = "beta",
716.                                                  Var.5 = "beta",
717.                                                  Var.6 = "beta",
718.                                                  Var.7 = "beta",
719.                                                  Var.8 = "beta",
720.                                                  Var.9 = "beta",
721.                                                  Var.10 = "beta",
722.                                                  Var.11 = "beta"),
723.                               param.list = list(Var.1 = list(shape1 = SqdOps.Params[1
    ,"Alpha"],
724.                                                         shape2 = SqdOps.Params[
    1,"Beta"], ncp = 0),
725.                                                  Var.2 = list(shape1 = SqdOps.Params[2
    ,"Alpha"],
726.                                                         shape2 = SqdOps.Params[
    2,"Beta"], ncp = 0),

```

```

727.                                     Var.3 = list(shape1 = SqdOps.Params[3
, "Alpha"],
728.                                     shape2 = SqdOps.Params[
3, "Beta"], ncp = 0),
729.                                     Var.4 = list(shape1 = SqdOps.Params[4
, "Alpha"],
730.                                     shape2 = SqdOps.Params[
4, "Beta"], ncp = 0),
731.                                     Var.5 = list(shape1 = SqdOps.Params[5
, "Alpha"],
732.                                     shape2 = SqdOps.Params[
5, "Beta"], ncp = 0),
733.                                     Var.6 = list(shape1 = SqdOps.Params[6
, "Alpha"],
734.                                     shape2 = SqdOps.Params[
6, "Beta"], ncp = 0),
735.                                     Var.7 = list(shape1 = SqdOps.Params[7
, "Alpha"],
736.                                     shape2 = SqdOps.Params[
7, "Beta"], ncp = 0),
737.                                     Var.8 = list(shape1 = SqdOps.Params[8
, "Alpha"],
738.                                     shape2 = SqdOps.Params[
8, "Beta"], ncp = 0),
739.                                     Var.9 = list(shape1 = SqdOps.Params[9
, "Alpha"],
740.                                     shape2 = SqdOps.Params[
9, "Beta"], ncp = 0),
741.                                     Var.10 = list(shape1 = SqdOps.Params[
10, "Alpha"],
742.                                     shape2 = SqdOps.Params
[10, "Beta"], ncp = 0),
743.                                     Var.11 = list(shape1 = SqdOps.Params[
11, "Alpha"],
744.                                     shape2 = SqdOps.Params
[11, "Beta"], ncp = 0)),
745.                                     cor.mat = Dorms.Costs.CorrPD,
746.                                     sample.method = "LHS",
747.                                     seed = sim.seed,
748.                                     max.iter = 10)
749.
750. Dorms.Sim.Costs <- Dorms.Sim %%% Dorms.Scalers + 1774.29
751.
752. Dorms.Sim.Costs <- as.data.frame(Dorms.Sim.Costs)
753.
754. ggplot(Dorms.Sim.Costs, aes(x= Dorms.Sim.Costs[,1])) +
755.   geom_histogram(binwidth=50, colour="black", fill="white") +
756.   geom_vline(aes(xintercept=mean(Dorms.Sim.Costs[,1])), color="green",
757.             linetype="solid", size=1) +
758.   geom_vline(aes(xintercept=quantile(Dorms.Sim.Costs[,1], c(.05))),
759.             color="red", linetype="solid", size=1) +
760.   geom_vline(aes(xintercept=quantile(Dorms.Sim.Costs[,1], c(.25))),
761.             color="red", linetype="solid", size=1) +
762.   geom_vline(aes(xintercept=quantile(Dorms.Sim.Costs[,1], c(.75))),
763.             color="red", linetype="solid", size=1) +
764.   geom_vline(aes(xintercept=quantile(Dorms.Sim.Costs[,1], c(.95))),
765.             color="red", linetype="solid", size=1) +
766.   geom_vline(aes(xintercept=quantile(Dorms.Sim.Costs[,1], c(.5))),
767.             color="blue", linetype="solid", size=1) +
768.   aes(y = ..density..) +

```

