THESIS

THE DEVELOPMENT OF A SIMPLIFIED ASSET MANAGEMENT MODEL FOR FIXED US AIR FORCE INSTALLATIONS

Submitted by

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In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Fall 2014

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ABSTRACT

THE DEVELOPMENT OF A SIMPLIFIED ASSET MANAGEMENT MODEL FOR FIXED US AIR FORCE INSTALLATIONS

Water utility infrastructures that support Air Force installations are not only important to but also expensive to maintain and repair. While the Air Force strategic asset management structure focuses on mid- to long-term planning for budget allocation, at the installation level many issues confront the effectiveness of this program. Problems arise at every level within the installation's utility asset management program from asset inventory to condition assessments and failure consequence assessment. With inaccurate asset inventories, data disparities and uncertain information on system condition, installations are forced to take a "worst first" approach to maintenance operations. The largest issues confronting utility management at the installation level are time and money. Reductions in force size and spending provide the impetus to create a simplified method for asset management.

To solve this complex problem, an investigation of various approaches to utility asset management has been conducted to encompass the intent of the Air Force's existing activity management framework. Using pre-existing information and new methods, a risk management model was developed to bolster the efficacy of the pre-existing management system. Knowledge-based condition assessments and criticality assessments allow utilities engineers to calculate infrastructure risk for their planning horizons, rather than strategic planning horizons. This research includes analytical and mathematical approaches that formulate the backbone of the simplified process. This study also provides a user-focused data model and an implementation strategy to outline the processes required to improve management conditions. By laying the groundwork for how utility infrastructures can be better managed, conclusions about feasible approaches are made considering the Air Force's monetary and manpower constraints.

The research was validated through a case study at Francis E. Warren Air Force Base. A discovery was made that through both a paradigm shift in the calculation and communication of failure consequences, improvements can be made to the process by which infrastructure is managed at the installation level. The research concludes with an analysis of the roles of key factors in the process of asset management as practiced by the defense industry and fee-based public utilities. The implications of this research primarily benefit multi-layered organizations that currently use a top-down approach to asset management. By aiding the ability for lower levels to aggregate data and determine priority, improved levels of service, more effective mission support and reduced outages may be realized.

ACKNOWLEDGEMENTS

Dr. Grigg,
Dr. Bailey,
Dr. Glick,
Lt Col Jay Carson (ret),
Mr. Thomas Sweeney
Mr. Donald Kincaid,
AFIT/CES,
Friends & Family

To my best friend and muse, Sarah

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1.0 Introduction

The Air Force has one of the most diverse, dynamic and difficult missions in the United States Department of Defense. The scope of the mission entails operations in the air, in space and cyberspace. With its hugely diverse mission set, there comes an equally broad portfolio of support infrastructure. Currently the portfolio includes 184 million cubic yards of pavements, 615 million square feet of buildings, 9 million acres of land, 66,300 dorm rooms and over 74,000 military family housing units for a total plant replacement value of $240 billion (Gill, Hartford, & Saroni, 2013). In order to manage such a large and diverse portfolio, the Air Force adopts a comprehensive asset management approach. This approach “Integrates requirements to deliver installation support services needed for mission execution at lowest life-cycle cost (Headquarters, 2012c).” The purposes of this methodology are to extend infrastructure lifecycle, reduce both capital and operating cost and, most importantly, reduce mission impact from degraded or failing infrastructure assets. Asset management in the Air Force follows a model that strategically prioritizes projects for sustainment and renewal. Higher levels of the organization use this model to distribute funds where they will be most effectively utilized. A unique challenge presented by implementing this asset management model is the management of water distribution infrastructure. A water distribution system is a complex engineering and ecological system, and causes of varied performance levels are often difficult to determine (National Research Council, 2005). Water is also a critical component of the US Air Force mission support. The infrastructure and management that support all water assets are critical in ensuring the mission is successfully accomplished. Water poses implications to personnel and operations security through its supply and distribution quality and quantity. A robust water distribution system can be counted on to provide the necessary pressure and flow to fight a fire, prepare food for Airmen or support medical procedures. Aging water systems that may have leaks or quality issues cannot be counted on, and must be improved to ensure reliability.

