Estimating Total Cost of Ownership for United States Air Force Chiller Assets

THESIS

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Abstract

In order to make the most cost-effective choice when purchasing high-value assets, organizations must be able to quantify and compare the costs associated with acquiring, maintaining and disposing the alternatives. Currently, the United States Air Force (USAF) Civil Engineer (CE) enterprise has no standardized model to accurately and efficiently predict the total cost of ownership (TCO) for the acquisition of new assets. As such, acquisition efforts throughout the enterprise are disjointed and performed without leveraging the considerable buying power wielded by an organization as large as the USAF. This research developed a TCO model using a standard, dollar-based approach that combined linear additive and regression modeling techniques. The model was derived from existing operations and maintenance and contract spending data associated with heating, ventilation, and air conditioning. The TCO model provides USAF acquisition, contracting, and civil engineering professionals a tool with which to project life-cycle costs, negotiate prices, and justify spending decisions. Furthermore, the model provides a proof of concept to the CE enterprise that will allow for the expansion of TCO modeling to other categories of spending.

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I. Introduction

Background

The cost to own and operate the average United States (US) federal government acquisition program has been growing at a rate greater than inflation over the past decade (U.S. Department of the Navy, 2014). Despite increasing budgets, especially in defense, federal agencies have less fieldable resources than planned due to program cost overruns (FY04 – 10 Presidential Budget). These escalating costs for programs that fail to meet delivery quotas are a direct result of disjointed acquisition management, inability to capture total program costs, and lack of communication (Rung, 2014). For example, in 2014 there were more than 3,300 distinct contracting units under the major federal contracting agencies managing $428B--12% of the 2014 federal budget across the US federal government (OMB, 2015). These units work mostly by funneling information upward to their parent agencies, with only occasional collaboration across organizations and little sharing of information and best practices. This degree of fragmentation and lack of coordination drives costly redundancies and inefficiencies in procurement actions, contracting vehicles, and overall acquisition efforts (Dodaro, 2015). In addition to duplication and unnecessary complexity, there is also a failure to leverage institutional knowledge held by thousands of acquisition professionals (OMB, 2015). The continual decrease of acquisition personnel, loss of subject matter expertise, and gaps in data/information transfer will only exacerbate these inefficiencies and drive costs higher. All of these issues are tied together by the underlying fact that accounting

for the total cost paid by the federal government for any given acquisition is not done

properly (GAO, 2016). Without understanding the true cost of ownership for the assets

purchased by the government, reducing those costs is impossible.

In May 2005, the Office of Management and Budget (OMB), Office of Federal

Procurement Policy (OFPP) released a memorandum for all federal government agency

Chief Acquisition, Financial, and Information Officers announcing strategic sourcing as a

requirement for all federal agencies (Johnson, 2005). While guidance from OFPP

required strategic sourcing within all federal agencies, systematic and collaborative

approaches across all government agencies was needed. As a result, the Department of

the Treasury and General Services Administration (GSA), with support from OFPP,

partnered to launch the Federal Strategic Sourcing Initiative (FSSI) in November of 2005,

inviting all Federal agencies to participate and work together to address OMB's

requirement of buying better. With additional OMB guidance in December 2012 (Zients,

2012), the Strategic Sourcing Leadership Council (since renamed the Category

Management Leadership Council - CMLC) was established and Strategic Sourcing

Accountable Officials were assigned to help agencies optimize performance, minimize

price, and increase the value of each dollar spent. As a result of the FSSI and support of

the CMLC, the federal government has awarded nine sourcing solutions generating over

$439 million in savings from 2010 – 2014 (OMB, 2015). This new, coordinated effort is

called category management.

While the category management effort is federal government-wide, the United States Air Force (USAF) has taken the lead in implementation. While the categories of spending which category management covers are broad (OMB, 2015), this research will focus on the specific category of facilities and construction spending within the USAF as a proof of concept. Efforts to implement a category management model across the USAF are ongoing; however, there are no service-wide standardized cost models available to provide decision makers with the cost information they need to implement category management practices (Brannon et al., 2018). Without knowing the total cost over the lifespan of an asset, optimal purchasing decisions cannot be made because the majority of an asset's total cost of ownership (TCO) comes after the initial purchase (Uddin et al., 2013). The facilities and construction category of government spending is the largest portion of any category, representing 17.7% of contracted spending in FY14 (GSA, 2017a). Facilities and construction acquisitions are not immune to the government-wide inability to model TCO. The USAF specifically owns, operates and maintains thousands of Real Property Installed Equipment (RPIE) systems that are vital to USAF facility function (AFCEC/CIT, 2017). These facilities support everything from the control of the runway operation to intrusion and fire detection. At the most basic level, properly functioning facility systems allow for comfortable, productive work environments that can account for millions of dollars in lost work-hours if neglected (Bluyssen, 2012). Failure of any one system at one of these key facilities may lead to failure of the mission itself; such failures warrant an examination of these support

systems as an extension of the weapons systems they enable and treatment of their acquisition with proportionate consideration.

Facility systems are composed of a variety of types and components that are designed to work in concert to control the interior and exterior environment of the facility. In the USAF, these facility systems are purchased and maintained by the Civil Engineering (CE) career field as individual items (Brannon et al., 2018). Category Management is a framework that allows an opportunity to consider these systems on all installations/bases as one "larger system" with the goal of gaining efficiencies in cost, performance, and resilience (OMB, 2015). Large cost reduction opportunities are found when the focus broadens from only the initial procurement of the system(s) and expands to consider the maintenance and repair cost of systems as well. Proper maintenance and repair minimizes system downtime (increasing uptime and reliability) resulting in life-cycle cost efficiencies (Steenhuizen et al., 2014). Because of the low up-front cost (relative to the facility to which they are attached) and infrequent nature of purchasing most systems, a lowest price technically acceptable (LPTA) acquisition analysis is generally used when choosing most facilities equipment (DiNapoli et al., 2014). Often times life cycle or TCO analysis is only completed as a part of new facility construction or renovation of existing structures where only the total package is analyzed (Brannon et al., 2018). Limited manpower is often used as justification for using LPTA for the acquisition of relatively low-priced assets. It takes a great deal of time and effort to accurately map the TCO for a given system (DiNapoli et al., 2014).

Additionally, the Federal Acquisition Regulation (FAR) has specific rules on when contracting officers are allowed to use non-LPTA acquisition, referred to as the trade-off process ("Federal Acquisition Regulation, 48 C.F.R. § 15.101-1," 2014). Without the ability to quickly provide total cost analysis that meets FAR requirements, LPTA will remain the main contract vehicle for acquisition despite the potential for paying much higher TCO over an asset's service.

Research Focus

The purpose of this research is to develop a TCO model for facilities and construction equipment. A proof of concept model will be developed using USAF-wide data on the largest subset of the facilities and construction category – heating, ventilation, and air conditioning (HVAC) air chillers (Brannon et al., 2018). Focusing on the largest sub-category of the facilities and construction category provides an opportunity for more cost savings as well as access to a large set of historical data based on USAF maintenance and purchasing records. By providing a practical TCO model that can be standardized and implemented enterprise-wide, stakeholders in the acquisition and deployment of facility and construction assets will gain clarity on how their decisions affect the life-cycle costs of HVAC systems. The increased clarity will inform decisions that save money for the Air Force while providing tangible justification for those decisions. This research will:

1. Develop a TCO model for air chiller systems that statistically defensible if legally challenged; and

2. Develop a TCO model that reduces the time requirement of tradeoff analysis so that the manpower cost of analysis is negligible compared to simpler methods.

II. Literature Review

Introduction

This chapter contains a literature review of the work done in the fields relevant to the research statement presented previously. This chapter summarizes and organizes the reviewed literature in four main sections: (1) the principles of category management that are applicable to this research; (2) the concept of using spend under management as a tool for successful category management; (3) a description of the facilities and construction category of United States (US) government spending; and (4) a review of total cost of ownership (TCO) modeling as well as the gaps in existing work that this research will fill.

Category Management

Category management is a retailing and purchasing concept in which the range of products purchased by a business organization or sold by a retailer is broken down into discrete groups of similar or related products known as product categories. Category management is a systematic, disciplined approach to managing a product category as a strategic business unit (NACS, 2018). While the process of category management has been well documented and refined (Blattberg et al., 1995; Blattberg & Deighton, 1996; Gruen, 1998; Paydos & Conti, 1997), there has been little systematic research on the elements that impact category management performance. McLaughlin and Hawkes (1994) reported what was perhaps the first major survey of category management practices through the study of 60 leading supermarket retailers and 26

wholesalers concerning the current status and future prospects for category management. Their work shows that both retailers and wholesalers face formidable constraints which are impeding more rapid integration of category management. The most common constraint is data management; most companies have too much data, too little information in easily accessible forms, a lack of trained personnel to interpret data to make informed category management decisions. While the literature on category management is consistent when discussing the constraints involved (Gruen, 1998; Gruen & Shah, 2000; Lindblom et al., 2009; McLaughlin & Hawkes, 1994), there is also an agreement on the benefits of category management. Research has shown that the effect of one of the common outcomes of category management, unique reduction of available products (within limits), led to increases in consumer satisfaction (Broniarczyk et al., 1998). Additionally, implementing category management has been found to improve manufacturer/supplier/customer relations, streamline inventory management, and improve profits through reduced costs (Gruen & Shah, 2000).

The relationship of retailer and manufacturer is not a perfect description of the category management framework the US federal government wishes to implement. It does, however, provide guiding theories that may be adapted to achieve success. From a federal government stand point, category management is an approach based on industry leading practices that streamline and manage entire categories of spending across government more like a single enterprise (Rung, 2014). This approach to category management includes strategic sourcing, but also includes a broader set of strategies, such as developing common standards and improving data

analysis/information sharing to leverage the government's buying power and reduce contract duplication (GAO, 2016).

Gruen and Shah (2000) provide four primary and three secondary findings that must be considered in order to achieve successful category management. First, objectivity of the category plan is of critical importance to the long-term success of the supplier-retailer relationship, and to the performance of the category. Second, in category management situations within supplier companies, brand management pressure on the customer business development (CBD) team – although not as important as plan objectivity – is an important consideration for category management teams. Third, suppliers revealed a wide array of self-serving tactics when developing category plans that would be difficult for the retailer to monitor. Fourth, every retailer has difficulty fully implementing category plans, and this is a major challenge to manufacturers and retailers alike. The three secondary factors likely to impact the objectivity and implementation of category plans include suppliers' resource commitment to category management, the amount of joint pre-planning by the supplier and retailer, and the retailers' experience-based trust in the category management system (Gruen & Shah, 2000).

One of the most consistent and compelling findings from the literature is the importance of category management plan objectivity (Blattberg & Deighton, 1996; Gruen & Shah, 2000). In category management, the plan must fully consider the available data, such that the plan offers the optimal assortment of choices and pricing. For example, in the study of factors that affect the internal resistance to marketing plan

acceptance, objectivity of a marketing plan (based on the logic of the plan) was considered to be one of the critical characteristics that determined the degree of plan implementation (Silverman, 1996). In category management, development of the plan is only one half of the picture: the plans must be put into effect. Implementation refers to the actual carrying out of category plans on the retailers' shelves. Generally, at the minimum it involves the rearrangement, addition, and deletion of products, brands, and stock keeping units (SKUs). Retailers often rely on the manufacturers' CBD teams to provide the labor to reset the shelves. Generally, manufacturers and suppliers do nothing more than deliver the products in question while contractors or government personnel handling stocking, arranging, and managing inventory. As such, the generally high cost of implementing category management plans on the manufacturing/supply side (Gruen & Shah, 2000) will be much less for government applications (pending special requirements the government may have). Consistent with the literature in strategic management, the key to formal planning effectiveness is the actual implementation of that planning (Camillus, 2015). Exploratory interviews revealed that the implementation of category management plans vary greatly, and it is the top concern in category management for many companies. The manufacturers find it frustrating to learn that the time and money resources allocated to developing a category plan get wasted through improper and/or incomplete implementation. Although the degree of implementation is a function of various inputs, both suppliers and retailers mentioned that objective plans were critical for achieving the necessary buy-in from both the retailers and competing suppliers in the category. Because of the

high focus that the literature places on objectivity, focusing on the accuracy and objectively quantifying how much the federal government spends within each category and then bringing that spending under active management is a pivotal requirement to successful category management within the federal government. While the steps toward proper implementation require considerable time and resources, when done properly category performance will improve and the parties involved will realize all of the positive of category management (Camillus, 2015; Gruen & Shah, 2000).

The relationship of retailer and manufacturer is not a perfect description of the category management framework the US federal government wishes to implement. It does, however, provide guiding theories that may be adapted to achieve success. From a federal government stand point, category management is an approach based on industry leading practices that streamline and manage entire categories of spending across government more like a single enterprise (Rung, 2014). This approach to category management includes strategic sourcing, but also includes a broader set of strategies, such as developing common standards and improving data analysis/information sharing to leverage the government's buying power and reduce contract duplication (GAO, 2016). Under the category management initiative, federal procurement spending is organized into 10 common categories such as information technology (IT), travel, and construction, which, according to Office of Federal Procurement Policy (OFPP), altogether accounted for $275 billion in fiscal year 2014 federal spending (OMB, 2015). When applying category management to the government for research purposes, one can think of the government as the retailer

while suppliers and manufacturers can be treated the same as in private industry category <mark>management.</mark> The While the body of literature on the topic of category management lays out the objectives, benefits, challenges, and requirements associated with successful category management, it does so with a focus on private business (mostly in the retail sector). As such, the principles presented are not perfectly applicable to organizations such as the United States federal government who do not serve traditional customers with traditional products. Despite the imperfect analogy of manufacturer/supplier and customer, the concept of systematically and objectively managing purchases based on categories is applicable to the federal government. While this research does not seek to identify the path to successful category management within the federal government, it will provide a means of objectively quantifying purchasing decisions in order to achieve the objectivity that is crucial to success.

Spend Under Management

Spend under management (SUM) is the percentage of an organization's spend that is actively managed according to category management principles (Zeiger, 2017). Increasing SUM will eliminate redundancies, increase efficiency, and deliver more value and savings (GSA, 2018a). SUM is a model designed to assess agency and government-wide category management maturity, and to highlight successes as well as development areas across all categories and federal agencies (GAO, 2016). Within the context of the government-wide category management initiative, OMB defines SUM as spend on

contracts that meet defined criteria for management and data-sharing maturity. OMB

uses the following tiered rating scale to evaluate agency spend (GSA, 2017b):

- Tier 3, Best-in-Class (BIC) Solutions – Dollars obligated on BIC contracts.

- Tier 2, Multi-Agency Solutions – Dollars obligated on multi-agency contracts that

  satisfy rigorous standards set for leadership, strategy, data, tools, and metrics.

- Tier 1, Mandatory-Use Agency-Wide Solutions – Dollars obligated on agency-

  wide contracts with mandatory use or mandatory-consideration policies, along

  with standards set for data-sharing and other criteria.

- Tier 0, Spend NOT Aligned to Category Management Principals – Dollars

  obligated on contracts that do not fit into one of the three tiers above. Agencies

  should analyze Tier 0 spend to find opportunities for shifting to higher-tier

  solutions.

Using vetted, approved buying channels like BIC solutions helps bring more of

the government's SUM. As agencies work to increase SUM, the government will build

more robust government-wide buying data, that will result in keener insights on buying

behaviors and ultimately result in better means of improving the way the government

buys common goods and services.

Under category management, the federal government has established targets

for SUM BIC solutions (GAO, 2016). As such, agency progress toward implementing

category management should be tracked and measured. The most current category

management governance document (OMB, 2015) indicates that SUM will be used as the

principal measure by which OMB will assess adoption of category management. Because

of the effectiveness of using SUM as a performance evaluation tool, OMB will evaluate

SUM results, that includes agency adoption of BIC solutions and then review with

agency leaders progress toward meeting goals.

Adopting SUM guidelines gets the federal government one step further to

achieving success in objectively quantifying spending. However, there is no application

in literature of applying SUM within an organization similar to the US federal

government. Furthermore, adopting a SUM framework within category management is

not effective without a means of accurately identifying costs. As such, one can see how

the gap in existing literature perpetuates the need for a well-defined total cost of

ownership model when examining SUM.

Facilities and Construction Spending

The facilities and construction category of OMB category management initiative

represents one of the ten major categories of spending targeted. Consisting of $77.2B

out of the $275B (28%) in spending in fiscal year (FY) 2014 (GSA, 2016), the facilities and

construction sub-categories include construction-related materials and services, facility-

related materials and services, and facilities purchase and leasing activities. The

breakdown of these sub-categories into functional groupings provides an in-depth

breakdown of the spending and is shown below in Figure 1.

