AIR FORCE ASSET MANAGEMENT: PREVENTIVE VERSUS REACTIVE WORK

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AIR FORCE ASSET MANAGEMENT: PREVENTIVE VERSUS REACTIVE WORK

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LIST OF SYMBOLS AND ABBREVIATIONS

AF	Air Force
AFCAMP	Air Force Comprehensive Asset Management Plan
DoD	Department of Defense
EEIC	Element of Expense Investment Codes
ERDC	Engineering Research and Development Center
HLM	Hierarchical Linear Modeling
HVAC	Heating, Ventilation, Air Conditioning
IWIMS	Interim Work Information Management System
M&R	Maintenance and Repair
O&M	Operations and Maintenance
PEC	Program Element Code
PRV	Plant Replacement Value
SD	Standard Deviation
SMS	Sustainment Management System
SUS	Sustainment
R&M	Restoration and Modernization

SUMMARY

To combat reactive maintenance and the “run-to-failure” asset management model, the U.S. Air Force has taken steps to ensure facility condition assessment tracking and asset service life monitoring. The purpose of this study is to investigate how effectively the Air Force has embraced the sustainment of assets and to determine if such trends can be observed at the base level. To do this, a study of the Air Force’s overall spending is analyzed, comparing the amount of funds requested to support asset preservation versus asset restoration over the last four years. A hierarchical linear analysis is then accomplished for a case study of five bases for fiscal years 2010 to mid-2017. This has determined the possible effects of preventive maintenance on reactive maintenance and repair work orders. Results of the macro-study reveal that the percentage of total funds requested for sustainment projects has increased since 2013. In the fiscal year (FY) 2013, only 10% of the total requested funds were assigned to sustainment projects. By the FY 2017, sustainment funds requested made up 36% of the total. Though the transitioning nature of asset management, project-type descriptions, and the continued optimization of the scoring model are factors to consider, it appears that asset sustainment has become more prevalent. The results of the case study suggest that there is little correlation between preventive maintenance and corrective maintenance trends. More data as preventive asset management integrates into practice may reveal different results, but at this stage, preventive maintenance has neither consistently increased or appear to have effected reactive maintenance frequency, labor hours, or cost.

CHAPTER 1. INTRODUCTION

This chapter will cover the background to the research and detail the issues facing Air Force infrastructure. Then, the research questions will be identified. The chapter will close with an overview of the remainder of the paper.

1.1 Background

Asset management is a continually developing means to optimize how organizations purchase, care for, and dispose of resources. Optimal asset management will ensure that facilities and their systems operate effectively throughout and even beyond their manufacturer-determined useful life. Conversely, ineffective asset management can cause lasting effects and decrease an organization's ability to correct deficiencies over time. The United States Air Force is one such organization; one that is trying to correct a history of inefficient resource management strategies. Today, degradation plagues federally-owned facilities and assets, a situation caused by several issues. First, there was a focus on the construction costs for facilities and an ignorance of the operations and maintenance costs required to keep the facility functional. Initial construction is certainly expensive, however over the life of a facility it is only 29% of a buildings' total cost (Gardner, 2013). Second, due to the first issue, funds allocated for appropriate maintenance and repair have been insufficient. The struggle to determine the best method suited to use taxpayer dollars on asset maintenance and repair (M&R) work has been ongoing. In 1989, the Department of Defense (DoD) proposed to Congress a plan to ensure that the built environment could be sustained by asking for one percent of the plant replacement value (PRV) annually for recurring work and service calls, and 0.75 percent of the PRV annually for non-recurring work to include minor construction (Ottoman, 1997). However, in a benchmarking study related to M&R and recapitalization, a minimum of two percent of the PRV should be allocated to M&R and another two percent to non-recurring recapitalization annually (Westfall, 2010). A third issue, compounding the problem, was the fact that the DoD regarded operations and maintenance (O&M) as a residual funding category and only allocated money toward it after all other needs were met. Fourth, even as the DoD sought to save money by demolishing unneeded buildings, M&R budgets have decreased faster than the amount of space to be maintained (GAO, 1997). Fifth, the lack of funding coupled with a "run-to-failure" mentality led to continually deferred maintenance. Finally, while the DoD was facing aging facilities, it failed to assign accountability among leadership for assets and lacked the data to defend maintenance and repair budgets (NRC, 2012). In 1996, the Federal Facilities Council identified the need to make preventive maintenance the "cornerstone of a solid cost-effective [maintenance and repair] program" (NationalAcademies, 1996). The call for increased preventive maintenance has driven the need to identify those maintenance needs and when during an asset's life they should be accomplished.

In 2013, the DoD owned 2.3 billion square feet of real estate and spent 55% of its real property maintenance funds on emergency reactive maintenance or repair work. The financial pressures which led to decreased efforts to inspect aging infrastructure caused the neglect of systems which may have benefitted from preventive maintenance. Avoiding reactive repair work and keeping DoD budgeting decisions within the preventive and proactive maintenance domain required a method by which buildings, their systems, and their components could be tracked throughout their lifecycle. The system, developed by the Engineering Research and Development Center (ERDC), was called the BUILDER Sustainment Management System (SMS) and was implemented as an Air Force Asset Management tool in 2013 ("BUILDER Sustainment Management System," 2014).

The BUILDER system is a program which lists all the facilities within a base. From there, each facility is broken down into systems (for example, the HVAC system), components (a chiller unit), and subcomponents (the compressor). Ideally, each subcomponent, component, system, and facility is assessed and assigned a condition index between zero (failed) and 100 (new condition). Based on this condition index, the useful life of the infrastructure is tracked, and maintenance can be scheduled to prevent failure and extend useful life. The condition index is used as part of the Air Force's risk assessment scoring model, which determines the likelihood of failure and the consequence of that failure. Lower condition indexes signify that components are at greater risk, therefore allowing the Air Force to determine which projects should be funded at what time to prevent failure and adequately extend the useful life of assets.

1.2 Research Questions

When BUILDER and the risk-based scoring model were introduced to improve the asset management program for the U.S. Air Force, the predicted outcomes included improved investment strategies, lifecycle tracking for infrastructure, complete asset accountability, real estate value accuracy, and asset condition awareness. One of the most significant goals of these changes was to motivate a transition from a reactive maintenance approach to a deliberate maintenance strategy. To measure the effectiveness of the changes, two levels of analysis are utilized. The first seeks to determine if Air Force asset managers have made an effort to request more funding for projects to sustain assets over the long term. The second level of analysis will determine, using case studies, the effect of preventive maintenance on the number, labor hours, and cost of reactive maintenance. The motivation for this research stemmed from curiosity about these trends and effects: has the Air Force been successful in requesting more funds towards sustaining existing infrastructure? Are these trends seen Air Force-wide as well as at base-level? Have these trends affected the amount of reactive maintenance and repair work required at the base-level? The answers to these questions could help determine the effectiveness of the changed brought about with the BUILDER software and the preventive maintenance asset management strategy.

1.3 Overview

This thesis begins with a literature review which will delve into the importance of and differences between different types of maintenance, the value of well-timed maintenance, and asset management strategies that are recommended for successful budgeting. It will also assess the Air Force Planning and Programming rules, project funding process, and how BUILDER works and is implemented to assist in the understanding of the research. The research method will then be described, followed by the results. The following discussion will describe the implications of the results and the limitations of the study. Finally, the conclusions section will summarize the findings and recommend additional studies based on the results discussed in this paper.

CHAPTER 2. LITERATURE REVIEW

This chapter will first discuss the different types of maintenance strategies and their characteristics. The benefits of preventive maintenance, along with evidence from literature, will follow. Risk matrices will be introduced before delving into the BUILDER program and the Air Force risk-based scoring model.

2.1 Maintenance Strategies

In an asset management guide written by the Army Corps of Engineers, four types of maintenance are identified: reactive, preventive, predictive, and proactive. Reactive maintenance, also known as "run-to-failure" or "corrective" maintenance, is fixing what has broken. Preventive maintenance is regularly scheduled inspection, cleaning, lubricating, etc. Predictive maintenance is maintenance based on inspection or performance data. Finally, proactive maintenance is designing or installing equipment to more effectively improve maintenance (Chalifoux & Baird, 1999). Where required maintenance can be predicted, it is in the facility manager's best interest to schedule operations in advance as it will decrease the rate of failure. A visual for this is provided by the Condition Based Maintenance Plus DoD Guidebook. Figure 1 shows how assets experience a decreasing rate of failure as the type of maintenance approach shifts from corrective to preventive, predictive, and proactive respectively. For each approach, pros and cons are listed based on the requirements to accomplish each approach.

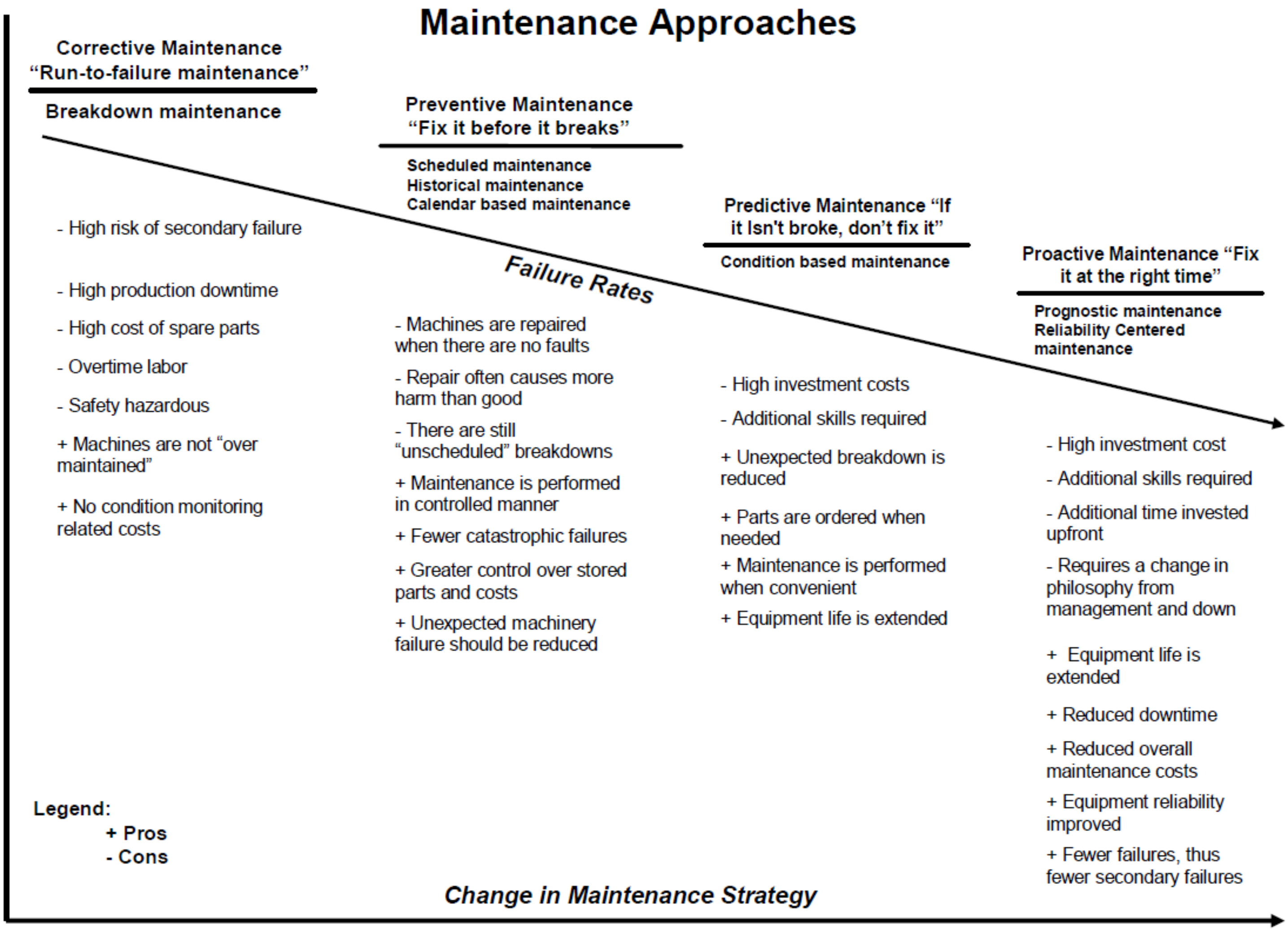


Figure 1: Trend in Failure Rates According to the Maintenance Approach (Bell, 2008)

2.2 Preventive Maintenance

The science behind the argument which states that proactively and preventively maintaining an asset can save more money in the long run than the initial cost of the building itself is not clear-cut. Facilities and their systems are becoming increasingly intricate with new technology, environmental and building code standards, and evolving user requirements. The purpose and goals of the company also affect the asset management principles they adopt. An example of success can be found in a study done on an Egyptian Glass Company. They experienced many benefits by switching from reactive maintenance to proactive maintenance such as increased through-put, decreased production losses, increased equipment effectiveness, and cost savings from system failure prevention (Ismail Mostafa, 2004). The method to bring about change came in the form of software which could monitor asset condition data and assess maintenance needs. This type of software is increasingly invaluable as the complexity of building components and number of assets increases. Technologies designed to track, prioritize, and predict work can keep systems functioning properly before failure occurs. The more difficult it is to manage and schedule maintenance and repair work, the greater the risk of purely reactive operations becomes. Servicing component breakdowns and system failures takes more time, effort, and money to accomplish than it would have cost before the breakdown occurred (Marrano, 2010).

The most apparent advantage to making the maintenance strategy of a company more effective is the economic impact. By keeping facilities and facility components running smoothly, fewer spending spikes will be observed as fewer assets will break down or fail in ways that require contracted repair or replacement. In a study on Italian manufacturing firms, a survey-based empirical research strategy was employed to determine how user satisfaction was impacted by preventive and condition-based maintenance. For approximately 100 firms, preventive and condition-based maintenance produced greater satisfaction in terms of equipment availability performance, regardless of the firm’s size (Chinese & Ghirardo, 2010). Also, inconveniences like relocating personnel in an office while repair work is completed, for example, will be less frequent. Budgeting will become easier as sustainment management systems will be able to track the conditions of assets and identify approximately when maintenance must occur. Assets will also last longer, reducing long-term costs associated with replacement. The Engineer Research and Development Center (ERDC) provided conceptual graphs that show the potential impact of increasing preventive maintenance and repair based on the condition of the asset over time (Figure 2 & Figure 3). Along the y-axis, CI stands for the Condition Index of an asset, were a score of 100 represents a brand new or perfect asset condition and a score of 0 representing total failure. The service life gain shown in Figure 3 is a result of a well-timed repair.

Figure 2: Typical Asset Service Life (SL) (Marrano, 2010)

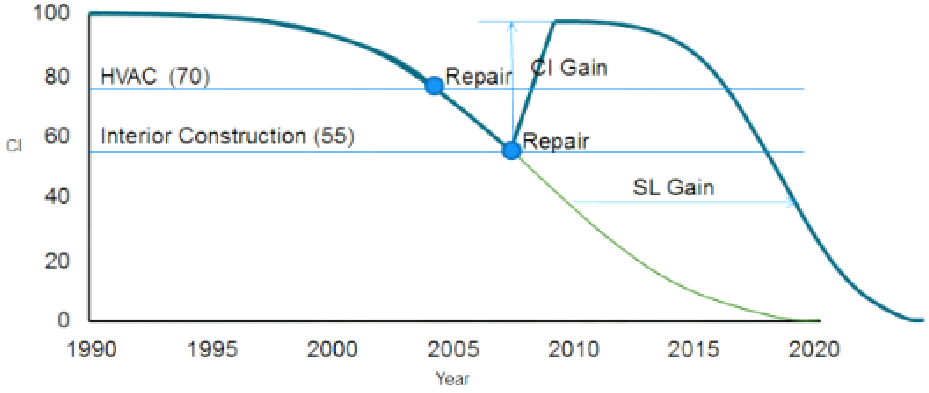
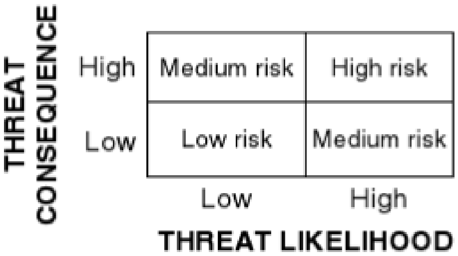


Figure 3: Asset Service Life (SL) when Appropriate Maintenance or Repair is Conducted (Marrano, 2010)

One of the benefits of a well-timed maintenance program is economic. A study conducted to determine if different maintenance strategies were linked to performance was accomplished using a survey. Plant managers and maintenance managers provided information about their plants and responded to questions concerning maintenance practices and performance measures for the past two years. Maintenance strategies were defined as either aggressive, proactive, or reactive based on the responses. Finally, the performance measures were compared between the three maintenance types. The results revealed a negative correlation between companies that conducted reactive maintenance and reductions in production costs. For proactive maintenance, the correlation with reduced production costs was positive (Swanson, 2001). Determining a system to rank maintenance work based on urgency or, the importance of an asset and the impact if its failure, is a valuable method for businesses. This fact is urged in a paper written in 1978 entitled Reliability Centered Maintenance, a report sponsored by the DoD. The document contains details of a comprehensive study conducted to outline the logical discipline of the triedand-true maintenance practices of United Airlines. The DoD was looking for an in-depth plan to implement for its own aircraft. The publication encourages identifying the most valuable assets based on the impact of their failure to the overall business strategy – a risk-based methodology (Nowlan & Heap, 1978). Labi (2014) discusses risk assessment in great detail. He describes the risk assessment framework as a method to determine how soon things will go wrong and what the consequences of that failure will be (Labi, 2014). Using a risk-based methodology as a guideline for asset maintenance, organizations can determine the threat to functionality based on the importance of an asset and how likely a failure will occur. For example, if a company has two HVAC units, one that services expensive electronic equipment and another that services office space, it may decide that the consequence of failure for the unit servicing the electronics is more severe than the consequence of failure for the unit servicing the offices. However, if the unit servicing the office space has a higher likelihood of failure, it may be in the company's best interest to service that one first. The decision-making process is not one-dimensional. To help visualize the Simplified Risk Matrix, refer to Figure 4. It shows the levels of risk for a high threat consequence and low threat consequence versus a high threat likelihood and a low threat consequence. An asset with low threat likelihood and low threat consequence corresponds to a low risk. Conversely, an asset with high threat likelihood and high threat consequence corresponds to a high risk.



THREAT CONSEQUENCE		THREAT LIKELIHOOD Low	THREAT LIKELIHOOD High
	High	Medium risk	High risk
	Low	Low risk	Medium risk

Figure 4: Simplified Risk Matrix (Labi, 2014)

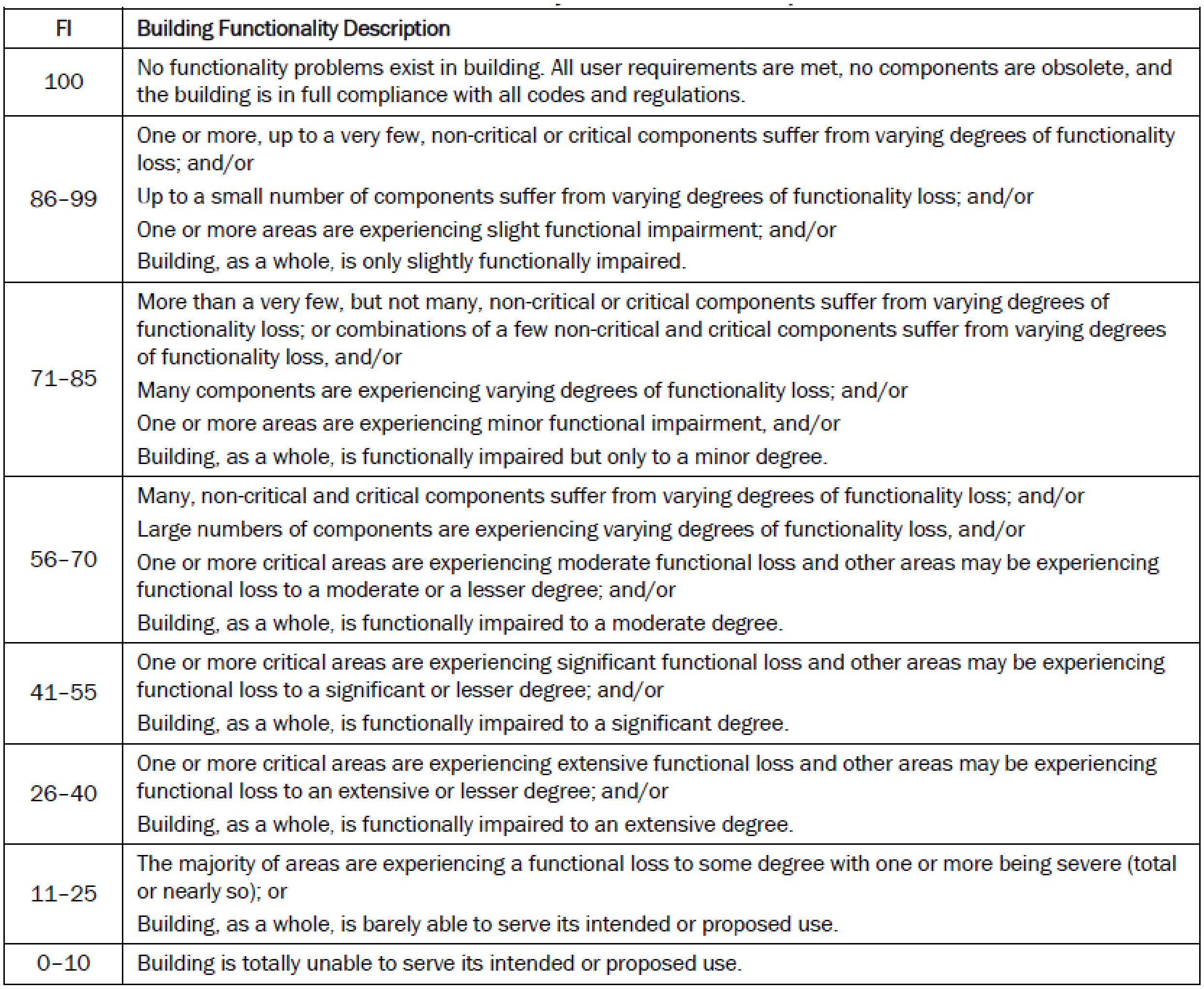
Decisions considering risk are not one-dimensional and both the consequence and likelihood will change over time. In the example with the HVAC units, the consequence may change with the seasons, employee demographics, and updated technologies. Similarly, the likelihood of failure will typically increase as the asset ages and decrease with subsequent repairs. Effective maintenance strategies should directly relate to the condition and operation status of the asset as it changes over time. The facility and its components' lifecycle cost can be decreased and its lifecycle increased when maintenance schedules are built on need as opposed to assumptions. Maintenance schedules should thus consider the capacity, material, and use of assets (Iijima & Takata, 2016).

2.3 BUILDER and the Risk-Based Project Scoring Model

The BUILDER Sustainment Management System is a database which functions like a Computerized Maintenance Management System (CMMS). It is important to note that CMMS has many functions beyond the scope of BUILDER, but as far as listing the assets, reporting their condition, and displaying lifecycle data, the systems are comparable. BUILDER breaks assets down into four distinct levels. The highest level is the facility level, then the systems within that facility, the components of that system, and finally the subcomponents (the lowest level). The inventory uses the UniFormat II classification system (Grussing, 2012). The first challenge a company faces when implementing BUILDER is the inventory. Like a CMMS, all the assets owned by the company must be imported or loaded into the system. As many details as are available should be included such as manufacturer, make/model, serial number, year installed, and previous maintenance and repair work. This process can take a significant amount of time when inventories are non-existent or in different formats throughout the enterprise. A DoD-specific data point is the Mission Dependency Index (MDI). This value indicates the mission-related importance of an asset and therefore helps to determine the consequence of failure (Grussing, Gunderson, et al., 2010). Though BUILDER can store ownership information (like which squadron is assigned to a building), it is not meant to function like a Computer-Aided Facility Management (CAFM) program or an Integrated Workplace Management System (IWMS). Such functions within the Air Force are conducted using ACES-RP (Automated Civil Engineer System – Real Property) and are not within BUILDER's scope.

Once the inventory has been loaded into the BULIDER software, the next step is condition assessments. The program requires a "starting point" from which to build prediction models. The condition of an asset is represented by a number between zero and 100. Maintenance personnel will inspect each asset and assign it a condition index based on Table 1. The table shows a range of condition indexes to describe varying levels of functionality in the first row (where FI stands for Functionality Index). The second row provides a description of the condition of the facility or asset according to the corresponding functionality index (Grussing, Marrano, & Walters, 2010). While determining the exact value within the range is a subjective decision, the table provides a higher level of guidance than was utilized in the past when condition assessments were not conducted.

Table 1: Functionality Index Interval Descriptions (Grussing, Marrano, et al., 2010)



FI	Building Functionality Description
100	No functionality problems exist in building. All user requirements are met, no components are obsolete, and the building is in full compliance with all codes and regulations.
86-99	One or more, up to a very few, non-critical or critical components suffer from varying degrees of functionality loss; and/or Up to a small number of components suffer from varying degrees of functionality loss; and/or One or more areas are experiencing slight functional impairment; and/or Building, as a whole, is only slightly functionally impaired.
71-85	More than a very few, but not many, non-critical or critical components suffer from varying degrees of functionality loss; or combinations of a few non-critical and critical components suffer from varying degrees of functionality loss, and/or Many components are experiencing varying degrees of functionality loss; and/or One or more areas are experiencing minor functional impairment, and/or Building, as a whole, is functionally impaired but only to a minor degree.
56-70	Many, non-critical and critical components suffer from varying degrees of functionality loss; and/or Large numbers of components are experiencing varying degrees of functionality loss, and/or One or more critical areas are experiencing moderate functional loss and other areas may be experiencing functional loss to a moderate or a lesser degree; and/or Building, as a whole, is functionally impaired to a moderate degree.
41-55	One or more critical areas are experiencing significant functional loss and other areas may be experiencing functional loss to a significant or lesser degree; and/or Building, as a whole, is functionally impaired to a significant degree.
26-40	One or more critical areas are experiencing extensive functional loss and other areas may be experiencing functional loss to an extensive or lesser degree; and/or Building, as a whole, is functionally impaired to an extensive degree.
11-25	The majority of areas are experiencing a functional loss to some degree with one or more being severe (total or nearly so); or Building, as a whole, is barely able to serve its intended or proposed use.
0-10	Building is totally unable to serve its intended or proposed use.

When the inventory is uploaded and condition assessments are complete, the BUILDER software will use colors to indicate the condition of assets. A red color will indicate an asset in poor condition, a yellow color will indicate an asset in moderate condition, and a green asset will indicate an asset in good condition. BUILDER will also build a graph to display the predicted life of an asset. As components or subcomponents are maintained, repaired, or replaced, the condition index will be updated and the graph will display an upgraded lifecycle prediction. While BULIDER will not schedule work, or have maintenance personnel data like a CMMS, it can be a useful tool in risk-based and preventive maintenance strategies.