1.1 Problem Statement

Of the many infrastructure management issues of a military installation, water utilities present a major challenge. As in cities, some of the oldest buried pipes date back to the 19th century (National Research Council, 2005). With underground pipes out of sight, investment decisions are easy to delay where budgetary limitations exist. Additionally, a water distribution system's condition is difficult to directly monitor. Because of this, preventative maintenance is usually challenging, as there are no indicators of degradation until an asset has already failed. This forces installations to adapt a "worst first" approach and sustainment funding usually flows retroactively to a failed asset. Further complicating the issue is the climate of increased budgetary restrictions within the Department of Defense. The operating environment of increasing fiscal constraints and growing national debt within the federal government shapes the manner in which investments are made (National Research Council, 2005). The RAND Corporation conducted a study of budgetary limitations in the Air Force in the coming years and identified a need for more careful strategic management of investment choices (Arena, Graser, & DeLuca, 2013). Exacerbating the problem is the issue of information management. Inaccurate work orders, real property records along with misplaced documentation have all led to a problem with utilities asset management on installations. The turnover of personnel, mission evolution and resulting poor records management have been realized in the resulting issues with obtaining reliable data. Inventory issues, unknown condition and importance criteria are all areas where gaps exist at the lowest level, the utilities engineer. While the Air Force has adopted asset management models to carefully prioritize funding and strategically plan for future requirements, the planning horizon of these models makes risk-based asset management difficult at the installation level. This model focuses on strategic budget planning, and does not necessarily help engineers at the lower levels of the organization assess risk in their infrastructure. This forces planners to make judgments about condition and cost savings to improve the priority score and receive funding. The requirement exists for a simplified method for engineers at lower levels to conduct asset management in order to provide a risk-based failure prediction model. This simplified model will take the framework from the strategic level and adapt its principles to more readily implementable approaches for near-term planning. This model will assist engineers in understanding what assets exist on an installation, what condition they are in, how important they are and what to fix first in the future.

1.2 Approach and Scope of Research

The presentation of this thesis will follow a two-phase approach. The goal of the first phase is to develop a simplified asset management model (SAMM) to aid short-term planning and asset visibility. An analysis of the Air Force's activity management program (AMP) with focus on condition assessment and infrastructure criticality will provide references and general structure as to how the simplified model should be constructed. Comparing the Air Force AMP with models used in the private sector will also assist in strengthening the simplified model.

The second phase of research involves developing a strategy for implementation of the simplified asset management model. Along with the implementation methodology, a comparative analysis will uncover various barriers to success in adapting such a model in a multilayered organization such as the Air Force. An added benefit realized from this research is its adaptability in organizations of similar structure.

The scope of research encompasses Air Force-owned potable water, non-potable water, and Fire Emergency Services (FES) systems to the five-foot line surrounding facilities outlined below:

- Wells
- Distribution lines
- Potable water treatment plants
- Pumps
- Valves
- Hydrants
- Storage Tanks

1.3 The need for a Simplified Asset Management Model

The need for a simplified asset management model stems from the varying degrees between operational, tactical and strategic asset management in a multi-layered organization such as the US Air Force. At each level, the elements that make up the asset management process are varied with the different planning horizons that each level focuses on. Gordon and Shore (1998) indicated three planning horizons that demonstrate the difficulty in asset management decision-making: Tactical, operational and strategic. The structure of the US Air Force can be broken down into these levels and as the Air Force's enterprise asset management model illustrates, great focus is placed upon the strategic level. These three levels coincide with planning varied horizons and with these different planning horizons comes a variance in the type and quality of information that is used to make decisions. The following can summarize the differences in the three levels:

- Each level has different levels of service
- Each level has different consequences of failure
- Each level has different amount of system knowledge
- Each level has different planning horizons
- Each level has different missions (but all form the highest level)

Though the Air Force has a hierarchal structure to ensure lower levels accomplish sub-missions that contribute to the overall Air Force mission accomplishment, the inherent complexity in adapting a strategically focused asset management model in an operational environment provides the impetus to the simplified model. This need is clearly illustrated through comparison with public utilities sector. A fee-based public utility uses asset management to bolster its performance and enhance the level of service provided to customers. In a defense organization, water utilities provide ancillary support functions that enhance the mission, but do not directly contribute to it. The lack of a clear link between the organization's mission and its asset management program along with the lack of fee-generated revenues complicates the problem of asset management further. The simplified model is designed to provide useful decision support information for engineers at the lowest level about condition, potential failure and more effectively link mission criticality to levels of service.