```

769. labs(title="Dormitory Facility Simulated Costs with Mean,
770.         5%, 25%, 50%, 75%, and 95% Percentiles") +
771.   xlab("Cost ($)") +
772.   ylab("Density")
773.
774. quantile(Dorms.Sim.Costs[,1], c(.05, .25, .5, .75, .95))
775. mean(Dorms.Sim.Costs[,1])
776.
777.
778.
779. #For more detailed analysis:
780. quantile(EdTrng.Sim.Costs[,1], c(.01, .05, .15, .25, .5, .75, .85, .95, .99))
781. quantile(SqdOps.Sim.Costs[,1], c(.01, .05, .15, .25, .5, .75, .85, .95, .99))
782. quantile(Dorms.Sim.Costs[,1], c(.01, .05, .15, .25, .5, .75, .85, .95, .99))
783.
784.
785.
786. #MODEL VALIDATION
787.
788. ###Applied five specific projects with data
789. #to create cost estimate ranges for comparison
790.
791. Valid.Params <- read.csv("Thesis/Data/ValidationParameters.csv",
792.                          header = TRUE, sep = ",", row.names = 1)
793. Valid.Params <- data.matrix(Valid.Params)
794.
795. #Ed & Training Facilities
796. ##Whiteman 2005 CDC:
797. Whiteman.CDC <- (EdTrng.Sim.Costs*Valid.Params["Whiteman.CDC", "Scope"]*
798.                 Valid.Params["Whiteman.CDC", "ACF"]/
799.                 Valid.Params["Whiteman.CDC", "EscalF"])/1000
800.
801. ##Eielson 2007 Chapel:
802. Eielson.Chapel <- (EdTrng.Sim.Costs*Valid.Params["Eielson.Chapel", "Scope"]*
803.                  Valid.Params["Eielson.Chapel", "ACF"]/
804.                  Valid.Params["Eielson.Chapel", "EscalF"])/1000
805.
806.
807. #Sqd Ops Facilities
808. ##Hanscom 2008 Aq Mgt Fac:
809. Hanscom.AqMgt <- (SqdOps.Sim.Costs*Valid.Params["Hanscom.AqMgt", "Scope"]*
810.                 Valid.Params["Hanscom.AqMgt", "ACF"]/
811.                 Valid.Params["Hanscom.AqMgt", "EscalF"])/1000
812.
813. ##Kirtland 2012 AFNWC Cent:
814. Kirtland.AFNWC <- (SqdOps.Sim.Costs*Valid.Params["Kirtland.AFNWC", "Scope"]*
815.                  Valid.Params["Kirtland.AFNWC", "ACF"]/
816.                  Valid.Params["Kirtland.AFNWC", "EscalF"])/1000
817.
818.
819. #Dorm Facility
820. ##Lackland 2009 ATC Dorm:
821. Lackland.Dorm <- (Dorms.Sim.Costs*Valid.Params["Lackland.Dorm", "Scope"]*
822.                 Valid.Params["Lackland.Dorm", "ACF"]/
823.                 Valid.Params["Lackland.Dorm", "EscalF"])/1000
824.
825.
826.
827. #Plot the cost estimation histograms with vertical indicator lines and
828. ##comparison cost estimates for each facility

```