To understand the project scoring model, it is important to comprehend the vocabulary and abbreviations that will follow. Program Element Codes (PECs) describe the funding pool through which a project will be funded. Projects are assigned PECs based on their Element of Expense Investment Codes (EEICs) which designate different types of work. These EEICs are more specific about the type of work and describe maintenance, repair, construction, and demolition, to name a few. Maintenance work is always considered a sustainment project because it is keeping an asset in working condition, but repair work can be either sustainment (SUS) or restoration and modernization (R&M), depending on the purpose of the repair. For example, it is expected that carpet will need to be replaced at regular intervals so although this would be considered repair work, it is classified as SUS because it is scheduled and designed to enable assets to reach their expected service life. R&M repair work is work needed to restore assets damaged due to poor sustainment practices or accidents like fire or natural disasters (USAF/A4C, 2016).

Projects are listed based on importance and condition or by consequence of failure and probability of failure. Figure 5 shows the Air Force project scoring model (very similar to the risk matrix described by Labi).

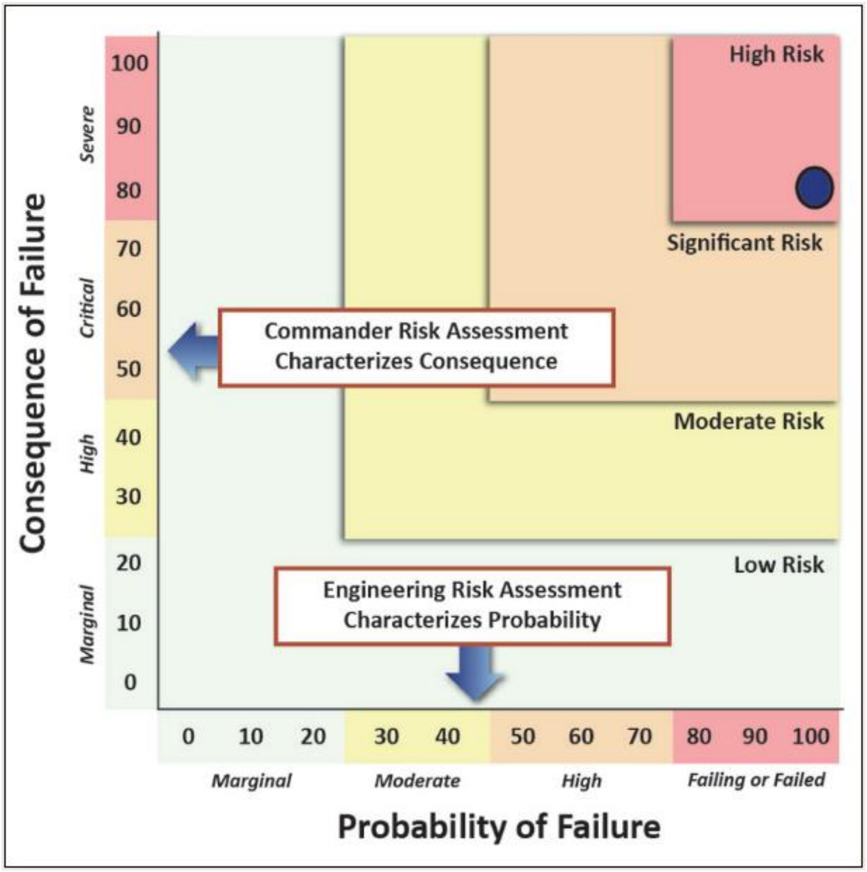


Figure 5: The Air Force Project Budgeting Scoring Model (Barrera & Payne, 2015)

The consequence of failure is determined based on two factors: the base commander's priorities and the mission dependency index, which classifies how vital the asset is to the overall mission. The probability of failure is a value determined by the condition index identified by BUILDER. The lower the condition index, the poorer the condition of the asset and, therefore, the higher the probability of failure.

The scoring system best described as follows:

> "A risk-based framework provides a simple, standardized way for installation commanders to accurately capture mission impact against the physical condition of key assets. This framework is both executable at the tactical level and informative at the strategic level." (Barrera & Payne, 2016)

The projects, once listed based on this risk-management model, are submitted to compete for a finite amount of funding for civil engineering projects. Once the projects are scored Air Force-wide, an approved list is released called the Air Force Comprehensive Asset Management Plan (AFCAMP). This list designates the monetary pool through which each project will be funded. Details on the AFCAMP will be discussed in the Methods section.

Sustainment management systems like BUILDER will easily integrate into Building Information Modeling (BIM) technology. Qing, Tao, and Ping (2014) propose a Building Lifecycle Management Platform for this integration. The system they describe combines BIM, usually utilized to design and construct a project, with Lifecycle Management (or sustainment management), which is a function of BUILDER. In this way, new projects can populate the lifecycle management component, thereby eliminating the need for initial condition assessments. With all the design and construction information already available, sustainment management systems will be even more effective as BIM data is carried throughout a facility's useful life. With proper continuity of information and updates, sustainment management systems could greatly simplify maintenance procedures (Qing, Tao, & Ping, 2014).

CHAPTER 3. METHODOLOGY

As mentioned in the introduction, two studies were accomplished the answer the research questions. The first was a macro-analysis, using data from the global U.S. Air Force. The second considered five individual bases. In this section, the methodologies for both studies is described.

3.1 The Macro-Study Methodology

The first analysis conducted was at a macro-level: it considered Air Force spending globally based on the AFCAMPs. As previously mentioned, the AFCAMPs are records of the amount of funds requested for various work types, or “pools” of money. The pools of interest to this research were PEC’s which indicated SUS and R&M projects. The budget analysis was conducted using available data from fiscal year 2013 through fiscal year 2017. Air Force bases worldwide submit project lists annually for the upcoming fiscal year, to include projects desired for the following year if said project is large or complicated and requires time for design or additional planning. The data was requested from the Construction Tasking Order Representative at the Air Force Civil Engineer Center in the spring of 2017. Five spreadsheets, one for each fiscal year, detailed the list of projects requested for that year and identified which have been approved for funding. Altogether, there were approximately 5,500 projects requested each year, with an average of 2,700 accepted for funding. The projects accepted for funding were included in the analysis, resulting in approximately 13,400 data points. SUS requirements are projects which keep assets in good working order. R&M requirements are projects designed to fix assets that have failed or have nearly failed. The term “other” describes “everything else,” which includes demolition, environmental, and new construction projects. The sum of the SUS, R&M, and other projects were then determined. “Other” projects identify requests that are funded using different pools such as demolition, environmental, energy, design projects. These results were analyzed by determining the percentage of the total approved funds on the AFCAMP for each funding pool. This way, the percentage of money allocated for SUS projects versus R&M projects could be compared over time.

3.2 The Case Study Methodology

The case study was conducted on five different bases within the continental U.S. between fiscal years 2010 to June 2017. The data, made available by the Air Force Life Cycle Management Center, provided information on every work order from those bases in those years as recorded in the Interim Work Information Management System (IWIMS). IWIMS was a CMMS used by the Air Force before beginning to transition to Tririga in 2015. The data included any work order which was completed, in progress, drafted, or backlogged. This means that any negative trends are not the product of a growing backlog, but a representation of less work identified for that LUC.

The data provided the fiscal year, base name, facility number, craft, Labor Utilization Code (LUC), labor hours, and cost for each work order. Fiscal year (FY) is a budgeting period from October of the previous year until the end of September in the identified year. For example, FY 2014 is a period of time between October 1, 2013, through September 30, 2014. The base name has been replaced with identifiers 1-5 to protect the identity of case study participants. Each base has similar population sizes and similar geographic locations (to ensure comparable climates), but each belongs to a different Air Force Major

Command. This means simply that their missions, type of equipment and facilities, and requirements differ. The facility numbers are identifiers for different facilities and infrastructure within the bases. The craft identifies the nature of the work accomplished. Some examples of crafts include electric system, pavement, and HVAC work. Some craft identifiers, such as landscaping and entomology, were eliminated from the dataset as they were determined irrelevant. Additionally, because there were so many categories of craft and some had very few observations, crafts were generalized into six systems groups: plant operations (water, heat, electric, waste), primary facility systems (electric, plumbing, HVAC), horizontal and vertical construction (roads/sidewalks, facilities), environmental controls and alarm systems, specialized teams and systems, and contractor work/project management. These variables are treated as categorical in the analysis and their descriptive statistics are shown in Table 2. Column one shows the variable, column two displays the number of observations for that variable, and column three shows the percentage of the total N observations in the overall dataset. Note that facility number is not shown due to the large number of distinct values.

Table 2: Descriptive Statistics for Categorical Variables

Categorical Variables	N	Percent
Fiscal Year		
2010	8,352	12.7
2011	7,885	11.9
2012	8,545	12.9
2013	8,622	13.1
2014	8,915	13.5
2015	9,008	13.6
2016	9,213	14.0
2017	5,456	8.3
Base Code		
1	18,338	27.8
2	10,457	15.8
3	9,021	13.7
4	6,965	10.6
5	21,215	32.1
System Groupings		
Plant Operations (water, heat, electric, waste)	767	1.2
Primary Facility Systems (electric, plumbing, HVAC)	38,210	57.9
Horizontal/Vertical construction (roads/sidewalks, facilities)	12,844	19.5
Environmental controls and Alarm systems	9,576	14.5
Specialized teams and systems	2,816	4.3
Contractor work/project management	1,783	2.7

Note. Total *N* = 65,996. There are 2,976 facilities nested in the five bases.

The LUCs identify the type of work, for example, emergency, routine, or urgent work. Though 16 LUCs exist, the ones of interest to this study were LUC 11, 12, 14, 16, 18, 19, which correspond to recurring, emergency, urgent, recurring, work requests, and plant operations, respectively. Other LUCs, primarily those used to indicate indirect work such as supervision and leave, were eliminated from the dataset. Recurring work is repetitive work expected to be done at regular intervals and usually identified by the shop expected to complete the work. This type of work includes preventive maintenance. Emergency work is work that must be responded to immediately and usually poses a risk to life, health, or safety. This type of work could be a pipe burst, electrical line down, or a power outage. Emergency work can be the result of failed or delinquent preventive maintenance. Urgent work must be responded to quickly but does not pose a significant threat to operational effectiveness or government property. Routine work is corrective maintenance and most times it is identified by the users within a facility. Emergency, urgent, and routine work are all considered corrective maintenance. Work requests include all other maintenance and repair requests from users, and plant operations are actions required to continue providing utilities which are generated by the base itself (like electricity production or waste water treatment). After trimming and reformatting of the data, a column for count, labor hours, and cost were added. The count column identified how many times a particular type of work (LUC) was accomplished to a specific facility within a specific base within a specific year. Labor hours and cost columns showed the sum of the labor hours or cost corresponding to a type of work within the facility within the base within the year. The cost-values were adjusted for inflation and translated into 2017 values using the average inflation rate between January 2010 and June 2017 of 1.73%. Finally, the data was put into long-form wherein each variable is a column-heading, allowing for the analysis of specific measurements of LUCs to be studied as variables. A column for each LUC measured in each of the three ways mentioned (count, labor hours, and cost) was created. A summary of the data in this form is shown in Table 3. The columns display the variable, the number of observations, minimum values, maximum values, the mean, and the standard deviation (SD). Because some of the LUC-cost data points were negative values, they were excluded, resulting in a smaller N than the total N of 65,996.

Table 3: Descriptive Statistics for the Outcomes of the Case Study

Variable	Observations	Minimum	Maximum	Mean	SD
Recurring Work - Count	65,996	0	8	0.53	0.58
Emergency Work - Count	65,996	0	4	0.22	0.47
Urgent Work – Count	65,996	0	4	0.38	0.60
Routine Work - Count	65,996	0	6	0.71	0.71
Work Orders/Requests - Count	65,996	0	5	0.11	0.34
Plan Operations - Count	65,996	0	5	0.16	0.41
Recurring Work - Labor Hours	65,996	0	23,925	12.98	191.48
Emergency Work - Labor Hours	65,996	0	1,021	2.34	12.30
Urgent Work - Labor Hours	65,996	0	2,777	8.43	40.20
Routine Work - Labor Hours	65,996	0	13,906	28.54	134.56
Work Requests - Labor Hours	65,996	0	21,609	12.48	222.58
Plan Operations - Labor Hours	65,996	0	163,296	35.66	1,390.87
Recurring Work - Cost	65,996	0	$ 1,438,885	$ 816.07	$ 11,783.79
Emergency Work - Cost	65,996	0	$ 94,346	$ 155.33	$ 987.73
Urgent Work – Cost	65,992	0	$ 324,345	$ 649.49	$ 3,816.20
Routine Work – Cost	65,982	0	$ 872,612	$ 2,024.48	$ 8,703.46
Work Orders/Requests - Cost	65,949	0	$ 5,236,750	$ 2,169.11	$ 44,768.82
Plant Operations - Cost	65,991	0	$ 11,854,189	$ 2,292.15	$ 100,977.31

Note. Negative costs recoded as missing.

The data, being nested into three distinct levels (time, facilities, and bases) were analyzed using Hierarchical Linear Modeling (HLM). This type of statistical analysis is appropriate for clustered data because nested observations violate the traditional regression assumption of independence and homoscedasticity. Linear regression models assume that all observations are independent; however, for this case study data, observations within clusters share common setting (for example, within bases). Homoscedasticity is the assumption that, for all values of the predictor variable, the variance around the regression line is the same. A commonly used example to describe clustering in HLM datasets are students within classrooms within schools. The performance of a student will vary based upon to which classroom they are assigned and to which school they attend. Students within the same classroom share something in common that students from another classroom will not be exposed to. Variance in schools adds another level of commonality between students who attend the same school as compared to students who attend a different school. These levels of variance are accounted for using HLM which produces a more accurate inferences.

For the data studied, the count, labor hours, and costs for a type of work vary between years at different facilities within different bases. Each facility has multiple observations for each year. Yearly count, labor hours, and costs are nested within facility and those facilities are nested within bases. This nested structure of the data dictated the assignment of the levels: year as level 1, facility as level 2, and base as level 3.

To begin the analysis of the data, the means of the variables were determined and plotted against the year to identify aggregate trends in the data. However, these figures do not account for differences between bases, facilities, and craft codes. The visual displays of trends were followed by fitting an "empty model" without covariates to determine how much variance in the outcome occurs at each level. Finally, the full HLM model was fit that treated the year and the systems group (the generalized craft code) as fixed effects. Fixed effects are factors for which all possible levels are present. In the case of this study, the only available years are 2010 through 2017; therefore, each level is included. The same is assumed for the systems groups and therefore it is treated as a fixed effect. The outcome of fixed effects is analyzed built on a baseline, which was 2010 for the fiscal year (as it was the first year chronologically) and plant operations for the systems group (chosen arbitrarily). Because systems group is chosen arbitrarily, figures are used to interpret results

– given that the model can only be interpreted with reference to the baseline. Due to significant skew in the dependent variables, the HLMs were fit to natural log transformed versions of the outcomes. Because some of the values were zero and would therefore result in an undefined log value, a value of 0.01 was added to each variable before taking the logs. Results were un-logged and shown in percentage for interpretation. These results were compared with the aggregated analysis which did not factor for base and facility to demonstrate the added accuracy of HLM.

CHAPTER 4. RESULTS

This chapter details the results of the studies. The macro-study is presented first. Descriptive statistics are included to create an understanding of the data before analysis. The case study follows, with each step described in the Methods section included.

4.1 The Macro-Study Results

Each year, a range of 4,700 to 6,200 requirements were identified to compete for funding. Of these, an average of 2,700 were selected each year. Approval rates varied from 55-63% annually. The projects requested and approved varied in cost and size. Table 4 shows the annual average cost, maximum cost, and minimum cost for each project type (R&M, SUS, or Other).

Table 4: Descriptive Statistics for Project Costs for Each Fiscal Year

Year and PEC	Minimum	Maximum	Mean
Fiscal Year 13/14			
R&M	$ 10,000	$ 15,000,000	$ 79,123
SUS	$ 84,115	$ 8,803,754	$ 29,506
Other	$ 150	$ 26,000,000	$ 183,015
Fiscal Year 14/15			
R&M	$ 11,300	$43,000,000	$ 136,696
SUS	$ 30,000	$ 81,200,000	$ 83,171
Other	$ 100	$ 99,428,908	$207,533
Fiscal Year 15/16			
R&M	$ 60,000	$ 15,750,700	$ 673,657
SUS	$ 5,000,000	$ 81,200,000	$ 546,553
Other	$ 5,000	$ 13,700,000	$ 505,746
Fiscal Year 16/17			
R&M	$ 1000	$ 22,216,090	$ 162,160
SUS	$ 22,048	$ 58,200,000	$ 148,309
Other	$ 60	$ 15,000,000	$ 87,037
Fiscal Year 17/18			
R&M	$ 2,500	$ 41,578,300	$ 190,688
SUS	$ 5,200	$ 21,559,000	$ 172,656
Other	$ 60	$ 11,600,000	$ 100,417

The sum of the R&M project costs, SUS project costs, and Other project costs are shown in Table 5 for each fiscal year. The total amount allocated for each fiscal year is shown for each year. Additionally, to normalize the data, the total for each project type was compared to the total approved funding amount for the fiscal year. This information is displayed as a percentage in the rightmost column in Table 5.

Table 5: Approved Funding and Percentage on AFCAMPs

	Funds Allocated	Percentage
Fiscal Year 13/14		
R&M	$ 225,499,325	27.13%
SUS	$ 84,091,496	10.12%
Other	$ 521,591,612	62.75%
Total	$ 831,182,433	
Fiscal Year 14/15		
R&M	$ 542,547,235	31.98%
SUS	$ 330,106,272	19.46%
Other	$ 823,700,396	48.56%
Total	$ 1,696,353,903	
Fiscal Year 15/16		
R&M	$ 443,864,076	39.03%
SUS	$ 360,117,010	31.67%
Other	$ 333,229,862	29.30%
Total	$ 1,137,210,948	
Fiscal Year 16/17		
R&M	$ 561,324,903	39.31%
SUS	$ 515,965,599	36.14%
Other	$ 350,482,341	24.55%
Total	$ 1,427,772,843	
Fiscal Year 17/18		
R&M	$ 653,297,275	39.68%
SUS	$ 591,518,874	35.93%
Other	$ 401,540,576	24.39%
Total	$1,646,356,725	

To visualize the data, the percentages per year of R&M versus SUS projects are displayed graphically in Figure 6. Other projects were excluded for the sake of comparison between the target project types. As Figure 6 shows, the percentage of funds allocated for SUS projects each fiscal year has increased. Results show that the percent of funds assigned to SUS projects has increased by a total of 26% since fiscal year 2013 and only 13% for R&M projects over the same amount of time. R&M percentages also increased, but at a slower rate before leveling out in fiscal years 15/16, 16/17, and 17/18.

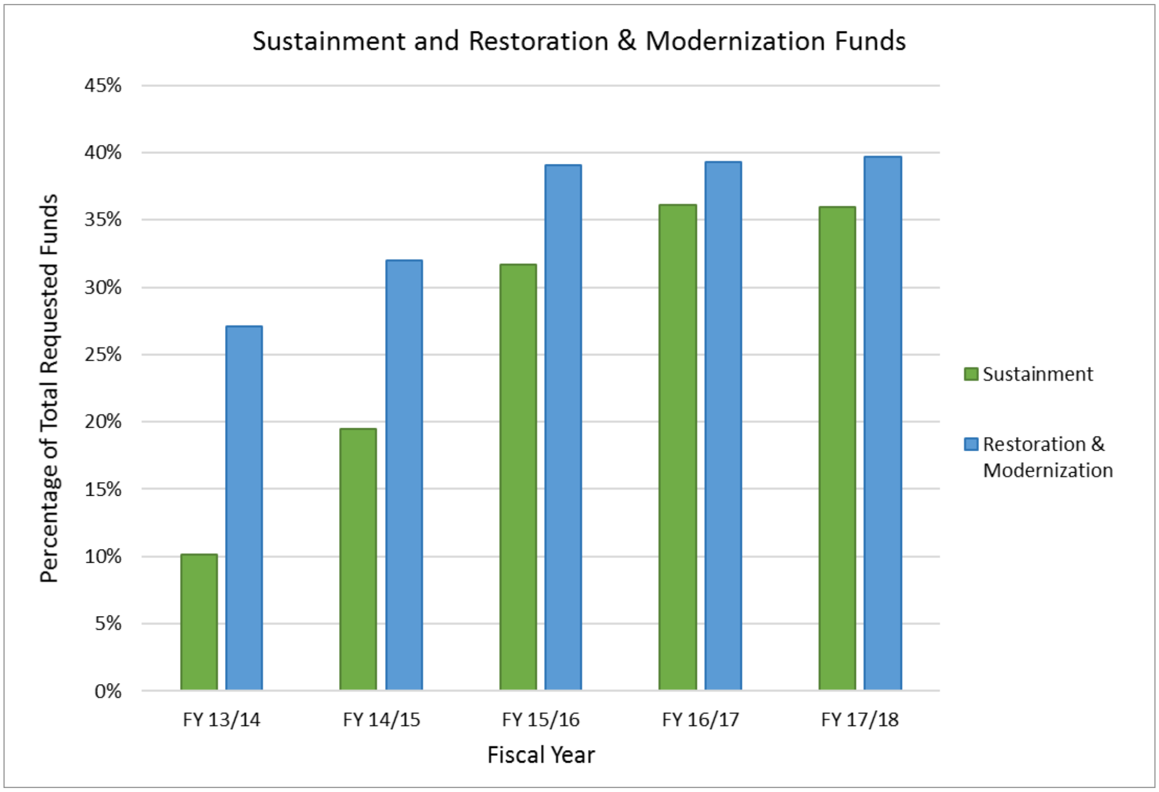


Figure 6: Sustainment and Restoration & Modernization Funds Over the Last Five Fiscal Years

To analyze the gap between SUS and R&M funds, Figure 7 displays the difference in the percentage of funds allocated to SUS versus R&M. The graph shows that the percent difference between the project classifications has decreased from 17% to about 4% over the last five years. This would indicate that the Air Force may be "closing the gap" between SUS and R&M activities.

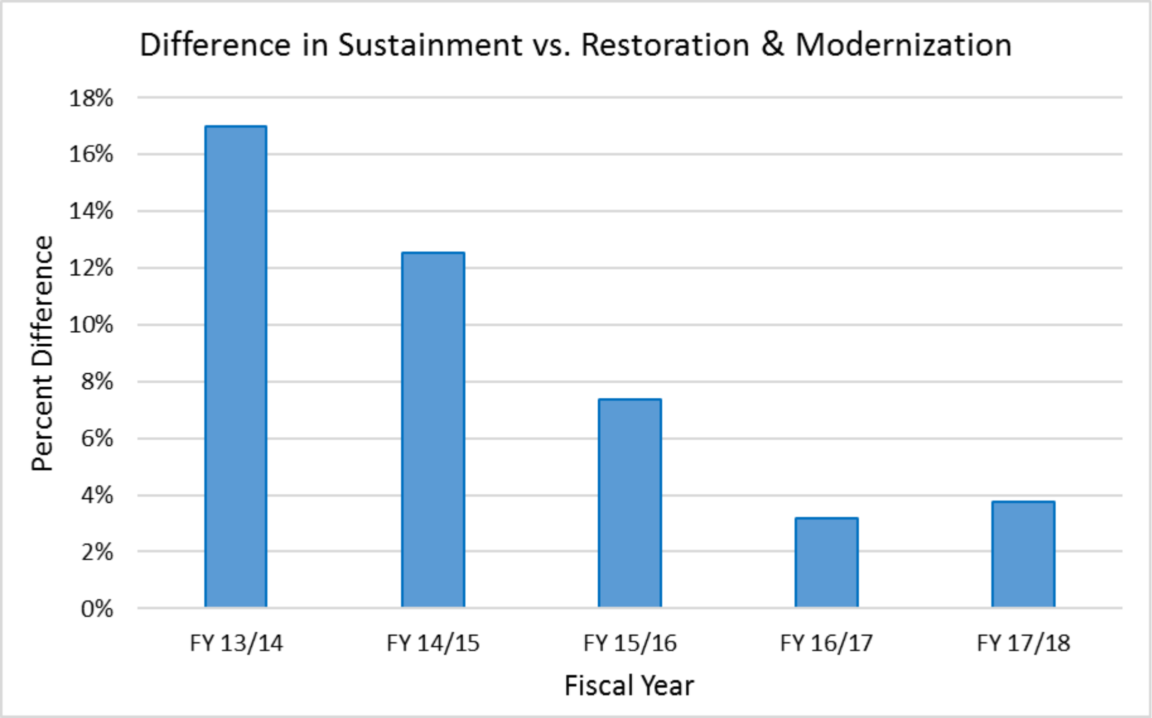


Figure 7: Difference in Percentages of Sustainment and Restoration & Modernization Funds Over the Last Five Fiscal Years

4.2 The Case Study Results

The first objective when analyzing the case study data was to visualize trends over time before adjusting for base, facility, or systems group. This was done by taking the means and standard deviations across all bases and facilities for each LUC (11, 12, 14, 16, 18, and 19) and measurement (count, labor hours, and cost). It is worth mentioning for this investigation that fiscal year 2017 was only six months in at the time this data was taken and that Base 4 data for this year is missing. The sample size was still significantly large though; therefore, it was conjectured that the missing information would not alter the results shown below significantly. Additionally, the research assumes that, since there is nothing drastically different about the end of the year versus the beginning of the year and nothing drastically different about Base 4 versus the other bases, the results are not significantly affected. Another important note is that the government shutdown in 2013 caused budgetary and workflow issues for the DoD and therefore many functions shut down at bases throughout the world. Only variables which identified preventative or corrective maintenance are displayed below; graphs for work order requests and plant operations variables are available in Appendix A. For all graphs, the points represent means at each year and the bars represent 95% confidence intervals. Figure 8 shows the trend in the mean count of recurring work. Though it is not always linear, there is a positive overall trend from 2010 to 2017 in the number of times recurring work was executed. This indicates that the number of times maintenance and repair personnel set out to accomplish things like preventive maintenance have increased over the years.