1.3.1 Water Utilities as a Focus Area

While the concepts and conclusions of this research are applicable to enterprise-wide adoption with slight variance between infrastructure categories, water infrastructure provides a challenging and useful exercise to research possible solutions. Water infrastructure was chosen as the study focus area due to its inherent complexity over other forms of infrastructure along with its relatively undeveloped state in the Air Force's asset management portfolio. Most of water infrastructure is buried and out of sight, meaning the direct monitoring of condition state is not usually practical. Measuring criticality is also a difficult challenge, as the levels of service provided by water utilities do not directly contribute to the accomplishment of the Air Force mission, they provide support roles. Furthermore, the relatively harsh environment in which water infrastructure operates accelerates its decay. Finally, the integrated management of water utilities is one of the final infrastructure categories that do not possess its own maintenance management system (MMS) in the Air Force. Thus, the research of methods to simplify the process may benefit the adoption of integrated technology in the future.

1.4 Research Objectives

The objectives of this research are to improve installation utility asset management through simplified methods that bolster the accuracy and efficacy of the asset register. Special focus is placed on methods for improved condition assessment applied to underground utilities as well as methods that more accurately portray an asset's importance. In an effort to make this implementable on Air Force installations, the model should:

- Align with tactical, operational and strategic Air Force goals
- Align with pre-existing asset management processes
- Simplify and streamline the installation inventory process for utility assets
- Streamline process for condition assessment using existing Activity Management Plan (AMP) framework and other risk-based condition and criticality models.
- Realign criteria that determine criticality to align with lower levels of Air Force organization.

Simplifying the process for engineers at the installation level provides a method to obtain more accurate and reliable data pertaining to utility condition and priority. The research is conducted to provide installations with a tool kit they may use if they do not have a complete register of their utilities inventory including their asset's condition or importance. We can summarize our research objectives by developing a "Simplified Asset Management Model" (SAMM) that incorporates asset location, condition assessment and importance relative to the relevant mission and the water system.

2.0 Literature Review

In order to exact a simplified approach to asset management, the core principles of the concept are investigated to garner a clear delineation between strategic and tactical asset management. Asset management speaks to a strategic approach to infrastructure investment, but the very nature of strategic investment often complicates the nature of tactical decisions due to the planning horizon. The concept is defined and key themes are explored that will help generate a more tactical approach to Air Force infrastructure asset management. The implementation of asset management is also very important, so methods for implementation are also reviewed that may benefit the execution of the simplified model.

2.1 Asset Management Definition

Until relatively recently, the reporting of fixed assets such as roads, buildings, bridges or other infrastructure on accounting sheets was difficult due to how the government required they be reported. These assets were of fixed value, with no consideration for depreciation or actual usability. Simply stated, the government did not account for whether the bridge was in need of repair or whether or not it was actually safe to cross, it only mandated that the bridge be accounted for with a fixed value. In 1999, the Government Accounting Services Board (GASB) established statement 34 about public infrastructure assets and redefined how the country accounted for its infrastructure by clearly defining an infrastructure asset. GASB 34 states "Infrastructure assets are long-lived capital assets that normally can be preserved for a significantly greater number of years than most capital assets and that normally are stationary in nature. Examples of infrastructure assets include roads, bridges, tunnels, drainage systems, water and sewer systems, dams, and lighting systems. Buildings, except those that are an ancillary part of a network of infrastructure assets, are not considered infrastructure assets (1999)." This definition clearly defines what is covered under the umbrella of asset management. Typically, organizations define asset management to accommodate for their own needs. For the sake of detail, several different definitions of asset management are evaluated to determine trends embedded in the concept.