```

829.
830. #Education & Training Simulation Validation: Whiteman CDC
831. ggplot(Whiteman.CDC, aes(x= Whiteman.CDC[,1])) +
832.   geom_histogram(aes(y = ..density..), binwidth=250,
833.     colour="black", fill="white") +
834.   geom_vline(aes(xintercept=quantile(Whiteman.CDC[,1], c(.5)),
835.     color="50th Percentile",
836.     linetype="50th Percentile", fill = "50th Percentile"),
837.     size=1) +
838.   geom_vline(aes(xintercept=7685.91190, color="Actual Cost",
839.     linetype="Actual Cost", fill = "Actual Cost"),
840.     size=1) +
841.   geom_vline(aes(xintercept=7600.000, color="Initial PA",
842.     linetype="Initial PA", fill = "Initial PA"),
843.     size=1) +
844.   stat_function(fun = dnorm, geom = "area",
845.     args = c(mean = 6494.09202, sd = 2757.41225),
846.     aes(colour = "UFC Estimate", linetype = "UFC Estimate",
847.       fill = "UFC Estimate"), alpha = .3) +
848.   geom_segment(aes(x = 6494.09202, xend = 6494.09202, y = 0, yend = 0.000145),
849.     color="purple",
850.     linetype="solid") +
851.   stat_function(fun = dnorm, geom = "area",
852.     args = c(mean = 5719.05785, sd = 730.78312),
853.     aes(colour = "AFCESA Estimate", linetype = "AFCESA Estimate",
854.       fill = "AFCESA Estimate"), alpha = .4) +
855.   geom_segment(aes(x = 5719.05785, xend = 5719.05785, y = 0, yend = 0.000546),
856.     color="black",
857.     linetype="dashed") +
858.   scale_colour_manual(name="Project Cost Values",
859.     values=c("red", "green", "black", "blue", "purple4"),
860.     breaks=c("50th Percentile", "UFC Estimate", "Actual Cost",
861.       "AFCESA Estimate", "Initial PA")) +
862.   scale_linetype_manual(name="Project Cost Values",
863.     values=c("dotted", "solid", "dashed", "longdash", "solid"),
864.     breaks=c("50th Percentile", "UFC Estimate", "Actual Cost",
865.       "AFCESA Estimate", "Initial PA")) +
866.   scale_fill_manual(name="Project Cost Values",
867.     values=c("NA", "white", "grey", "white", "plum3"),
868.     breaks=c("50th Percentile", "UFC Estimate", "Actual Cost",
869.       "AFCESA Estimate", "Initial PA")) +
870.   labs(title="Education & Training Facility Simulated Costs:
871.     Whiteman CDC") +
872.   xlab("Cost ($1,000's)") +
873.   ylab("Density") +
874.   theme(axis.text=element_text(size=14),
875.     axis.title=element_text(size=14),
876.     legend.text=element_text(size=14),
877.     legend.title = element_text(size=18, face="bold"),
878.     legend.position="bottom",
879.     legend.box="horizontal",
880.     plot.title = element_text(size=16, face="bold"),
881.     legend.key = element_blank()+
882.     guides(colour = guide_legend(ncol = 3))
883.
884.
885. #Education & Training Simulation Validation: Eielson Chapel
886.   ###NOTE: AFCESA Cost Handbook did not have
887.   ###Standard Deviation Information to plot for this facility type
888. ggplot(Eielson.Chapel, aes(x= Eielson.Chapel[,1])) +

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```

889.   geom_histogram(aes(y = ..density..), binwidth=750,
890.                 colour="black", fill="white") +
891.   geom_vline(aes(xintercept=quantile(Eielson.Chapel[,1], c(.5)),
892.                 color="50th Percentile",
893.                 linetype="50th Percentile", fill = "50th Percentile"),
894.             size=1) +
895.   geom_vline(aes(xintercept=12998.688, color="Actual Cost",
896.                 linetype="Actual Cost", fill = "Actual Cost"),
897.             size=1) +
898.   geom_vline(aes(xintercept=14400.000, color="Initial PA",
899.                 linetype="Initial PA", fill = "Initial PA"),
900.             size=1) +
901.   stat_function(fun = dnorm, geom = "area",
902.                 args = c(mean = 23125.62198, sd = 5043.17557),
903.                 aes(colour = "UFC Estimate", linetype = "UFC Estimate",
904.                     fill = "UFC Estimate"), alpha = .3) +
905.   geom_segment(aes(x = 23125.62198, xend = 23125.62198, y = 0, yend = 0.0000791),
906.               color="purple",
907.               linetype="solid") +
908.   geom_segment(aes(x = 16077.32703, xend = 16077.32703, y = 0, yend = 0.0000791,
909.                   colour = "AFCESA Estimate", linetype = "AFCESA Estimate",
910.                   fill = "AFCESA Estimate")) +
911.   scale_colour_manual(name="Project Cost Values",
912.                       values=c("red", "green", "black", "blue", "purple4"),
913.                       breaks=c("50th Percentile", "UFC Estimate", "Actual Cost",
914.                                 "AFCESA Estimate", "Initial PA")) +
915.   scale_linetype_manual(name="Project Cost Values",
916.                         values=c("dotted", "solid", "dashed", "longdash", "solid"),
917.                         breaks=c("50th Percentile", "UFC Estimate", "Actual Cost",
918.                                   "AFCESA Estimate", "Initial PA")) +
919.   scale_fill_manual(name="Project Cost Values",
920.                    values=c("white", "white", "grey", "white", "plum3"),
921.                    breaks=c("50th Percentile", "UFC Estimate", "Actual Cost",
922.                              "AFCESA Estimate", "Initial PA")) +
923.   labs(title="Education & Training Facility Simulated Costs:
924.         Eielson Chapel") +
925.   xlab("Cost ($1,000's)") +
926.   ylab("Density") +
927.   theme(axis.text=element_text(size=14),
928.         axis.title=element_text(size=14),
929.         legend.text=element_text(size=14),
930.         legend.title = element_text(size=18, face="bold"),
931.         legend.position="bottom",
932.         legend.box="horizontal",
933.         plot.title = element_text(size=16, face="bold"),
934.         legend.key = element_blank()) +
935.   guides(colour = guide_legend(ncol = 3))
936.
937.
938. ##Squadron Operations Simulation Validation:
939.   ###Hanscom Aquisition Management Facility
940.   ggplot(Hanscom.AqMgt, aes(x= Hanscom.AqMgt[,1])) +
941.     geom_histogram(aes(y = ..density..), binwidth=600,
942.                   colour="black", fill="white") +
943.     geom_vline(aes(xintercept=quantile(Hanscom.AqMgt[,1], c(.5)),
944.                   color="50th Percentile",
945.                   linetype="50th Percentile", fill = "50th Percentile"),
946.               size=1) +
947.     geom_vline(aes(xintercept=12236.46316, color="Actual Cost",
948.                   linetype="Actual Cost", fill = "Actual Cost"),