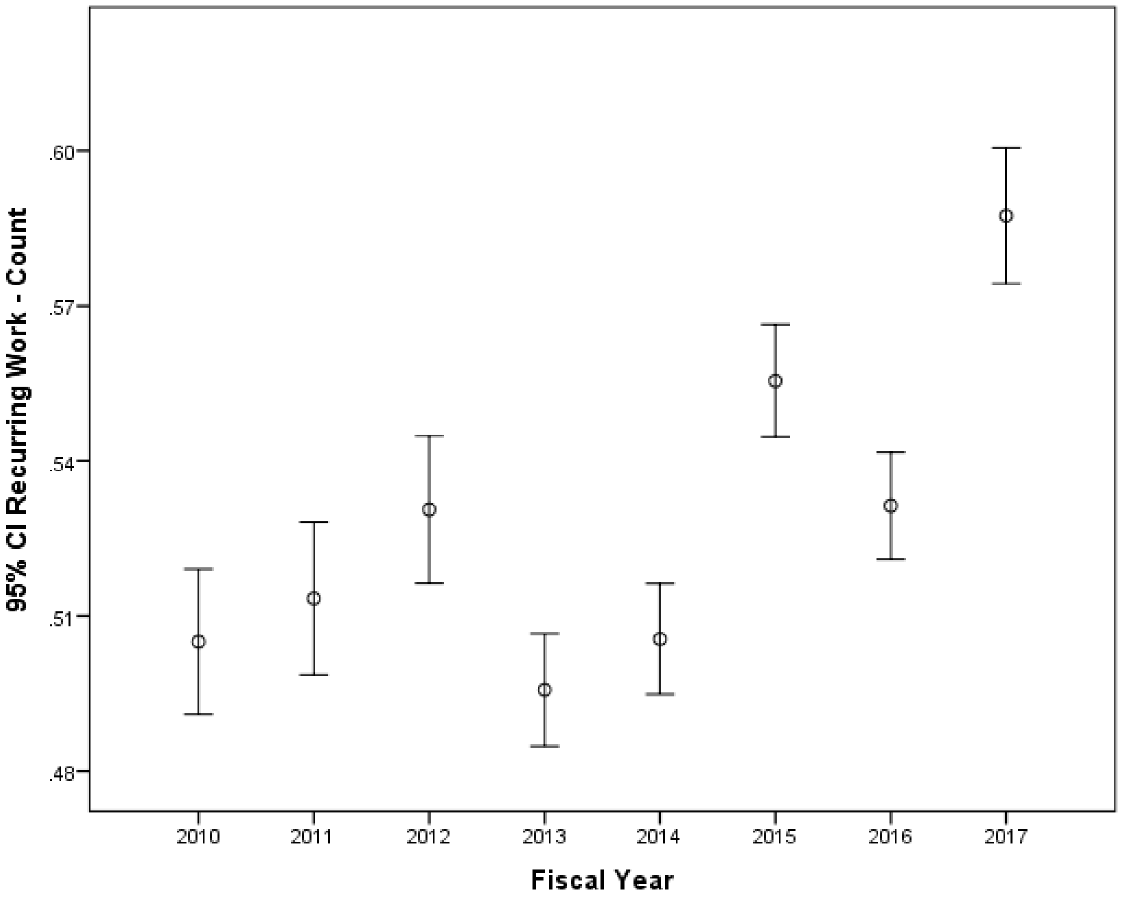


Figure 8: Means and standard deviations of recurring work count by year across all bases and facilities

Figure 9 is again a measure of the mean frequency of work, but in this case, it is emergency work. There is a dip in 2012 and 2013 before another rise and fall. Overall, before accounting for facility and base-level variability and controlling for fixed effects, the trend is negative.

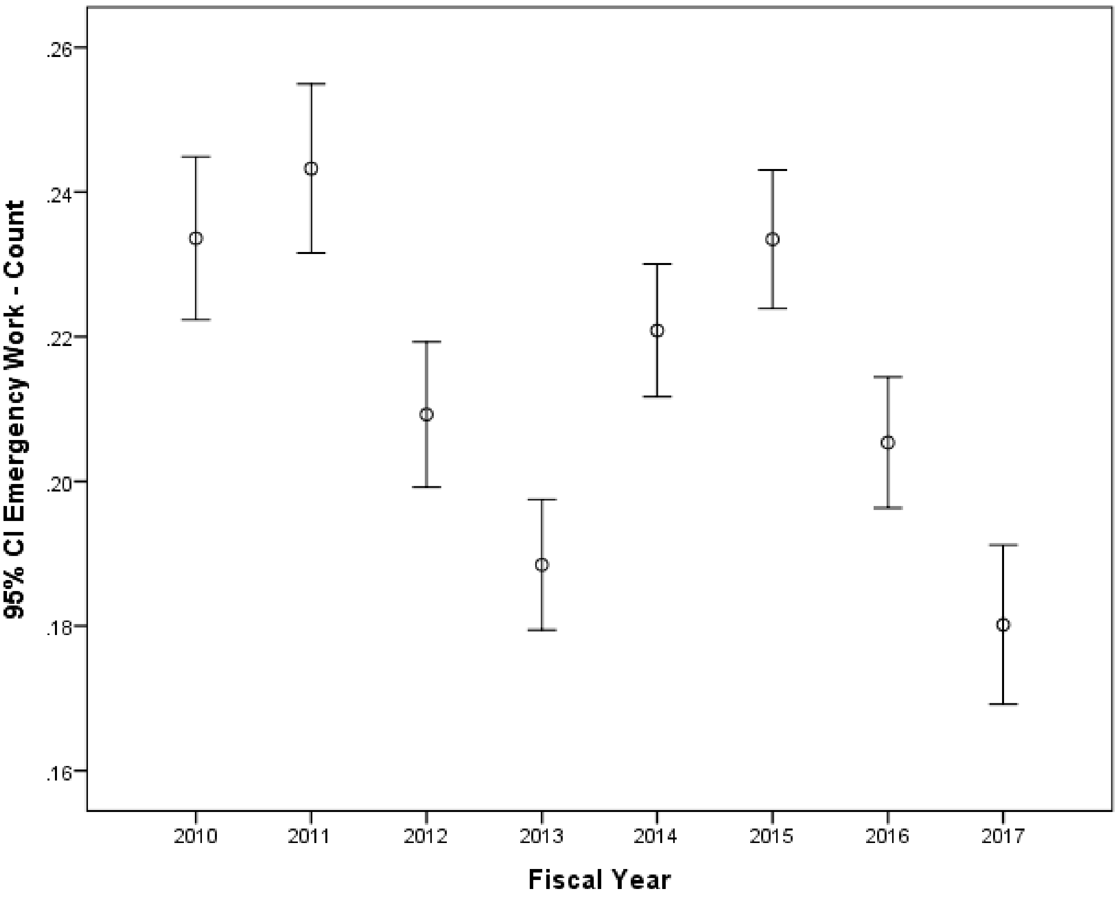


Figure 9: Means and standard deviations of emergency work count by year across all bases and facilities

Figure 10 shows the trend of the means of the frequency of urgent work over time. Urgent work is sometimes defined as recoded emergency work. Once emergency work has mitigated the primary issue (stopped the flow of water from a burst pipe), urgent work embodies other requirements to return the facility or equipment to working condition (replacing the pipe and the drywall). Though a positive trend permeates the first seven years of data, it drops drastically in 2017.

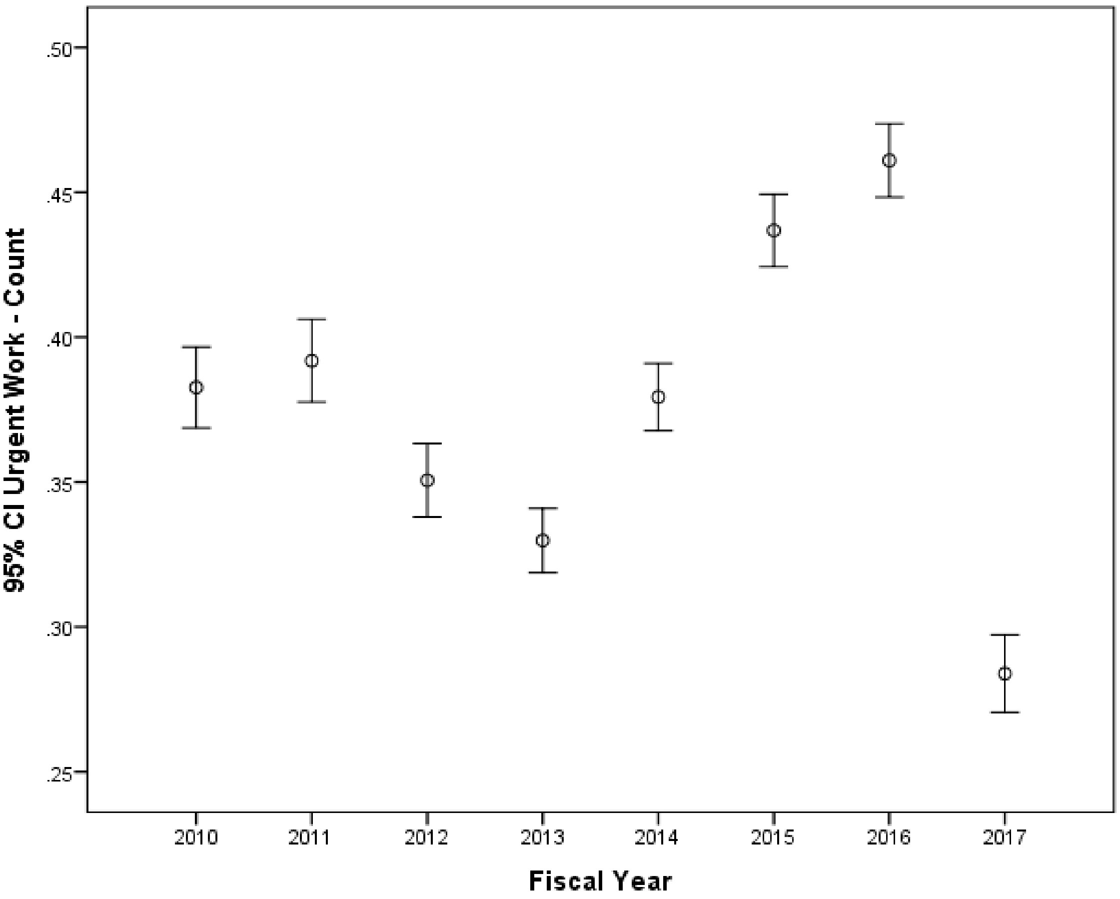


Figure 10: Means and standard deviations of urgent work count by year across all bases and facilities

Figure 11 shows the mean frequencies of routine work over time. Routine work is corrective maintenance on facilities or equipment. There appears to be a negative trend from 2012-2017.

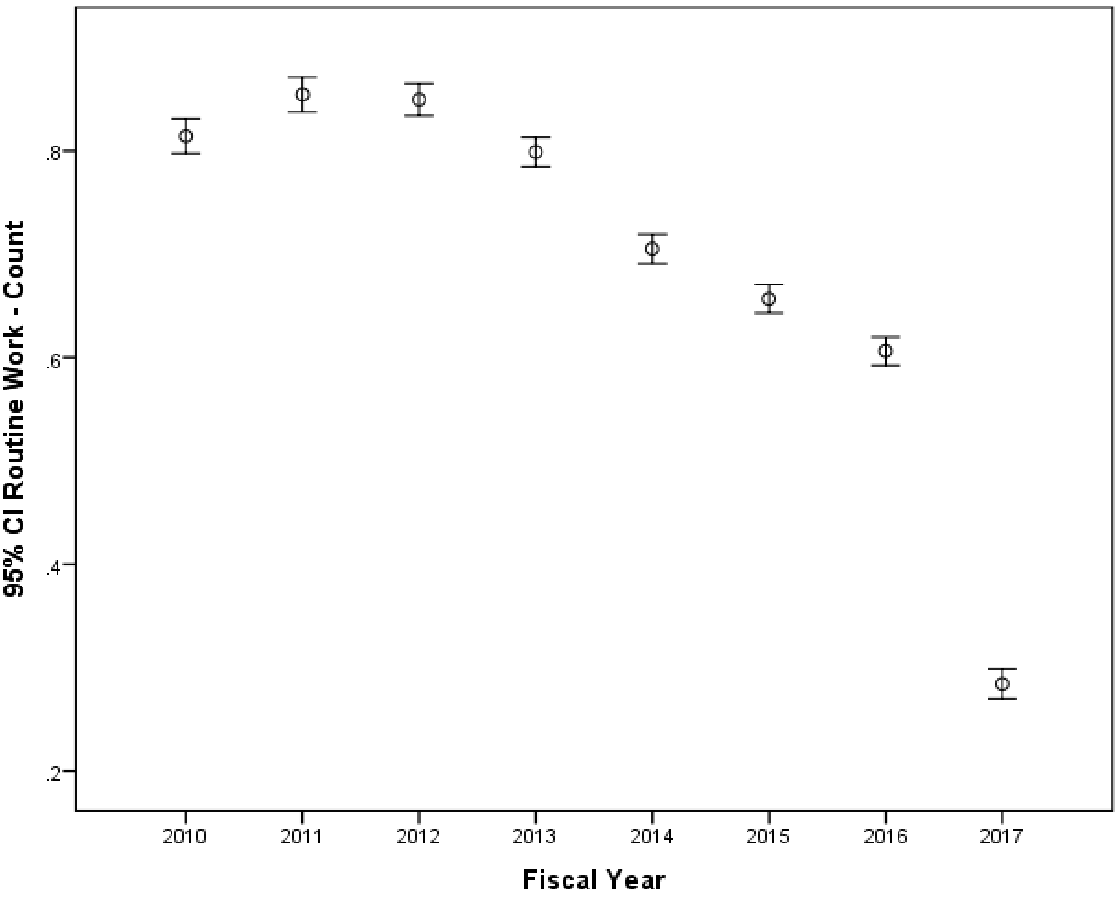


Figure 11: Means and standard deviations of routine work count by year across all bases and facilities

Figure 12 shows the means and standard deviations of recurring work hours over the years. It is difficult to say that there is any positive or negative trend, especially considering the confidence intervals in 2014, 2015, and 2016. The graph demonstrates that though the counts of recurring work seem to be rising, the mean labor hours seem to be more consistent over the years.

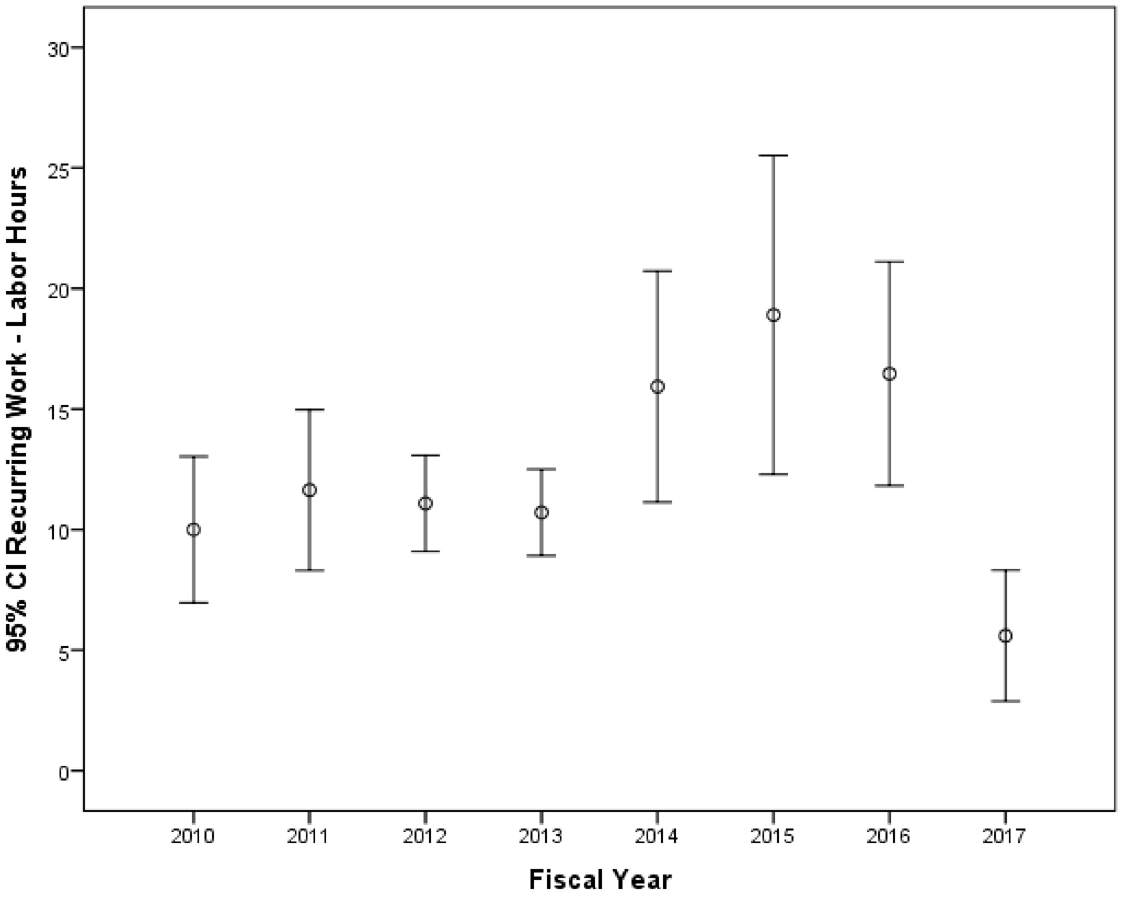


Figure 12: Means and standard deviations of recurring work hours by year across all bases and facilities

Figure 13 displays the means and standard deviations of emergency work hours by year. Here, though the trend is less than apparent, there is a clear jump in the number of labor hours spent on emergency work orders in 2014. It could be a possible side-effect of the government shutdown which may have left a lot of equipment in disrepair and on the verge of failure.

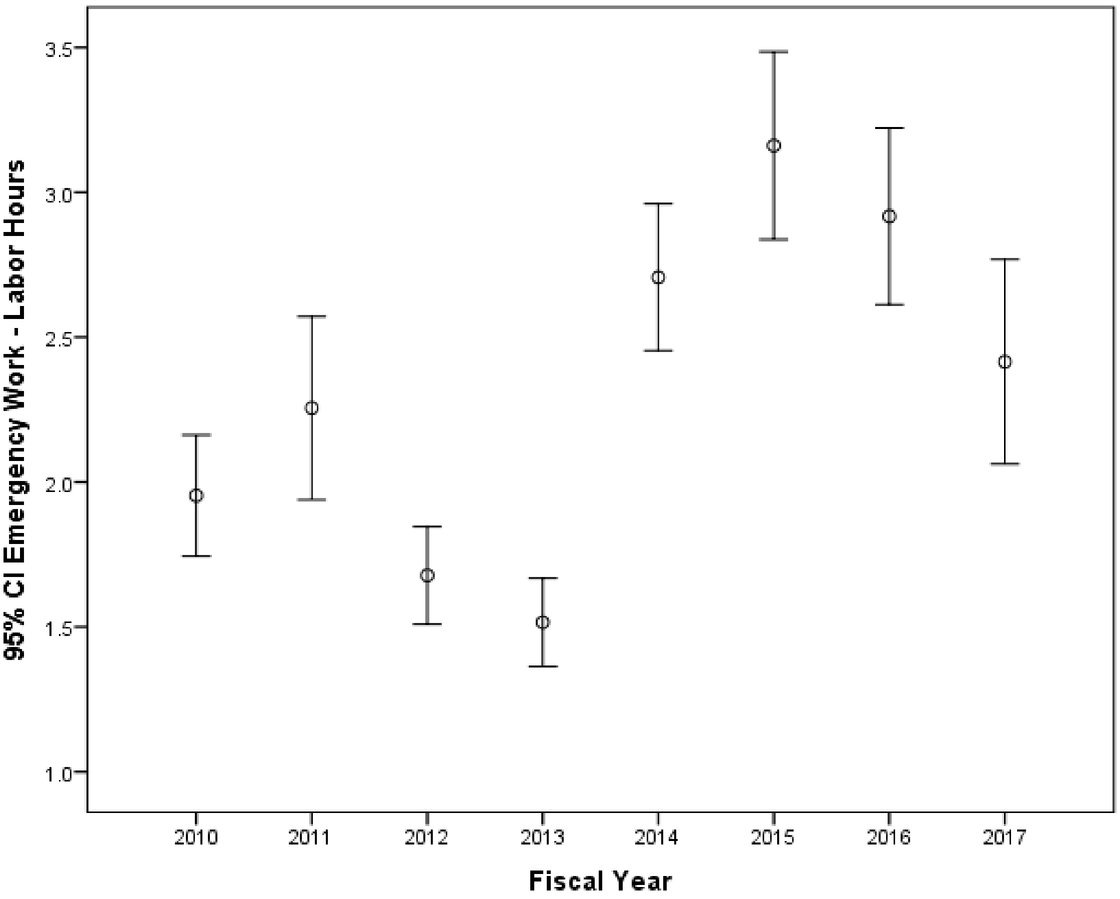


Figure 13: Means and standard deviations of emergency work hours by year across all bases and facilities

Figure 14 shows urgent work labor hours means over time. What appears to be a steady allocation of labor hours jumps in 2014-2016. Again, urgent work is sometimes recoded emergency work and the 2014 spike matches emergency labor hours means.

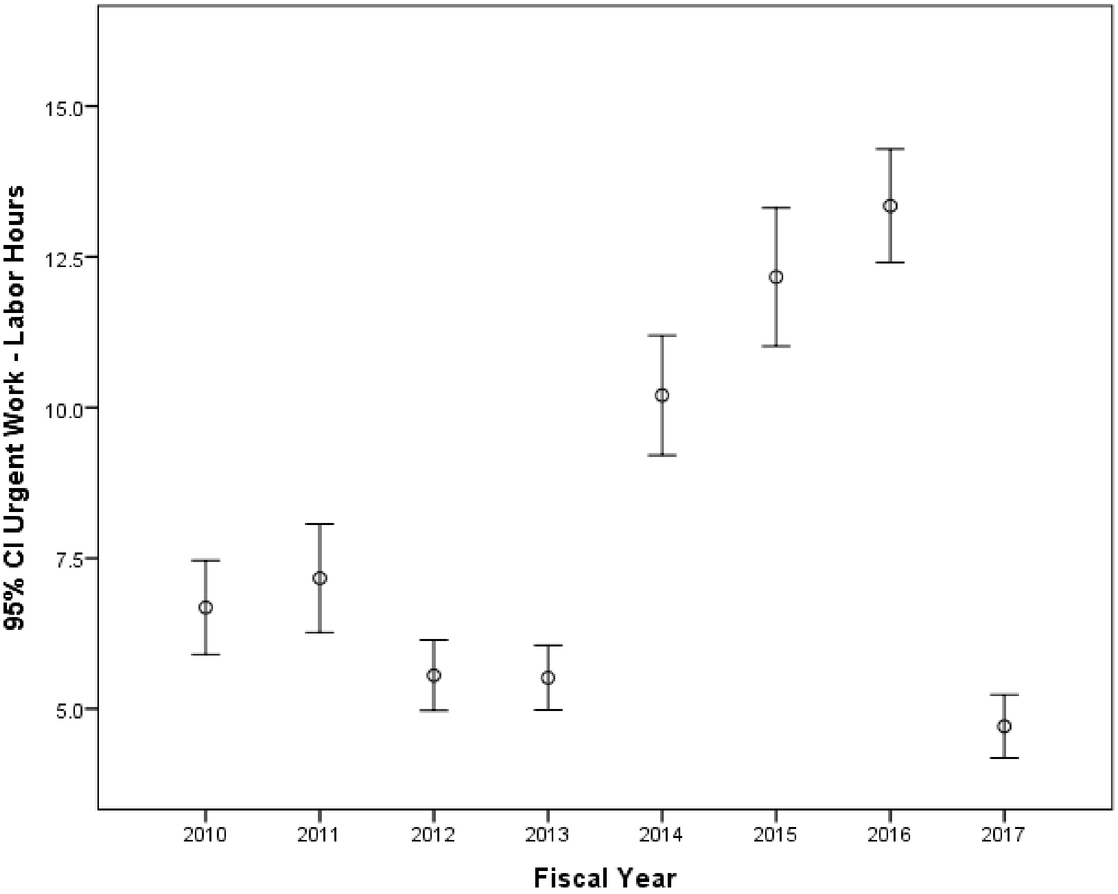


Figure 14: Means and standard deviations of urgent work hours by year across all bases and facilities

Figure 15 shows the means and standard deviations of routine work based on labor hours over time. There is a negative trend for this type of work measured in labor hours, much like the trend for the mean count values for this type of work. Between count and labor hours, routine corrective maintenance has had the most consistent and apparent trend.

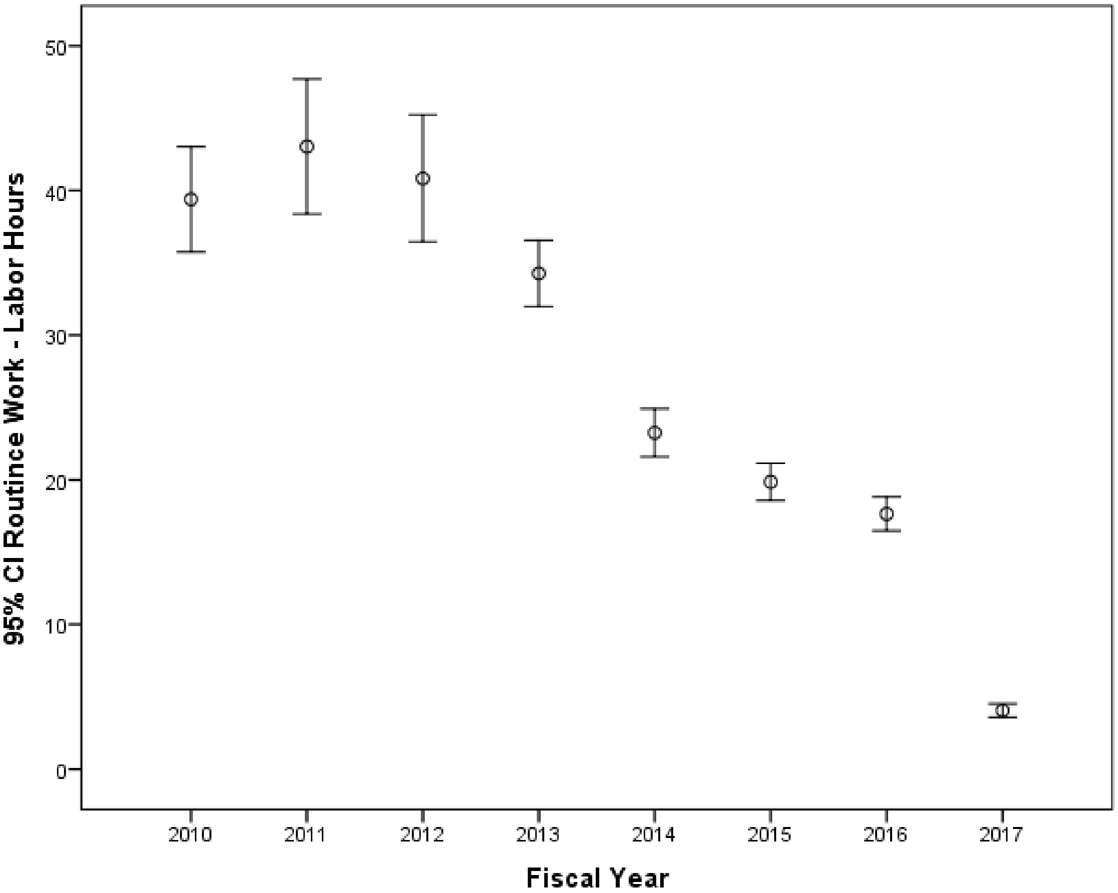


Figure 15: Means and standard deviations of routine work hours by year across all bases and facilities

Figure 16 displays the means and standard deviations of recurring work inflation-adjusted cost over the years. There seems to be a slight increase in mean cost in 2014-2016 before the dip in 2017. Despite this, there seems to be a steady trend for the cost, much like the labor hours graph for this work type.