Category			Facilities & Construction $73B		
Sub- Category	Construction Related Materials $1.6B	Construction-Related Services $21B	Facilities Purchase and Lease $458M	Facility-Related Materials $778M	Facility Related Services $49B
Functional Groupings	Heavy Equipment $297M	A&E - All Real Property $4.3B	Purchase - All Real Property $17M	Land/Grounds Maint. Equip. $25M	Nat. Resources /Conservation $774M
	Temporary Structures $440M	Site Preparation $21M	Lease./Rent. - All Real Property $441M	HVAC & Plmb. Equip & Cmpnts $426M	Environmental Systm Protection $3.6B
	Building Materials $865M	Construction - All Real Property $16.9B		Electr. Systems and Components $140M	Maint./Repair/Install of Equipment $1.4B
	Mod./Install. of Above Items $10M			Paints and Adhesives $140M	Operation of Govt. Facilities $21.3B
	Lease/Rent of Above Items $35M			Cleaning Equip. & Compounds $31M	Utilities $2.1B
				Lease./Rent. of Above Items $16M	Demolition $359M
					Fac. Sprt - Jant/ Lndscp/Pest/Trsh $6.5B
					Maint./Repair/Alt. of Facilities $13.1B

Figure 1 - FY 2014 Facilities and Construction Spending adopted from (GSA, 2016)
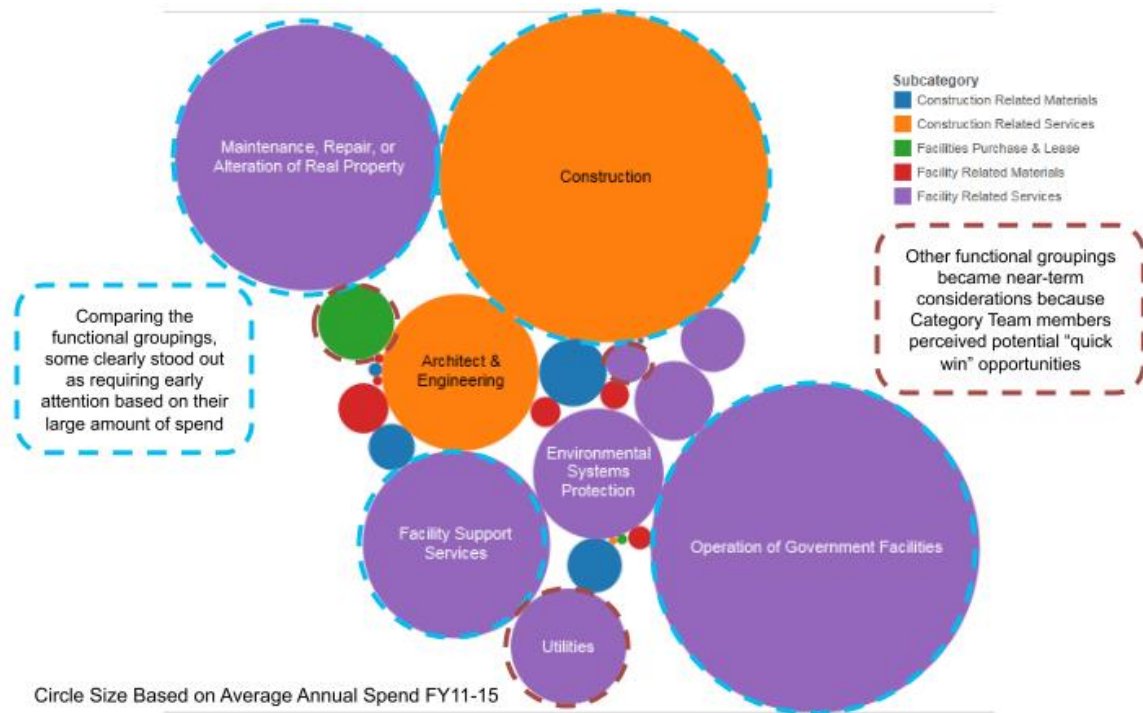
Figure 2 - Functional Grouping Size Comparison (GSA, 2016)

Furthermore, one can see the breakdown of functional group sizing in Figure 2. This sub-category comparison provides a visual means showing the impact of each sub-category as a means of potential targeting for cost savings. In order to manage the facilities and construction category of spending, the United States General Services Agency (GSA) has implemented the Building Maintenance and Operations (BMO) strategic sourcing solution is a comprehensive and flexible solution covering all high-demand BMO services. BMO is an open-market, multiple-award, indefinite delivery, indefinite quantity (MA-IDIQ), governmentwide contract vehicle supporting the strategic sourcing initiative to reduce costs and drive efficient purchasing by federal agencies (GSA, 2018b). BMO falls under the BIC Acquisition Solutions mandated by OMB. These BIC solutions are vetted, well-managed, and recommended (and in some cases required)

for use (GSA, 2018a). The overall goal of BIC solutions is to bring more spending under management in order to build better government-wide purchasing data that can be analyzed to improve the way the government buys common goods and services. BIC solutions are characterized by five requirements that must be met before implementation (GSA, 2017a): (1) rigorous requirements definitions and planning processes, (2) appropriate pricing strategies, (3) data-driven demand management strategies, (4) category and performance management practices, and (5) independent validation and reviews by category teams. The scope of BMO spans many areas of expertise and includes the primary services required to provide a total solution to maintain and operate federal buildings and assets. All awarded contractors are required to offer a certain set of services and some may offer optional services as well. BMO is setup to allow agencies the flexibility of purchasing services all-inclusive or individually. The BMO solution will use a zonal approach, creating reasonably sized regions in which small businesses can realistically compete and operate in order to promote small business participation. The BMO vehicle is a 10-year contract with one 5-year base and one 5-year option at the parent contract level. Agencies seeking longer than a 5-year task order (1-year base period and four 1-year options) must request a deviation from their own agency. By implementing BMO to manage the facilities and construction spending category, OMB is working to get customers and industry involved in upfront planning and requirements definition to create a vehicle that generates the best value and meets socioeconomic goals, tracks/analyzes/shares data, then monitors and shares vendor and solution performance with continuous feedback loop from customers and

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contractors (GSA, 2017a). As BMO (and other BIC) solutions come online, OMB hopes

that top solutions will spread while inferior strategies fall to the wayside as acquisition

experts in other agencies gain confidence to begin tapping into the vehicles while paving

the way for first-time users to begin utilizing high-value acquisition tools.

Total Cost of Ownership

Total cost of ownership (TCO) is defined most simply as the total cost of any

good or service from acquisition to demolition or disposal (Saccani et al., 2017). Defining

everything that falls within the span of a good's lifetime is much more complex. In

addition to the capital costs of acquisition, TCO may include, but is not limited to, such

elements as order placement, research and qualification of suppliers, transportation,

receiving, inspection, rejection, maintenance, replacement, downtime caused by failure,

and disposal costs. These cost elements may be unique by item or type of purchase

(Ellram, 2005). Before 1980, most American firms would define TCO as the bottom line

of a supply contract and the most common criterion for selecting suppliers was to

choose the lowest bidder—thus a desire for low cost took precedence over quality

(Ellram & Siferd, 1993). Acceptance of a relatively high defect rate was accompanied by

a willingness to carry extra inventory which led to overly tasked inventory managers,

expediters, and inspectors (Ellram & Siferd, 1993). Suppliers were pitted against each

other since the threat of losing a contract to a competitor was thought to be the best

way to "keep a supplier in line" (Leenders et al., 1980). In the early 1980s, attitudes

began a shift that resulted in American firms adopting TCO en masse (Ellram & Siferd,

1993) as a key underpinning to the practice of strategic sourcing (Anderson & Katz, 1998).

The use of TCO analysis is preferred to life-cycle cost analysis (LCCA) as the latter focuses primarily on capital or fixed assets (Fernandez, 1990; Jackson & Ostrom, 1980). The emphasis is understanding the purchase price of the asset and also on determining how much it actually costs the organization to use, maintain and dispose of that asset during its lifetime. Since pre-transaction costs tend to be de-emphasized under LCCA, LCCA is congruent with TCO but represents only a subset of TCO activity. TCO is broader in scope and includes the pre-purchase costs associated with a particular supplier. Zero-base pricing (Burt et al., 1990) and cost-based supplier performance evaluation (Monckza & Trecha, 1988) both advocate understanding suppliers' total costs. Traditional approaches to supplier selection and ongoing evaluation include selecting and retaining a supplier based on price or qualitatively evaluating the supplier's performance using categorical or weighted point/matrix approaches (NAPM, 1991). While the latter approaches are preferred to a "price only" focus, they tend to de-emphasize the costs associated with all aspects of a supplier's performance and generally disregard internal costs. Examination of such costs is a strength of the TCO approach (Soukup, 1987). Thus, the use of TCO modeling is superior to LCCA for organizations trying to build supplier relations, leverage high volume spending, and negotiate contracts based on an in-depth understanding of supplier pricing (Ellram, 2005).

In contrast to TCO, zero-base pricing focuses heavily on understanding the supplier's pricing structure and the supplier's cost of doing business. Cost-based supplier performance evaluation has a narrower scope than TCO by focusing primarily on the external costs of doing business with a supplier rather than on both the internal and external costs, as does TCO (Ellram, 2005). From a theoretical standpoint, economists have discussed the importance of going beyond price to encompass transaction cost analysis in purchasing from external sources when considering TCO. Economists have viewed transaction cost analysis primarily from a make-or-buy perspective—i.e., considering internal production of goods or services versus buying in the market (Coase, 1937; Walker, 1988; Williamson, 1985).

Turning to applications of transaction cost analysis in the marketing literature, Heide (1994) notes that transaction specific investments may involve human assets that are difficult/costly to replace. In terms of purchasing, this could include suppliers' employees, such as engineers, account executives, and customer service personnel who have specialized knowledge and are dedicated to making the account run smoothly. For example, a supplier's concurrent engineering and after-sales support may significantly lower the buying organization's cost of doing business with this supplier versus the free market. In dealing with external uncertainty, which creates an environment conducive to opportunistic behavior, the marketing literature notes that opportunism is decreased when there is an interpenetration of organizational boundaries (Heide & John, 1990). Heide and John (1990) also found organizational interpenetration was relevant to the

TCO of buyer-supplier relationships. These costs include dedicating assets such as key account personnel. Likewise, Heide and John (1990) found that there should be a reduction in transaction costs from creating such close relationships. Examples of this include a reduction in the costs of soliciting/evaluating proposals from numerous suppliers as well as time spent searching for and evaluating potential new suppliers. Previous literature on TCO analysis defined transaction costs based on: costs that are incurred prior to actual sale; costs associated with the sale--e.g., price; and costs after the sale has occurred--e.g., disposal (Ellram, 1993). Such cost considerations are supported by the marketing literature's application of transaction cost analysis to specific assets and opportunism. TCO analysis is a valuable tool and philosophy to support the application of the theory of transaction cost analysis to buyer-seller relationships.

TCO Barriers and Benefits

The complexity of TCO may limit its widespread adoption. Lack of readily available accounting and costing data in many organizations is a major barrier. This situation has the potential to change as more organizations implement activity-based costing (Ellram, 1994a; Kaplan, 1992; Roehm et al., 1992). However, this change has been very slow in coming. Another complicating factor is that there is no standard approach to TCO analysis. Research and a review of the literature have indicated that TCO models used vary widely by company and may even vary within companies depending on the buy class and/or item purchased (Burt et al., 1990; Ellram, 1993;

Ellram & Siferd, 1993; Fernandez, 1990; Henry & Elfant, 1988). Thus, user training and education are needed to support TCO efforts. Further, TCO adoption may require a cultural change away from a price orientation in procurement and towards total cost understanding (Ellram, 1993; Ellram & Siferd, 1993). That potential for cultural change is a major reason why TCO is regarded as a philosophy rather than as merely a tool. An additional factor which complicates TCO is that TCO costs are often situation-specific. The costs which are significant and relevant to decision making vary based on many factors – such as the nature, magnitude and importance of the buy (Ellram, 1994a; Schmenner & others, 1992).

However, TCO provides many benefits that are documented in the literature (Burt et al., 1990; Ellram, 2005; Ellram & Siferd, 1993; Monckza & Trecha, 1988; Saccani et al., 2017) and confirmed by case study analysis (Ellram, 1994b, 2005; Fuller, 2016; Naguib, 2009). Some of the primary benefits of adopting a TCO approach are that TCO analysis:

- provides a consistent supplier evaluation tool that improves the value of supplier performance comparisons among suppliers and over time;
- helps clarify and define supplier performance expectations both in the firm and for the supplier;
- provides a focus and sets priorities regarding the areas in which supplier performance would be most beneficial creating major opportunities for cost savings--this supports continuous improvement

- improves the purchaser's understanding of supplier performance issues and cost structure;

- provides excellent data for negotiations;

- provides an opportunity to justify higher initial prices based on better quality/lower total costs in the long run and;

- provides a long-term purchasing orientation by emphasizing the TCO rather than just price.

This list of benefits provides a summary of some of the key benefits of adopting a TCO philosophy in purchasing. It is important to note that use of TCO is reserved for certain items/services where the organization feels that such analysis can provide the greatest benefit (Ellram, 2005).

Dollar-based Versus Value-based TCO Models

According to Ellram (2005), a dollar-based TCO model is one that relies on gathering or allocating actual cost data for each of the relevant TCO elements. For instance, if a dollar-based model indicated a TCO for a component, it would be possible to trace then every cost that makes up that TCO on a cost element-by-cost element basis. While determining which cost elements to include and gathering the data to determine the TCO may be complicated, explaining the results of a dollar-based approach is relatively straightforward. Ellram (2005) contrasts the dollar-based approach with value-based TCO models that combines cost/dollar data with other

performance data that are often difficult to "dollarize". These models tend to become

rather complex, as qualitative data are transformed to quantitative data. They often

require very lengthy explanations of each cost category. The total cost derived from

value-based models is not directly traceable to dollars spent in the past, spent currently

or estimated to be spent in the future, as are the dollar-based TCO results. However, the

way in which the supplier's performance is scored within categories and points allocated

among categories reflects the buying organization's estimate of the cost of various

performance discrepancies. Organizations which choose a value-based approach prefer

it because as costs and the organization's priorities change, the "weighting" of cost

factors can be changed accordingly. Value based models require a great deal of fine

tuning and effort to develop the proper weightings and point allocations so that they

reflect the TCO. Like dollar-based TCO analysis, value-based models are derived from

historical data and/or estimates of future costs. Value-based models tend to focus on a

small number of major cost issues, generally around three or four. Calculations beyond

this point tend to become too complex.

Unique Versus Standard TCO Models

The organizations studied tended to use unique models that are specially

developed for each buy. These models may share a common set of total cost factors,

such as quality, delivery and service while the relevant data need to be developed

separately for each buy. Organizations chose to use a unique versus a standard type of

model for a number of reasons. Figure 3 provides an overall summary of the relative

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advantages of the different TCO models while Figure 4 provides an overview of the

appropriate application of each model.

Model advantages	Disadvantages
Dollar-based – direct cost	
Tailor factors considered to decision	Time consuming
Very flexible	Does not make sense for repetitive decisions
Alter level of complexity to fit decision	Not cost beneficial for low dollar buys
Help identify critical issues	
Dollar-based – formula	
Easy to use once system is in place	Time consuming to establish system
Excellent for repetitive decisions where costs for key factors can be determined	Formulae need to be periodically reviewed and updated
	Inflexible to different types of decisions
	Considers a limited set of factors
Value-based model	
Can incorporate issues where costs cannot be determined	Time consuming to develop; only good for important and/or repetitive decisions
Considers the importance of factors using weighting	Much judgement in establishing weightings
Easy to use for repetitive decisions	

Figure 3 - Comparison of TCO models adopted from (Ellram, 2005)

Type of model	Primary uses
Dollar-based – direct cost	Supplier selection Supply base reduction Make versus buy/outsource Process improvement
Dollar-based – formula	Supplier volume allocation Supply base reduction Ongoing supplier evaluation Process improvement
Value-based	Supplier selection Make versus buy/outsource Process improvement

Figure 4 - Primary uses of various types of models adopted from (Ellram, 2005)

Modeling TCO for Chiller Assets

While the concepts of assigning the TCO are well documented in literature, the techniques are generally limited to the company-level scale and not focused on a certain class of assets (Ellram, 2005). As such, the development of a practical TCO model for individual asset types is missing from the literature at large. Case studies of TCO models employed by certain organizations are the norm in TCO literature since developing a "one size fits all" TCO model is not feasible (Ellram, 2005). Theoretically, developing an asset specific TCO model for an owned asset is simple – all costs associated with the life-cycle of that asset are accounted for and totaled (Ellram, 1993). Once the TCO for an asset or alternative assets is determined, informed decisions can be made as long as the TCO is complete and expressed in equivalent terms (Eschenbach, 2011). If all costs are

known, TCO analysis is straightforward. Forecasting the TCO over the lifespan of an asset when some costs must be assumed is more difficult (Fuller, 2016).