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949.         size=1) +
950.   geom_vline(aes(xintercept=12800.000, color="Initial PA",
951.                 linetype="Initial PA", fill = "Initial PA"),
952.             size=1) +
953.   stat_function(fun = dnorm, geom = "area",
954.               args = c(mean = 12314.13119, sd = 2285.31379),
955.               aes(colour = "UFC Estimate", linetype = "UFC Estimate",
956.                   fill = "UFC Estimate"), alpha = .3) +
957.   geom_segment(aes(x = 12314.13119, xend = 12314.13119, y = 0, yend = 0.000175),
958.               color="purple",
959.               linetype="solid") +
960.   stat_function(fun = dnorm, geom = "area",
961.               args = c(mean = 11539.11473, sd = 2353.69597),
962.               aes(colour = "AFCESA Estimate", linetype = "AFCESA Estimate",
963.                   fill = "AFCESA Estimate"), alpha = .4) +
964.   geom_segment(aes(x = 11539.11473, xend = 11539.11473, y = 0, yend = 0.000169),
965.               color="black",
966.               linetype="dashed") +
967.   scale_colour_manual(name="Project Cost Values",
968.                      values=c("red", "green", "black", "blue", "purple4"),
969.                      breaks=c("50th Percentile", "UFC Estimate", "Actual Cost",
970.                               "AFCESA Estimate", "Initial PA")) +
971.   scale_linetype_manual(name="Project Cost Values",
972.                        values=c("dotted", "solid", "dashed", "longdash", "solid"),
973.                        breaks=c("50th Percentile", "UFC Estimate", "Actual Cost",
974.                                "AFCESA Estimate", "Initial PA")) +
975.   scale_fill_manual(name="Project Cost Values",
976.                    values=c("white", "white", "grey", "white", "plum3"),
977.                    breaks=c("50th Percentile", "UFC Estimate", "Actual Cost",
978.                             "AFCESA Estimate", "Initial PA")) +
979.   labs(title="Squadron Operations Facility Simulated Costs:
980.          Hanscom Acquisition Management Facility") +
981.   xlab("Cost ($1,000's)") +
982.   ylab("Density") +
983.   theme(axis.text=element_text(size=14),
984.         axis.title=element_text(size=14),
985.         legend.text=element_text(size=14),
986.         legend.title = element_text(size=18, face="bold"),
987.         legend.position="bottom",
988.         legend.box="horizontal",
989.         plot.title = element_text(size=16, face="bold"),
990.         legend.key = element_blank()+
991.   guides(colour = guide_legend(ncol = 3))
992.
993.
994. ##Squadron Operations Simulation Validation: Kirtland AFNWC
995. ggplot(Kirtland.AFNWC, aes(x= Kirtland.AFNWC[,1])) +
996.   geom_histogram(aes(y = ..density..), binwidth=700,
997.                 colour="black", fill="white") +
998.   geom_vline(aes(xintercept=quantile(Kirtland.AFNWC[,1], c(.5)),
999.                 color="50th Percentile",
1000.                linetype="50th Percentile", fill = "50th Percentile"),
1001.             size=1) +
1002.   geom_vline(aes(xintercept=24355.24536, color="Actual Cost",
1003.                 linetype="Actual Cost", fill = "Actual Cost"),
1004.             size=1) +
1005.   geom_vline(aes(xintercept=25000.000, color="Initial PA",
1006.                 linetype="Initial PA", fill = "Initial PA"),
1007.             size=1) +
1008.   stat_function(fun = dnorm, geom = "area",