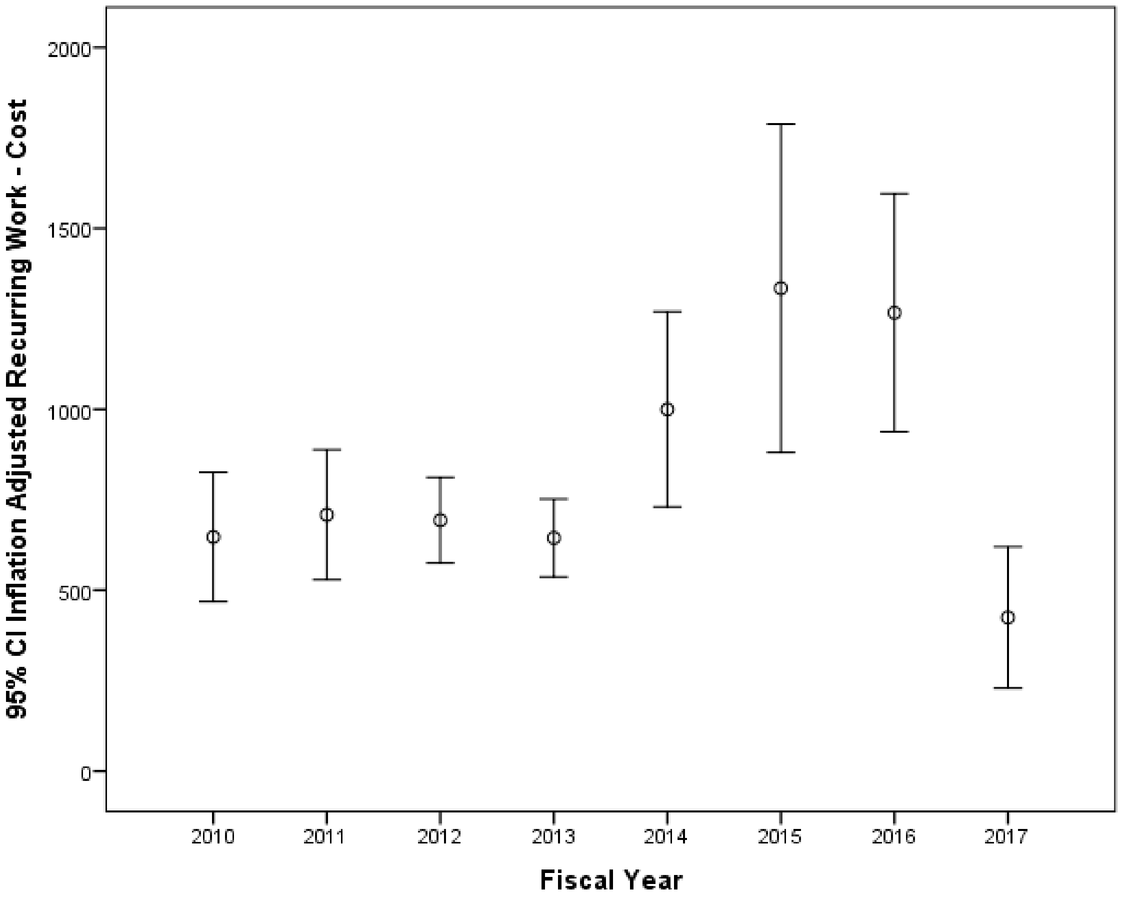


Figure 16: Means and standard deviations of recurring work inflation-adjusted cost by year across all bases and facilities

Figure 17 shows the means and standard deviations of the inflation-adjusted cost of emergency work over time. The trend seems to have a slight negative trend before climbing upwards in 2014 and 2015. This trend mimics the mean emergency work labor hours trend as well.

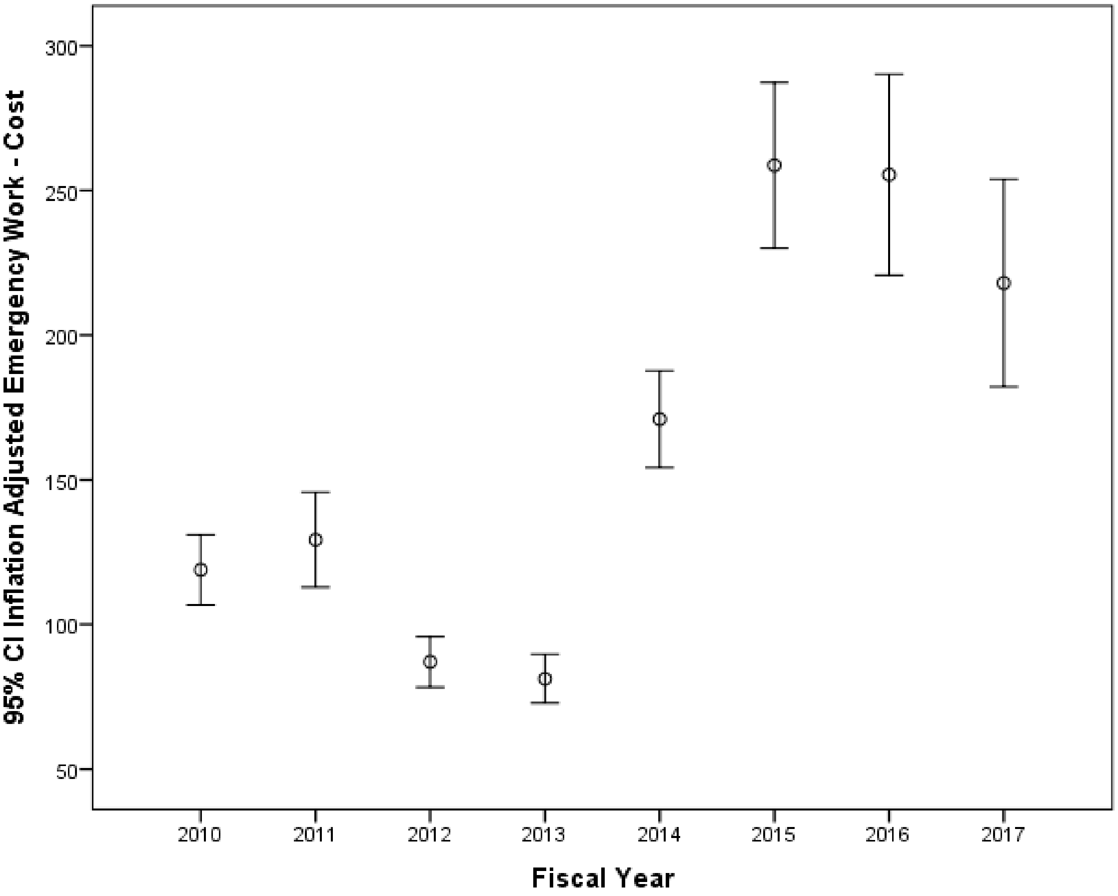


Figure 17: Means and standard deviations of emergency work inflation-adjusted cost by year across all bases and facilities

Figure 18 shows that the means of the cost of urgent work follows much the same trend as urgent work labor hours. The seemingly steady trend spikes in 2014-2016. Heavy volumes may suggest a period of "catching up" after the government shutdown in 2013 before the mean cost of urgent work dips back to 2010-2013 levels in 2017.

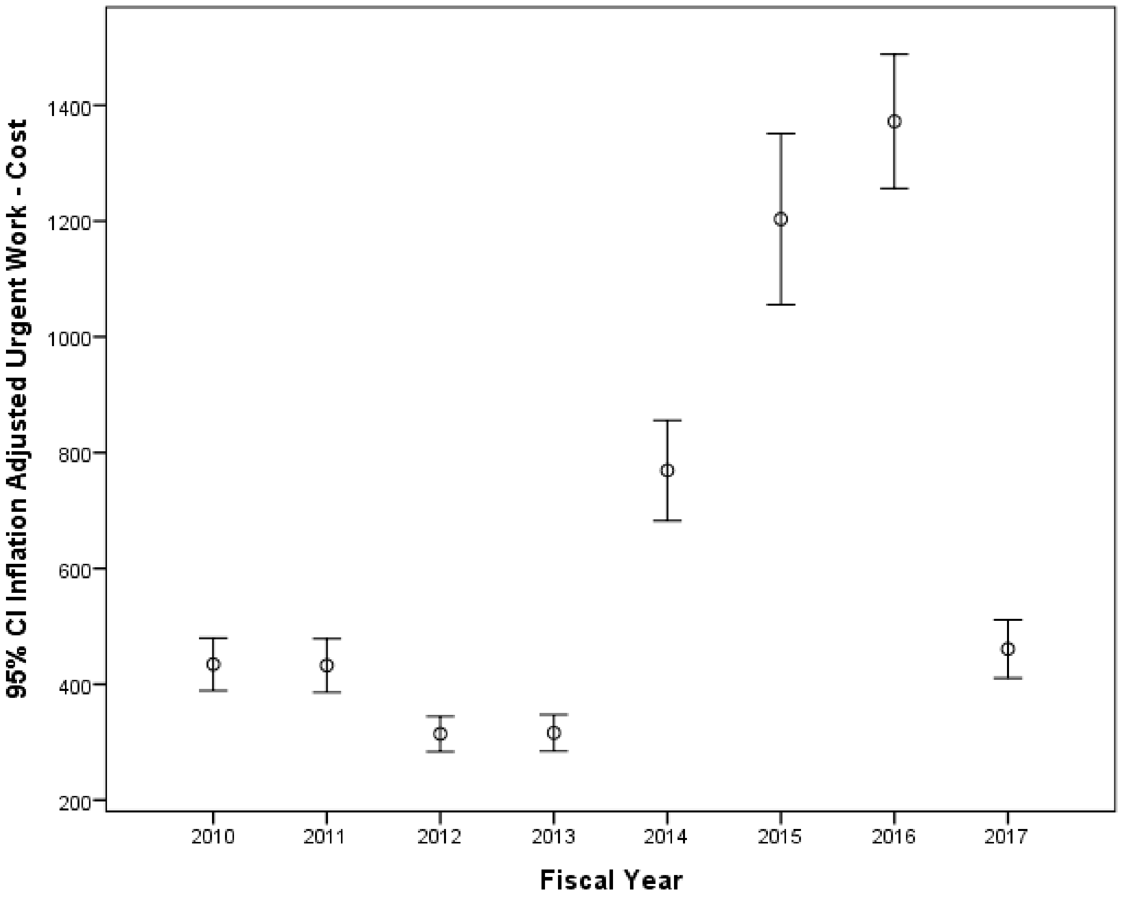


Figure 18: Means and standard deviations of urgent work inflation-adjusted cost by year across all bases and facilities

Figure 19 displays the means and standard deviations of routine work cost by year. The trend is slightly negative overall from 2010-2016, before dipping drastically in 2017. The trends for routine work have been the most consistent and negative.

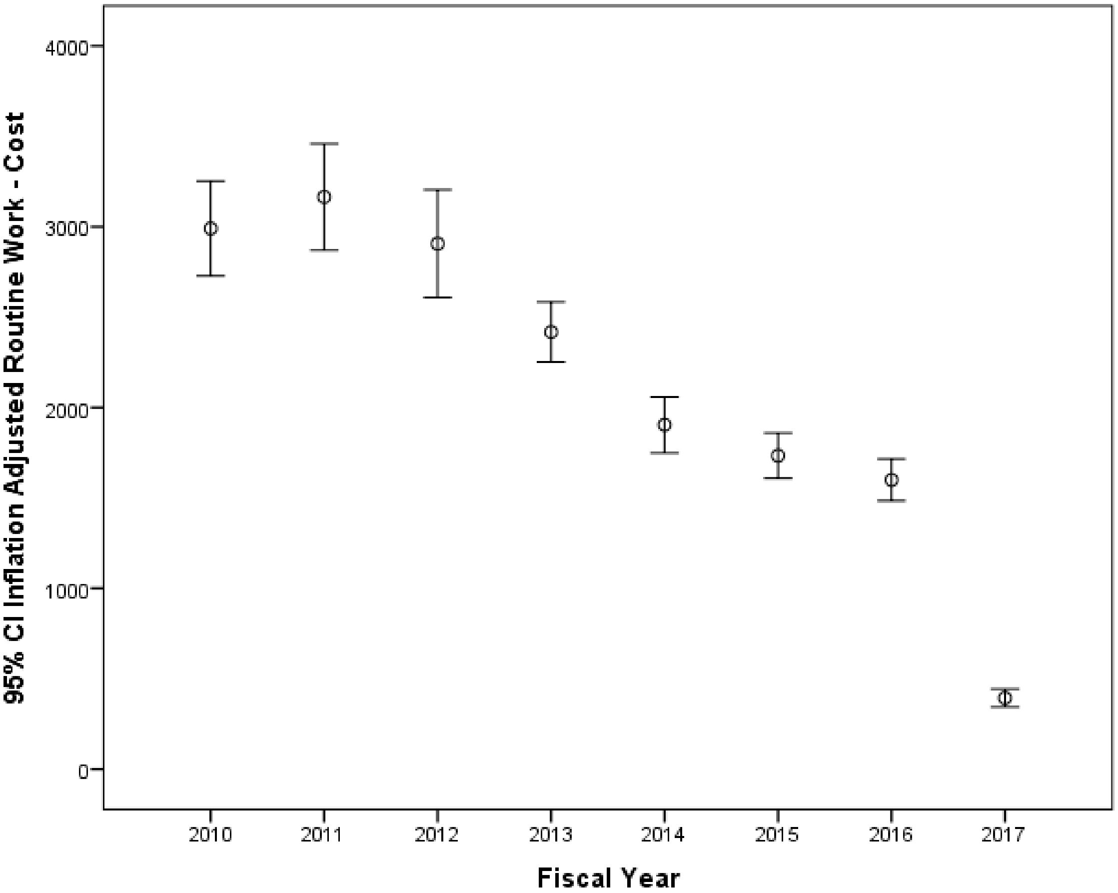


Figure 19: Means and standard deviations of routine work inflation-adjusted cost by year across all bases and facilities

Observing the trends has revealed that, for the most part, labor hours and cost follow approximately the same patterns for all LUCs. Recurring work, though it was difficult to identify trends for labor hours and cost, had a positive trend in frequency. An increase in recurring or preventive maintenance was one of the goals of the Air Force's new asset management strategy and this trend could indicate that bases are embracing a preventive maintenance culture. Emergency work count, labor hours, and cost all jump upward in 2014 before tapering downward toward 2016. Aging infrastructure will continue to fail and that is a possible explanation for the apparent increase in emergency work. It may take several more years before the effects of increasing preventive maintenance show in the data. Urgent work, for all three types of measurement, seems to steadily increase throughout the years from 2010-2016 before dipping in 2017. Routine work had mostly downward trends from 2010-2017. This could indicate that routine corrective maintenance has been less necessary over the years.

The next step to analyze the data was to fit the empty model. This provided the means to calculate the intraclass correlation coefficients representing the amount of variance attributable to each level of the model. They are shown in Table 6. Based on these results, very little variance is attributable to level three, the base. Only 1.3% - 6.1% of the variance in dependent variables comes from which base at which it occurs. At level two, the facility level, 16.2% - 34.4% of the variance for all variables occurs. Level one, the year, is accountable for 60.8% - 82% of the variance for all variables. In other words, the dependent variables do not vary as much from one base to another as much as they do between facilities and from year to year.

Table 6: Variance by Level

	Level 1 (Year)	Level 2 (Facility)	Level 3 (Base)
Recurring Work – Count	0.608	0.344	0.048
Emergency Work – Count	0.800	0.170	0.030
Urgent Work – Count	0.715	0.224	0.060
Routine Work – Count	0.621	0.335	0.044
Work Orders/Requests – Count	0.819	0.168	0.013
Plan Operations – Count	0.657	0.305	0.038
Recurring Work - Labor Hours	0.727	0.221	0.052
Emergency Work - Labor Hours	0.790	0.180	0.030
Urgent Work - Labor Hours	0.708	0.231	0.061
Routine Work - Labor Hours	0.638	0.325	0.037
Work Orders/Requests - Labor Hours	0.780	0.196	0.024
Plan Operations - Labor Hours	0.808	0.169	0.023
Recurring Work – Cost	0.661	0.291	0.047
Emergency Work – Cost	0.794	0.177	0.030
Urgent Work – Cost	0.706	0.233	0.061
Routine Work – Cost	0.622	0.340	0.038
Work Orders/Requests – Cost	0.821	0.162	0.018
Plant Operations – Cost	0.772	0.206	0.022

The final analysis was accomplished using the full models. Table 7 shows the model with the log count of each LUC as the outcome. The fixed effects are in the top panel and the variance components are in the lower panel. Though the fixed effects results are interpreted like regression coefficients, the variance components are included as a reference to the part of the model that accounts for the clustering and therefore are typically not interpreted. Negative values indicate a negative correlation, positive values indicate a positive correlation. Values followed by asterisks are considered statistically significant. One asterisk identifies a p-value, or probability value, less than 0.05. This means that the value indicates that the null hypothesis should be rejected in favor of the alternative hypothesis. Two asterisks indicate a probability value less than 0.01, which constitutes even stronger evidence against the null hypothesis. Three asterisks identify a p-value less than 0.001. Standard errors are shown below the values in parenthesis. The first column displays the fixed effect, fiscal year in the first panel and the variance components in the second panel. Though systems group was also analyzed as a fixed effect, the results do not reveal pertinent information to the research questions and therefore those results are only included in Appendix B for reference. The first row of the table lists the dependent variables, the LUCs. The results present the model with log count of each LUC as the outcome.

Table 7: Multilevel Models of Work Counts (Year)

	Recurring	Emergency	Urgent	Routine	Work Orders	Plant Ops
Fiscal Year=2011	-0.085**	0.057*	0.048	0.120***	-0.042*	0.247***
	(0.027)	(0.025)	(0.029)	(0.028)	(0.020)	(0.022)
Fiscal Year=2012	-0.151***	-0.142***	-0.205***	0.146***	-0.082***	0.111***
	(0.026)	(0.025)	(0.029)	(0.028)	(0.020)	(0.022)
Fiscal Year=2013	-0.121***	-0.218***	-0.212***	0.074**	0.036	-0.040
	(0.026)	(0.025)	(0.029)	(0.028)	(0.020)	(0.022)
Fiscal Year=2014	-0.155***	-0.035	0.049	-0.206***	0.056**	0.080***
	(0.026)	(0.025)	(0.029)	(0.028)	(0.020)	(0.022)
Fiscal Year=2015	0.027	0.003	0.238***	-0.374***	-0.010	-0.000
	(0.026)	(0.025)	(0.028)	(0.028)	(0.019)	(0.022)
Fiscal Year=2016	0.009	-0.095***	0.352***	-0.554***	0.214***	0.037
	(0.026)	(0.025)	(0.028)	(0.027)	(0.019)	(0.021)
Fiscal Year=2017	-0.029	-0.321***	-0.364***	-1.856***	-0.071**	0.004
	(0.030)	(0.028)	(0.033)	(0.032)	(0.022)	(0.025)
Level-3 Base Variance Component	-0.585	-1.056***	-0.543	-0.850**	-2.085***	-0.986**
	(0.319)	(0.320)	(0.320)	(0.326)	(0.336)	(0.321)
Level-2 Facilities Variance Component	0.235***	-0.275***	0.060***	0.303***	-0.599***	-0.080***
	(0.016)	(0.017)	(0.016)	(0.015)	(0.020)	(0.016)
Level-1 Error Variance Component	0.517***	0.455***	0.598***	0.565***	0.223***	0.320***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Observations	65,817	65,817	65,817	65,817	65,817	65,817

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The year results are analyzed by un-logging the values, which will show the percent change from the baseline of 2010. Due to the log-transformation, results were un-logged by taking the natural number *e* to the power of the value of the result minus one. Then, multiplication by 100 to see the results in a percentage which signifies the percent difference in expected outcome from the baseline. These un-logged values are displayed in Table 8. Bold values considered significant in Table 7.

Table 8: Work Counts Percentage

	Recurring	Emergency	Urgent	Routine	Work Orders	Plant Ops
Fiscal Year=2011	**-8.15%**	**5.87%**	4.92%	**12.75%**	**-4.11%**	**28.02%**
Fiscal Year=2012	**-14.02%**	**-13.24%**	**-18.54%**	**15.72%**	**-7.87%**	**11.74%**
Fiscal Year=2013	**-11.40%**	**-19.59%**	**-19.10%**	**7.68%**	3.67%	-3.92%
Fiscal Year=2014	**-14.36%**	-3.44%	5.02%	**-18.62%**	**5.76%**	**8.33%**
Fiscal Year=2015	2.74%	0.30%	**26.87%**	**-31.20%**	-1.00%	0.00%
Fiscal Year=2016	0.90%	**-9.06%**	**42.19%**	**-42.54%**	**23.86%**	3.77%
Fiscal Year=2017	-2.86%	**-27.46%**	**-30.51%**	**-84.37%**	**-6.85%**	0.40%

The results of the year coefficient for recurring work show that, after accounting for facility and base-level variability and controlling for systems group, the years 2011 through 2014 are significantly different from the year 2010, the baseline. Year 2015 through 2017 are not statistically different from the baseline of 2010. Because the years 2011 through 2014 have negative values, the expected count would decrease initially but then increase in 2015 such that the values would not be statistically different from 2010. The -8.15% value means that the outcome in 2011 is 8.15% less than the outcome in 2010. The trend would dip initially, dip again into 2012, increase slightly but stay below 2010 values in 2013, then drop a little farther than 2012 values in 2014. Recall that, in Figure 8 before the control for systems group as a fixed effect and facility and base as random effects, the trend was different, increasing initially.

The results of the year coefficient for emergency work shows that all but years 2014 and 2015 are significantly different than year 2010. The percentages seem to follow the trends from Figure 9 more closely than recurring work count; however, the HLM still provides a more accurate model. The same can be said for urgent work counts, where all the trends line up more closely to Figure 10. For urgent work counts, all but 2011 and 2014 are statistically different from 2010. All expected outcomes for routine work count are statistically different from the baseline of 2010. Values raise initially, then begin a steep decline in the expected value. These results follow a similar trend to Figure 11. Work orders and plant operations were less than revealing in their trends, as was observed in the first model (Figure 20 and Figure 21 can be found in Appendix A).

The years following BULDER's implementation did not show a statistically significant increase in recurring work. The only statistically different values in recurring work frequency were in the first few years and those values showed a decrease in the mean number of times preventive maintenance was accomplished. Emergency and urgent work both saw increases in frequency between 2013 and 2014, but both eventually dipped in 2017 to a level below 2013 counts. Routine work saw a drastic decrease between 2013 and 2014 and continued to drop as the years passed.

The same model was accomplished for labor hours and the results are shown in Table 9. The same procedure for un-logging the values was accomplished and those results are displayed in Table 10. Again, bold values are considered statistically significant.

Table 9: Multilevel Models of Log Labor Hours (Year)

	Recurring	Emergency	Urgent	Routine	Work Orders	Plant Ops
Fiscal Year=2011	0.096*	0.083*	0.068	0.195***	-0.073*	0.307***
	(0.042)	(0.034)	(0.042)	(0.044)	(0.029)	(0.030)
Fiscal Year=2012	0.057	-0.212***	-0.334***	0.168***	-0.150***	0.144***
	(0.041)	(0.033)	(0.042)	(0.043)	(0.028)	(0.030)
Fiscal Year=2013	-0.064	-0.310***	-0.340***	0.015	-0.145***	0.117***
	(0.041)	(0.033)	(0.042)	(0.043)	(0.028)	(0.030)
Fiscal Year=2014	0.137***	-0.009	0.135**	-0.553***	-0.064*	0.100***
	(0.041)	(0.033)	(0.042)	(0.043)	(0.028)	(0.030)
Fiscal Year=2015	0.305***	0.041	0.413***	-0.841***	-0.077**	0.011
	(0.041)	(0.033)	(0.041)	(0.043)	(0.028)	(0.030)
Fiscal Year=2016	0.134***	-0.066*	0.628***	-1.143***	0.020	0.096**
	(0.041)	(0.033)	(0.041)	(0.043)	(0.028)	(0.030)
Fiscal Year=2017	-0.794***	-0.404***	-0.626***	-3.267***	-0.246***	-0.155***
	(0.047)	(0.038)	(0.048)	(0.050)	(0.032)	(0.034)
Level-3 Base Variance Component	-0.132	-0.729*	-0.126	-0.523	-1.121***	-1.067***
	(0.318)	(0.320)	(0.320)	(0.328)	(0.323)	(0.323)
Level-2 Facilities Variance Component	0.387***	0.068***	0.477***	0.763***	-0.130***	-0.133***
	(0.017)	(0.016)	(0.015)	(0.015)	(0.019)	(0.017)
Level-1 Error Variance Component	0.961***	0.757***	0.974***	1.016***	0.587***	0.645***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Observations	65,817	65,817	65,817	65,817	65,817	65,817

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 10: Work Labor Hours Percentage

	Recurring	Emergency	Urgent	Routine	Work Orders	Plant Ops
Fiscal Year=2011	**10.08%**	**8.65%**	7.04%	**21.53%**	**-7.04%**	**35.93%**
Fiscal Year=2012	5.87%	**-19.10%**	**-28.39%**	**18.29%**	**-13.93%**	**15.49%**
Fiscal Year=2013	-6.20%	**-26.66%**	**-28.82%**	1.51%	**-13.50%**	**12.41%**
Fiscal Year=2014	**14.68%**	-0.90%	**14.45%**	**-42.48%**	**-6.20%**	**10.52%**
Fiscal Year=2015	**35.66%**	4.19%	**51.13%**	**-56.87%**	**-7.41%**	1.11%
Fiscal Year=2016	**14.34%**	**-6.39%**	**87.39%**	**-68.11%**	2.02%	**10.08%**
Fiscal Year=2017	**-54.80%**	**-33.24%**	**-46.53%**	**-96.19%**	**-21.81%**	**-14.36%**

For labor hours, the significant values of recurring work occur in all but 2012 and 2013. Though values seem to be increasing initially, from about 10.08% in 2011, 14.68% in 2014 and 35.66% in 2015, they dip back down to only 14.34% higher than the base in 2016 and then tumble to -54.8% of 2010 by 2017. Emergency work labor hours only rise in 2011, the remaining significant values are at various levels below 2010 values. Urgent work labor hours dip then rise before tumbling like recurring work did in 2017. Routine work expected labor hours once again have a more consistent trend than other work types as values initially rise 21.53% above 2010 values in 2011, then only 18.29% in 2012, before decreasing steadily from 2014 through 2017. Work order requests labor hours have mostly negative values and plant operations are consistently positive before 2017. Routine work is the only work type for which trends seem to be consistent and negative.

Table 11 shows the inflation-adjusted log cost outcomes. Outcomes followed by asterisks are statistically significant. Table 12 displays the un-logged values in percentage. Bold values correspond to statistical significance.