The National Cooperative Highway Research Program defines asset management as:

- "Methodologies that integrate infrastructure inventory, condition assessments, minimum acceptable condition levels, and funding decisions … may help achieve better operational and financial results (Biehler et al., 2008)."

Gregory Baird mentioned in a 2011 American Water Works Association Publication:

- "In general, public asset management incorporates the management of all things that are of value to a jurisdiction, its mission and purpose, and citizen's expectations (2011)."

Vanier defines asset management using several questions (2001):

- What do you own?
- What is it worth?
- What is the deferred maintenance?
- What is its condition?
- What is the remaining service life?
- What do you fix first?

The British Standards Institute (BSI) states in its Publically Available Standard (now adopted by the International Organization for Standards) 55:

- "Systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks, and expenditures over their life cycles for the purposes of achieving its organizational strategic plan (2004)."

Finally, The Environmental Protection Agency identifies key activities that are generally regarded as "steppingstones" to effective asset management (2008):

- Asset inventory development
- Assess condition
- Determine residual life
- Evaluate lifecycle and replacement costs/economic valuation
- Set target levels of service
- Determine risk exposure
- Optimize operations and maintenance investment strategy
- Optimize capital investment strategy
- Determine funding strategy
- Build an asset management plan

The simplified model is developed to optimize operation and maintenance operations by generating a risk-based predictive failure model of the infrastructure on an installation. This predictive model is designed to fill the gaps that exist at the lowest level of the organization, enabling the communication of risk to craftsmen who work with the system every day. Taking key points that generate this type of model, the concept is narrowed to the following concepts:

- Inventory
- Condition & Lifecycle
- Levels of Service
- Criticality
- Risk assessment

2.1.1 Inventory

The basis of any effective asset management program revolves around a robust inventory (Federal Real Property Council, 2004; Grigg, 2006; US Environmental Protection Agency, 2008; Vanier, 2001). Inventory is the backbone for condition assessment, project prioritization and sustainment decision support (Grigg, 2010). Ideally, utilities should use records wherever available in order to bolster the accuracy of their asset inventories. Where records are absent, utility-locating techniques should be used to determine end points type and depth if possible. Hao et al notes that locating buried infrastructure in the absence of comprehensive and accurate maps, and moreover determining the condition of this buried infrastructure, is highly problematic (2012).

In a typical US Air Force Civil Engineer squadron, the Requirements and Optimization office primarily handles asset inventory (Headquarters, 2012c). This office is tasked to integrate legacy customer service roles with requirements and optimization. The idea is to merge all data about a particular asset into one location for more effective asset management. Data associated with a particular water infrastructure asset is stored in several different locations. The lack of integrated sustainment management systems in the water utilities segment leads to difficulties in accurately collecting and logging data regarding infrastructure location, performance and criticality. In the absence of reliable data, determining a precise infrastructure inventory of what an agency owns and where it is located is nearly impossible (Harnly, 2012). Adaptation of technology and data practices is critical to the adaption of asset management, as it forms the backbone of the decision support process (Bernstein, Russo, Laquidara-Carr, Buckley, & Logan, 2013).

Establishing an accurate asset register with the appropriate level of detail is one of the more difficult tasks of asset management (US Army Corps of Engineers/IWR, 2013). The EPA recommends collecting the following known information about the system (US Environmental Protection Agency, 2008):

- Condition
- Age
- Service History
- Useful Life

As the asset management process iterates, fidelity will be improved as more useful information is added to the inventory.