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1009.         args = c(mean = 18180.48649, sd = 3282.06491),
1010.         aes(colour = "UFC Estimate", linetype = "UFC Estimate",
1011.             fill = "UFC Estimate"), alpha = .3) +
1012.   geom_segment(aes(x = 18180.48649, xend = 18180.48649, y = 0, yend = 0.000122),
1013.               color="purple",
1014.               linetype="solid") +
1015.   stat_function(fun = dnorm, geom = "area",
1016.               args = c(mean = 13393.40631, sd = 2460.81908),
1017.               aes(colour = "AFCESA Estimate", linetype = "AFCESA Estimate",
1018.                   fill = "AFCESA Estimate"), alpha = .4) +
1019.   geom_segment(aes(x = 13393.40631, xend = 13393.40631, y = 0, yend = 0.000162),
1020.               color="black",
1021.               linetype="dashed") +
1022.   scale_colour_manual(name="Project Cost Values",
1023.                       values=c("red", "green", "black", "blue", "purple4"),
1024.                       breaks=c("50th Percentile", "UFC Estimate", "Actual Cost",
1025.                                 "AFCESA Estimate", "Initial PA")) +
1026.   scale_linetype_manual(name="Project Cost Values",
1027.                         values=c("dotted", "solid", "dashed", "longdash", "solid"),
1028.                         breaks=c("50th Percentile", "UFC Estimate", "Actual Cost",
1029.                                   "AFCESA Estimate", "Initial PA")) +
1030.   scale_fill_manual(name="Project Cost Values",
1031.                     values=c("NA", "NA", "grey", "NA", "plum3"),
1032.                     breaks=c("50th Percentile", "UFC Estimate", "Actual Cost",
1033.                               "AFCESA Estimate", "Initial PA")) +
1034.   labs(title="Squadron Operations Facility Simulated Costs:
1035.           Kirtland AFNWC Sustainment Center") +
1036.   xlab("Cost ($1,000's)") +
1037.   ylab("Density") +
1038.   theme(axis.text=element_text(size=14),
1039.         axis.title=element_text(size=14),
1040.         legend.text=element_text(size=14),
1041.         legend.title = element_text(size=18, face="bold"),
1042.         legend.position="bottom",
1043.         legend.box="horizontal",
1044.         plot.title = element_text(size=16, face="bold"),
1045.         legend.key = element_blank()) +
1046.   guides(colour = guide_legend(ncol = 3))
1047.
1048.
1049. ##Dormitory Simulation Validation: Lackland Dorm
1050. ###Legend Order: Percentiles, Actual Cost, AFCESA, Initial PA, UFC
1051. ggplot(Lackland.Dorm, aes(x= Lackland.Dorm[,1])) +
1052.   geom_histogram(aes(y = ..density..), binwidth=1000,
1053.                 colour="black", fill="white") +
1054.   geom_vline(aes(xintercept=quantile(Lackland.Dorm[,1], c(.5)),
1055.                 color="50th Percentile",
1056.                 linetype="50th Percentile", fill = "50th Percentile"),
1057.             size=1) +
1058.   geom_vline(aes(xintercept=54544.98613, color="Actual Cost",
1059.                 linetype="Actual Cost", fill = "Actual Cost"),
1060.             size=1) +
1061.   geom_vline(aes(xintercept=75515.000, color="Initial PA",
1062.                 linetype="Initial PA", fill = "Initial PA"),
1063.             size=1) +
1064.   stat_function(fun = dnorm, geom = "area",
1065.               args = c(mean = 35202.25882, sd = 7246.98803),
1066.               aes(colour = "UFC Estimate", linetype = "UFC Estimate",
1067.                   fill = "UFC Estimate"), alpha = .3) +
1068.   geom_segment(aes(x = 35202.25882, xend = 35202.25882, y = 0, yend = 0.0000550),