Table 11: Multilevel Models of Log Inflation-Adjusted Cost (Year)

	Recurring	Emergency	Urgent	Routine	Work Orders	Plant Ops
Fiscal Year=2011	-0.015	0.126*	0.078	0.273***	-0.107*	0.425***
	(0.061)	(0.056)	(0.068)	(0.069)	(0.052)	(0.049)
Fiscal Year=2012	-0.198**	-0.361***	-0.562***	0.265***	-0.220***	0.169***
	(0.060)	(0.055)	(0.067)	(0.068)	(0.051)	(0.048)
Fiscal Year=2013	-0.148*	-0.519***	-0.557***	0.037	0.067	0.164***
	(0.060)	(0.055)	(0.067)	(0.068)	(0.052)	(0.048)
Fiscal Year=2014	-0.016	-0.069	0.176**	-0.789***	0.110*	0.095*
	(0.060)	(0.055)	(0.067)	(0.068)	(0.051)	(0.048)
Fiscal Year=2015	0.332***	0.104	0.762***	-1.058***	-0.031	0.075
	(0.060)	(0.055)	(0.067)	(0.067)	(0.051)	(0.048)
Fiscal Year=2016	0.233***	-0.088	1.108***	-1.556***	0.309***	0.178***
	(0.060)	(0.055)	(0.066)	(0.067)	(0.051)	(0.048)
Fiscal Year=2017	-0.431***	-0.626***	-0.767***	-4.835***	-0.339***	-0.018
	(0.069)	(0.063)	(0.077)	(0.078)	(0.059)	(0.055)
Level-3 Base Variance Component	0.272	-0.245	0.326	-0.069	-0.916**	-0.492
	(0.318)	(0.320)	(0.320)	(0.328)	(0.328)	(0.323)
Level-2 Facilities Variance Component	0.920***	0.551***	0.947***	1.220***	0.370***	0.446***
	(0.017)	(0.016)	(0.015)	(0.015)	(0.019)	(0.017)
Level-1 Error Variance Component	1.348***	1.254***	1.450***	1.461***	1.190***	1.124***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Observations	65817	65817	65813	65803	65771	65812

Table 12: Work Cost Percentages

	Recurring	Emergency	Urgent	Routine	Work Orders	Plant Ops
Fiscal Year=2011	-1.49%	**13.43%**	8.11%	**31.39%**	**-10.15%**	**52.96%**
Fiscal Year=2012	**-17.96%**	**-30.30%**	**-42.99%**	**30.34%**	**-19.75%**	**18.41%**
Fiscal Year=2013	**-13.76%**	**-40.49%**	**-42.71%**	3.77%	6.93%	**17.82%**
Fiscal Year=2014	-1.59%	-6.67%	**19.24%**	**-54.57%**	**11.63%**	**9.97%**
Fiscal Year=2015	**39.38%**	10.96%	**114.26%**	**-65.29%**	-3.05%	7.79%
Fiscal Year=2016	**26.24%**	-8.42%	**202.83%**	**-78.90%**	**36.21%**	**19.48%**
Fiscal Year=2017	**-35.01%**	**-46.53%**	**-53.56%**	**-99.21%**	**-28.75%**	-1.78%

Besides 2011 and 2014, all recurring work cost outcomes are significant. Years 2012-2013 show values that are 17.96% and 13.76% lower than 2010 respectively. The expected values jump to 39.38% and 26.24% above the baseline in years 2015 and 2016 respectively before dipping to 35.01% below the baseline in 2017. Emergency work significant values start higher in 2011, drop below the baseline in 2012-2013, rise above in 2015, then drop again by 2017. Urgent work significant expected values for cost are about 43% lower than 2010 in 2012 and 2013 but then rise as high as 203% above the baseline in 2016. Values drop about 54% below the baseline in 2017. Once more, routine work expected cost values sit above the baseline in 2011 and 2012 then drop steadily from 2014-2017. Work orders expected values start below, rise above, then dip and plant operations has significant values all above the baseline throughout the years.

As was seen in the trend data before the HLM model results, urgent and routine work had very similar trends in expected cost values compared to expected labor hours values. The cost data reveals little that labor hours did not and similarly to those results, the year 2017 returns values both below the baseline of 2010 as well as below the values in 2013 when the Air Force's new asset management policies were first implemented.

CHAPTER 5. DISCUSSION

The Air Force has been combating the “run-to-failure” maintenance approach for many years. High failure rates, production downtime, and budgetary concerns have motivated new asset management policies to include preventive maintenance. Tools like the BULDER program and the policies implementing new asset management practices were introduced in 2013. The goal was to help facility managers become more aware of assets, their conditions, and the risks incurred by failure of such equipment. The hope was to begin accomplishing the right work at the right time. The aim of this study was to determine the impact of the Air Force’s new asset management strategy on the organization’s funding requests and on preventive versus reactive work trends at base-level.

5.1 Macro-Study Discussion

The switch from reactive to preventive maintenance has known benefits, as mentioned in the literature by Ismail Mostafa (2004), Chinese and Ghirardo (2010), and Swanson (2001). Sustaining assets is the focus of a preventive maintenance strategy. As displayed in Figure 6, trends indicate an increase in funds allocated to sustainment projects since 2013. This percentage increase was 26% between fiscal year 2013 and 2017 for sustainment projects. Reactive work also increased, but only by 13% in the same timeframe which is indicative of the fact that some assets will continue to break down regardless of increased preventive maintenance efforts due to existing conditions or age. Assets which have been operated in a run-to-failure mentality may be too far gone to prevent failure with preventive maintenance. The amount of increase in R&M funds decreased year to year, however, and leveled out between fiscal year 2015, 2016, and 2017. This may indicate that fewer assets are failing, thus implying that increasing sustainment efforts may be preventing failure.

Additionally, Figure 7 showed the percent difference between project classifications decreased from 17% to 4% over the past five years. This would indicate that the Air Force may be “closing the gap” between SUS and R&M activities. These results may suggest that the new asset management system and BUILDER program could be affecting a change from reactive maintenance and repair to preventive maintenance and repair. It is difficult to affirm that these results prove the impact of BUILDER as several other factors may be responsible for the trends. As mentioned in the beginning of this thesis, the Air Force asset management principles have been in flux for many years. Inconsistency in policy may have been the cause.

Several limitations exist for this study, as policies, budgets, and political climates are all factors which can impact the data. First, the integrated priority lists that the Air Force releases are lists of approved projects for the upcoming fiscal year. Once the approved lists are out, installations begin the work required to begin their project from most urgent to least using the risk-based methodology described by Labi (2014). Throughout the fiscal year, projects are changed, canceled, or re-appropriated, meaning that the values analyzed in this study are not the final amounts spent in each funding pool once the fiscal year has ended. Though they are the funds allocated to each pool, a more accurate account of how much money or what percentage of money the Air Force actually spent on SUS, R&M, or other projects could be obtained if the final spending dollars were studied. This data would be difficult to collect because there is no continuous method for storing or displaying this information centrally, yet.

Additionally, changing policy and funding sources may have led to a lack of standardization in annual expenditure allocation. Asset managers requesting funds for projects have had to train and re-learn the specifics of what qualifies as a sustainment or a restoration project. For example, the Air Force Instruction 32-1032, Planning and Programming Appropriated Fund Maintenance, Repair, and Construction Projects, has been revised twice in the past two years. This document defines the thresholds for different types of projects. For example, until September 2015 the threshold for a project to be considered “minor construction” (a type of R&M) was $750,000, but in the revised version it is $1,000,000. Minor construction projects exceeding this amount were placed into a different funding category, “unspecified minor military construction” which competes for a completely different pool of funds. The increase from $750,000 to $1,000,000 increases the number of projects eligible for R&M funding since a R&M project worth $800,000 in fiscal year 2015 was considered in a different funding pool but the same project in the fiscal year 2016 would be competing for R&M funding. An increase in projects eligible for R&M funding may have set percentages for R&M higher in fiscal years 16 and 17. Had the change in policy not been made, percentages for those two years may have been less, which would have resulted in a decrease in R&M funding requests as opposed to a leveling-out as shown in the results.

At times, projects are often not cut-and-dry SUS or R&M. Many times a project will be developed for a single building or a single unit which will encompass more than one type of funding or EEIC. For example, if a facility requires sustainment on the roof and restoration in a breakroom, the funding type that makes up the majority of the project will designate the PEC and therefore determine the funding pool from which the project is executed. The total cost of the project may not be spent on one type of work or the other, but the total cost of the project will come from the funding pool for one type of work or the other. This may skew results because projects paid for with R&M dollars may have had a portion of the work labeled as SUS or vice versa. Further networking and research are required to determine if the final dollar amounts for each EEIC are recorded after funds are allocated and projects are completed.

Finally, it is sometimes a subjective process when determining if a project is SUS or R&M. Air Force programmers are trained thoroughly to differentiate between different types of projects; however, it is not always definitive. Identifying project EEICs is not always easy and, although check-and-balance procedures are in place, more than 3,000 projects are requested each year that compete for Operations and Maintenance dollars. It is not uncommon for one individual to categorize a project as sustainment repair when it may look like restoration and modernization repair on paper. For example, a roof replacement would be considered repair but it is SUS repair if it has reached the end of its useful life and is replaced with similar materials. However, if the user is looking for an upgrade or modernization of an old roof, even if it has reached the end of its useful life and needs to be replaced, replacing it with new materials is easily considered R&M repair instead. It comes down to the interpretation of the Air Force Instruction 32-1032 and whoever is in the final decision-making stage ultimately determines that interpretation. With the newer iterations of the instruction, it is difficult to have differences of opinion, but the human element which cannot be removed from project definition and classification will always constitute a possibility of error. Considering the limitations listed, this is likely the least significant, though worth mentioning.

5.2 Case Study Discussion

The case study involved using Hierarchical Linear Modeling to determine the trends in LUCs with respect to count, labor hours, and cost clustered within fiscal years, clustered within facilities, and clustered within bases. For all LUCs measured in each way, it was discovered that the level which accounted for most of the variance in results was the year, followed by the facility, followed by the base. LUCs measured in count, labor hours, and cost varied more from one facility to the next than from one base to the next and varied more from one year to the next than from one facility to the next. The results suggest that time is a more significant factor in the prediction of LUC frequency, hours, and cost than facility or base.

The HLM models, once results were translated into percentages, showed somewhat tumultuous trends over time and pre/post 2013. There appears to be little correlation between increases in recurring work and decreases in emergency work for count, labor hours, and cost. Routine maintenance was the only one of the six LUCs studied to have a predictable downward trend for count, labor hours, and cost between 2013 and 2017. The declining trend in routine maintenance could suggest that new asset management practices have reduced the need for this type of corrective maintenance. However, of the three types of corrective maintenance, routine work is the least pressing compared to urgent and emergency work. Decreases in routine work are coupled with increases in urgent work from 2014-2016 for all measures. Though all work types drop in 2017, increases in urgent work suggest that more equipment was breaking down in more critical ways in the years directly following 2013. The work was not so critical as to be coded emergencies but the increase, especially in the cost of urgent work over time, suggests that new asset management principles have not accomplished the goal to reduce corrective maintenance through preventive maintenance in the short term.

Work orders were included in the study to see if negative trends could identify the success of BUILDER to predict work before it was requested by the user. As shown in the results, however, trends are less than apparent. Work orders are difficult to identify patterns for intrinsically, as they do not always identify problems or equipment breakdowns but user requests for things like painting and equipment installation. Little can be inferred about the success of BULDER's predictive capabilities through these results. Plant operations were included because it was assumed that this type of work, which is a top priority as it affects the function of important utilities, would have a more consistent, gently-sloping trend over time. The hope was that significant increases or decreases in plant operations could point to underlying issues which may have explained significant increases or decreases in other types of work. Trends for this type of work are also difficult to interpret as, besides a sharp increase from 2010 to 2011 and mostly down thereafter, predictions do not line up significantly with trends for other types of work.

All statistically significant values for the year 2017 had expected outcomes for all LUCs measured in each way at a value lower than the 2010 and 2013 values. For most variables, this was a drastic dip, suggesting that something about the 2017 fiscal year resulted in much less work being accomplished overall. A possible influence in 2017 may have been the implementation of Tririga, bringing a host of changes to Air Force asset management at the base level. All bases in the case study were scheduled to switch to the new CMMS in fiscal year 2016; the focus on training, the growing pains of having a new system, and the adaptation to the new classification system could very well have contributed to the low values.

The primary limitation to this study is time. The BUILDER program in particular is not a plug-and-play system as it requires inventory input and condition assessments for all facilities, systems, and components. There was no Air Force-mandated format for equipment inventories in the past; therefore, filling the database has been a task which varies in difficulty from base to base. In fact, the timeline for bases to have facilities and systems inputted and assessed was September of 2017, four years post-implementation. Components and sub-components, except in a few cases for ambitious bases with proper resources, have not been uploaded into the system yet. The full impact of BUILDER on Air Force asset management will become more clear as the years progress, the inventory is more complete, the condition assessments more regular, and the asset managers more on the same page concerning the direction and goals of new asset management policies.

Additionally, the implementation of Tririga introduced another change in Air Force asset management practices that likely affected the results, 2017 in particular. This combined with the probability that BUILDER data had only just begun to be useful may have impacted trends. With Tririga, a new work classification system was rolled-out which would replace LUCs with priority levels. Though the switch will not occur until Tririga is up and running, the redefinition of work classification may have permeated how asset managers assigned work leading up to 2017.

Another factor which may have influenced the results is subjectivity. Much like the limitation mentioned for the macro-study, input data into the system is subject to human error. The temptation to code a high-ranking officer's request as an emergency is a phenomenon that can exist within base-level personnel. Therefore, training at both top and bottom levels is incredibly vital. Though this type of limitation may seem arbitrary giving the vast quantity of data collected, it is worth mentioning.

This study is significant in that it attempts to expand on the argument that preventive maintenance and the sustainment of assets is more beneficial than run-to-failure methods. Further, it attempts to identify shifts in work type consistent with the asset management culture the Air Force is trying to create through programs like BUILDER and new asset management practices. It observes Air Force asset management from two levels. The macro-study found trends in requested funds for sustainment and restoration projects. The case study revealed trends in preventive versus reactive work at a micro-level. These analyses advance the understanding of how changing maintenance methods is affecting the culture, work allocation, and fund-request allocations across the Air Force.

CHAPTER 6. CONCLUSIONS

6.1 Study Conclusions

Sustainment has become more prevalent within U.S. Air Force asset management practices. Since 2013, Air Force Asset Management practices have effectively pushed project funding in the direction of preventive and predictive maintenance. It is too soon to say that the Air Force is saving money or that equipment life has directly increased based on the macro-study data. However, it seems that increasing funding allocations toward sustainment has at least curbed the increase in funding allocations to restoration projects, revealing a possible correlation to increased preventive maintenance and a lessened need for corrective maintenance.

The case study tells a different story, one that suggests that work accomplished at base-level is more tumultuous and patterns less apparent. Though there was a decrease in routine reactive maintenance through the years, the increase in urgent work suggests that more critical equipment failure was occurring before 2017. Despite the assumption that increased recurring preventive maintenance would lead to a decrease in emergency corrective work, there is little evidence from the data to support that theory. Considering the limitations however, over time these trends may become more apparent.

6.2 Recommendations

As noted by the limitations of the macro-study, efforts could be made to assess the amount of money actually spent on SUS versus R&M as opposed to the amount of money approved for spending as was the basis of this study. Additionally, determining not just allocations to different PECs but breaking it down further into EEICs would present more accurate numbers. It would also be interesting to duplicate this study in another five years to determine if SUS ever equals or surpasses R&M funds. Though R&M funds will never become nonexistent, it would be interesting to determine the most efficient percentages between the two. Over the years, it may be possible to develop an industry benchmark identifying the percentage of asset management money that should ideally be allocated to proactive versus corrective maintenance.

The case study could be expanded in many ways, as the data is extensive and continues to grow. An interesting study would include facility characteristic data such as age, function, renovation records, and use alterations. Including a variable like facility age could create graphs displaying trends in emergency work over time using legacy data and the data which continues to be collected now that BUILDER is in effect. The Air Force is changing the work classification system from LUCs to priority levels. Training for the new classification system is ongoing, but if implemented correctly, emergency work would get a priority of one, followed by preventive maintenance and plant operations, then corrective maintenance, then enhancement work. This hierarchy ensures that preventive maintenance is not “only completed if time allows” but puts it at a higher priority level than corrective maintenance. A comparison of count, labor hours, or cost of the LUC system to the count, labor hours, or cost of the new classification system could be an interesting and valuable study.

The case study included only five bases, chosen due to having similar size and geographic climate. An extension of this study could be done on other bases throughout the U.S. or the world. Expanding the bases studied may provide further insight. Adding the base characteristics, like the facility characteristics, would advance the study.

A qualitative study is another way in which this research could be expanded. Determining from the asset managers themselves the nature of the changes in asset management principles which began in 2013. A survey-based study could reveal whether new practices have made an effective difference.

Another future study, which could expand literature on the benefits of condition-based maintenance, could be an analysis of equipment lifecycles before and after Air Force policy changes. Determining the effects of less-reactive maintenance on equipment life could provide more evidence to the viability of preventive maintenance practices. This would require extensive equipment data and a record of all replacements and significant corrective maintenance.

Further recommendation concerns the BUILDER program itself. Though it has a good starting point as a predictor of asset lifecycles, BUILDER may require software optimization. The program predicts the reliability of the component level (of the four levels identified at the beginning of this thesis: facility, system, component, and subcomponent levels), the average of which is used as the overall system's reliability and, therefore, condition index. However, Alley et al. (2015) found that the software's lifecycle prediction algorithms may be inaccurate compared to real-world data. They developed probabilistic models using fault trees and fuzzy logic based on risk and then compared the results to real-world data. The study revealed that the existing model within the BUILDER software could not adequately predict failure in systems (p-value of 1.0) but that the model developed using real-world data had a much more significant predictability (p-value of 0.12). One of the implications of the study is that BUILDER data could become much more accurate in the future, thus allowing for preventive maintenance practices on systems to be as effective as they are on the components. This study was an analysis of plumbing, HVAC, fire protection, and electrical systems (Alley, 2015). Expanding these data to include the other systems assessed by BUILDER will optimize the predictability of systems and allow for more effective asset management.

APPENDIX A.

VARAIABLE TRENDS OVER TIME

Appendix A shows the values over time for LUCs which displayed no clear trends for the specified measurement (count, labor hours, or cost).

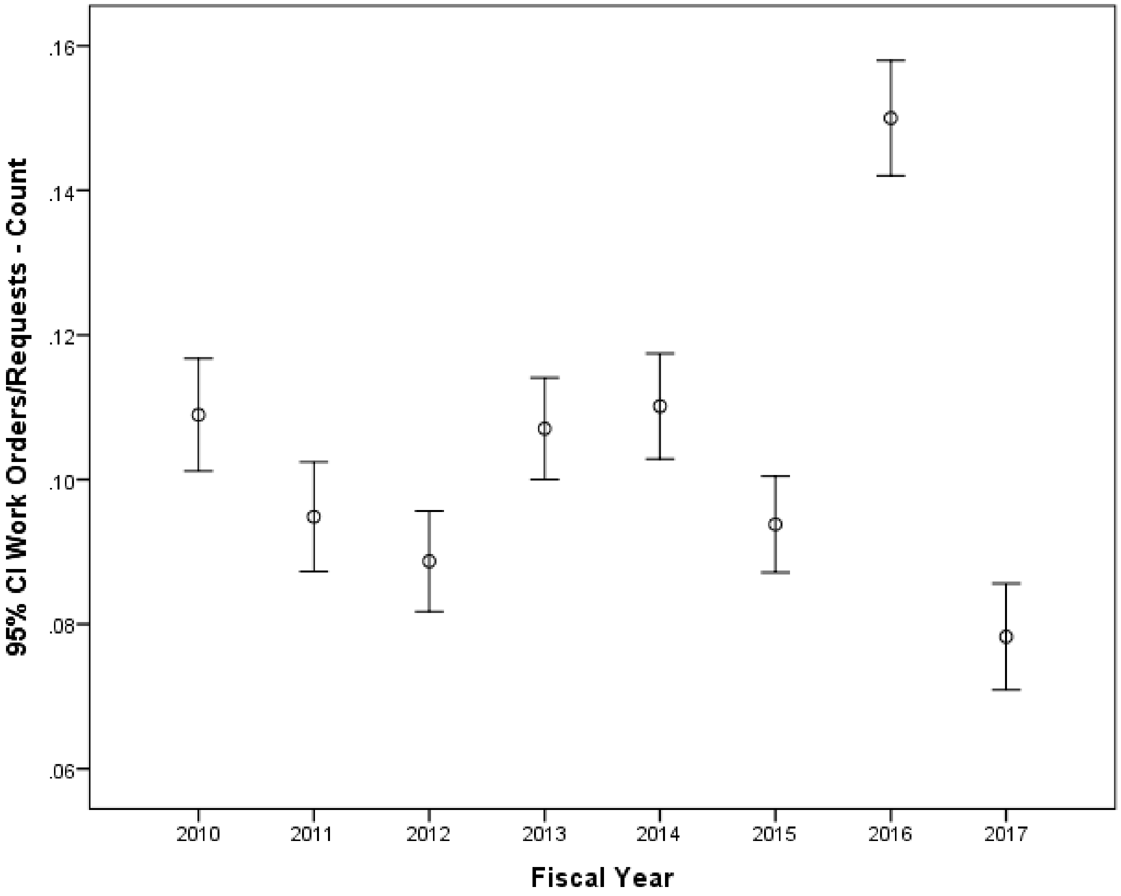


Figure 20: Means and standard deviations of work orders/requests count by year across all bases and facilities

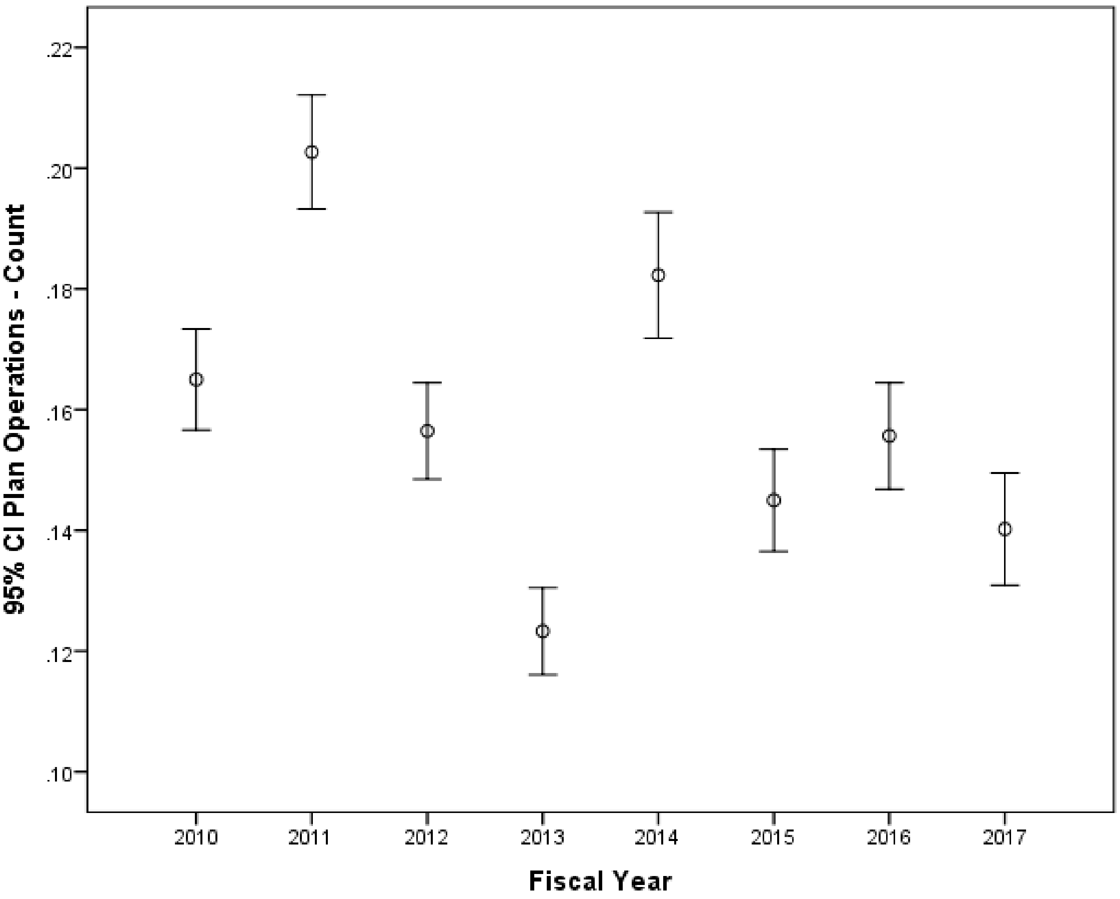


Figure 21: Means and standard deviations of plant operations count by year across all bases and facilities

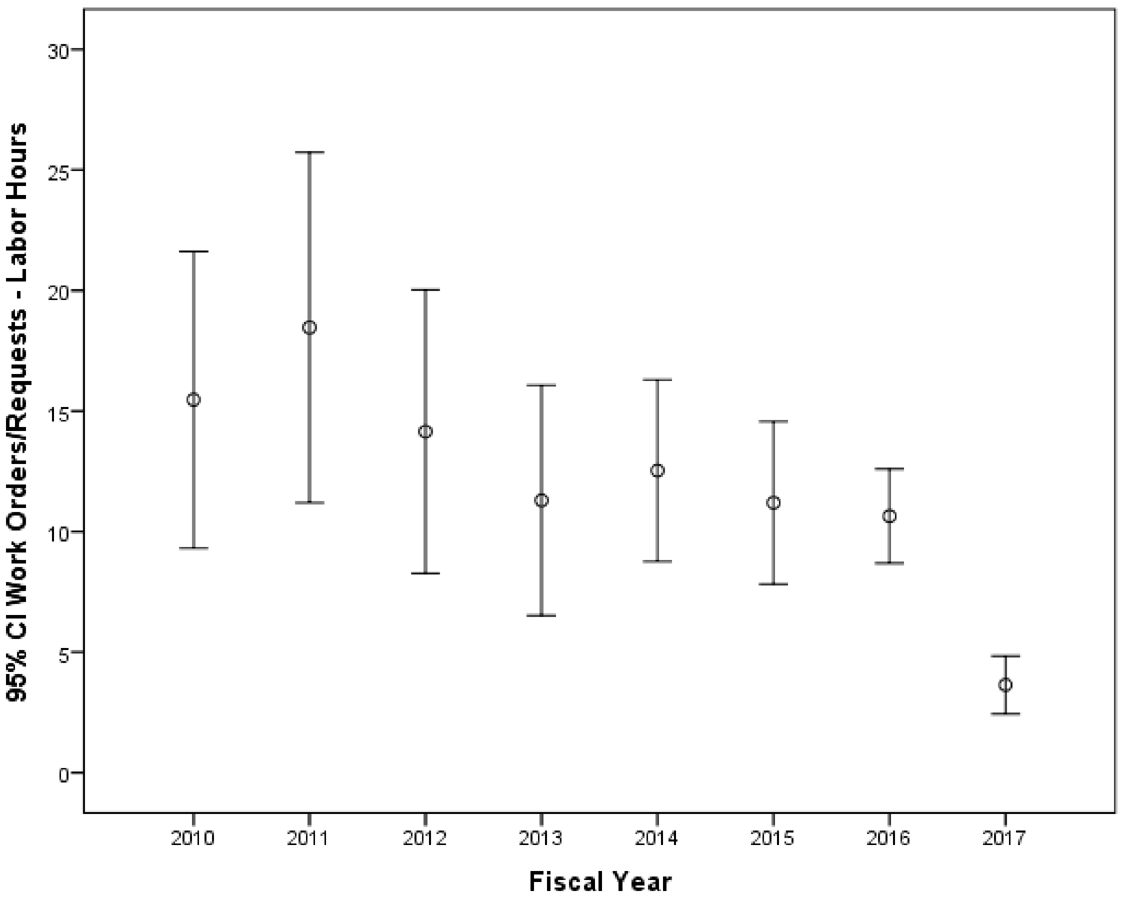


Figure 22: Means and standard deviations of work orders/requests hours by year across all bases and facilities