While there is chiller specific literature on forecasting unknown costs over an asset's service life, there is a general agreement within academic studies and industry reviews on the major costs that contribute to the TCO of a chiller asset (Guarino, 2013; Naguib, 2009; Picard, 2017; Trane, 2007). The installation, energy, maintenance, and repair costs represent the four major cost categories generally agreed upon by the limited chiller-specific TCO analysis in literature. Of the four major categories, each is can be broken down and analyzed more specifically. In his paper for the Professional Retail Store Maintenance Association, Curt Picard provides a thorough breakdown of each major cost category (Picard, 2017):

- **Installed Cost**: total cost of installation that includes all design, engineering, equipment, labor, incidentals, air distribution, and energy controls. Every aspect of the total installation is included in this cost.
- **Energy Cost:** total cost of the energy required to operate the units or system. This includes the electric costs to operate the cooling and ventilation components as well as electrically powered heating components if applicable. Natural gas costs for heating are also included in this category.
- **Maintenance Cost:** the cost of routine preventive maintenance associated with the equipment.

- **Service/Repair Cost:** the cost of all repairs made to the system including replacement parts and the labor for the repair.

While the cost category definitions discussed in literature are straightforward, quantifying the costs associated with each category can be difficult (Naguib, 2009). Quality and efficiency of equipment, factory installed options, geographic location, temperature set points, store operating hours, cost of energy, cost of labor, cost of repair parts, preventive maintenance scopes, and types of controls are all contributory factors. The most accurate way to determine this cost for a specific system is through mining the historic data for each of the categories above. This information can then be evaluated to determine cost of ownership per ton, per unit, per square foot, or as a function of the initial installed cost. The data can be further evaluated based upon equipment age and geographic location to assist in determining possible trends (Picard, 2017). Despite the agreement of the variables associated with chiller total cost, there is no standard, validated, and non-proprietary way of accurately modeling chiller TCO available. The two closest alternatives discovered were developed by: (1) the Air Force Civil Engineer Center (AFCEC) in conjunction with the Air Force Installation Management Support Center (AFIMSC); and (2) the Trane HVAC manufacturer--a subsidiary of the Ingersoll Rand Corporation. These models will be detailed below but present challenges. The USAF model is still a very initial attempt to model TCO and has not been validated with real-world data. The Trane model is based on proprietary software that must be

purchased and provided a "black box" model in which the user may not get all of the

clarity on cost projections that he or she desires.

AFCEC at Tyndall Air Force Base, Florida and AFIMSC Detachment 6 at Wright-

Patterson Air Force Base, Ohio have developed an initial TCO model for chillers using an

additive linear model to account for all costs (Uddin et al., 2013). While the model was

created using USAF and private industry subject matter expertise, BUILDER (USACE,

2012), and Interim Work Information Management System (CENTECH, n.d.) data, there

was no statistical validation done on the model (Brannon et al., 2018). However, the

model proposed by AFCEC and AFIMSC (Equation 1) is consistent with literature while

expounding upon certain areas as defined below

$$TCO = IP + PM + SR + ER + MC + Training_{Initial} \qquad (1)$$
$$+ Training_{Advanced} + Supply_{Parts} + Supply_{Storage}$$
$$+ Acq + Security$$

where,

IP $\qquad = Initial\ Purchase\ (USD);$

PM $\qquad = Preventative\ Maintenance\ (USD);$

SR $\qquad = Sustainment\ Repair\ (USD);$

ER $\qquad = Emergency\ Repair\ (USD);$

MC $\qquad = Maintenance\ (USD);$

$Training_{Initial}$ $\qquad = Initial\ Training\ of\ Maintenance\ Personnel\ (USD);$

$Training_{Advanced}$ $\qquad = Advanced\ Training\ of\ Maintenance\ Personnel\ (USD);$

$$Supply_{Parts} \qquad = Cost\ of\ Parts\ (USD);$$

$$Supply_{Storage} \qquad = Cost\ of\ Parts\ Storage + Bencstock\ (USD);$$

$$Acq \qquad = Cost\ of\ Future\ Acquisition\ Actions\ (USD);\ and$$

$$Security \qquad = Cost\ to\ Secure\ a\ System +\ loss\ from\ threats\ (USD.$$

- **Initial Purchase (IP)** – Initial installation occurs when a facility is first built or when an old system has completely failed and is replaced. Initial installation cost is the single cost considered for Low-price, Technically-acceptable (LPTA) contract award, however it is generally not the largest life-cycle cost (Uddin et al., 2013).

- **Preventative Maintenance (PM)** – Systems require regular maintenance such as changing belts, fluids, and adding lubricants, in order to work to the manufacturer's intended life span and to keep coverage. Manufacturers specify different timelines, parts, materials, and procedures for preventative maintenance which are added to work plans for technicians' action. PM has a high life-cycle cost ranging from 3-5 times the installation cost (Brannon et al., 2018). The Air Force performs PM using Air Force personnel (military or civilians) or base operations support contracts. The TCO for systems is dominated by maintenance and repair. Personnel must be trained, have supplies and parts, and must have a good relationship with manufacturers.

- **Sustainment Repair (SR)** – Sustainment repair is work done ahead of an emergency--fixing problems early when the repair can be planned to reduce

mission impact or down-time. Similar to PM, sustainment requires knowledge of manufacture-specific systems, parts and supplies, and training and practice. The Air Force's goal is to have the competency to do sustainment work in-house; however, in-house workers lack proficiency because of the large variety of Heating, Ventilation, and Air Conditioning (HVAC) equipment installed at most bases. Most sustainment repairs are contracted, as indicated in the expenditure analysis.

- **Emergency Repair (ER)** – Emergency repairs are required when a component breaks and must be repaired without any pre-planning or warning. This type of repair causes the greatest amount of down-time. Troubleshooting, fault diagnosis, parts ordering, remediation, and repair all occur after the outage has started. Emergencies are by far the costliest repairs because the mission of the Air Force will suffer and linked costs increase until the emergency is resolved. Availability of parts and knowledge of systems for rapid fault diagnosis are essential.

- **Monitoring and Controls (MC)** – HVAC systems are the largest consumers of energy in a typical facility (ASHRAE, 1996). Monitors and controls are used as part of the HVAC system to track and reduce the energy demand of the systems. These monitors and controls can be designed and installed independently of the HVAC unit and operate as a remote, automated (or semi-automated) virtual technician. The monitors and controls are often called Industrial Control Systems

(ICS) or Energy Management Control Systems (EMCS). ICS use wired or wireless internet connections to communicate with a computer-based dashboard.

- **Replacement (Aqc)** – At the end of its useful life, or when most economical using Asset Management principles, a system is replaced. There is more to replacement cost than just the simple system price--there is a switching cost to be considered. Switching costs include new training, supply, logistics, and possibly retrofitting an existing space or configuration. When replacing a system, the entire TCO equation should be evaluated for cost comparison.

- **Training (initial + advanced)** – There are two aspects of training for Air Force maintenance personnel. The HVAC Career Field Education and Training Plan (CFETP) was used to estimate the costs for minimal training to operate and maintain multiple systems (Department of the Air Force, 2017). Additional training must also be provided above the CFETP to ensure advanced troubleshooting and repair of specific systems. Advanced training requires the manufacturer to be involved in order to certify that the maintainer can use proprietary systems for fault diagnosis or have access to proprietary code for digital faults. The cost of this training is specific for each manufacturer. Currently the Air Force only does this training for the top manufacturer used at the base; any repairs required on other complex systems are outsourced or contracted.

- **Supply (Parts + Storage)** – Supply and logistics costs also increase with multiple manufacturers. Chiller systems are built as factory units, or one-off special design units. There is little parts-interchangeability between the various

manufacturers. Supply knowledge, storage, and costs (because bulk purchase is limited) each increase as the variety of chiller manufacturers increase. Acquisition costs also increase as in-sourced maintainers lack proficiency to maintain all the systems on the base, and contracts must be written to repair the disparate systems. Additionally, the physical storage of spare parts and materials increases with additional manufacturers due to lack of interoperability. The ability to have commonly used and/or critical parts on-hand is essential to providing timely response to correct failures of essential systems. Like training, these parts are manufacturer specific so standardization would result in a similar decrease in sunk inventory cost, needed storage space, and inventory maintenance costs for an identical level of assurance.

- **Security** – For control systems, security has become the largest threat and area for cost growth in the HVAC system. Control systems are both physical/mechanical parts of the HVAC system requiring maintenance of mechanical parts. More importantly, they are digital devices connected through the internet of things (IOT) to centralized computers where a graphical interface allows for monitoring and control of the base's entire HVAC system. Loss of security may have many forms: it may be the loss of the ability to upgrade all systems on the base to the correct security posture; installing a system that has malicious software pre-installed; or any number of clever ruses used by hackers to infiltrate and control items and information on an information network. Manufacturers keep proprietary information very close-hold.   Disparate

manufacturer systems are not easily combined to allow single-point viewing, and disparate systems can nearly never be combined to allow for single-point control. Thus, when multiple systems are introduced on a base the maintainers must fully duplicate all aspects of security, computer hardware for monitoring and control. These truths add to huge costs and reliance on out-sourced contracts for control system operations, maintenance, and repair. There is little training, supply, or security provided by the Air Force.

In addition to the TCO concepts developed in the literature and by the USAF, HVAC industry leader Trane has developed its own TCO model that considers the elements of first cost, installation cost, financing cost, commissioning cost, energy costs, repair costs, and maintenance costs (Trane, 2007). The general characteristics of the TCO model presented by Trane are once again consistent with the models presented previously. Additionally, Trane has developed a line of proprietary software to evaluate different chiller systems based on energy and economic comparisons. This System Analyzer software uses information about the building, its location (weather), and the chiller systems under consideration to automate four sets of calculations to predict the energy consumption and life-cycle costs of the chiller system: (1) building cooling and heating loads based on local weather; (2) equipment cooling and heating loads; (3) energy consumed by the CHILLER system; and (4) costs of owning and operating the CHILLER system. The program's output reports provide a concise overview of the critical information allowing for a straightforward comparison of alternatives (Trane, 2013).

While the modeling efforts conducted by the USAF and Trane provide a starting point for chiller TCO modeling, there are limitations. Neither model provides a framework for estimating unknown data for the required inputs. This is especially limiting for organizations such as the USAF that do not have datasets with all of the required information. The model developed by Trane is part of a proprietary software package that: (1) operates with a "black box" construct that gives the user no insight into what process the model uses to arrive at a TCO value, and (2) may not be available to organizations due to software interoperability limitations. The model presented by AFCEC/IMSC is more transparent but fails to account for operation costs (energy usage) or utilize equivalent annual worth to make costs comparable across time. There is a final possible cost modeling software currently used by the US federal government, the Building Life Cycle Cost (BLCC) Program developed by the National Institute of Standards and Technology (NIST) ("Building Life Cycle Cost Programs," n.d.). BLCC, too, falls short of providing a true TCO model as it focuses on either total facility TCO (too broad) or energy savings alternatives that do not fully account for other major elements of TCO (too specific). This clear gap in the existing body of work requires a model that is both transparent, easy to use by a wide range of personnel, and easily fieldable given existing software access constraints.

III. Methodology

Introduction

This chapter presents the development of a total cost of ownership (TCO) model for United States Air Force (USAF) heating, ventilation, and air conditioning (HVAC) chiller equipment. The model is intended to allow personnel involved in the acquisition and fielding of chiller equipment to develop accurate TCO estimates for comparing purchasing alternatives. The model is developed in two stages: (1) a formulation stage that defines the TCO model and identifies/processes the available data; and (2) an implementation stage that creates cost factors to estimate the variables identified in the formulation state and outlines the assumptions of model implementation. The following sections describe these stages in detail.

TCO Model

This stage presents the formulation of a model that will estimate the TCO for a given piece of chiller equipment. After examining the available data, model formulation is accomplished in two steps: (1) identifying the model variables; and (2) processing the raw data.

Decision Variables

The TCO model incorporates the four major costs associated the service life of a chiller asset based on industry standards and existing literature to create the TCO dependent variable: (1) initial purchase and installation, (2) preventative maintenance (parts/labor), (3) unplanned repair (parts/labor), and (4) energy costs. Equation (2) uses

the two system characteristics chiller capacity (tons) and cooling type (air or water) as independent variables to predict TCO. The independent variables were chose based on the fact they would be easily available to decision makers. The data used to build the TCO model shown in (2) was based on cooling type and capacity; therefore, using only those two independent variables minimized the chance of compounded measurement error and collinearity within the model (Montgomery et al., 2012). Additionally, regression analysis would not make sense if costs were used as independent variables – the output TCO model would simply be a summation of all costs. The coefficients presented in Equation (2) were based on a multiple regression analysis (Figure 5) of the data provided in the ASHRAE chiller TCO analysis study (Naguib, 2009). The model utilizes weights of 208,000 (b_1), 1525 (b_2), and 116500 (b_0) for type, capacity, and intercept, respectively.

$$TCO = b_0 + [b_1 CAP] + [b_2 CT] \tag{2}$$

where,

CAP $\qquad = Cooling\ Capcity\ (tons)$; and

CT $\qquad = Cooling\ Type\ Dummy\ Variable\ (Air = 0, Water = 1).$

Source	SS	df	MS		Number of obs	=	10
					F(2, 7)	=	697.91
Model	5.7329e+11	2	2.8664e+11		Prob > F	=	0.0000
Residual	2.8750e+09	7	410714286		R-squared	=	0.9950
					Adj R-squared	=	0.9936
Total	5.7616e+11	9	6.4018e+10		Root MSE	=	20266

yrCost	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
type_dummy	208000	12817.4	16.23	0.000	177691.7	238308.3
Cap	1525	45.31635	33.65	0.000	1417.844	1632.156
_cons	116500	16339.04	7.13	0.000	77864.31	155135.7

Figure 5 - TCO Model Multiple Regression Analysis

The ASHRAE study data used to develop equation (2) was developed for use as a TCO comparison of water and air-cooled chillers ranging from 100 to 500 tons in cooler capacity. Theoretical data for energy usage, M&R, and initial costs are calculated based on a 20-year design life for each type and size of chiller based on size distinct geographic locations. The Chicago climate zone (ASHRAE Standard 90.1-2007 Zone 5) data was used as it most closely approximated the location of WPAFB. For energy data, approximately 600 energy simulations were run using a typical office building in the U.S. Department of Energy's (USDOE) DOD-2.2 energy simulator. Chiller coefficients of performance were based on the minimum ASHRAE efficiency requirements (ARI, 2003; ASHRAE, 2007) for industry standard air and water-cooled chillers using U.S. Energy Information Administration (USEIA) utility costs from 2007-2008. Installed costs were estimated using modular chilled-water systems in order to better delineate the chiller system costs from overall HVAC, providing a better cost comparison. Finally, maintenance costs included preventative maintenance and repair that were based on actual maintenance

contract costs for different cities, systems, and capacities. These contracts included

annual cost of labor, insurance premiums, material costs, and water treatment.

For energy data, an attempt was made to extrapolate chiller-specific energy use

from facility level energy data in order to calculate costs. This was not possible due to an

incomplete list of chiller equipment, which prohibited confident assignment of facility

cooling energy based on accepted percentages. Given the lack of usage and efficiency,

neither empirical or simulation-based energy costs could be completed. As such,

estimates of energy costs over the lifespan of a given chiller were completed using the

proportions presented by ASHRAE (Naguib, 2009). The proportion of TCO represented

by energy costs in a given climate zone are based on the maintenance/repair costs and

as initial purchase costs. Therefore, energy cost estimation error is compounded by any

error present in estimating either of those two parameters.

Equation (2) was quantified using equivalent present (calendar year 2018) worth

in United States Dollars (USD). The function used for determining present worth is

shown in equation (3).

$$P = F \left(\frac{1}{1+i} \right)^n \tag{3}$$

where,

P $\quad = present\ value\ (USD);$

F $\quad = future\ value\ (USD);$

i $\quad = discount\ rate\ (\%);$ and

n $\quad = number\ of\ periods\ (years).$

Equation (3) was modified to calculate present value when costs were presented as past values e.g. a cost in 2009 USD that needed to be in 2018 USD. In that case, the present (2018) was treated as a future and was used.

$$F = \frac{P}{\left(\frac{1}{1+i}\right)^n}$$ (4)

The variables in equation (4) are consistent with equation (3). For this analysis, *n, number of periods,* is based on the difference between the annual dollar equivalent in which costs are presented and 2018 (assuming annual compounding). The *discount rate, i*, is 2.3% as determined by the 10-year average rate of change for air conditioning and refrigeration equipment from 1999-2009.(Abate et al., 2009).

Data

The empirical data used for this analysis was provided by the 88th Civil Engineer Group at Wright-Patterson Air Force Base (WPAFB), Ohio. Chiller equipment specification and initial cost data were retrieved from the BUILDER Sustainment Management System (SMS), a web-based software application developed by the United States Army Corps of Engineers (USACE) Engineer Research and Development Center's (ERDC) Construction Engineering Research Laboratory (CERL) to help civil engineers, technicians and managers decide when, where and how to best maintain building infrastructure (USACE, 2012). The BUILDER data used in this research came from two custom reports designed specifically for USAF infrastructure data management: Final 03A – Component Section Report and QC 05 – Section Details Report (USACE, 2018).