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1069.         color="purple",
1070.         linetype="solid") +
1071.   stat_function(fun = dnorm, geom = "area",
1072.     args = c(mean = 38045.36039, sd = 8202.67265),
1073.     aes(colour = "AFCESA Estimate", linetype = "AFCESA Estimate",
1074.       fill = "AFCESA Estimate"), alpha = .4) +
1075.   geom_segment(aes(x = 38045.36039, xend = 38045.36039, y = 0, yend = 0.0000486),
1076.     color="black",
1077.     linetype="dashed") +
1078.   scale_colour_manual(name="Project Cost Values",
1079.     values=c("red", "green", "black", "blue", "purple4"),
1080.     breaks=c("50th Percentile", "UFC Estimate", "Actual Cost",
1081.       "AFCESA Estimate", "Initial PA")) +
1082.   scale_linetype_manual(name="Project Cost Values",
1083.     values=c("dotted", "solid", "dashed", "longdash", "solid"),
1084.     breaks=c("50th Percentile", "UFC Estimate", "Actual Cost",
1085.       "AFCESA Estimate", "Initial PA")) +
1086.   scale_fill_manual(name="Project Cost Values",
1087.     values=c("NA", "NA", "grey", "NA", "plum3"),
1088.     breaks=c("50th Percentile", "UFC Estimate", "Actual Cost",
1089.       "AFCESA Estimate", "Initial PA")) +
1090.   labs(title="Dormitory Facility Simulated Costs:
1091.     Lackland ATC Dormitory") +
1092.   xlab("Cost ($1,000's)") +
1093.   ylab("Density") +
1094.   theme(axis.text=element_text(size=14),
1095.     axis.title=element_text(size=14),
1096.     legend.text=element_text(size=14),
1097.     legend.title = element_text(size=18, face="bold"),
1098.     legend.position="bottom",
1099.     legend.box="horizontal",
1100.     plot.title = element_text(size=16, face="bold"),
1101.     legend.key = element_blank()) +
1102.   guides(colour = guide_legend(ncol = 3))
1103.
1104. #-----
1105. #NOTE: the above graphs had legend formatting issues which the author
1106. ##could not resolve. As an alternative, the following simplified graph
1107. ##prints a partial legend usable instead of some of the
1108. ##line legend elements printed above.
1109. ##This section is merely a work-around to a formatting problem.
1110. ggplot(Lackland.Dorm, aes(x= Lackland.Dorm[,1])) +
1111.   geom_histogram(aes(y = ..density..), binwidth=1000,
1112.     colour="black", fill="white") +
1113.   geom_vline(aes(xintercept=quantile(Lackland.Dorm[,1], c(.5)),
1114.     color="50th Percentile",
1115.     linetype="50th Percentile"),
1116.     size=1) +
1117.   geom_vline(aes(xintercept=54544.98613, color="Actual Cost",
1118.     linetype="Actual Cost"),
1119.     size=1) +
1120.   geom_vline(aes(xintercept=75515.000, color="Initial PA",
1121.     linetype="Initial PA"),
1122.     size=1) +
1123.   scale_colour_manual(name="Project Cost Values",
1124.     values=c("red", "green", "blue"),
1125.     breaks=c("50th Percentile", "Actual Cost", "Initial PA")) +
1126.   scale_linetype_manual(name="Project Cost Values",
1127.     values=c("dotted", "solid", "longdash"),
1128.     breaks=c("50th Percentile", "Actual Cost", "Initial PA")) +