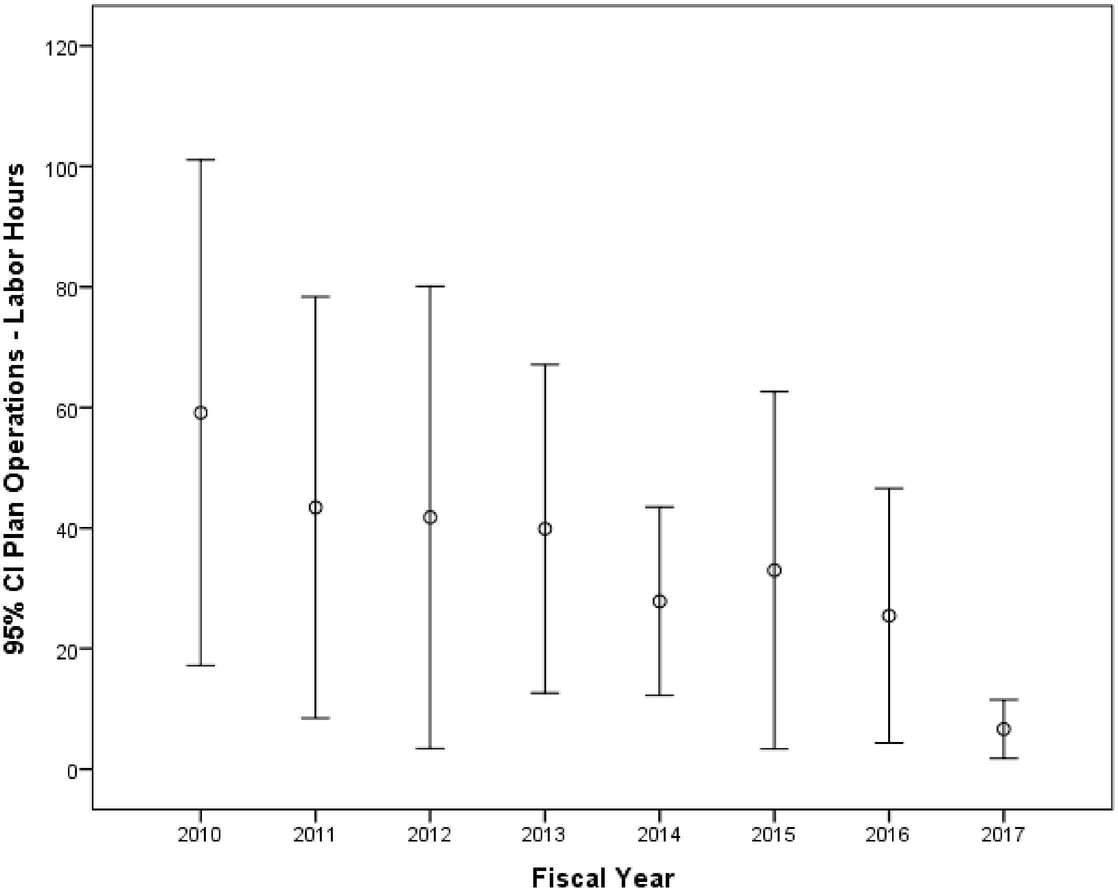


Figure 23: Means and standard deviations of plant operations hours by year across all bases and facilities

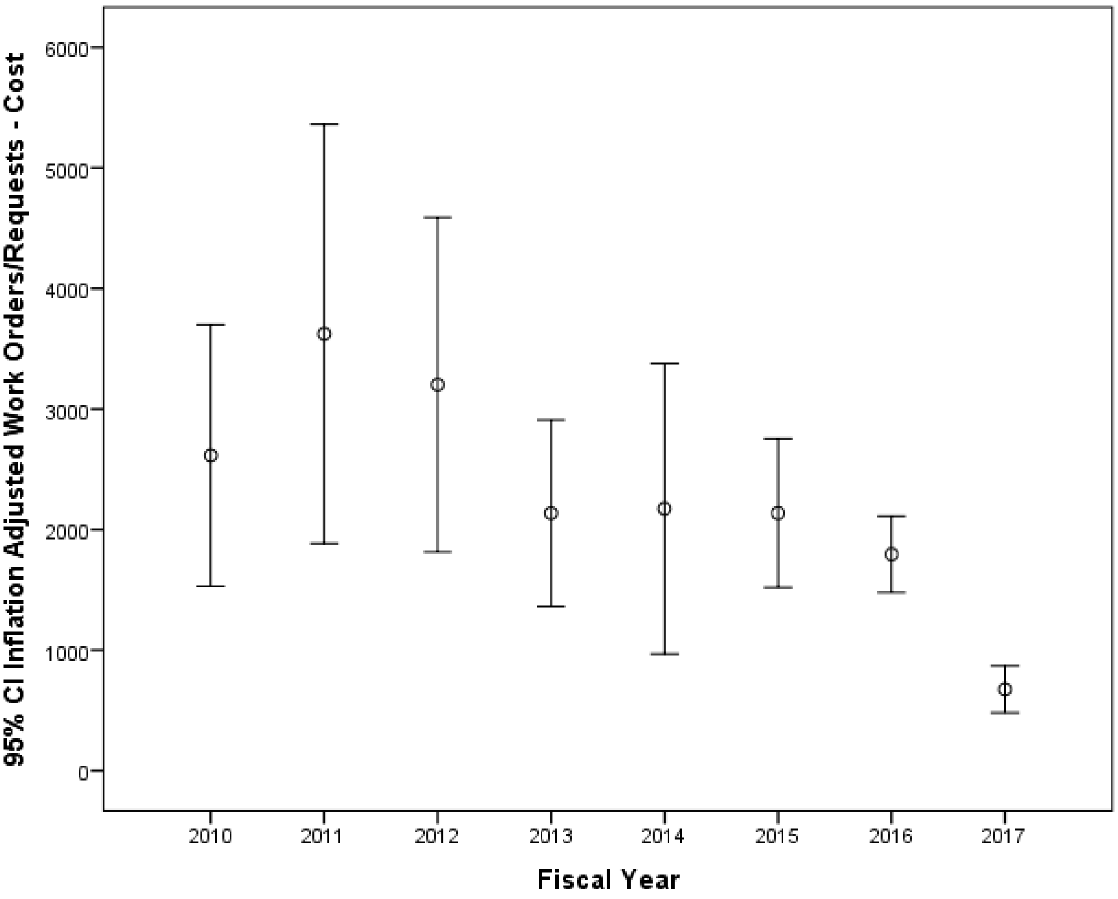


Figure 24: Means and standard deviations of work orders/requests inflation-adjusted cost by year across all bases and facilities

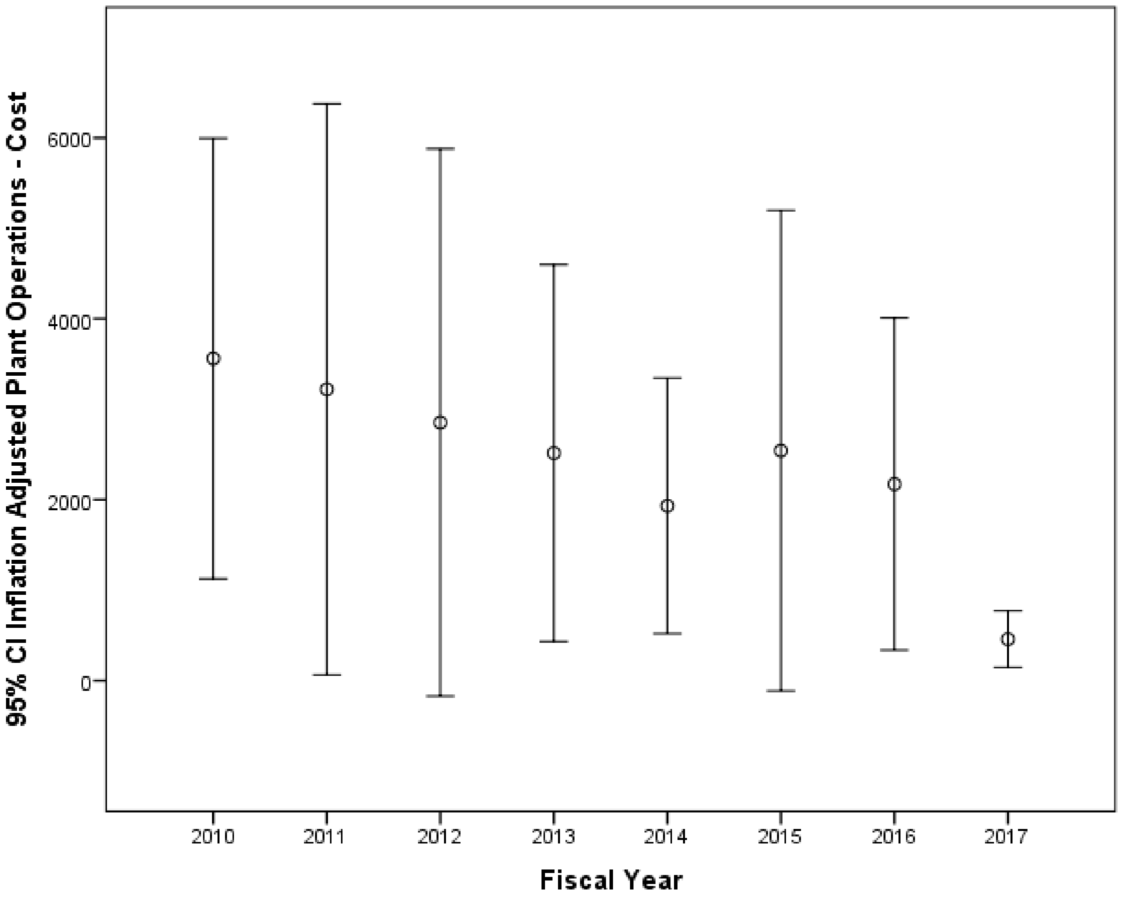


Figure 25: Means and standard deviations of plant operations cost by year across all bases and facilities

APPENDIX B

SYSTEMS GROUP RESULTS

Systems group was treated as an additional fixed effect. The tables and graphs which show the results are below. Outcomes are shown in percentages as compared to the arbitrary baseline of plant operations.

Table 13: Multilevel Models of Work Count (Systems Groups)

	Recurring	Emergency	Urgent	Routine	Work Orders	Plant Ops
Primary Facility Systems	1.555***	0.782***	1.109***	1.153***	0.091	-0.571***
	(0.065)	(0.060)	(0.070)	(0.068)	(0.048)	(0.053)
Construction	-0.338***	0.426***	0.904***	1.951***	0.454***	-0.977***
	(0.066)	(0.062)	(0.071)	(0.069)	(0.049)	(0.054)
Environment and Alarms	1.780***	0.797***	0.944***	0.775***	-0.093	-0.853***
	(0.067)	(0.062)	(0.072)	(0.070)	(0.049)	(0.055)
Specialized Systems	0.358***	0.715***	1.195***	1.600***	0.210***	0.158**
	(0.073)	(0.068)	(0.079)	(0.076)	(0.054)	(0.060)
Contractor Work	0.194*	-0.730***	-0.846***	-1.242***	0.474***	0.402***
	(0.078)	(0.072)	(0.084)	(0.081)	(0.057)	(0.064)
Constant	-3.557***	-4.520***	-4.399***	-3.022***	-4.351***	-3.457***
	(0.259)	(0.169)	(0.271)	(0.206)	(0.075)	(0.177)

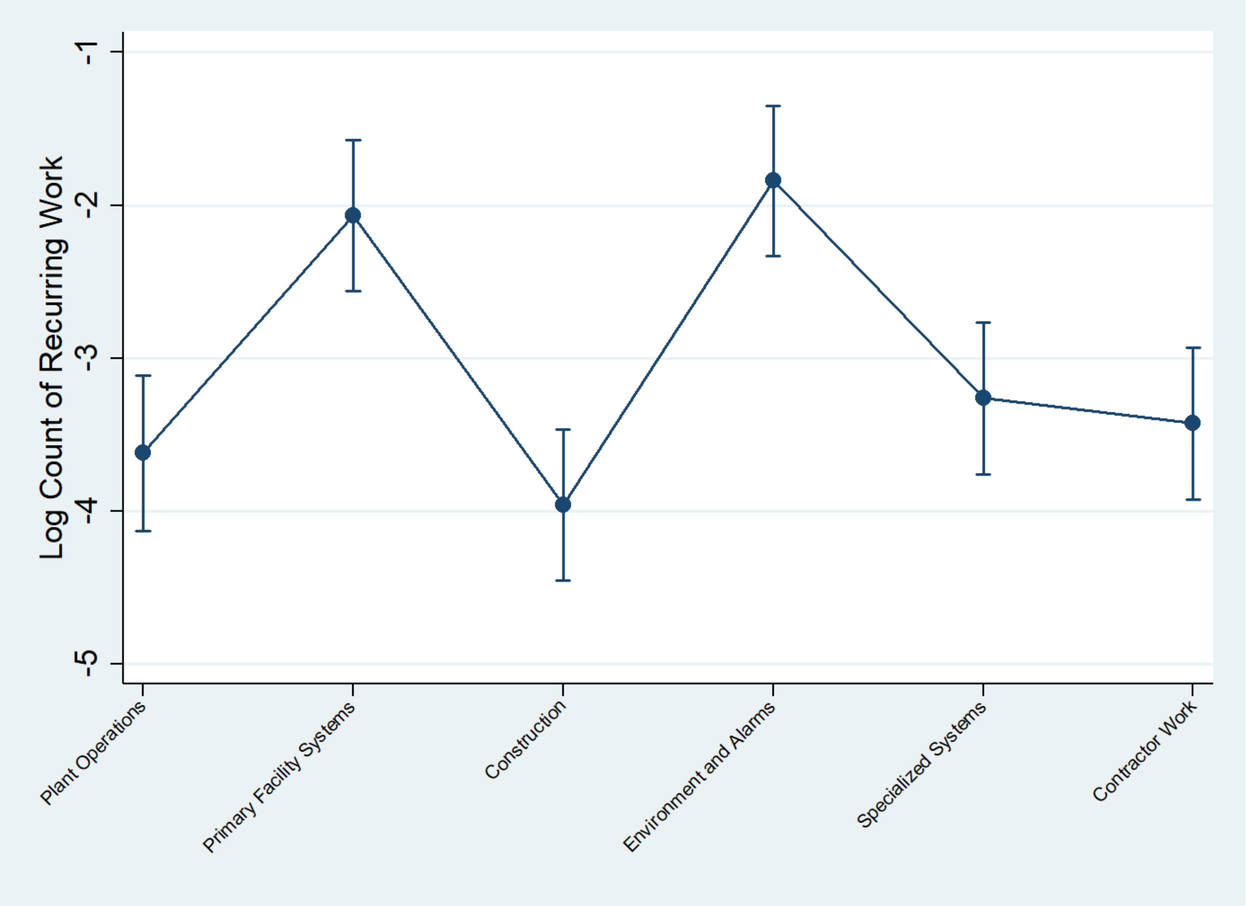


Figure 26: Predicted log recurring work count by systems group.

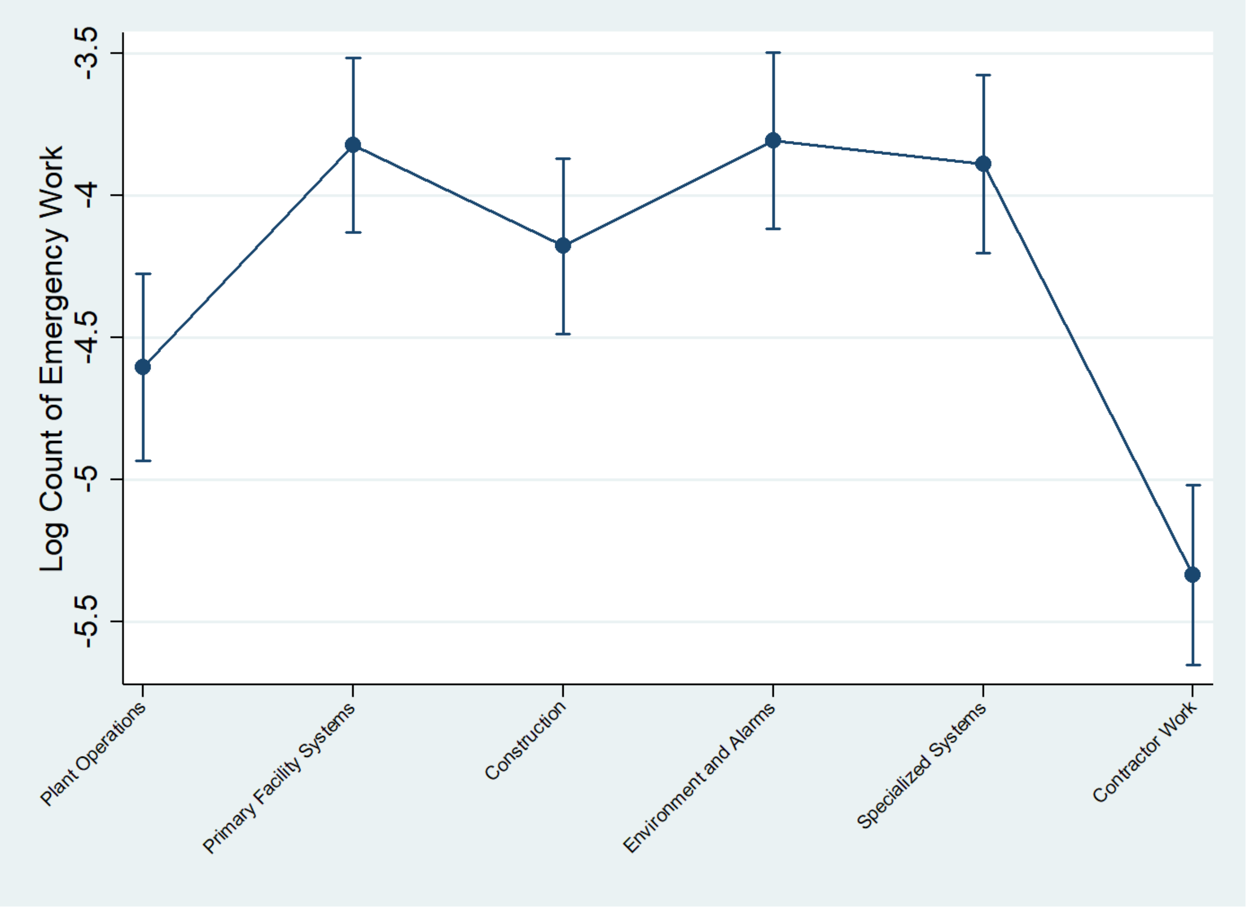


Figure 27: Predicted log emergency work count by systems group.

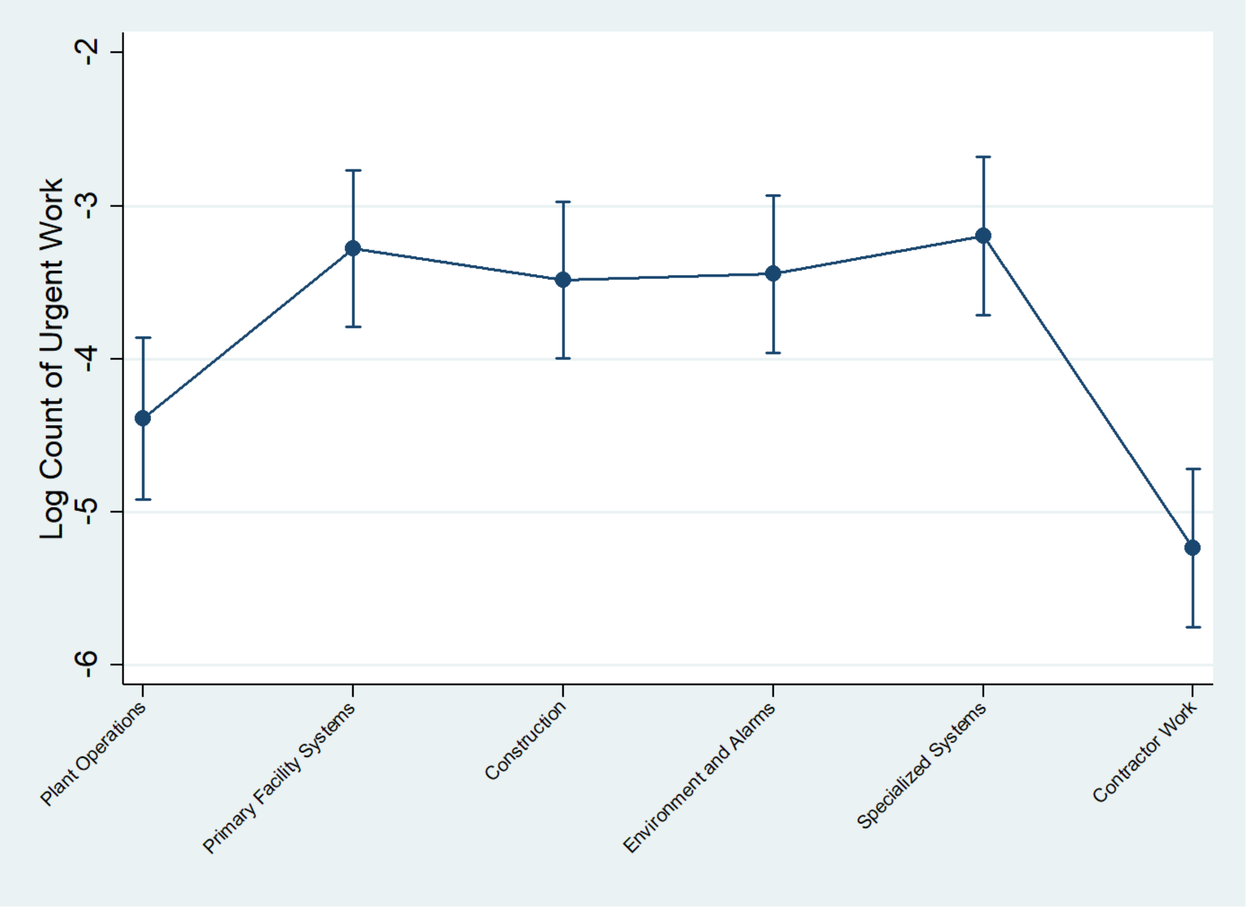


Figure 28: Predicted log urgent work count by systems group.

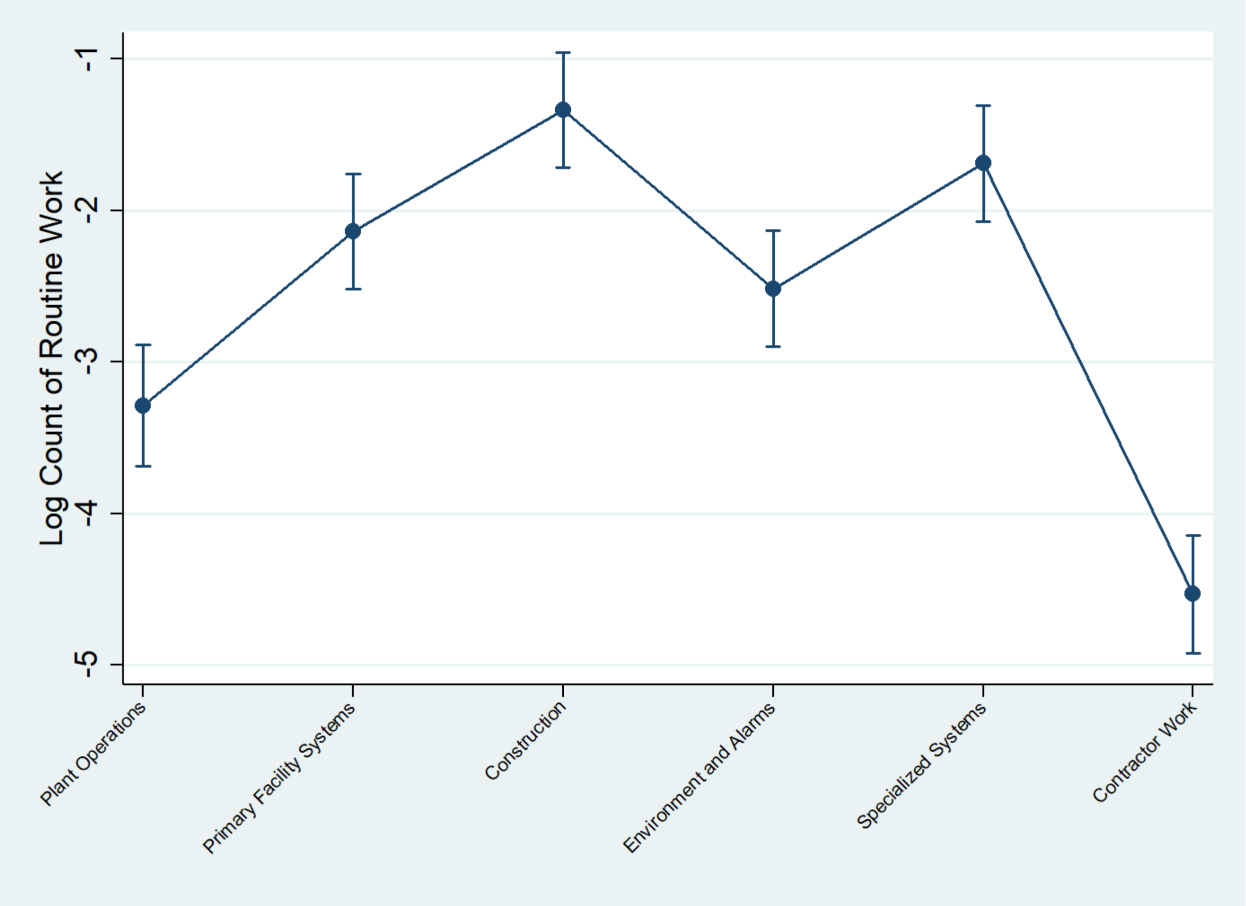


Figure 29: Predicted log routine work count by systems group.