2.1.2 Condition Assessment

Knowing the condition of assets is a critical part in determining whether to repair or replace an asset and is an instrumental data point in asset inventory. Hao et al concluded that proactive warning of impending failure may be achieved through the routine assessment of buried infrastructure, leading to reduced operational risk (Hao et al., 2012). Assessing an asset's condition means to evaluate its readiness to perform to its designed level (Grigg, 2006). It is useful in calculating risk to interdependent infrastructure, levels of service or an agency's mission. The execution of condition assessments presents various issues in the industry, summarized by time commitment and relative inaccuracy of data. No method for predicting failures will ever be 100 percent accurate, but agencies can improve the integrity of condition information using the information that already exists among records and personnel within the organization (Grigg, 2006). The National Research Council concluded that agencies that attempt to assess the condition of entire portfolios on a multi-year cycle find the process inefficient and expensive. Furthermore, the council discovered that some agencies are taking a "knowledge-based" approach to condition assessment. The concept tailors the frequency and type of inspection based on the importance of the asset to the system or to other factors that may advance condition degradation. Assessing the condition of underground assets presents a unique challenge, as environments are often varied and assets are out of sight (Costello, Chapman, Rogers, & Metje, 2007). The inability to directly observe condition means that utilities must take various invasive and non-invasive approaches to assess condition or use other methods to determine a relative probability of failure.

Methods that may yield information regarding condition of systems include hydraulic analysis, physical condition assessment and facility condition index methods. Hydraulic analysis measures the hydraulic integrity of the water supplied by the distribution system. Indicators of hydraulic integrity may include pressure, flow, velocity and water loss (Oxenford et al., 2012). Methods of hydraulic measurement would compare design pressure, flow and velocity with actual measured values. Leak detection indicates where water loss occurs along the distribution system, which provides useful information and may help determine problems with water quantity or quality. The analysis of physical condition can be conducted in a destructive or non-destructive manner. Commonly practiced methods for physical condition assessment include direct inspection, sounding, coupon sampling, controlled destructive evaluation, remote field eddy current and acoustics (Grigg, 2006). Finally, the facility condition index value uses the expected lifespan of an asset along with its residual value and compares this value to deferred maintenance. Using the ratio of deferred maintenance to the residual value (based on an asset's expected lifespan) an index is calculated that represents a rough estimate of condition (Vanier, 2001). The facility condition index formula is presented below:

$$FCI = \frac{Deferred\ Maintenance}{Replacement\ Value} \quad (1)$$

Remaining service life models present a useful option for engineers to assess condition based on the estimated remaining service life of an asset. Remaining service life depends on many factors such as test data, in-service data and first hand knowledge (National Research Council, 2012). Remaining service life models consider risk and probability to aid in decision support. Risk tolerance may be high, allowing for extended maintenance effort. One such model that uses the remaining service life of an asset is the Weibull Model. Weibull models have been commonly used in failure forecasting and maintenance planning (Abernethy, 1979).

This presentation of condition assessment methods represents a small snapshot of the available methods in the industry today. There is evidence in the literature that much potential exists in the use of what resources an organization already has to assess the condition of its assets (Grigg, 2006). Through the integration of data, first-hand experience and careful planning, the visibility of condition will render itself over time to provide effective decision support.

2.1.3 Levels of Service

Levels of service (LoS) form the second arm of the EPA's water infrastructure asset management model. Levels of service help set targets for asset management and assist in communicating stakeholders the implications of certain decisions (US Environmental Protection Agency, 2003). Service levels can relate to water quantity, quality, environmental standards or other standards. It is important that organizations cater their service levels to what is important to them. An important point that is prevalent in the literature is that levels of service are often focused on what engineers do and not what is provided to the customer. This creates a misunderstanding of what the asset does and how that translates to what the customer receives. In order to overcome this misunderstanding, a framework is proposed by Duff that takes the activities of an engineering organization such as a water utility and presents it in commonly digestible terms. Figure 1 presents this conceptual illustration.

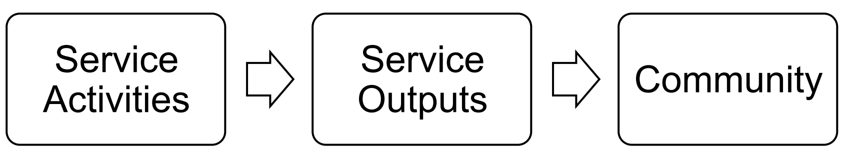


Figure 1 – Service Activities to the Community (Duff, n.d.)

This model is particularly useful in describing how the Air Force uses activity management to link Civil Engineering activities to mission accomplishment. The adaption of this model to Air Force Activity Management is illustrated later.