The Final 03A – Component Section Report (sample shown in Figure 6) is a list of component-sections defined within the builder inventory along with their asset/section identification code, remaining service life (RSL), condition index (CI) ratings sorted by building, system, component, and material/equipment category. This report was used to generate equipment initial cost and building information for where equipment was installed. The QC 05 – Section Details Report (sample shown in Figure 7) lists the section details (a combination of material and equipment categories plus component subtype). The QC 05 report was used to generate the asset/section identification code, installation date, design life, remaining design life (RDL), CI rating, equipment make/model/serial number, capacity, and manufacture date. Before the data from the two reports were combined, the results were filtered and records for categories other than D303001, chilled water systems, were removed. The two datasets were combined using asset/section ID numbers that were unique to each piece of chiller equipment (Figure 8). In total, 192 chillers were identified from the BUILDER data. This list is only a subset of the total chiller asset inventory at WPAFB – an exhaustive field survey would be required to fully identify all chiller assets at the base.

Component Subtype	Section Name	Section Install Date	CRV	Section CI	RSL (years)	Asset ID
Chiller, Centrifugal, Water Cooled	Main Mech Chiller 3	2009	$519,089	87	10	7ed6a2ee-493d-44dc-afe8-ffe86e798881
Chiller, Centrifugal, Water Cooled	Chiller	1998	$489,000	36	0	1bccef0f-1a60-4b83-8041-de7c233e6b3c
Chiller, Centrifugal, Water Cooled	Chiller	1993	$489,000	58	4	05fc43ad-c1d5-4df2-92d7-ea61a4f7f7cb
Chiller, Centrifugal, Water Cooled	CH-1 - CHILLER - 8300	2012	$489,000	87	11	c77badbf-431d-4437-b486-de65dd635ed1
Chiller, Centrifugal, Water Cooled	CH-2 - CHILLER - 8300	2012	$489,000	70	6	1c68c30c-a186-4465-a736-0174e3bc54ae
Chiller, Centrifugal, Water Cooled	CH-3 - CHILLER - 8300	2012	$489,000	70	6	8a1ac903-c266-4cf2-8d24-37d40f9b6c7c
Chiller, Centrifugal, Water Cooled	9109 Chiller 4	2007	$489,000	89	11	5d85e760-87e3-4b83-b210-fd00b2a1a419
Chiller, Centrifugal, Water Cooled	9109 Chiller 5	2012	$489,000	87	11	679d1b4d-5e7e-43e7-bc09-45bfdd93d1e8
Chiller, Centrifugal, Water Cooled	9109 Chiller 6	2006	$489,000	70	6	32f424ce-2e86-4316-88f6-b1bcf084128b
Chiller, Centrifugal, Water Cooled	W161 Chiller 1 - 500 TN	1995	$489,000	49	2	bcf5c946-99b6-409e-a603-a5161f0e5425
Chiller, Centrifugal, Water Cooled	W161 Chiller 2 - 500 TN	1995	$489,000	30	0	99d9138f-0de8-4786-bf2e-0b8d83940773
Chiller, Centrifugal, Water Cooled	W161 Chiller 3 - 500 TN	1995	$489,000	30	0	f5eb6b55-60f8-40d3-a35d-d1e751a80a6e
Chiller, Centrifugal, Water Cooled	RM 716--CHILLER 3 (R-134A)	2011	$502,000	79	8	ed59e1b1-c093-41d9-a947-a9a91d06e013
Chiller, Centrifugal, Water Cooled - 400 TN	N015--Chiller 3	2017	$240,000	84	8	2b3ab438-a250-4dd3-a811-37d6ce9ce087
Chiller, Centrifugal, Water Cooled - 1500 TN	N015--Chiller 1	2017	$984,000	84	8	4ce11607-d23e-4fe2-bb55-fe7108e97704
Chiller, Centrifugal, Water Cooled - 1500 TN	N015--Chiller 2	2017	$984,000	84	8	c2088e47-56ac-4eac-81e8-6b3b501c1527
Chiller, Reciprocating, Air Cooled	ROOFTOP AIR CLD CHILLER	1988	$113,380	10	0	2173a78d-77c9-463e-b5b3-d48a8fc3eb73
Chiller, Reciprocating, Air Cooled	Future Redundant Chiller S186	2017	$110,000	83	7	ff6e8efb-68f0-4565-91be-03c8001c5a50
Chiller, Reciprocating, Air Cooled	N/A	1997	$113,380	60	4	b4df4e9f-a23f-45d2-a94c-c17be12a3999
Chiller, Reciprocating, Air Cooled	EXT NE--CHILLER	1996	$107,000	51	2	41c9c9b0-5db5-44c0-bde6-027c28356789

Figure 6 - Final 03A Report Sample (after processing)

Component Subtype	Section Name	Section Install Date	Section Age	Section RDL	Model	Serial Number	Capacity	Manufacturer	Section ID
Chiller, Rotary Screw	Door 9 Air Cooled Screw Chiller	2011	7	13	RTAA1104XT01A3CO GABF	V06L00717	R22 98 & 73 Lbs/circuit R	TRANE Series	049cff89-58d4-4ac7-8405-049543dcae84
Chiller, Rotary Screw	N/A	2006	12	8	RTAA0704XR01A300GBF	U06A06097	70 TONS	TRANE, INC.	05d4a5af-1a88-4e37-8048-409fa1439bb6
Chiller, Centrifugal, Water Cooled	Chiller	1993	25	-5	YTC3C3B3	YCBM045783		YORK	05fc43ad-c1d5-4df2-92d7-ea61a4f7f7cb
Chiller, Scroll	CH 1 & 2	2016	2	18	30RAP055		50 TON	CARRIER	07ae8a8c-2d06-4194-b035-1af7e965e6b9
Chiller, Reciprocating, Air Cooled - 60 TN	N/A	2010	8	12	YCAL0056		56 Ton	York	0a0aa7cd-9ce8-4e5a-b52d-80ed6bd9e48b
Chiller, Rotary Screw - 200 TN, Water Cooled Screw Liquid Chiller, Dual Compressors	Main Mech Chiller 1&2	1989	29	-9	YTC1C3C2CLE	MRP104581		York	0a3157f0-6f3c-4d38-bd49-b1782259f1ac
Chiller, Rotary Screw - 200 TN, Water Cooled Screw Liquid Chiller, Dual Compressors	Main Mech Chiller 1&2	1989	29	-9	YTC1C3C2CLE	MRP104582		York	0a3157f0-6f3c-4d38-bd49-b1782259f1ac
Chiller, Scroll	60 TON AIR COOLED CHILLER	2006	12	8	CGAFC604AKA1000D00000N00000W00	C06C01869	60 TON	TRANE, INC.	0a8d1189-8092-4bf9-ba5e-a796a17028d3
Chiller, Scroll	EXT SOUTH--CHILLER	2016	2	18	AGZ120EPMNN-ER00	STNU160400031	114 TONS	DAIKEN	0df8a3f8-b63c-4e5a-882a-6800ad1a1ece
Chiller, Rotary Screw - 130 TN, Air Cooled Screw Liquid Chiller	110 TON AIR COOLED CHILLER	1997	21	-1	RTAA1104XH01A3D0BK	U97C09171	110 tons	TRANE, INC.	0fff3f74-1c7f-4139-9458-673ab90f53c7
Chiller, Centrifugal, Water Cooled - 1000 TN	1999 TRANE CHILLER	1999	19	1	CVHF770	L99M05014M	770 TONS	TRANE, INC.	1058684a-7c28-4ff6-b9b3-eb544837ee7f
Chiller, Rotary Screw - 150 TN, Water Cooled Screw Liquid Chiller, Dual Compressors	Mechanical Room C	1991	27	-7	RTHA150FCN0LDUC3LF2LFNNV0GUQ	U91B03543	150 TON	TRANE, INC.	10eb8049-de03-4c69-90e1-31e60b0493bc
Chiller, Scroll	CHILLER	1995	23	-3				TRANE, INC.	115697b2-90a7-4ec7-8e3f-beafe386f3a6
Chiller, Reciprocating, Air Cooled - 50 TN	2FL RM 26--CHILLER (50 TON)	2000	18	2	30HL-050-A-600	3697G92854	50 Ton	CARRIER CORP.	1450cffa-525c-4cad-b729-ad4a54f03270
Chiller, Reciprocating, Air Cooled - 50 TN	EXT NW--CH 1	2012	6	14	CGAM 052F 2H02 AXD2 A1A1 A1AX XA1D 1A4X XXXX XB1A	U12M33701	52 TON	TRANE, INC.	14a941ee-8b3a-488e-8bc7-49a10931cbb1

Figure 7 - QC 05 Report Sample (after processing)

Component Subtype	Asset ID	CRV	Section Install Date	Section Age	Section RDL	Section CI	Serial Number	Manufacturer	Model	Capacity (tons)
Chiller, Centrifugal, Water Cooled	b16764cb-b6e1-4601-bb77-a5953dc81d38	$ 519,088.51	1993	25	-5	30	469514	CARRIER	10XB140004 01	14
Chiller, Centrifugal, Water Cooled - 1000 TN	7938bd82-368e-4cfd-a2d7-5bc4412b8b6d	$2,057,229.73	2011	7	13	87	3411Q21117	CARRIER	19XRV70704 75LFH64	890
Chiller, Centrifugal, Water Cooled - 200 TN	bbf9f19b-bb83-4759-a372-6b729ab35af2	$ 147,000.00	1994	24	-4	49	2893J46950	CARRIER	23XL2121EC 60	215
Chiller, Reciprocating, Air Cooled	3d5ee9df-46d1-437d-9b53-b92399326b98	$ 112,000.00	1982	36	-16	1	1494F91185	CARRIER	30GT-015-500	15
Chiller, Reciprocating, Air Cooled - 50 TN	1450cffa-525c-4cad-b729-ad4a54f03270	$ 158,000.00	2000	18	2	30	3697G92854	CARRIER	30HL-050-A-600	50
Chiller, Reciprocating, Water Cooled	2d23e811-d893-4c45-b867-99f21e26dad9	$ 118,000.00	1997	21	-1	70	0697F51703	CARRIER	30HL-050-A-600	50
Chiller, Reciprocating, Air Cooled - 50 TN	3b69f6fc-b645-4e7a-b047-348e8f5589f5	$ 156,000.00	1998	20	0	79	0998F27043	CARRIER	30HL-050-A-600	50
Chiller, Reciprocating, Air Cooled - 20 TN	27bbffa0-f438-4f22-ab3a-2d600d913992	$ 45,000.00	1997	21	-1	73	4797F10552	CARRIER	30HWA018-A-600FG	18
Chiller, Reciprocating, Air Cooled - 110 TN	e352eb16-5477-4e95-9df6-fe075d25f415	$ 241,000.00	2010	8	12	78	1911Q19191	CARRIER	30HXA106N	106
Chiller, Rotary Screw - 200 TN, Water Cooled Screw Liquid Chiller	86d0908c-102d-45d8-bb4b-e38a01a9a604	$ 129,000.00	2005	13	7	73	0610Q18148	CARRIER	30HXA106R	200
Chiller, Scroll	171a74b3-1320-486f-86bc-a9eb314b5075	$ 16,500.00	2005	13	7	80	4905Q04955	CARRIER	30RAN045-611	45
Chiller, Scroll	bc52c3ee-9069-466e-a56c-ec5a0cfe8dee	$ 16,500.00	2015	3	17	87	0510Q39008	CARRIER	30RAP0156D A06100	14

Figure 8 - Sample of Combined Final 03A and QC 05 BUILDER Databases

The final two empirical datasets used for this analysis came from the

USAF TRIRIGA database, an integrated workplace management system (IWMS) designed

to increase the operational, financial and environmental performance of USAF facilities

and real estate (IBM, 2018). These datasets show all of the preventative maintenance

(PM) and repair (emergency and high/medium sustainment) performed at WPAFB from

1 May 2017 through 30 September 2018. TRIRIGA data provides work order information

including work details, equipment type, and the costs associated with the work. These

datasets contained 247 chiller-specific repair work orders and 1129 chiller-specific PM

work orders (sample dataset shown in Figure 9).

Theoretical data was incorporated into this analysis as a means of

estimating cost factors for the relevant decision variables and checking the quality of

empirical data provided. Two sources were used for the theoretical data: (1) the

Whitestone Facility Maintenance and Repair Handbook (Abate et al., 2009), and (2) an

American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) study on chiller TCO analysis (Naguib, 2009), which has already been discussed.

The Whitestone Handbook estimates component-level replacement, maintenance, and repair pricing using the Maintenance Task Database developed by USACE. It does not include operation cost estimation data. Developed in the 1980s, much of the labor information for this database is based on Engineered Performance Standards developed jointly by the U.S. Navy, Army, and Air Force. The Whitestone Handbook revises this data with models and components common to civilian construction (such as elevators, storefront doors and windows, and detailed wall and floor coverings). Labor requirements and material costs were updated through extensive interviews with manufacturers, distributors, and service providers. Equipment requirements are shown only for heavy HVAC and electrical equipment and roads. For M&R tasks it is assumed that the necessary equipment is included in contract overhead costs. The Whitestone database has over 1,200 components and more than 15,000 related M&R tasks and subtasks, although only chiller-specific tasks were used for this research. Task frequencies are the expected incidence of repair or replacement in the Washington, D.C. area. These frequencies are assumed to hold for other regions. The major exception to this assumption is HVAC equipment, for which specific frequencies are reported and used for this analysis of chillers (an HVAC system component). Additionally, geographic (original data taken from Washington, D.C., USA) and annual percent escalation cost factors are also included to account for location and time-based cost changes.

Data Processing

The raw empirical data used for this analysis contained irrelevant and redundant fields, missing values, improperly formatted entries, and values not consistent with accepted chiller cost estimation logic. As such, data processing was required in order to prepare the data for analysis. Once the BUILDER data was filtered to only show chiller equipment, data records missing key entries (component initial cost, size, type, and manufacturer) were removed and an attempt to find the missing data was used by either using similar entries, commercial cost estimates, or researching options based on existing data. The serial and model numbers for individual assets were used most often to determine missing data and allowed for the completion of 19 data records. For data records that still had crucial information missing after this process, removal of the 28 records were completed to avoid skewing the analysis. In addition to records that were incomplete, illogical data was examined. The data that did not make sense, mostly with respect to size versus initial cost, was scrutinized and if no there was no logical way for the data to be reconciled, those records were also removed. For example, if the BUILDER data stated that a 500-ton capacity chiller had an initial cost of less than $20,000 it was pulled for closer examination. Once it was judged as an incorrect data point and not something that could be remedied, the entry was removed. Five BUILDER data records were removed for not making logical sense. This was the final removal of BUILDER data and resulted in 159 complete records for individual pieces of chiller equipment.

For the TRIRIGA work order data, the only processing required involved removing work orders not relevant to chiller-specific work or work orders that could not be tied to chiller equipment from the BUILDER data by asset name. Using this process, the preventative maintenance and repair work order entries shrunk from 44,795 entries to 808 that were specific to individual chillers across WPAFB. Figure 9 shows the raw work order dataset while Figure 10 shows the combined TRIRIGA and BUILDER data. The final data processing step consisted of summing all of the work orders assigned to each individual chiller asset in order to determine the total cost of work completed for each piece of equipment, resulting in 94 records. The total data processing and aggregation process is summarized in Figure 11.