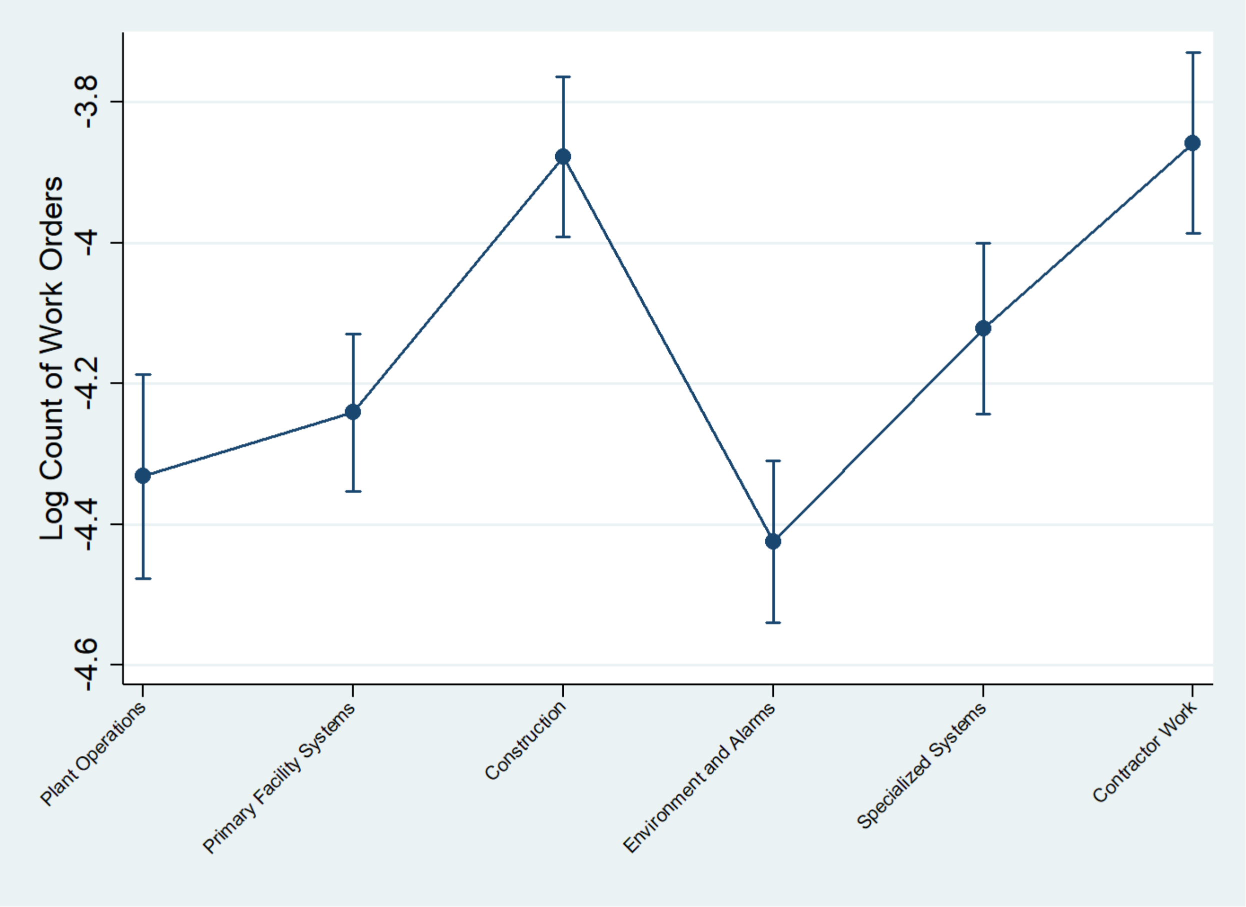


Figure 30: Predicted log work orders count by systems group.

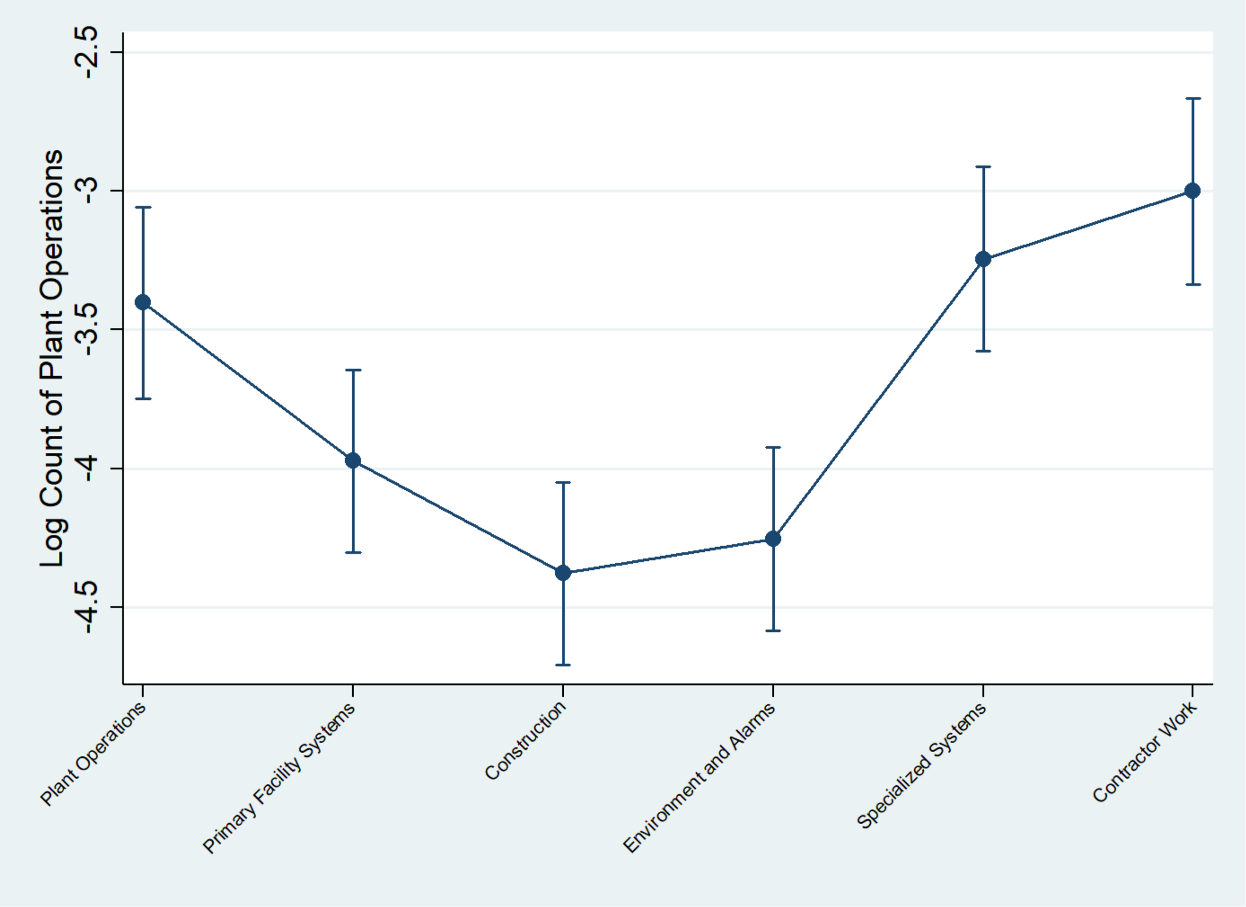


Figure 31: Predicted log plant operations count by systems group.

Table 14: Multilevel Models of Work Labor Hours (Systems Groups)

	Recurring	Emergency	Urgent	Routine	Work Orders	Plant Ops
Primary Facility Systems	1.840^{***}	1.380^{***}	2.189^{***}	2.585^{***}	0.251^{***}	-0.849^{***}
	(0.101)	(0.082)	(0.102)	(0.107)	(0.069)	(0.073)
Construction	-0.649^{***}	0.828^{***}	1.717^{***}	3.614^{***}	0.887^{***}	-1.404^{***}
	(0.103)	(0.083)	(0.104)	(0.109)	(0.070)	(0.074)
Environment and Alarms	1.902^{***}	1.342^{***}	1.843^{***}	1.849^{***}	0.108	-1.087^{***}
	(0.104)	(0.084)	(0.105)	(0.110)	(0.071)	(0.075)
Specialized Systems	0.540^{***}	1.176^{***}	2.129^{***}	3.252^{***}	0.533^{***}	0.482^{***}
	(0.113)	(0.092)	(0.114)	(0.120)	(0.077)	(0.082)
Contractor Work	-2.501^{***}	-0.827^{***}	-1.412^{***}	-2.159^{***}	-0.544^{***}	-1.427^{***}
	(0.120)	(0.098)	(0.122)	(0.128)	(0.083)	(0.087)
Constant	-3.491^{***}	-4.819^{***}	-4.862^{***}	-2.953^{***}	-4.332^{***}	-3.213^{***}
	(0.407)	(0.233)	(0.409)	(0.290)	(0.163)	(0.172)

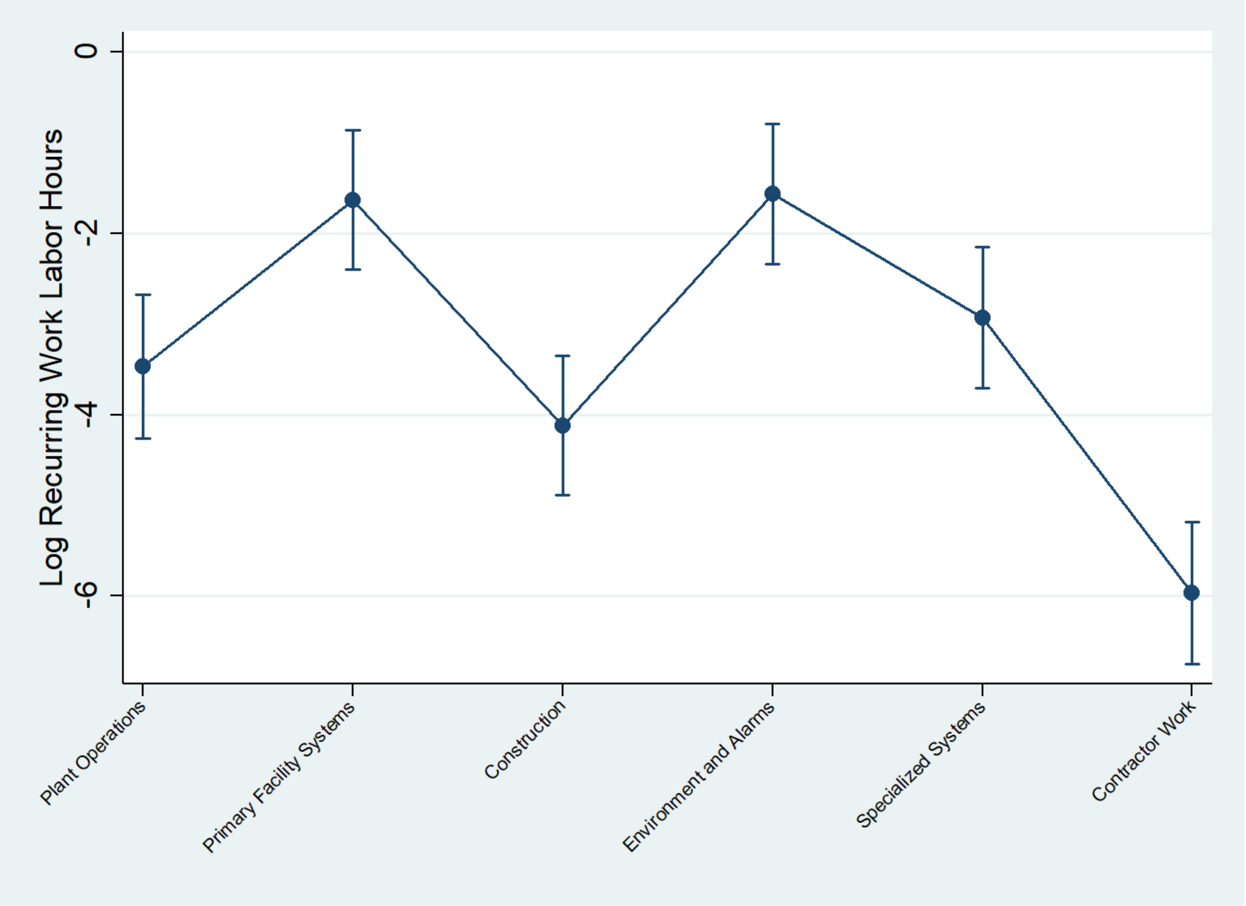


Figure 32: Predicted log recurring work hours by systems group.

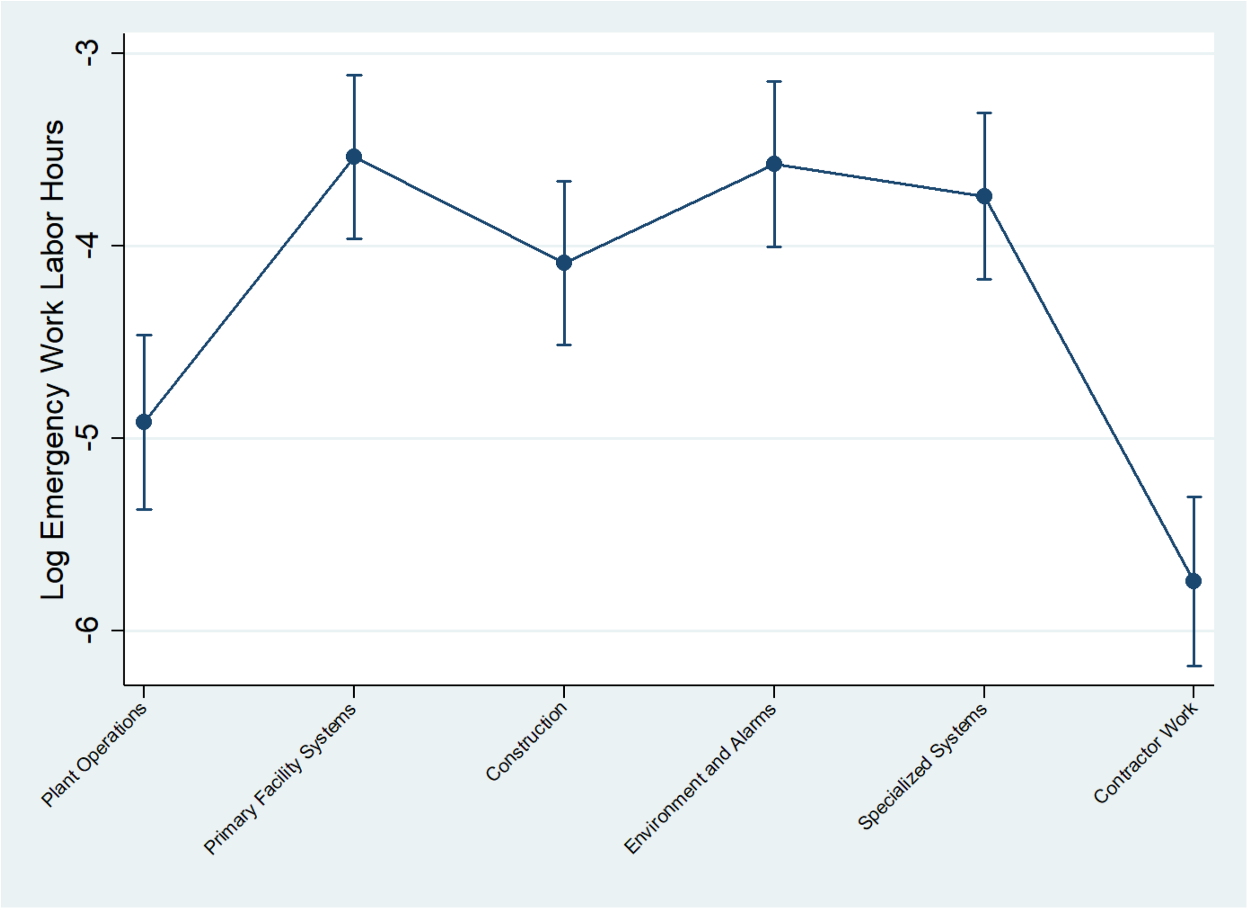


Figure 33: Predicted log emergency work hours by systems group.

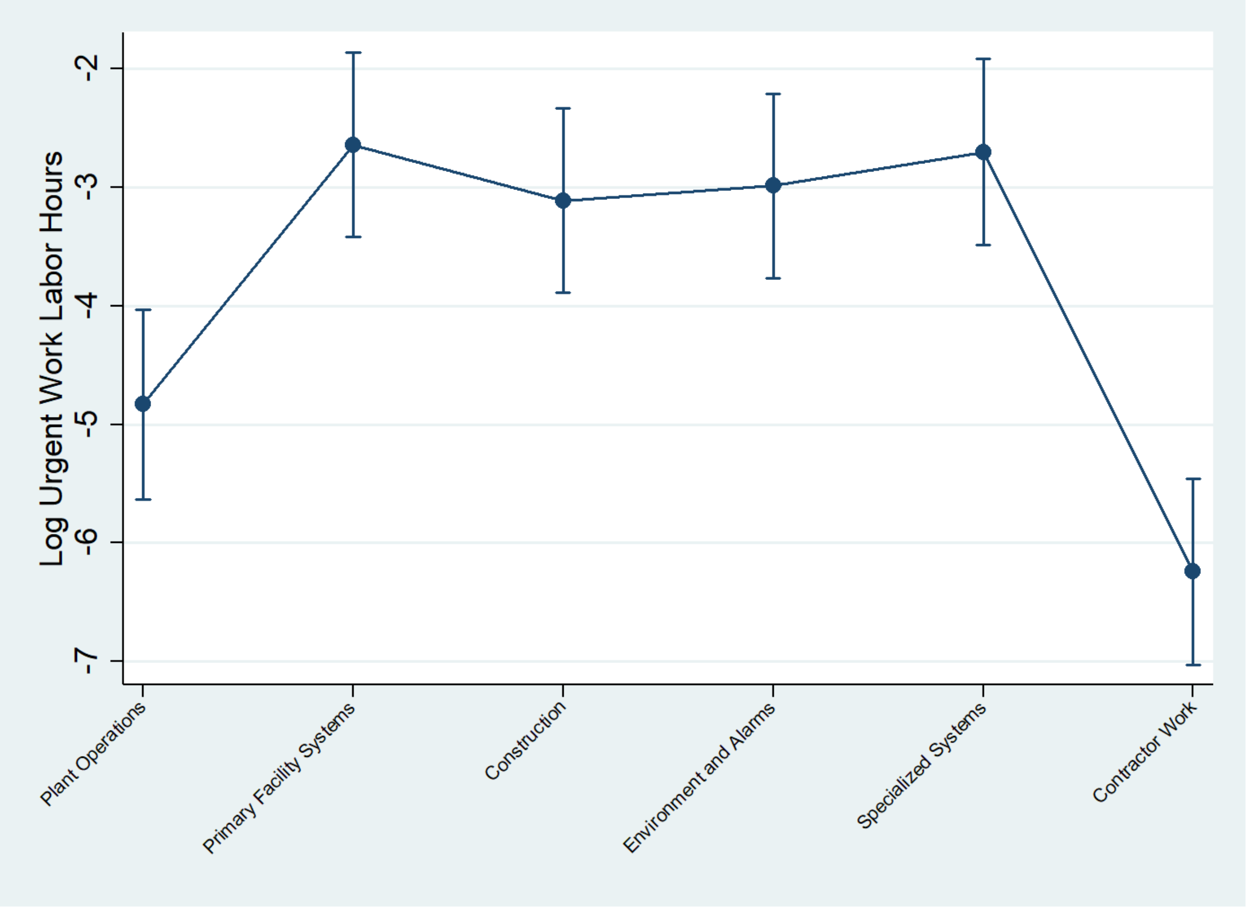


Figure 34: Predicted log urgent work hours by systems group.

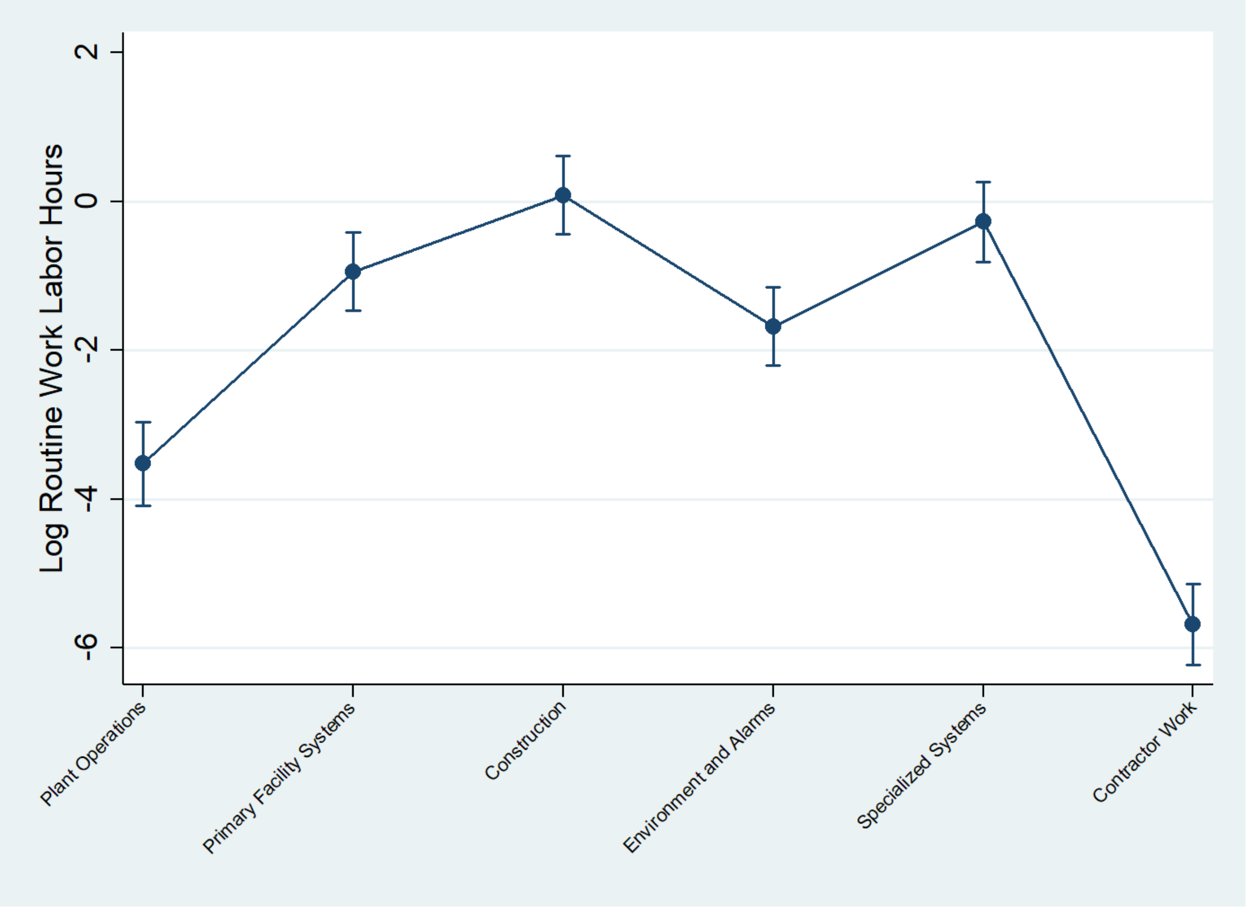


Figure 35: Predicted log routine work hours by systems group.

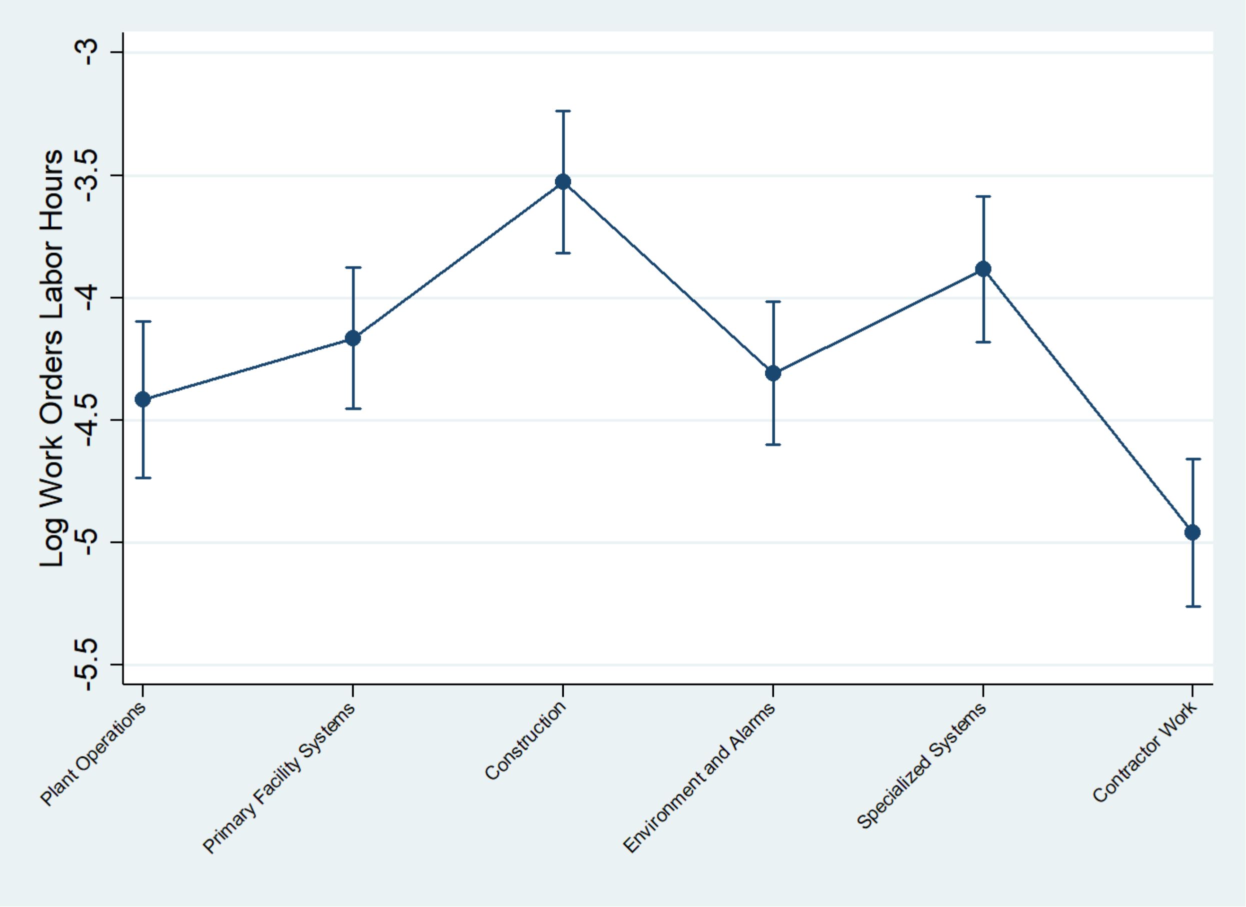


Figure 36: Predicted log work orders hours by systems group.