The EPA articulates the importance of service levels through several questions to be posed to asset managers (US Environmental Protection Agency, 2003).

- What levels of service do my stakeholders and customers demand?
- What do the regulators require?
- What is my actual performance?
- What are the physical capabilities of my assets?

In summary, Levels of Service provide targets for performance and make the process of asset management customer driven. One of the key points that can be drawn from LoS is that it directly affects the level of risk associated with an asset. Some service levels may carry more weight than others, such as regulatory requirements or meeting fire flow demands. The weight in which the LoS holds directly correlates to the level of permissible risk that may be taken with assets that fall within that LoS. Thus, a link is drawn between levels of service and risk management.

2.1.4 Risk and Risk Management

Risk and risk management is highlighted as a key process in asset management (Wijnia, 2010). Addressing risk in infrastructure determines the implications of failure from various points of view. By determining the implications of failure, a relative importance hierarchy among assets is created. Some assets are at a higher risk for failure due to their degraded condition, while some assets are higher risk due to their association with higher or more important service levels. The following questions summarize what risk management seeks to answer (Grigg, 2012):

- What can go wrong?
- What is the likelihood that it would go wrong?
- What are the consequences?

Answers to the first question pertain to what failure modes exist in the system. For a water distribution system, failure modes may include degraded water quantity, quality or a complete outage. Other failure modes include the inability to meet fire flow demands or peak hourly demands. The second question seeks to determine how probable the failure is. In terms of asset management, the probability of failure is determined by an asset's condition. If an asset is in good condition and there are no indicators that failure is imminent or occurring, the associated probability of failure is low. Conversely, if degraded service is recognized in the system and the condition of some assets is poor, the probability of failure is much higher. Finally, the consequence of such failure provides the final portion of risk. If an asset is of poor condition, yielding a high probability of failure, but the consequence of failure is very low, the risk to the organization is also low. Consequence is just as important as probability and in order to provide an accurate risk assessment, both must be present. Thus, the commonly accepted formula is presented in equation 2 (Grussing et al., 2010):

$$Risk = Probability\ x\ Consequence \qquad (2)$$

In order to determine the risks to an organization, The International Standards Organization (ISO) establishes a list of activities to manage risk (2009).

- Defining risk criteria (levels and targets).
- Risk identification and risk level assessment.
- Identifying risks requiring treatment.
- Applying treatment to identified risks.
- Optimizing treatment to identified risks.

The link between LoS and risk is seen in the first step where targets are set that establish the risk criteria. The second activity determines the permissible levels of risk that may be assumed along with what risks exist (e.g. mission failure, degraded service or standards noncompliance). Step three looks at all the risks in step two and identifies those that require attention or priority. In an asset management program, step 3 is the execution of equation 2, where the actual risk is calculated and prioritized based on asset criticality. Step four applies treatment to the risks that have been determined. Risk mitigation can take the form of repair or replacement of assets or simply identifying the lowered levels of service to the organization should action not be taken. Finally the treatment optimization stage seeks to improve upon methods that mitigate risk, be it through improved funding channels for remediation or effective risk communication.

In multilayered organizations with diverse mission portfolios, creating standardized risk criteria can be challenging. Each of the risk management activities speaks to a particular layer within the organization. While each layer works for one another (lower layers work to accomplish the mission of higher layers), the implications for asset failure and the risk associated with failure are varied. The National Research Council (2012) concluded in its 2012 report on Predicting Outcomes from Investments in Maintenance and Repair for Federal Facilities Repair for Federal Facilities that risks can be categorized by the following:

- Risk to federal agencies' missions
- Risk to safe, healthy, and secure workplaces
- Risk to efficient operations
- Risk to achieving public policy objectives