WT Priority	Facility Number	Task Name	Total Cost	Total Labor Cost	Total Operating Materiel Cost	Total Non-Inventory PO Line Items Cost	Name Asset
2A - Preventive Maintenance	10837	D30352201950 - A - WRIGHT-PATTERSON AFB - HVAC SHOP - ZHTV0001/10837	$37.87	$37.87	$0.00	$0.00	D3030 - COOLING GENERATING SYSTEM - AIR COOLED CONDENSING UNIT #1 - 10837 - EXT EAST
2A - Preventive Maintenance	10837	D30352201950 - A - WRIGHT-PATTERSON AFB - HVAC SHOP - ZHTV0001/10837	$37.87	$37.87	$0.00	$0.00	D3030 - COOLING GENERATING SYSTEM - AIR COOLED CONDESNING UNIT #2 - 10837 - EXT WEST
2A - Preventive Maintenance	10837	D30352201950 - A - WRIGHT-PATTERSON AFB - HVAC SHOP - ZHTV0001/10837	$37.87	$37.87	$0.00	$0.00	D3030 - COOLING GENERATING SYSTEM - AIR COOLED CONDESNING UNIT #3 - 10837 - EXT WEST
2A - Preventive Maintenance	11455	D30351302950 - A - WRIGHT-PATTERSON AFB - HVAC SHOP - ZHTV0001/11455	$208.27	$208.27	$0.00	$0.00	D3030 COOLING GENERATING SYSTEM - AIR COOLED CHILLER - 11455 - EXT SW
2A - Preventive Maintenance	20056	D4065100195008 - A - F/20056 - CHILLER - WRIGHT-PATTERSON AFB - ENVIRONMENTAL CONTROL SYSTEMS - YEARLY	$0.00	$0.00	$0.00	$0.00	D3030 COOLING GENERATING SYSTEMS - CHILLER - 20056 - BAY 11
2A - Preventive Maintenance	20056	D4065100195008 - A - F/20056 - WRIGHT-PATTERSON AFB - ENVIRONMENTAL CONTROL SYSTEMS - YEARLY	$227.21	$227.21	$0.00	$0.00	D3030 COOLING GENERATING SYSTEMS - CHILLER - 20056 - BAY 11
2A - Preventive Maintenance	20497	D30351103950 - A - WRIGHT-PATTERSON AFB - HVAC SHOP - AREA B - ZHTV0002/20497	$340.81	$340.81	$0.00	$0.00	D3030 COOLING GENERATING SYSTEMS - COOLING TOWER - 20497 -
2A - Preventive Maintenance	21615	D30352103950 - A - WRIGHT-PATTERSON AFB - HVAC SHOP - AREA B - ZHTV0002/21615 -	$227.21	$227.21	$0.00	$0.00	D3030 COOLING GENERATING SYSTEMS - CU 1 and 2 - 21615 - EXT EAST

Figure 9 - TRIRIGA Work Order Data Sample

WO Type	Capacity (tons)	Cooling type	BUILDER Asset ID	Chiller Specific PM Cost	Section Age (yrs)	Manufacturer	Current Replacement Value (USD)	Condition Index
2A - Preventive Maintenance	110	Air	049cff89-58d4-4ac7-8405-049543dcae84	$ 265.07	7	TRANE	$ 145,000.00	88
2A - Preventive Maintenance	51.8	Air	07ae8a8c-2d06-4194-b035-1af7e965e6b9	$ 1,438.98	2	CARRIER	$ 33,000.00	100
2A - Preventive Maintenance	56	Air	0a0aa7cd-9ce8-4e5a-b52d-80ed6bd9e48b	$ 151.47	8	York	$ 79,000.00	90
2A - Preventive Maintenance	114	Air	0df8a3f8-b63c-4e5a-882a-6800ad1a1ece	$ 1,666.18	2	DAIKEN	$ 17,000.00	100
2A - Preventive Maintenance	52	Air	14a941ee-8b3a-488e-8bc7-49a10931cbb1	$ 492.28	6	TRANE	$ 153,000.00	79
2A - Preventive Maintenance	45	Air	171a74b3-1320-486f-86bc-a9eb314b5075	$ 757.36	13	CARRIER	$ 16,500.00	80
2A - Preventive Maintenance	30	Air	17820b10-7e61-4aff-ab6d-610f33321e86	$ 681.62	11	TRANE	$ 48,500.00	79
2A - Preventive Maintenance	80	Air	1d61f86f-c0a7-4321-a136-c3d5eafd4852	$ 795.22	13	TRANE	$ 153,868.45	58
2A - Preventive Maintenance	40	Air	1fdbf626-7180-4223-8479-e857c203c8b4	$ 378.68	23	TRANE	$ 59,968.38	65
2A - Preventive Maintenance	60	Air	21d2326c-f8a6-4621-8be1-15cfdca5ddad	$ 537.57	4	YORK	$ 79,000.00	86
2A - Preventive Maintenance	52	Air	22815b70-b0f7-4f26-ad24-25f8cabb5bb5	$ 908.83	5	TRANE	$ 160,000.00	87
2A - Preventive Maintenance	15	Air	32f6b9c5-8da2-40aa-b66b-051f9bad8d8a	$ 757.36	3	TRANE	$ 107,000.00	99
2A - Preventive Maintenance	350	Air	3364acd3-1fd4-4e2d-b18d-1e6fbe634e57	$ 3,483.84	12	York	$ 791,552.85	92
2A - Preventive Maintenance	80	Air	3674660f-4d8e-4d5c-afbd-de16d06e0069	$ 833.09	15	TRANE	$ 153,868.45	58
2A - Preventive Maintenance	60	Air	3900de2e-9bc5-49c6-bfdb-56e17d8c34dc	$ 454.41	5	TRANE	$ 153,000.00	87

Figure 10 - Final Combined Dataset (TRIRIGA + BUILDER) Sample

Identification
- **28** records identified through the Whitestone Reference (n=18) and Naguib, 2009 (n=10)
- **53,952** records identified from Final 03A BUILDER data
- **50,645** records identified from QC 05 BUILDER data
- **20,454** records identified from TRIRIGA preventative maintenance report
- **21,343** records identified from TRIRIGA repair report

Preprocessing and Aggregation
- No further processing required for non-empirical data
- BUILDER data sorted by component and only records matching equipment type D303001, Chilled Water Systems were kept. After non-chiller equipment records were deleted, the Final 03A and QC 05 datasets were combined (**n=192**)

Final processing
- BUILDER data contained irrelevant and redundant fields, missing values, improperly formatted entries, and values not consistent with common sense (**n=159**)
  - **19** missing records completed using serial/model numbers
  - **28** missing records removed due to incomplete data
  - **5** records removed due to illogical CRV values
- TRIRIGA data sorted using the same approach from BUILDER data preprocessing and aggregation to identify chiller-specific records that could be assigned to specific assets from the BUILDER data using asset names (**n=808; 681 PM records + 127 MX records**)
- All preventative maintenance and repair records were summed to provide total costs for each piece of chiller equipment from the BUILDER data (**n=94**)
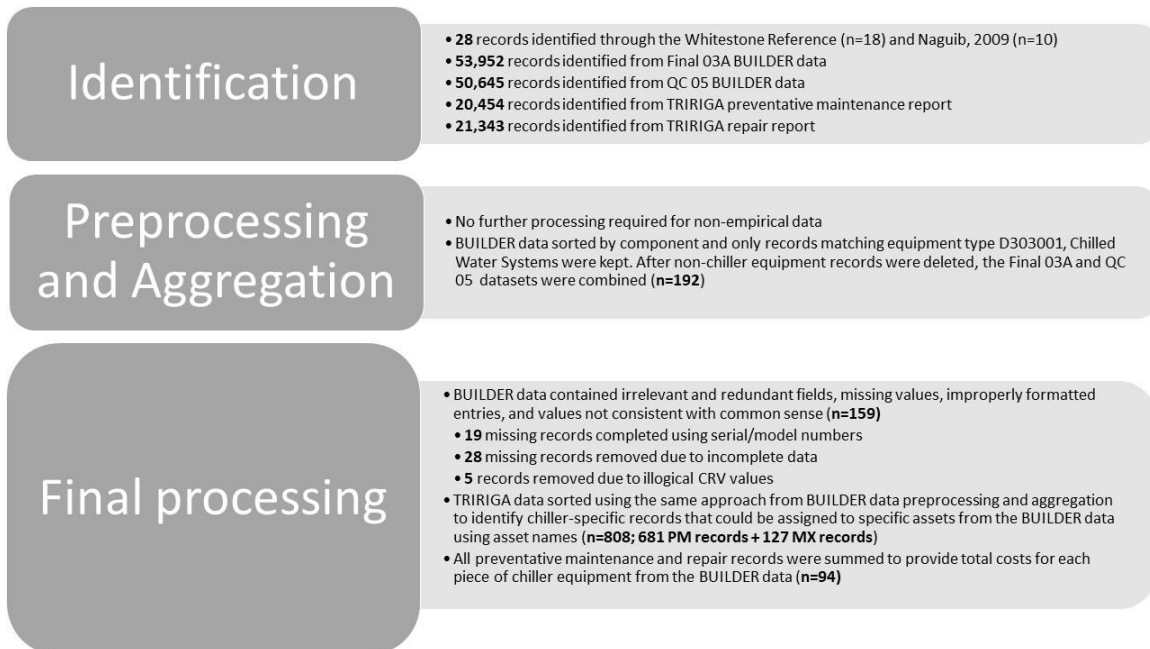
Figure 11 - Data Processing and Aggregation Methodology

Model Implementation

This stage presents the implementation of the specified model that will estimate the TCO for a given piece of chiller equipment. After the formulation phase was complete, implementation was accomplished in three steps: (1) estimating the parameters of each variable; (2) performing a comparative analysis between the data sources and; (3) identifying the assumptions made during implementation. Ideally, this analysis would be completed by developing a literature-based model then validating the model using sufficiently large empirical data and using theoretical data to compare and contrast the models in order to achieve accurate predictive ability. The combination of small (work order and number of chillers) and nonexistent (energy) empirical datasets complicates the analysis. While the small datasets were used for a comparative analysis to the theoretical data, energy costs were predicated based on theoretical relationships between initial purchase cost and maintenance/repair costs over the lifespan of a given chiller.

Variable Estimation

To develop a means of cost estimation for each of the three parameters of the TCO model, regression analysis was completed for both initial purchase cost (using component replacement value (CRV) as the proxy) and maintenance/repair data. Simple regression using chiller capacity as the independent variable (the predominant practice in literature) was completed with subsequent multiple regression used to explore additional significant independent variables. Once the regression analysis of the empirical data was complete, the same analysis was performed using the theoretical

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data. Only simple regression analysis was completed on the theoretical data given the absence of other possible variables.

All variables estimated through regression analysis were proposed linearly due to subjective graphical analysis (Montgomery et al., 2012) and lack of literature-based evidence that any specific cost factor exhibited non-linear behavior. Additionally, despite the logic that buying a chiller with zero cooling capacity (i.e. not buying a chiller at all) would yield zero cost, regressions were not forced to an intercept of zero. The decision not to force non-zero intercepts was done for three reasons: (1) If the curve is forced through zero, the intercept is set to 0 before the regression is calculated, thereby setting the bias to favor the low end of the calibration range by "pivoting" the function around the origin to find the best fit and resulting in one less degree of freedom (Montgomery et al., 2012); (2) forcing a regression with an intercept of zero is essentially creating a data point that does not exist – a method inconsistent with proper regression analysis (Montgomery et al., 2012); and (3) because standalone chillers are generally 10 tons or greater, the minimum size of represents costs that escalate at a steeper slope from zero compared to cost escalation based on the size of the chiller.

The comparison of regression results was performed as a means of quality checking the empirical data under the assumption that the empirical models should match the theoretical models in general trend and magnitude. Once the comparative analysis was completed, judgements on the quality of predictive capability could be made to give potential users insight into the accuracy of predicted costs. Due to only having 17 months of empirical maintenance and repair data and no access to energy

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data, the model validation was done through a comparison of individual cost factors instead of a more holistic approach that used the full model. The final step of model implementation and validation was used to model specified to predict the 20-year TCO for the chillers in operation at WPAFB and compare those values to that of our theoretical data.

Assumptions

The general assumption underscoring the analysis portion of this research is that of accurate and representative data. This is a key assumption in any effort, but given that the data used here was generated entirely by third parties not directly associated with this research, unknown quality issues may very well exist. The assumption of valid cost proportions in the ASHRAE study on chiller TCO (Naguib, 2009) is also applicable throughout this analysis, especially without a quality source of empirical data to validate energy costs. Finally, the data processing actions detailed previously are assumed to not create any undue skewing of the data.

From a more specific point of view, the use of component replacement value as a proxy for initial purchase of a chiller must be assumed. According the BUILDER database manager at WPAFB, CRV represents the cost to replace chiller equipment estimated from industry cost estimating tools (Horning, 2018). For maintenance/repair data, the key assumption is that only 16 months of data is representative enough to extrapolate 20-year TCO for a given piece of equipment. While the sample of chillers examined does contain a broad range of equipment ages and sizes, a long period of data collection would increase the confidence in a representative sample.

Finally, this analysis assumes that the theoretical proportions of TCO attributed to energy are reliable estimates due a lack of empirical energy data. Currently, the USAF only tracks facility level energy data. While there are monitoring and control systems in place on most modern chillers that could provide energy data, there is no formal collection or aggregation of this data into an accessible database.

IV. Analysis and Results

Introduction

The purpose of this chapter is to present the research findings, analysis, conclusions, and recommendations for future research. The chapter is organized in three major sections. First, the research findings compare the TCO model cost variables to both theoretical and empirical data in order to determine the validity of the model. Second, a data collection section is included in order to address the deficiencies within the empirical data that need to be addressed. Finally, a third section discusses the follow-on research that should be conducted in order to improve the predictive capability of this chiller TCO analysis.

Model Validation

Model validation was completed using the available data to determine the accuracy and confidence of predictions for the TCO model. This section is broken down into sections that correspond with the variables from the TCO model specified in Chapter 3: initial cost, maintenance plus repair, energy costs. A final summary of the model validation results is also included. Single regression analysis was completed using Microsoft Excel and multiple regression analysis was completed using Stata 14.

Initial Cost

The initial cost is broken down by type of chiller (air- or water-cooled) for more detailed analysis. Additionally, there were records in the WPAFB initial cost data that

contained unrealistic values based on industry standards that skewed the regression analysis. While a graphical analysis of the data identified the possibility of outliers, actual outliers were identified as points outside of a plus or minus three standard deviation range, $\pm$ 3 SD, around the mean, μ (Larose & Larose, 2015). Identifying and removing all data records that fell outside of the $\mu \pm$ 3 SD range eliminated the unrealistic data.

Since the empirical data contains more than just chiller capacity and type as a descriptor, a multiple regression analysis was completed using initial cost as the dependent variable with cooling capacity, manufacturer, and cooling type as the independent variables. The result, shown in Figure 12, shows that the only variable significant to initial cost at the 90% confidence level is cooling capacity. This serves as confirmation of simple regression comparison for all chiller types across the three datasets – while there may be cost differences based on cooling type and manufacturer, they are insignificant when estimating initial cost of purchase. Both the single and multiple regression analysis show that the theoretical dataset used to create the overall TCO model (Naguib, 2009) provides a realistic estimate of initial cost – the first step to showing overall TCO model validity.

```
     Source |       SS           df       MS      Number of obs   =        140
------------+-----------------------------       F(3, 136)       =      50.78
      Model |  1.0374e+13         3   3.4581e+12   Prob > F        =     0.0000
   Residual |  9.2624e+12       136   6.8106e+10   R-squared       =     0.5283
------------+-----------------------------       Adj R-squared   =     0.5179
      Total |  1.9637e+13       139   1.4127e+11   Root MSE        =     2.6e+05


               CRV |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------------+--------------------------------------------------------------
MfctSpecCapacitytons |  1039.388   102.7673   10.11   0.000     836.1595    1242.616
 ManufcturerDummyVar | -14510.54   17921.71   -0.81   0.420    -49951.82    20930.73
 CoolingTypeDummyVar |  42214.24   52075.22    0.81   0.419    -60767.67    145196.2
               _cons |  60995.96    49712.1    1.23   0.222    -37312.73    159304.7
```