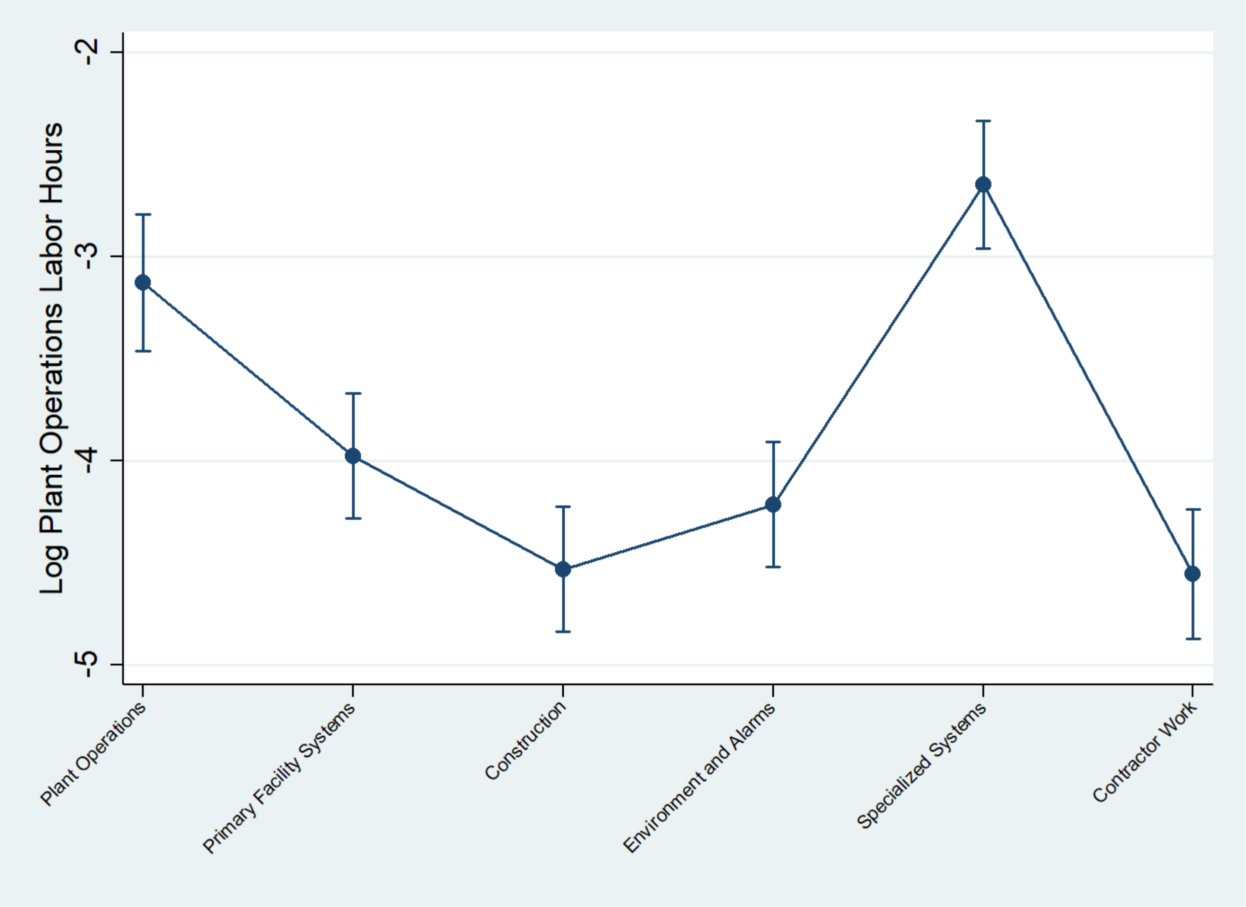


Figure 37: Predicted log plant operations hours by systems group.

Table 15: Multilevel Models of Work Inflation-Adjusted Costs (Systems Groups)

	Recurring	Emergency	Urgent	Routine	Work Orders	Plant Ops
Primary Facility Systems	3.396^{***}	2.048^{***}	2.890^{***}	3.101^{***}	0.139	-1.917^{***}
	(0.147)	(0.134)	(0.163)	(0.166)	(0.125)	(0.117)
Construction	-1.123^{***}	1.178^{***}	2.182^{***}	4.626^{***}	1.028^{***}	-2.796^{***}
	(0.150)	(0.136)	(0.166)	(0.169)	(0.128)	(0.120)
Environment and Alarms	3.458^{***}	2.014^{***}	2.370^{***}	1.967^{***}	-0.327^{*}	-2.397^{***}
	(0.152)	(0.138)	(0.168)	(0.170)	(0.129)	(0.121)
Specialized Systems	0.358^{*}	1.694^{***}	2.791^{***}	4.040^{***}	0.418^{**}	-0.083
	(0.165)	(0.150)	(0.183)	(0.186)	(0.141)	(0.132)
Contractor Work	-1.433^{***}	-1.374^{***}	-1.813^{***}	-2.941^{***}	1.202^{***}	-0.218
	(0.177)	(0.160)	(0.196)	(0.198)	(0.150)	(0.141)
Constant	-2.513^{***}	-4.758^{***}	-4.450^{***}	-1.070^{*}	-3.835^{***}	-1.644^{***}
	(0.605)	(0.376)	(0.641)	(0.454)	(0.223)	(0.300)

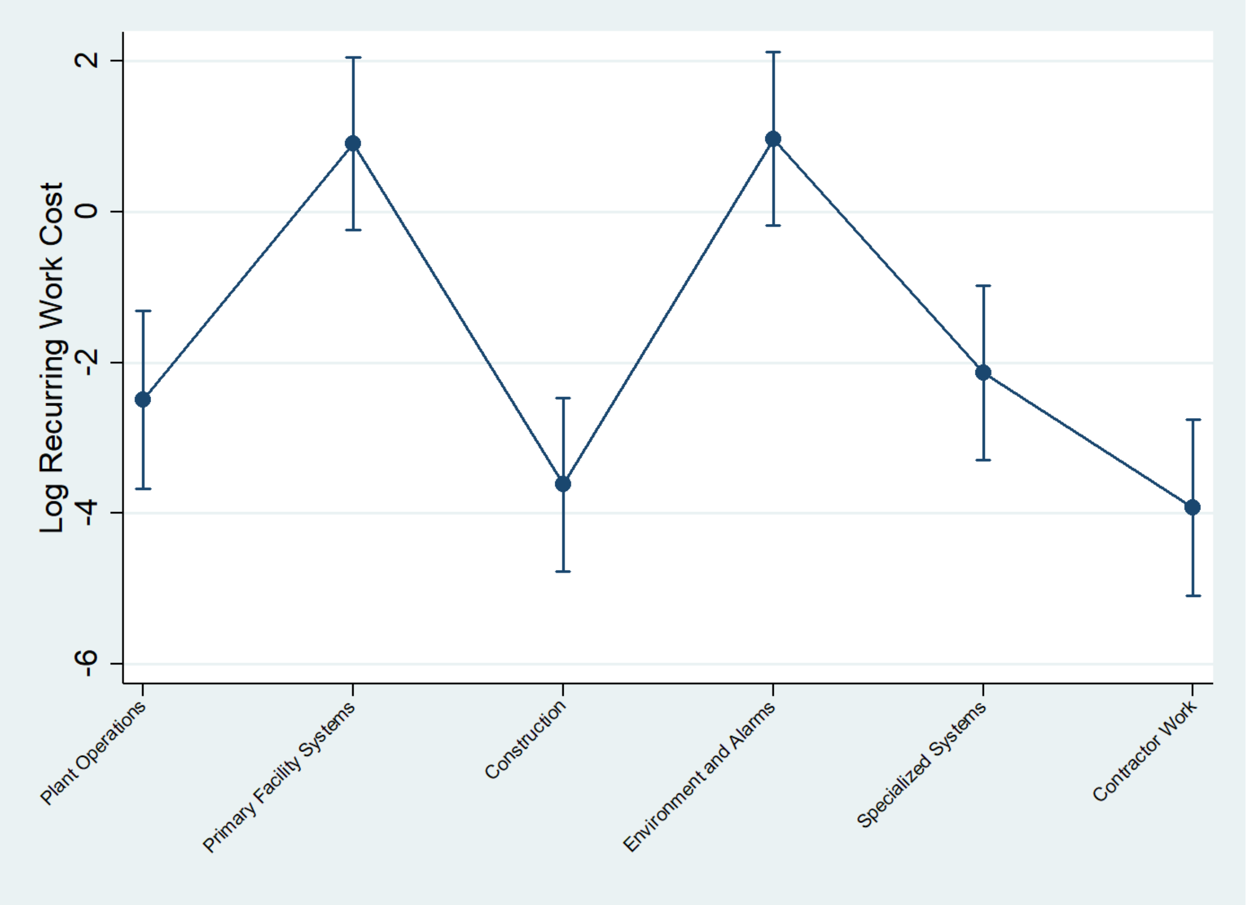


Figure 38: Predicted log recurring work cost by systems group.

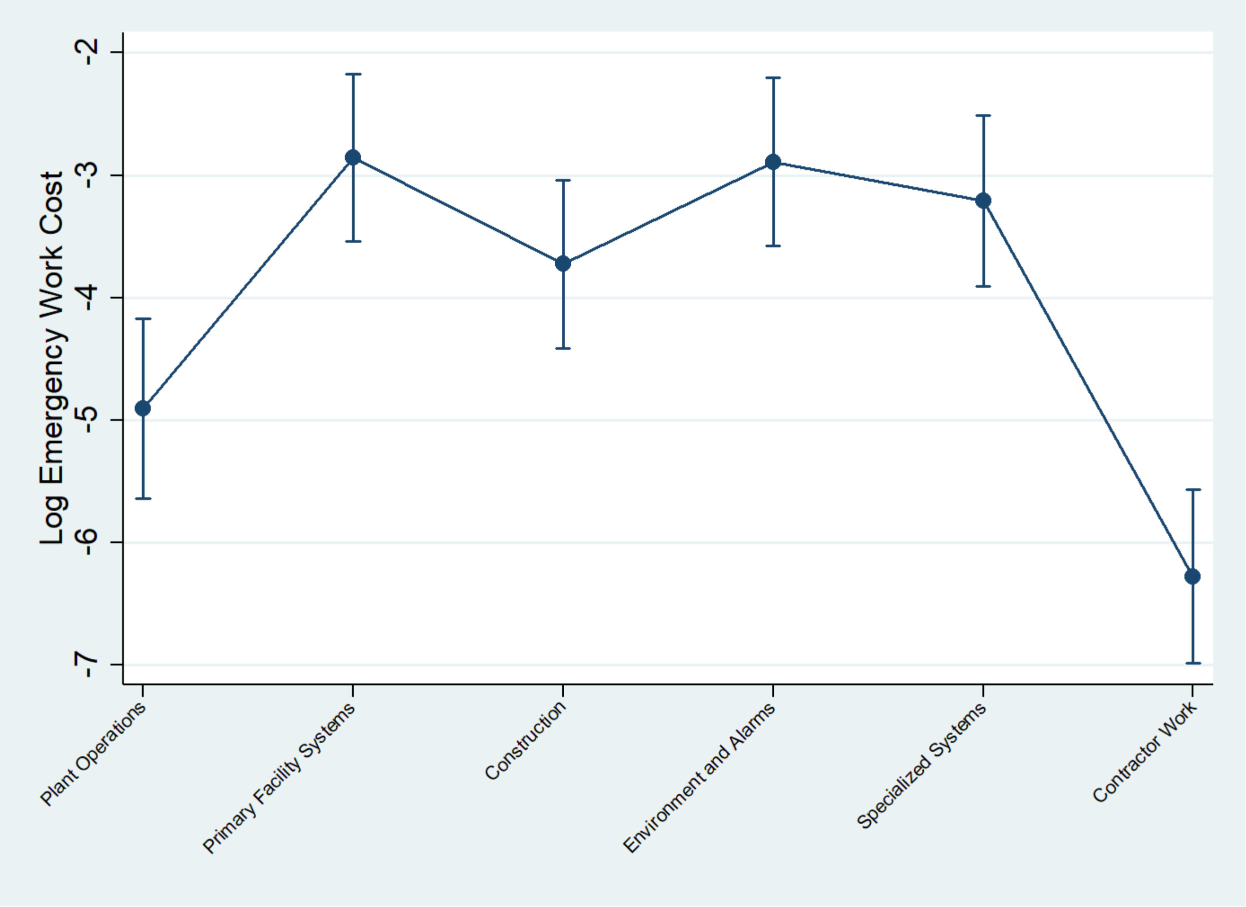


Figure 39: Predicted log emergency work cost by systems group.

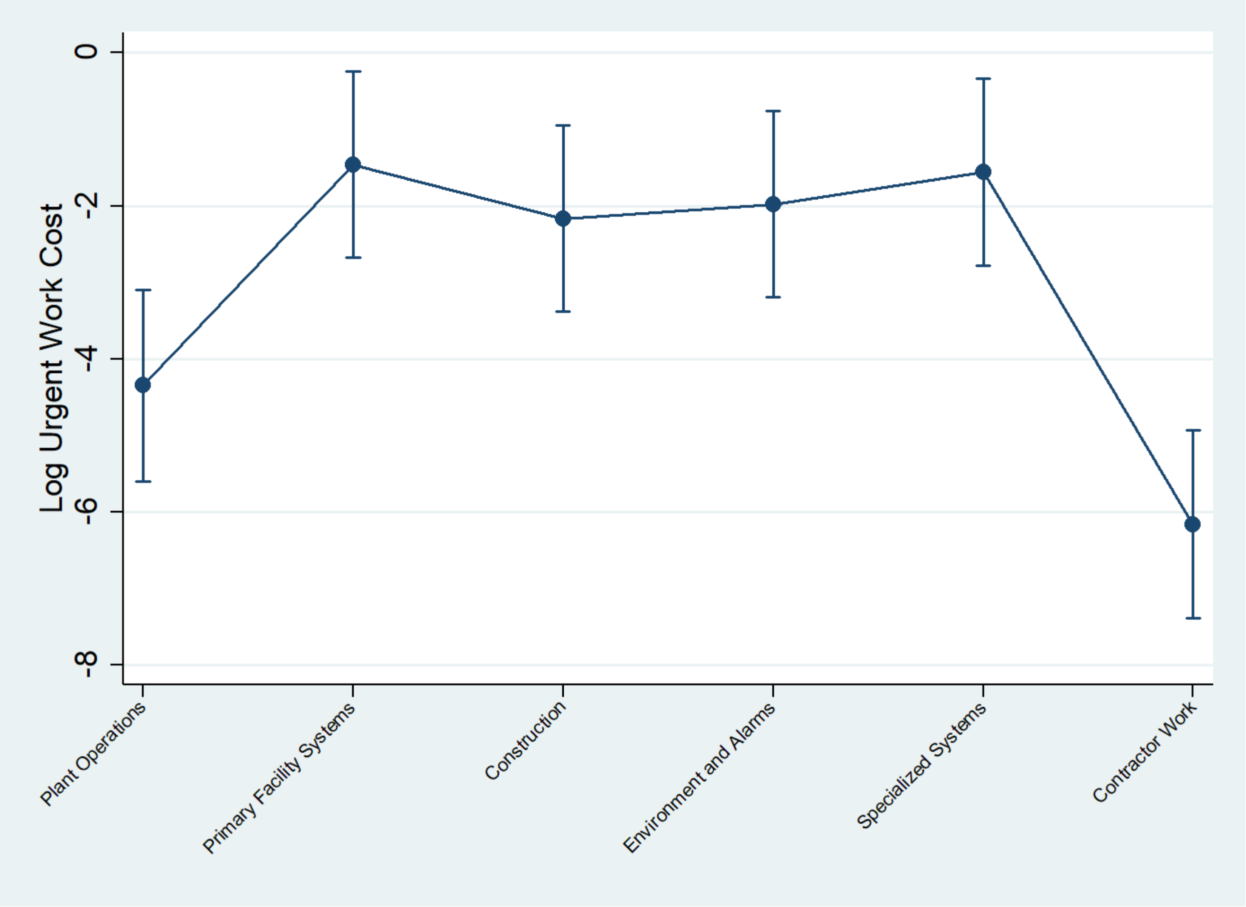


Figure 40: Predicted log urgent work cost by systems group.

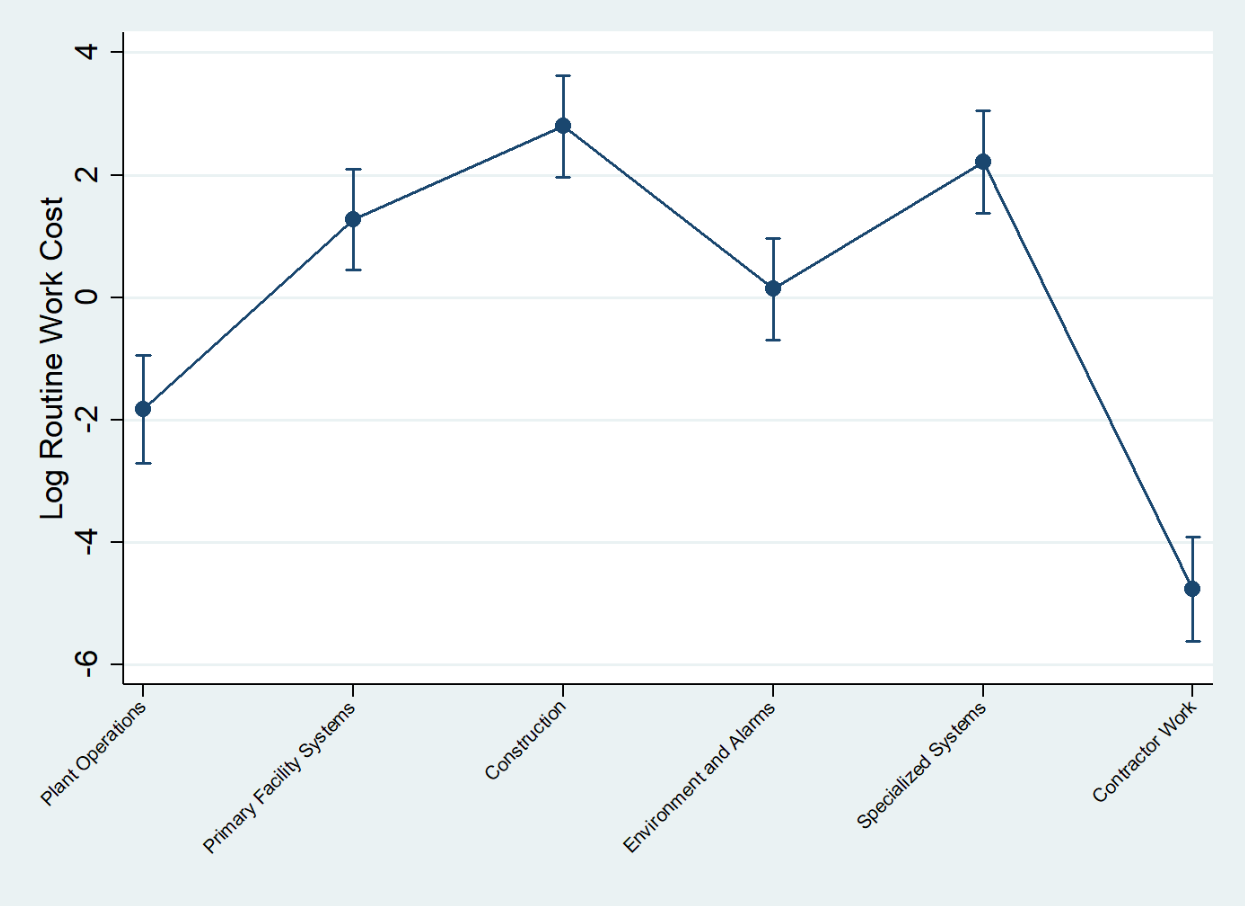


Figure 41: Predicted log routine work cost by systems group.

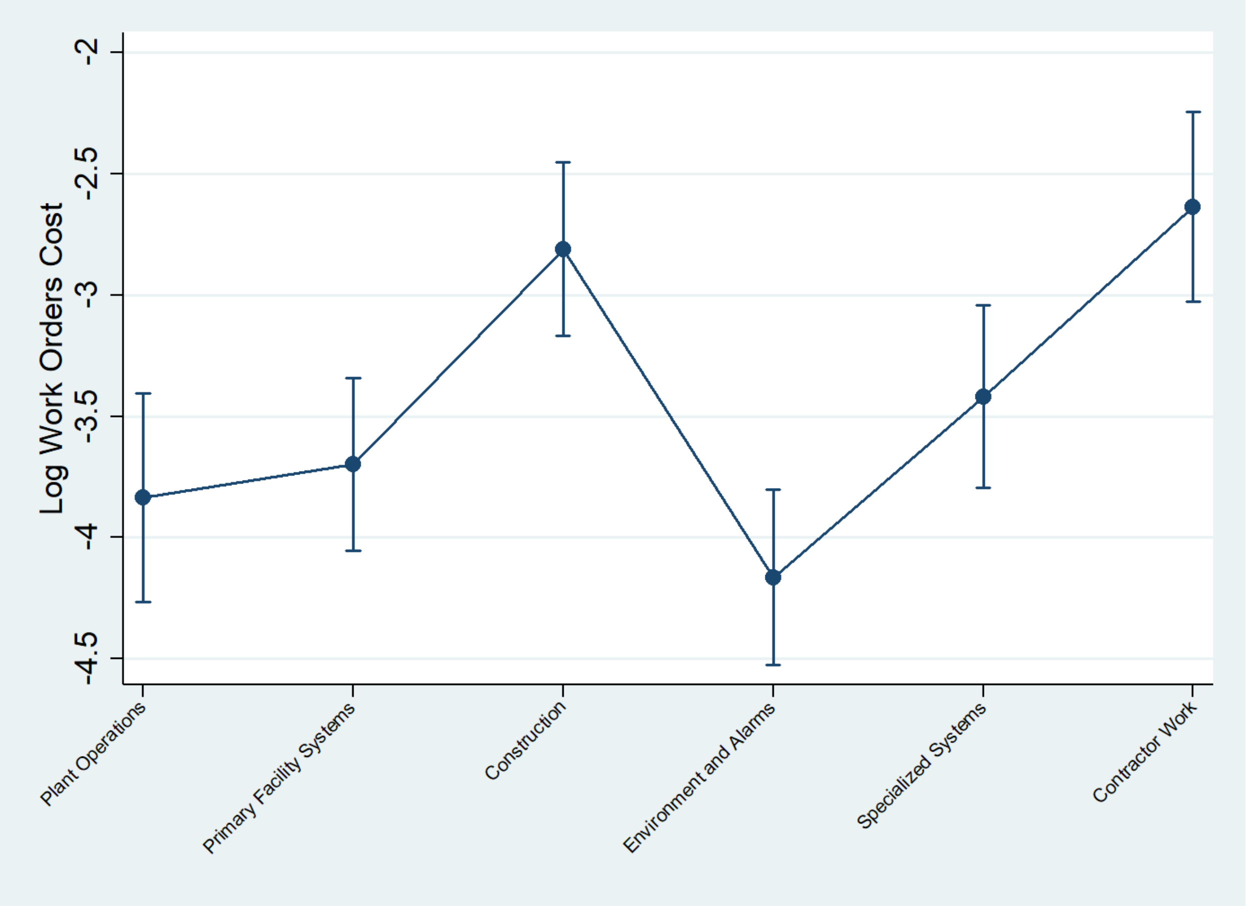


Figure 42: Predicted log work orders cost by systems group.

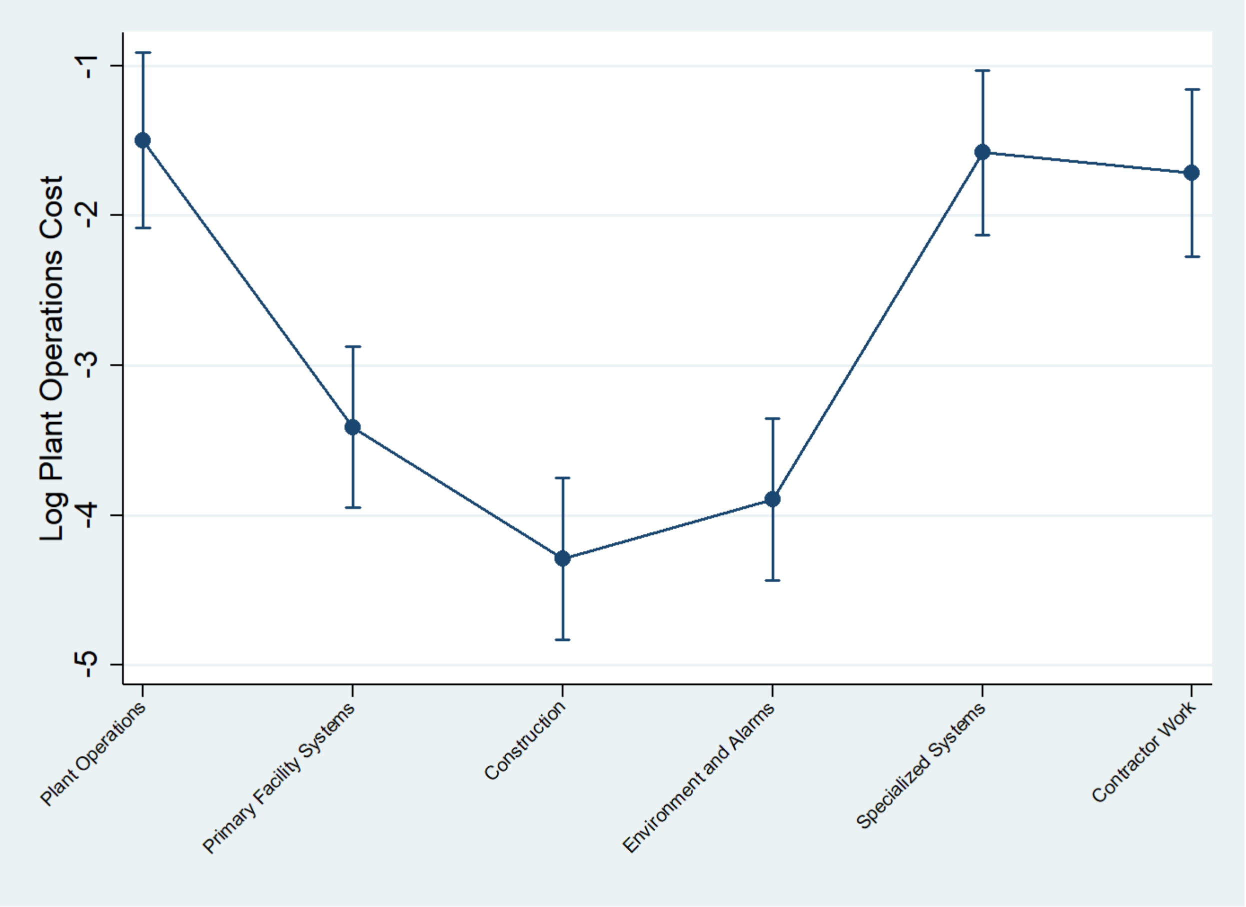


Figure 43: Predicted log plant operations cost by systems group.

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