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1129. labs(title="Dormitory Facility Simulated Costs:
1130.      Lackland ATC Dormitory") +
1131. xlab("Cost ($1,000's)") +
1132. ylab("Density") +
1133. theme(axis.text=element_text(size=14),
1134.      axis.title=element_text(size=14),
1135.      legend.text=element_text(size=14),
1136.      legend.title = element_text(size=18, face="bold"),
1137.      legend.position="bottom",
1138.      legend.box="horizontal",
1139.      plot.title = element_text(size=16, face="bold")) +
1140. guides(colour = guide_legend(ncol = 3))
1141. #-----END LEGEND FIX SECTION-----
1142.
1143.
1144. #Print results by facility summary:
1145. quantile(Whiteman.CDC[,1], c(.01, .05, .15, .25, .5, .75, .85, .95, .99))
1146. quantile(Eielson.Chapel[,1], c(.01, .05, .15, .25, .5, .75, .85, .95, .99))
1147. quantile(Hanscom.AqMgt[,1], c(.01, .05, .15, .25, .5, .75, .85, .95, .99))
1148. quantile(Kirtland.AFNWC[,1], c(.01, .05, .15, .25, .5, .75, .85, .95, .99))
1149. quantile(Lackland.Dorm[,1], c(.01, .05, .15, .25, .5, .75, .85, .95, .99))
1150.
1151.
1152. #Compare percent differences from actual costs
1153. #of the various estimates for each validation project
1154. Valid.Params <- read.csv("Thesis/Data/ValidationParameters.csv",
1155.      header = TRUE, sep = ",")
1156.
1157. #To plot projects in the order they appear in the csv file:
1158. ##Turn 'PROJ_NAME' column into a character vector
1159. Valid.Params$PROJ_NAME <- as.character(Valid.Params$PROJ_NAME)
1160.
1161. ##Then turn it back into an ordered factor
1162. Valid.Params$PROJ_NAME <- factor(Valid.Params$PROJ_NAME,
1163.      levels=unique(Valid.Params$PROJ_NAME))
1164.
1165.
1166. #Plot relative accuracy of estimates with Class 4 expected range
1167. ggplot(Valid.Params, aes(x=factor(PROJ_NAME))) +
1168.   geom_point(aes(y = Valid.Params[, "Sim_50th_Perc"], group=PROJ_NAME,
1169.      shape = "Simulation 50th Percentile",
1170.      colour = "Simulation 50th Percentile",
1171.      fill = "Simulation 50th Percentile"),
1172.      size = 3) +
1173.   geom_point(aes(y = Valid.Params[, "Initial_PA_Perc"], group=PROJ_NAME,
1174.      shape = "Initial PA",
1175.      colour = "Initial PA",
1176.      fill = "Initial PA"),
1177.      size = 3) +
1178.   geom_point(aes(y = Valid.Params[, "UFC_Estimate_Perc"], group=PROJ_NAME,
1179.      shape = "UFC Estimate",
1180.      colour = "UFC Estimate",
1181.      fill = "UFC Estimate"),
1182.      size = 3) +
1183.   geom_point(aes(y = Valid.Params[, "AFCESA_Estimate_Perc"], group=PROJ_NAME,
1184.      shape = "AFCESA Estimate",
1185.      colour = "AFCESA Estimate",
1186.      fill = "AFCESA Estimate"),
1187.      size = 4) +
1188.   ylim(-100, 100) +

```

```

1189. scale_x_discrete(labels=function(x) sub(" ", "\n", x, fixed=TRUE)) +
1190. scale_shape_manual(name="Cost Estimates",
1191.                     values=c(18, 17, 16, 15),
1192.                     breaks=c("Simulation 50th Percentile",
1193.                               "Initial PA", "UFC Estimate",
1194.                               "AFCESA Estimate")) +
1195. scale_colour_manual(name="Cost Estimates",
1196.                     values=c("black", "blue", "red", "purple"),
1197.                     breaks=c("Simulation 50th Percentile",
1198.                               "Initial PA", "UFC Estimate",
1199.                               "AFCESA Estimate")) +
1200. scale_fill_manual(name="Cost Estimates",
1201.                   values=c("black", "blue", "red", "purple"),
1202.                   breaks=c("Simulation 50th Percentile",
1203.                             "Initial PA", "UFC Estimate",
1204.                             "AFCESA Estimate")) +
1205. theme(axis.text=element_text(size=12),
1206.        axis.title=element_text(size=14),
1207.        legend.text=element_text(size=14),
1208.        legend.title = element_text(size=16, face="bold"),
1209.        plot.title = element_text(size=16, face="bold"),
1210.        legend.justification=c(1,1), legend.position=c(1,1)) +
1211. xlab("Validation Projects") +
1212. ylab("Percent Difference from Actual Value") +
1213. annotate("rect", xmin = "Lackland Dormitory", xmax = "Kirtland AFNWC",
1214.         ymin = -15, ymax = 25,
1215.         fill = "palegreen", color = "green4", alpha = .4) +
1216. annotate("text", x = "Lackland Dormitory", y = 26, hjust = 0, vjust = 0,
1217.         label = "Class 4 Expected Accuracy Range",
1218.         color = "darkgreen", size = 5, alpha = .8)
1219.
1220.
1221. ##      END CODE

```

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