Figure 12 - WPAFB Initial Cost Multiple Regression Analysis

The initial cost comparison is presented in Figure 13 through Figure 15 and contains the initial costs for all chiller types. The comparison without delineating chiller type confirm earlier trends while the fit for the empirical WPAFB data doubles (R_{WPAFB}^2 = 0.6632). The slope coefficients (range = 300 – 892.93), intercept values (range = 8415.3 – 150000) and model fits (R_{Naguib}^2 = 1, $R_{Whitestone}^2$ = 0.9687, and R_{WPAFB}^2 = 0.4976) once again demonstrate similar trends and orders of magnitude. The large disparities between intercept terms for these regressions does indicate that the three data sources are not perfect estimators of each other, but they do provide validation of the general behavior of the costs for initial costs. The consistency across these comparisons shows that the initial cost variable in the theoretical TCO model presented in chapter three is a valid estimator.
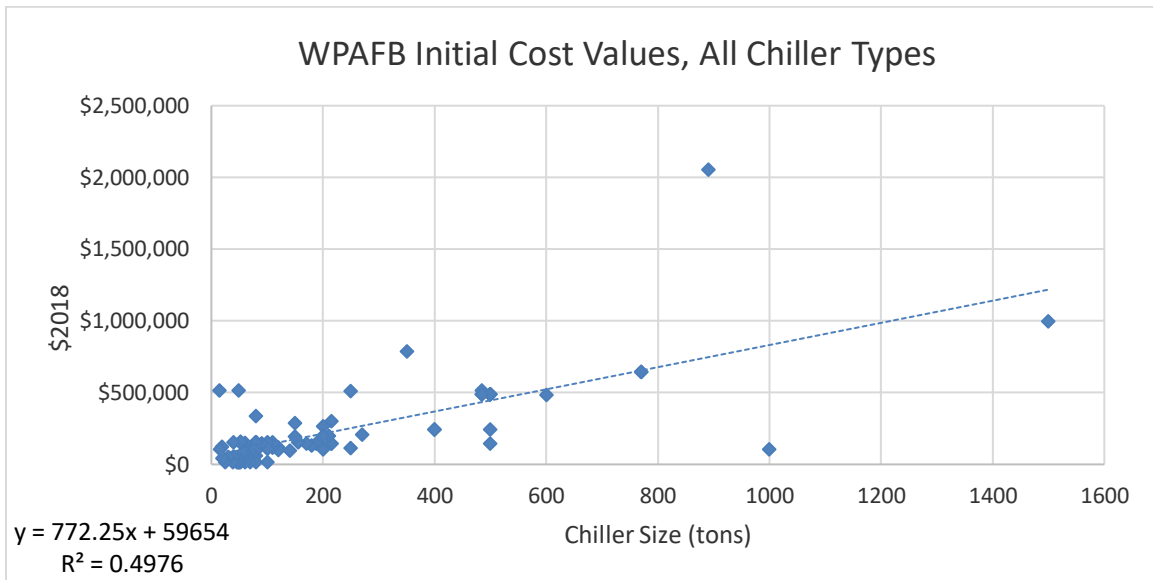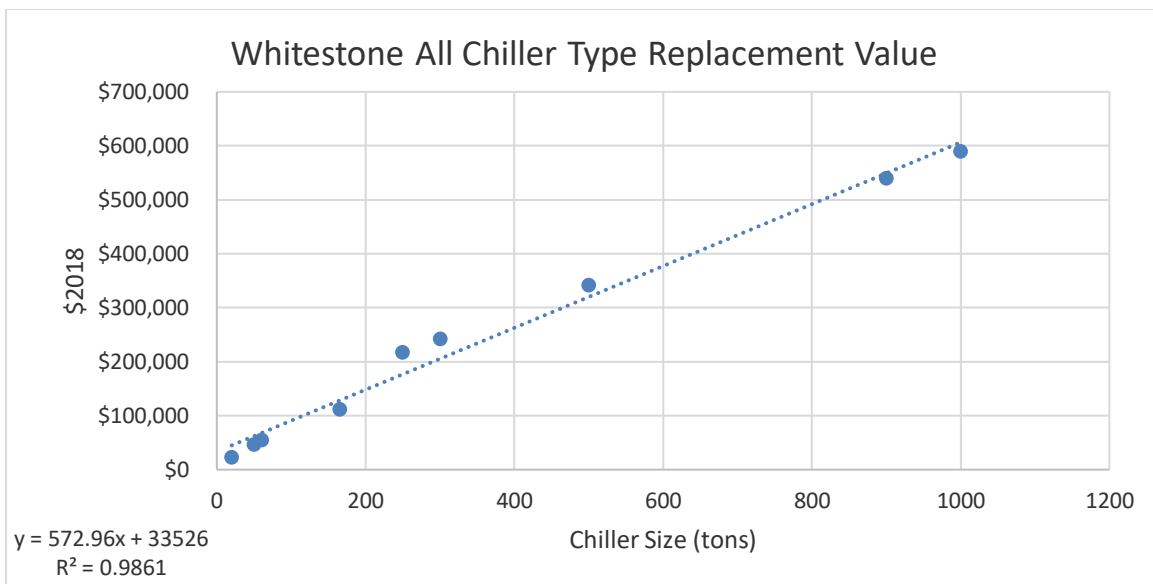
Figure 13 - WPAFB Chiller Initial costs

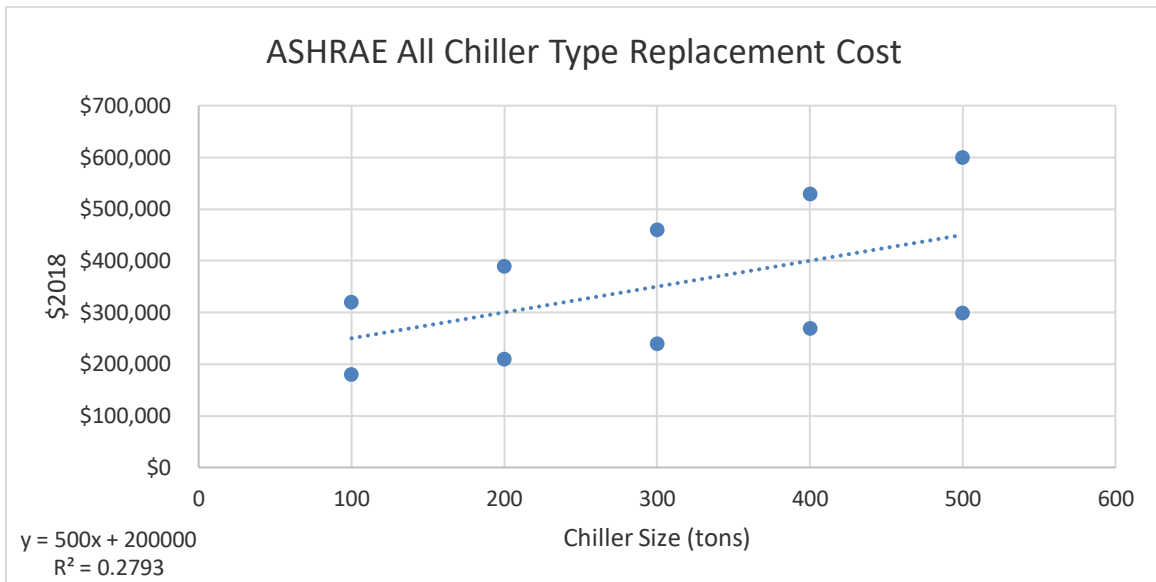Figure 14 - Whitestone Chiller Initial costs (Abate et al., 2009)

Figure 15 - ASHRAE Chiller Initial costs

Maintenance and Repair Costs

Before the maintenance and repair costs from the WPAFB data were combined or analyzed using the same single regression techniques used for initial cost, a multiple regression analysis was completed to determine if there were other significant variables that impact maintenance and repair costs. Specifically, the additional variables that were logical possible influencers were age of chiller, manufacturer, and condition index. Three stepwise regressions were completed employing a 90% significance level cutoff using maintenance, repair, and combined maintenance and repair costs as the dependent variables.

```
     Source |       SS          df       MS           Number of obs   =        87
------------+-------------------------------------    F(1, 85)        =     15.28
      Model | 16742472.2          1  16742472.2       Prob > F        =    0.0002
   Residual | 93145101.4         85  1095824.72       R-squared       =    0.1524
------------+-------------------------------------    Adj R-squared   =    0.1424
      Total |  109887574         86  1277762.48       Root MSE        =     1046.8


Chille~MCost |     Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
 Capacitytons |  1.744559     .44632     3.91   0.000     .857155     2.631962
        _cons |  946.0046   144.9859     6.52   0.000     657.7337    1234.275
```

Figure 16 - Maintenance Cost Stepwise Regression Results (p - 0.10)

```
     Source |       SS          df       MS           Number of obs   =        55
------------+-------------------------------------    F(0, 54)        =      0.00
      Model |          0          0         .          Prob > F        =         .
   Residual |  267335675         54  4950660.64       R-squared       =    0.0000
------------+-------------------------------------    Adj R-squared   =    0.0000
      Total |  267335675         54  4950660.64       Root MSE        =      2225


Chille~XCost |     Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
        _cons |  1422.786     300.02     4.74   0.000     821.2819     2024.29
```

Figure 17 - Repair Cost Stepwise Regression Results (p - 0.10)

```
     Source |       SS          df       MS           Number of obs   =        93
------------+-------------------------------------    F(0, 92)        =      0.00
      Model |          0          0         .          Prob > F        =         .
   Residual |  466149922         92  5066846.98       R-squared       =    0.0000
------------+-------------------------------------    Adj R-squared   =    0.0000
      Total |  466149922         92  5066846.98       Root MSE        =      2251


TotalWOCos~D |     Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
        _cons |  2062.039   233.4143     8.83   0.000     1598.458     2525.62
```

Figure 18 - Maintenance + Repair Cost Stepwise Regression Results (p - 0.10)

The output from the stepwise regressions show that, similar to initial purchase, cooling capacity is the only statistically significant variable for predicting maintenance costs. For repair and maintenance plus repair costs, one would interpret the results of the regressions as completely random with no influence from any of the available

variables. Here is where one can point to the lack of data (only 17 months' worth) as a reason for the apparently illogical result of the regressions. Additionally, it is illogical that age or condition would not play a part in the maintenance and repair costs since equipment deteriorates with age and requires more upkeep (Steenhuizen et al., 2014). The relatively small span of data with relation to the service life of a chiller prevents us seeing the full picture.

Despite the limitations of a small dataset, the stepwise regression does provide a basis for the assumption that cooling capacity is an appropriate variable for predicting maintenance costs. Assuming that repair costs follow a similar trend as repair costs that cannot be identified given such a small dataset, this informs our simple regression comparison of the theoretical and empirical datasets. Since cooling type is not identified as a significant variable (as with initial cost), only a comparison between the datasets with chillers of both cooling types is included here. Additionally, since the WPAFB empirical data only contains 17 months of data, it can only be compared to the other datasets in terms of general data trends, not magnitude, i.e. regression slope and not intercept. The single regression analysis is shown in Figure 19 through Figure 21.
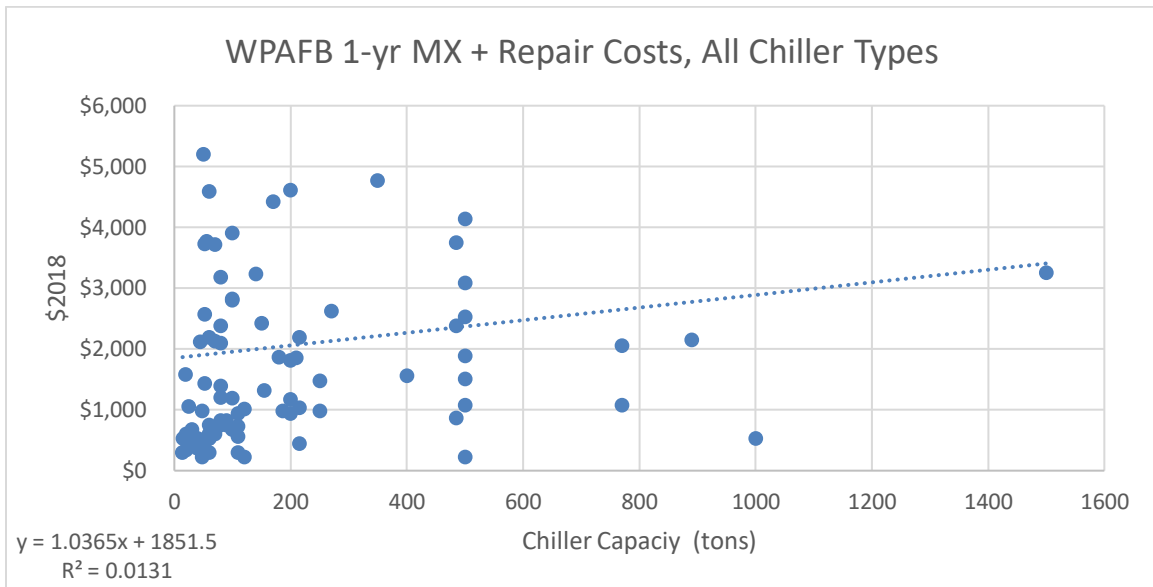
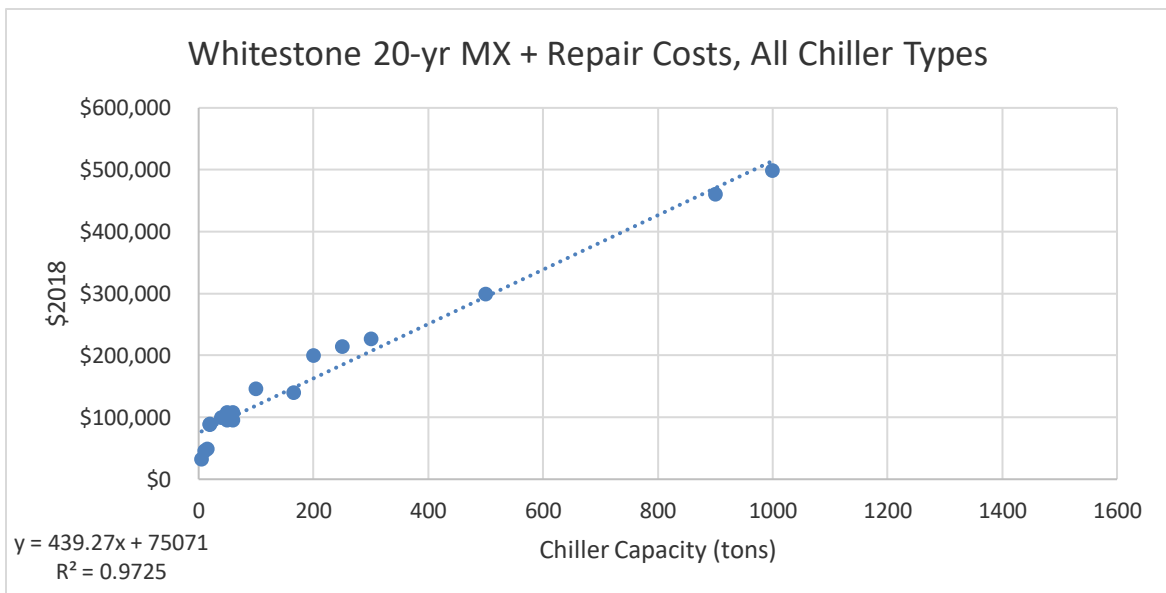Figure 19 - WPAFB Chiller Maintenance + Repair Costs

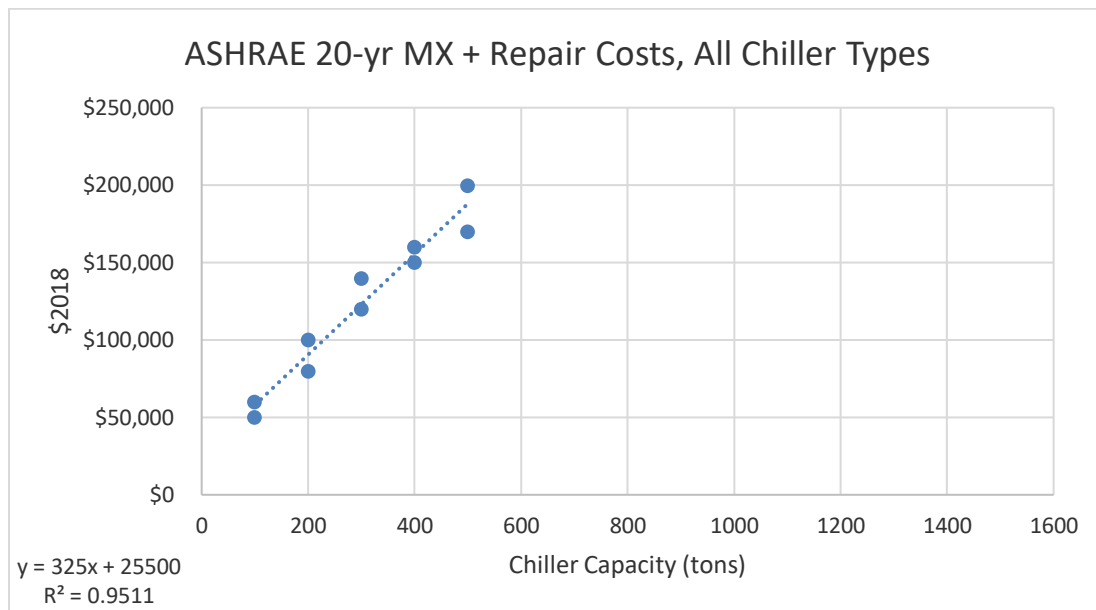Figure 20 - Whitestone Chiller Maintenance + Repair Costs (Abate et al., 2009)

Figure 21 - Naguib, 2009 Chiller Maintenance + Repair Costs

The single regression comparisons yield two conclusions: (1) the WPAFB data

compares poorly to the theoretical data – effectively confirming the conclusions made

using stepwise regression; and (2) a comparison of the two theoretical datasets show

very similar trends and magnitudes for estimating total maintenance and repair costs

over the lifespan of a chiller. The single regression models for both the Whitestone and

Naguib data show good fit ($R_{Whitestone}^2$ = 0.9725 and R_{Naguib}^2 = 0.9511) while the slopes

($M_{Whitestone}$ = 439.27 and M_{Naguib} = 325) and intercepts ($B_{Whitestone}$ = 75071 and B_{Naguib} =

25500) exhibit the same direction and similar magnitudes. Despite the lack of conclusive

interpretation drawn from the empirical WPAFB data, the comparison of the two

theoretical datasets provides confidence, albeit lower confidence than the initial cost

analysis, that the maintenance and repair variable of our overall TCO model is estimated

with acceptable accuracy.

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Energy Costs

The final variable in the TCO model is energy costs. This variable is unique in the respect that it is the only variable in this analysis with no empirical data available. While the lack of energy data is not ideal, it did not prevent an analysis from taking place.

During the validation phase for the first two variables of the TCO model, initial cost and maintenance plus repair, theoretical data was compared with empirical data and conclusions were made based on how well the theoretical data matched the empirical. Without the ability to do that for energy data, one can only make judgements based on the validity of the other variable examined. In this case, the energy data came from the ASHRAE chiller total cost study (Naguib, 2009). Being a purely theoretical dataset based on DOE energy simulation software, there is no doubt that the data will not translate perfectly to describing a much messier real-world system (Larose & Larose, 2015). However, the data from the ASHRAE study for initial cost and maintenance plus repair yielded regression curves that were similar enough to provide confidence in their descriptive validity. That being said, in this case with no empirical energy data, one must make the assumption that the theoretical energy data is equally valid at describing real-world energy usage by chiller equipment. As such, the final variable of the model is validated – providing the final piece to overall validation of a TCO model derived from theory. The approach to energy cost estimation used in this research, rather than energy simulation, was taken based on the lack of descriptive data for the chillers being studied. Technical details available for each chiller consisted of cooling type, size, manufacturer, and model. Attempts to identify efficiency coefficients and load curves

associated based on model numbers were unsuccessful as that information is proprietary by manufacturer and records at WPAFB did not contain the information.

Validation Conclusions

In an ideal world, the validation of the final TCO model presented by this research would have been carried out using ample amounts of empirical data collected over enough time to cover at least one fully expected design life of an average chiller. The validation protocol presented here is not ideal, but provides for foundational model that provides an approximation of chiller TCO given sparse, low-quality data. Since confidence in the model is rooted in a comparison of individual cost variables across datasets to make judgments on the whole, the model is obviously hindered by a small set of empirical data for maintenance plus repair and a complete lack of empirical data for energy usage. The model is useful, however, to decision makers for three reasons: (1) it provides a statistically valid process of model development that is supported by both existing academic literature and industry standards; (2) the model provides another level of cost estimating that required planners to consider TCO and apply its concepts to design and acquisition of chiller equipment; and (3) the assumptions and limitations are clearly laid out in a way that allows for continual improvement in the model as data collection schemes within the USAF improve. A final, holistic view of the model's output when using the 94 chillers examined by this research is shown in Figure 22. The plot shows both the breakdown of component costs and the predicted TCO over 20 years expected for the chillers at WPAFB. The plot mostly closely resembles the data

used to build the model (Naguib, 2009) for obvious reasons; the plot also resembles the

relationships illustrated through the cost factor plots from the WPAFB and Whitestone

Reference (Abate et al., 2009) data sources. Figure 22 also highlights the importance of

capturing energy costs for modeling TCO as energy represents the second largest cost
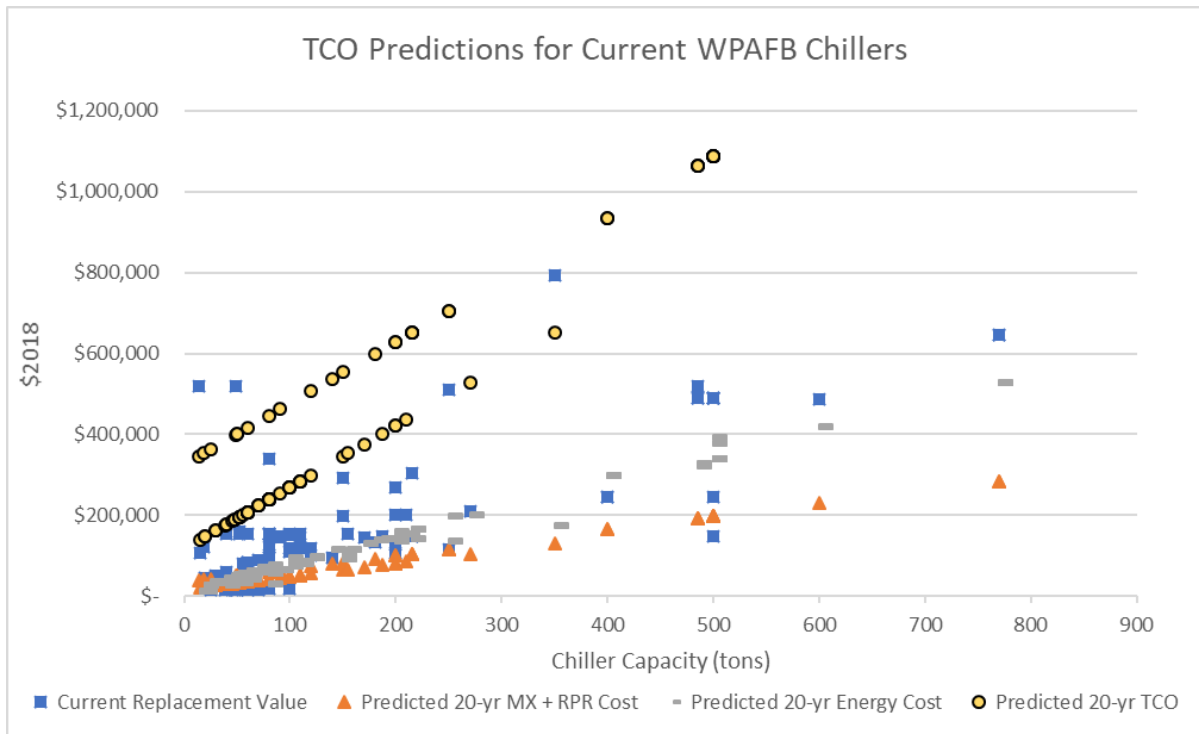
fraction of the TCO.

Figure 22 - TCO Predictions for WPAFB Chillers

Recommendations

The recommendations provided explain actions that should be taken to improve

the quality of analysis and accuracy of this research and subsequent work. Data quality

and opportunities for fortune research are the focus of this section.

Improved Data Collection

The lack of a consistent, purposeful data collection scheme for even the most basic elements involved with TCO analysis for chiller equipment provided for a challenging development phase and limited predictive model. The recommendations for improved data collection will be largely broken down based on the variables present in the TCO model. The recommendations, in order of how addressing each would improve this analysis, are: (1) lack of data and quality of existing data; (2) improving the implementation of consistent, active, and flexible data science policies across the USAF; and (3) integrating existing databases.

The most glaring deficiency of the model is the total lack of empirical energy data. Despite a USAF Energy Flight Plan (Department of the Air Force, 2017) designed to "a comprehensive approach to energy management to improve its ability to manage supply and demand in a way that enhances both mission capability and readiness" through the year 2036, the USAF does not require energy monitoring at any sub-level below a total facility. In order to know how money is spent on energy (or any category) and bring that spending under management, it must be measured. It is the total lack of energy monitoring for facility sub-systems that makes this the first priority for improving the USAF data collection approach for equipment TCO analysis. This recommendation can be applied generally to any category analysis in which usage data simply does not exist. The important takeaway for policy and decision makers is to think systematically about what is actually required to estimate a desired parameter and adjust the data collection scheme appropriately. While terabytes of data may seem impressive at first

sight, a lower amount of quality data that is directly applicable to the analysis being conducted will be much more productive than large amount of irrelevant data (Larose & Larose, 2015).

The concept of quality over quantity data is a crucial one that has yet to be fully implemented across the USAF although the recognition of this concept is taking hold at the higher levels of leadership (Crider, 2018). Data quality can be thought of as the degree to which data is fit for the desired purpose using accuracy, completeness, consistency, currency, and uniqueness (Loshin, 2014). While a full survey of USAF data collection is beyond the scope of this research, the likely hindrance to the implementing a focus on quality data collection in the USAF is threefold: (1) a lack of dedicated data scientists spread throughout the department; (2) corporate inertia that resists changing data collection schemes at tactical levels due a lack of manpower to focus on data (possible connection to the lack of data scientists), a lack of direction on how to change, a "this is how we have always operated" mindset, or some combination of all three; and 3) the incredible diversity present in USAF organizations and databases, even those within the same career field, that makes codifying and centralizing standard quality data collection daunting (Mikalef et al., 2018). Despite these challenges, the USAF must push forward with proactive, relevant data collection schemes that can be used to appropriately analyze problems. Additionally, the USAF must maintain a flexible quickly adaptable strategy that can shift to reflect changing data requirements while maintaining the consistency and quality of large datasets. A lack of knowledgeable data science professionals and well thought out direction will likely make any

implementation, especially large-scale changes, almost impossible to succeed. While quality data is listed second in the recommendation list (behind collecting targeted data where none currently exists), the concept of collecting data for a specific purpose should be considered as a requirement across all recommendations. For a concrete example of the limits low data quality places on analysis, one can look at BUILDER component replacement value (CRV) data used in this research. While CRV was the most comprehensive empirical data used, the data still contained CRV values that were unrealistic based on the other specifications from BUILDER and industry cost estimation data (Abate et al., 2009; Enersion, 2017; FPL, 2012b, 2012a). This lead to a lower level of confidence in the data in addition to the removal of those records, diminishing the statistical power of the analysis provided due to less data records (Cohen, 1992).

The implementation of the TRIRIGA integrated work management system is one bright spot in the infrastructure-related USAF data portfolio – developed as a financial audit readiness tool, TRIRIGA has already improved how the USAF tracks maintenance and repair data; time is the only thing required to build the size of that dataset. Examining the TRIRIGA software does, however, emphasize the importance of communication between databases. Disjointed databases that cannot "talk" required laborious, time-intensive efforts to create cohesive datasets. Joining datasets across platforms may not even be possible if export formats are different (generally not a problem given the prevalence of Microsoft Excel) or there are no common identifiers within data records that allow combination. The majority of analysis time for this research was spent pouring through thousands of records from BUILDER and TRIRIGA to

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removed unnecessary data and find common data identifiers that would allow for combination. Even once the best common link between the two datasets was identified, the matches were not perfect and combining of records was done using the judgement on whether equipment names were close enough to warrant a match. Those records without a match were removed, once again revising the issue of decreased data confidence and power of analysis. In an organization already constrained by limited manpower and data science expertise, issues like communication between datasets can make a significant difference; time not spent processing data to make it usable can be spent on meaningful analysis.

Additional Cost Factor Estimation

While the TCO model presented here provides an output based on the three largest cost over the service life of a chiller, there are other costs associated with the TCO of chiller equipment. The work done within the USAF on chiller TCO analysis (Brannon et al., 2018) provides the rationale for including training costs, inventory parts and storage, cost of acquisition (actions taken before initial purchase), the cost to secure systems from cyber-attacks, and the cost of system downtime. The foundational concept of TCO analysis is that every cost within the defined boundary should be included; therefore, there is no question as to the validity of accounting for these costs. Additionally, excluding certain can introduce omitted variable bias to the model – a phenomenon where the model may attribute the effect of the missing variables to the estimated effects of the included variables. The logic for excluding them from this analysis stems from (1) the complete lack of empirical and theoretical data for these

costs and (2) the omission of these costs in the current body of HVAC cost literature and industry guidelines (Abate et al., 2009; Crevat, 2017; Naguib, 2009; Trane, 2010).

While the lack of available data for the additional chiller TCO costs is not an excuse for not making an attempt at estimation, the lack of data coupled with the relatively low proportion of total cost makes it a reasonable omission. This research aimed to create a fieldable chiller TCO model that would provide decision makers involved with choosing chiller equipment a tool for validating acquisition decisions. As such, in order to provide a practical model that balanced theoretical estimation with empirical data, the model focused on what academic literature and industry standards used consistently as the bulk of TCO analysis (Carr & Ittner, 1992; Naguib, 2009; Trane, 2007, 2010). While the exact remaining proportion of TCO not accounted for by the three main costs is not quantifiable as result of this research, the omission of these additional costs from all literature on the topic indicates an insignificant portion of the TCO is represented by the additional costs. The approach taken in this research was to develop a model that could be fielded in a usable fashion and the inclusion of the more minor costs, while increasing the accuracy of the model, would have had limited value added and dubious accuracy given the lack of data available. Despite their omission, estimating and examining the costs not included would provide for meaningful future work which may determine that the omitted costs are not as minor as previously assumed, especially from an alternative analysis perspective. Training and supply, specifically, provide a potentially crucial vein of future research that could allow for significant cost savings given certain assumptions are met.

Training, Supply, and Standardization

The USAF Civil Engineer career field is unique from many other infrastructure-centric career fields in the U.S. because (1) there is a combat focus and mission set unique to the U.S. military and (2) roughly 60% of the personnel in the career field turnover consistently due to assignment changes. Focusing on the turnover of personnel and the diminished continuity created by such provides an avenue for TCO research on effect of asset standardization that may affect the cost of training and equipping personnel. When personnel move to different bases, they are often faced with completely different mission sets, job requirements, and circumstances (climate, funding, deployments, family separation, and organization structure to name a few). From a chiller equipment perspective, the personnel required to maintain and repair these assets may leave a base where one type or manufacturer of chiller is preferred to another base that is completely different. This turnover of personnel to new assignment creates a constant stream of new training requirements to create personal capable of maintaining the new types of equipment they may encounter. Even when not accounting for personnel moves, the USAF estimates that for each different manufacturer of chiller equipment present on a base, training requirements increase by 65% (Brannon et al., 2018). Additionally, the inventory of general HVAC equipment in the USAF has gotten so diverse that the technical education given new HVAC technicians is focused on general troubleshooting and minor repair with the assumption that manufacturer reps or contractors will be required for more advanced work (Brannon et al., 2018). This approach results in a system where the USAF pays for work twice: once

when USAF personnel perform initial troubleshooting and again when a third party examines the issue. Training is not the only elevated cost associated with a diverse equipment portfolio. The large bench stock required to deal with a vast array of systems requires more active inventory management, cost, and storage. Reduced interchangeability, a key facet of minimizing costs in facility management (Dhillon, 2002), also results from small differences amongst manufacturers prohibiting part swapping.

For TCO analysis, one can easily see where accounting for the additional costs created by diverse equipment portfolios is of interest. The analysis becomes even more interesting if the market for general HVAC and chiller specific equipment is consider competitively efficient (SBA, 2014). The idea that the market for chiller equipment compete efficiently while being subject to the same constraints (technology, regulation, demand, production capability, material availability, management quality, and market conditions) provides a baseline where one can assume that the initial costs, reliability (i.e. maintenance and repair costs), and operation (energy) of an equivalent size and type of chiller from any major manufacturer will be comparable within a negligible margin of difference. If the assumption were violated, a manufacturer would lose market share until the assumption held true again or until said manufacturer ceased doing business. This approach is important for analyzing how the USAF could save potentially large sums money through equipment standardization. If chiller equipment performance is considered practically equal due to competitive efficiency then initial, maintenance plus repair, and energy costs can be assumed equal while training and

supply costs take the focus of cost analysis. This line of thinking opens the door to options for measuring bench stock acquisition and storage costs as well as personnel productivity at installations with relatively standardized vs non-standardized equipment (assuming the differentiation exists). A standardization strain of research is especially interesting given the relatively even cost proportions of initial purchase, maintenance plus repair, and energy costs (Naguib, 2009).

Conclusion

The research presented here focused on developing a TCO model for predicting chiller equipment cost for the USAF under the umbrellas of federal category management. Knowing the TCO of any asset is a foundational requirement for understanding how much is spent and where the spending is inefficient. The new research developments of this study are a practical, fieldable model to provide a chiller TCO approximation that provides a first step toward implementing category management for the acquisition of USAF chiller assets. Developing a model based on existing research that is validated by a mix of empirical and theoretical data sources provides a novel result currently not present in the existing body of literature on general and chiller specific TCO. The study provides a detailed methodology for improved estimating additional costs as data becomes available. While sufficient empirical data was not present to perform full case study analysis, the recommendations provided as a result of this research, if adopted, will create a clear path to developing the predictive power of the base model significantly in future iterations. Additionally, a clear depiction

of the assumptions and constraints provides those who use the model a full understanding of the lenses through which the output should be viewed. The model should prove useful for those attempting to justify non-LPTA acquisition methods and allowing for design options that may not have been previously considered. Additionally, this TCO model required substantially less manpower to reach an output cost, which will lead to saved money on both the analysis and equipment acquisition fronts. Finally, recommendations and additional streams of research that will serve to improve the TCO model are identified for consideration by policy makers at all levels.

V. Conclusions and Recommendations

Chapter Overview

The linear regression model developed in this research provided a new total cost of ownership (TCO) estimation tool for chiller equipment with potential utility for making acquisition decisions and analyzing equipment alternatives. This chapter outlines these results and their implications. The first section of the chapter provides a summary of the research conclusions. Next, the chapter covers limitations of the research followed by the significance of the research. Finally, the chapter discusses recommendations for future research to continue and expand the work presented in this paper.

Conclusions of Research

This study provided some useful insights into the concepts and application of TCO estimation modeling. Once a descriptive TCO model was built, the graphical and single regression analysis of individual cost factors provided confirmation of the trends across the data. Single regression results were validated when multiple regression determined a lack significance of additional variables, effectively allowing for using individual cost factors to validate the overall TCO model. Additionally, the model provides an estimate of TCO using information that is readily available at the beginning of the equipment acquisition process. These attributes provide significant benefits over existing chiller TCO estimation models. The TCO model developed by this research provides an easy to use, transparent, and non-proprietary tool based on theory but

validated with empirical data. Additionally, the model can be fielded with minimal man-hours and additional cost variables can be taken into account following the model development steps outlined.

With a larger/more complete dataset, the model's accuracy could improve substantially. Specifically, robust empirical datasets would provide a better means of validating the model holistically instead of validation based on individual cost factors.

Limitations of Research

The key limitations of this research centered on a lack of data. The model was able to produce significant results; however, additional data could have improved the validation techniques and allowed for more advanced cost simulation techniques that account for uncertainty and provide TCO ranges based on a desired level of statistical confidence. Moreover, additional data may have identified additional significant characteristics of chiller equipment that have a significant effect on TCO.

Significance of Research

There are two significant ramifications from this research. First, this model provided a methodology to create a viable tool in early cost estimation efforts. The process for model development provided here provide users with a lack of quality data a means of estimating TCO. The model developed here may provide a comparison estimate or an alternative means for improving preliminary chiller equipment cost estimation. Additionally, the process provided here can be applied to large, high-quality datasets as well with better results. Second, this research provided an analysis of the

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work needed to estimate costs more accurately and provides a map for policymakers who want to make serious changes in how the USAF tracks and manages costs under the umbrella of category management.

Recommendations for Future Research

Future research could build upon this study in several ways. First, a future researcher could expand the model, validating and refining the results to include additional cost variables and equipment types. In particular, expanding the amount of empirical data available for model validation would provide a better level of accuracy and applicability. Follow-on research cold focus on identifying additional cost factors significant to TCO. Specifically, the effects of equipment standardization on TCO is of interest given the wide variety of chiller types, sizes, and manufacturers present across the USAF inventory. Using other, comparable organizations such as airports or university campuses to provide data for TCO analysis may provide yet another layer of validation and insight into TCO of chiller equipment.

Summary

This research succeeded in developing a TCO estimation for chiller equipment. The model, while constrained by data quality and quantity, produced results useful for the cost estimation process with implications for improving current estimation practices. This method also provided a process for developing TCO models while providing tangible insights and recommendations for improving the accuracy and usefulness of the model. Overall, these insights into USAF chiller equipment costs and

the subsequent model expand the foundation for future research and TCO

development. Building on these methods, the USAF can produce increasingly accurate

estimates with better clarity of the inherent risks and cost probabilities.

Bibliography

Abate, D., Towers, M., Dotz, R., & Romani, L. (2009). *The Whitestone Facility Maintenance And Repair Cost Reference 2009-2010* (14th ed.). Retrieved from http://docplayer.net/storage/27/11678584/1522579147/FSrkI4fsW-GxOClBXdMWGg/11678584.pdf

Anderson, M. G., & Katz, P. B. (1998). Strategic Sourcing. *The International Journal of Logistics Management*, *9*(1), 1–13.

ARI. (2003). 550/590: 2003 Performance rating of water-chilling packages using the vapor compression cycle. Arlington: ARI.

ASHRAE. (2007). Standard 90.1-2007. *Energy Standard for Buildings Except Low-Rise Residential Buildings*.

Blattberg, R. C., Briesch, R., & Fox, E. J. (1995). How Promotions Work. *Marketing Science*, *14*(3_supplement), G122–G132. https://doi.org/10.1287/mksc.14.3.G122

Blattberg, R. C., & Deighton, J. (1996). Manage Marketing by the Customer Euqity Test.

Brannon, M., McLaughlin, W., Morgan, M., Andrade, E., Adams, T., Gutierrez, H., … Ashely, D. (2018). *Category Intelligence Report - HVAC and Controls*.

Broniarczyk, S. M., Hoyer, W. D., & McAlister, L. (1998). Consumers' Perceptions of the Assortment Offered in a Grocery Category: The Impact of Item Reduction. *Journal of Marketing Research*, *35*(2), 166. https://doi.org/10.2307/3151845

Building Life Cycle Cost Programs. (n.d.). Retrieved from https://www.energy.gov/eere/femp/building-life-cycle-cost-programs

Burt, D. N., Norquist, W. E., & Anklesara, J. (1990). Zero Base Pricing. *Probus*.

Camillus, J. C. (2015). Reinventing Strategic Planning. *Strategy & Leadership*, *24*(3), 6–12. Retrieved from https://www.emeraldinsight.com/doi/pdfplus/10.1108/eb054552

Carr, L. P., & Ittner, C. D. (1992). Measuring the Total Cost of Ownership. *Journal of Cost Management*, *6*(3).

CENTECH. (n.d.). Interim Work Information Management System (IWIMS). Retrieved from http://www.centechgroup.com/company/116 IWIMS.pdf

Coase, R. (1937). The nature of the firm. Economica 4. Reprinted in: Coase R (1988) The

firm, the market and the law. University of Chicago Press, Chicago.

Cohen, J. (1992). Quantitative Methods in Psychology. *Psychological Bulletin*, *112*(1), 155–159. https://doi.org/10.1037/0033-2909.112.1.155

Crevat, P. (2017). Water and air cooled chillers : Efficiency and Total Cost of Ownership Comparison, (May). Retrieved from https://eurovent.eu/?q=file/2503/download&token=9CY_xtOx

Crider, K. (2018). Air Force Data Strategy. Retrieved from https://www.google.com/search?q=air+force+data+mangement&oq=air+force+data+mangement&aqs=chrome..69i57j0l5.3143j0j7&sourceid=chrome&ie=UTF-8

Department of the Air Force. (2017). United States Air Force Energy Flight Plan.

Dhillon, B. S. (2002). *ENGINEERING MAINTENANCE: A Modern Approach*. Boca Raton, FL: CRC Press. https://doi.org/10.1016/0005-2736(75)90287-4

DiNapoli, T. J., Traci, M., Kim, J., Nguyen, A., Stockdale, E., Yu, J., … Sun, R. (2014). Defense Contracting: Factors DOD Considers When Choosing Best Value Processes Are Consistent with Guidance for Selected Acquisitions, (July). Retrieved from http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA606830

Dodaro, G. L. (2015). *Opportunities to Reduce Fragmentation, Overlap, and Duplication and Achieve Other Financial Benefits*. *GAO-15-523T*. Washington, D.C.: GAO. Retrieved from http://www.dtic.mil/dtic/tr/fulltext/u2/a616314.pdf

Ellram, L. M. (1993). Total cost of ownership: elements and implementation. *International Journal of Purchasing and Materials Management*, *29*(3), 2–11.

Ellram, L. M. (1994a). A taxonomy of total cost of ownership models. *Journal of Business Logistics*, *15*(1), 171.

Ellram, L. M. (1994b). Total Cost of Ownership in Purchasing. *Center for Advanced Purchasing Studies, Tempe, AZ*.

Ellram, L. M. (2005). Total cost of ownership: An analysis approach for purchasing. *International Journal of Physical Distribution & Logistics Management*, *25*(8), 4–23. Retrieved from

https://www.emeraldinsight.com/doi/pdfplus/10.1108/09600039510099928

Ellram, L. M., & Siferd, S. P. (1993). Purchasing: The cornerstone of the total cost of ownership concept. *Journal of Business Logistics*, *14*(1), 163.

Enersion. (2017). Cost of the current cooling technology. Retrieved from http://enersion.com/cost-of-the-current-cooling-technology/

Eschenbach, T. G. (2011). *Engineering Economy: Applying Theory to Practice* (Third). New York, New York: Oxford University Press, Inc.

Federal Acquisition Regulation, 48 C.F.R. § 15.101-1. (2014). United States.

Fernandez, J. P. (1990). Life-cycle costing. *NAPM Insights*, (September), 6.

FPL. (2012a). Air-Cooled Chillers, 1–4. Retrieved from https://www.fpl.com/business/pdf/air-cooled-chillers-primer.pdf

FPL. (2012b). Water-Cooled Chiller Characteristics, 1–4. Retrieved from https://www.fpl.com/business/pdf/water-cooled-chillers-primer.pdf

Fuller, S. (2016). LIFE-CYCLE COST ANALYSIS (LCCA). Retrieved from https://www.wbdg.org/resources/life-cycle-cost-analysis-lcca

GAO. (2016). FEDERAL Smarter Buying Initiatives Can Achieve Additional Savings , but Improved Oversight and Accountability Needed, (October).

Gruen. (1998). Category Management: The New Science of Retailing. *Financial TImes: Mastering Marketing*, (October), 4–6.

Gruen, T. W., & Shah, R. H. (2000). Determinants and outcomes of plan objectivity and implementation in category management relationships. *Journal of Retailing*, *76*(4), 483–510. https://doi.org/10.1016/S0022-4359(00)00041-5

GSA. (2016). Facilities & Construction Category - Government-wide Category Management (Past Journey & Future Direction), (October). Retrieved from http://www.ncmbc.us/docs/16FEDCON/GSA2.pdf

GSA. (2017a). Facilities & Construction Category - Government-wide Category Management (Framework, Goals, & Implementation), (March). Retrieved from https://interact.gsa.gov/sites/default/files/F%26C Category Management Industry Day 2017_0.pdf

GSA. (2017b). Spend Under Management Tiered Maturity Model, 2–3.

GSA. (2018a). Best-in-Class & Spend Under Management.

GSA. (2018b). Building Maintenance and Operations. Retrieved from

    https://www.gsa.gov/acquisition/purchasing-programs/federal-strategic-sourcing-

    initiative/building-maintenance-and-operations

Guarino, D. (2013). Residential HVAC Contractors: Sell "Total Cost of Ownership" And

    Win. Retrieved February 7, 2018, from http://www.contractingbusiness.com/last-

    word/residential-hvac-contractors-sell-total-cost-ownership-and-win

Heide, J. B. (1994). Interorganizational governance in marketing channels. *The Journal of*

    Marketing, 71–85.

Heide, J. B., & John, G. (1990). Alliances in industrial purchasing: The determinants of

    joint action in buyer-supplier relationships. *Journal of Marketing Research*, 24–36.

Henry, J., & Elfant, C. (1988). Cost of ownership. *Purchasing Management*, (28 March),

    15–20.

Horning, J. (2018). CRV Explanation.

IBM. (2018). IBM TRIRIGA. Retrieved November 18, 2018, from

    https://www.ibm.com/us-en/marketplace/ibm-tririga

Jackson, D. W., & Ostrom, L. L. (1980). Life Cycle Costing in Industrial Purchasing. *Journal*

    of Purchasing and Materials Management, *16*(4), 8–12.

    https://doi.org/10.1111/j.1745-493X.1980.tb00020.x

Johnson, C. (2005). OFPP Memorandum, "Implementing Strategic Sourcing."

Kaplan, R. S. (1992). In defense of activity-based cost management. *Management*

    Accounting, 58–63.

Larose, D., & Larose, C. (2015). Data Mining and Predictive Analytics (Wiley Series on

    Methods and Applications in Data Mining), *25*(9), 1682–1690.

    https://doi.org/10.1007/s13398-014-0173-7.2

Leenders, M. R., Fearon, H. E., & England, W. B. (1980). *Purchasing and materials*

    management. Irwin Professional Publishing.

Lindblom, A., Olkkonen, R., Ollila, P., & Hyvönen, S. (2009). Suppliers' roles in category

management: A study of supplier-retailer relationships in Finland and Sweden. *Industrial Marketing Management*, *38*(8), 1006–1013. https://doi.org/10.1016/j.indmarman.2008.05.004

Loshin, D. (2014). *Understanding Big Data Quality for Maximum Information Usability Contents*. *White paper*. https://doi.org/https://dx.doi.org/10.1111/j.1600-6143.2008.02426.x

McLaughlin, E. W., & Hawkes, G. F. (1994). Category Management Current Status and Future Outlook. *Ood Industry Management Program, Department of Agricultural, Resource, and Managerial Economics, Cornell University*, *94*(28).

Mikalef, P., van de Wetering, R., & Krogstie, J. (2018). Big data enabled organizational transformation: The effect of inertia in adoption and diffusion. *Lecture Notes in Business Information Processing*, *320*(May), 135–147. https://doi.org/10.1007/978-3-319-93931-5_10

Monckza, R. M., & Trecha, S. J. (1988). Cost-based supplier performance evaluation. *Journal of Purchasing and Materials Management*, *24*(1), 2–7.

Montgomery, D. C., Peck, E. A., & Vining, G. G. (2012). *Introduction to Linear Regression Analysis* (5th ed.). Hoboken, New Jersey: John Wiley & Sons, Inc.

NACS. (2018). Category Management. Retrieved from https://www.convenience.org/Glossary

Naguib, R. (2009). Total Cost of Ownership For Air-Cooled and Water-Cooled Chiller Systems. *ASHRAE JOURNAL*, *51*(4), 42+.

NAPM. (1991). *Supplier Performance Evaluation: Three Qualitative Approaches*. *National Association of Purchasing Management*.

OMB. (2015). Government-Wide Category Management, (May), 1–42.

Paydos, T., & Conti, J. (1997). No Category Management & Information Technology, IBM White Paper. *International Business Machines White Papers*.

Picard, C. (2017). *HVAC: CONSIDERATIONS FOR TOTAL COST OF OWNERSHIP ABOUT THE PROFESSIONAL RETAIL STORE*. Dallas, TX. Retrieved from https://www.prsmnational.com/prsm2018/Custom/Handout/Speaker0_Session32

8_2.pdf

Roehm, H. A., Critchfield, M. A., & Castellano, J. F. (1992). Yes, ABC works with purchasing, too. *Journal of Accountancy*, *174*(5), 58.

Rung, A. (2014). Transforming the Marketplace: Simplifying Federal Procurement to Improve Performance, Drive Innovation, and Increase Savings.

Saccani, N., Perona, M., & Bacchetti, A. (2017). The total cost of ownership of durable consumer goods: A conceptual model and an empirical application. *International Journal of Production Economics*, *183*(December 2012), 1–13. https://doi.org/10.1016/j.ijpe.2016.09.021

SBA. (2014). Advocacy: the voice of small business in government.

Schmenner, R. W., & others. (1992). So you want to lower costs? *Business Horizons*, *35*(4), 24–28.

Silverman, S. N. (1996). Factors Affecting the Internal Resistance to Innovative Marketing Initiatives, unpublished dissertation. *University of Pittsburgh*.

Soukup, W. (1987). Supplier selection strategies. *Journal of Purchasing and Materials Management*, *23*(2), 7–12.

Steenhuizen, D., Flores-Colen, I., Reitsma, A. G., & Branco Ló, P. (2014). The road to facility management. *Facilities*, *32*(1/2), 46–57. https://doi.org/10.1108/F-09-2012-0072

Trane. (2007). Trane Total Cost of Ownership. Retrieved from http://www.trane.com/commercial/north-america/us/en/about-us/for-customers/financial-services/total-cost-of-ownership--tco-.html

Trane. (2010). HVAC Planning and TCO Analysis, (October 2007).

Trane. (2013). System Analyzer 1.1. Ingersoll Rand. Retrieved from https://www.trane.com/content/dam/Trane/Commercial/global/products-systems/design-analysis-tools/analysis-tools/system-analyzer/cds-slb004-en.pdf

U.S. Department of the Navy. (2014). Department of the Navy Total Ownership Cost (TOC) Guidebook, (June).

Uddin, W., Hudson, R. W., & Haas, R. (2013). *Public Infrastructure Asset Management*

(2nd ed.). McGraw-Hill Education.

USACE. (2012). BUILDER^{TM} Sustainment Management System. Retrieved from

https://www.erdc.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-

View/Article/476728/builder-sustainment-management-system/

USACE. (2018). BUILDER Custom Reports - Specific to US Air Force.

Walker, G. (1988). Strategic Sourcing, Vertical Integration, and Transaction Costs.

Interfaces, *18*(3), 62–73. https://doi.org/10.1287/inte.18.3.62

Williamson, O. E. (1985). *Yhe Economic Institutions of Capitalism: Firms, markets,*

relational Contracting. Free Press.

Zeiger, D. (2017). The Monthly Metric: Spend Under Management. Retrieved from

http://magazine.ism.ws/the-monthly-metric-spend-under-management/

Zients, J. (2012). Memorandum for the Heads of Exectutive Departments and Agencies.

Retrieved from https://www.nrc.gov/docs/ML1234/ML12345A356.pdf

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14. ABSTRACT
In order to make the most cost-effective choice when purchasing high-value assets, organizations must be able to quantify/compare the costs associated with acquiring, maintaining and disposing the alternatives. Currently, the United States Air Force (USAF) Civil Engineer (CE) enterprise has no standardized model to accurately and efficiently predict the total cost of ownership (TCO) for the acquisition of new assets. As such, acquisition efforts throughout the enterprise are disjointed and performed without leveraging the considerable buying power wielded by an organization as large as the USAF. This research will develop a TCO model using a standard, dollar-based approach that combines linear additive and regression modeling techniques. The model will be derived from existing operations/maintenance (O&M) and contract spending data associated with heating, ventilation, and air conditioning (HVAC). When complete, the TCO model will provide USAF acquisition, contracting, and civil engineering professionals a tool with which to project life-cycle costs, negotiate prices, and justify spending decisions. Furthermore, this model will provide proof of concept to the CE enterprise that will allow for the expansion of TCO modeling to other categories of spending.

15. SUBJECT TERMS
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