These risks often pertain to different levels within a federal organization. The first and last risks listed above are mostly realized by the organization at the highest level. If the mission of the agency as a whole fails due to an asset within it, the agency itself is accountable, not the lower levels of the agency that may have sustained the failed asset. Similarly, not achieving public policy objectives is a risk that is assumed by the entire organization. This particular risk drives many investment decisions that may not coincide with direct mission impact. An example of this is the funding of capital projects that directly contribute to executive orders to lower energy or water intensity or reduce federal facility footprints. The risks to life, health and safety along with the risk to efficient operations are realized across the entire agency, however the accountability usually falls on lower levels of the organization. An example would be a safety mishap at an Air Force installation caused by a failed asset. The installation itself would be accountable for the failure and its affects, not necessarily the institution as a whole. Similarly, lower levels as well as higher levels of the organization realize risks to efficient operations. At the lower levels, efficiency may mean more work can be done in a smaller window of time, or money can be allocated to sustain more infrastructures. At higher levels of the organization, efficiency may mean streamlining the funding process to lower levels or maximizing the allocation of funding from congress to the best possible project candidates. This variance in risk association and accountability illustrates the conundrum with establishing priority in a multi-layered organization. The consequence of failure is often difficult to balance across many different objectives and sub-agencies that formulate an organization's mission.

2.1.5 Consequence of Failure

Determining the consequence of a failed infrastructure asset is a crucial step in the asset management process. As previously discussed, measuring the consequence of failure seeks to associate an importance or criticality to a particular asset. Difficulty in determining importance and criticality stems from the complex nature of a multi-layered organization. A simple comparison between an Air Force Installation and a public water utility illustrates these complications. Generally speaking, the mission of a water utility is simply to provide water to its customers. Each asset directly supports the mission of providing water. Levels of service would be set in accordance with its mission and would link activities to services. These service levels would likely be associated with quantity, quality and maintaining compliance with standards. The consequence of infrastructure failure might be degraded service levels to the utility's customers. In this example, a direct link is observed between levels of service and failure consequence. Comparing this example with a diverse, multi-layered organization such as the US Air Force demonstrates the issues with establishing failure consequence. The US Air Force uses the Mission Dependency Index (MDI) to determine criticality among assets. Using an asset's category code, a number from 0-100 is obtained that offers a value pertaining to that asset's particular contribution to the mission (Folz & Nichols, 2014). When focusing on water utilities, which perform ancillary support roles to the mission, levels of service do not necessarily directly relate to failure consequence. A sample level of service for a system of assets would be to "provide potable water." This level of service would be prioritized by the mission dependency index, which considers one single mission as its benchmark. Here, a misalignment exists between levels of service and failure consequence. In this case, water utility projects would receive lower priority due to their “distance” from the mission, where assets such as airfields would receive much higher scores because the flying mission directly depends on them.

This example illustrates the complicated nature of determining the consequence of failure in an organization where assets are indirectly supporting the mission. In a water utility, levels of service are inextricably linked to failure consequence, where in more diverse organizations, that link is difficult to make. The problem is most effectively presented using two questions:

- What are the organization’s most important assets?
- Who is asking?

The “who” in this pair of questions refers to the stakeholder that the failure consequence measurement is targeted. The literature revealed that the consequence of failure or importance criteria is determined by one or more of three components listed below.

- Organizational-Driven Importance: How important is the asset to the mission of the organization. An example of this would be the Mission Dependency Index.
- Level of Service Driven Importance: Importance is driven by levels of service, usually dictated by what the customer expects from the system. This is seen in most water utility asset management Programs.
- Interdependent Importance: How important the asset is to the system or facility it supports. System-driven importance is most commonly seen in roof systems. Each roof system may have different criticality due to the varying importance of the facility it supports.

In an organization such as the US Air Force, which on a particular installation has its own water utility, all three of these importance criteria are realized at various levels of the organization but only one is truly recognized as a metric to enhance priority. This results in an overly leveled and overly generalized failure consequence, meaning the true consequence of failure to each stakeholder is not recognized due to its indirect role in supporting the organization.

One solution to the issue of flattened mission dependency was presented by Antelman and Dempsey (2003) in the Naval Facilities Command (NAVFAC) MDI model. This concept uses an asset's interruptability, relocatability, and replacability to determine a quantitative score. This data is collected via interview at organizations tied to an asset. The interview assesses the intra-dependency and interdependency of an asset to the organization or organizations it supports. Intra-dependency is the mission dependency within a particular organization's mission. Interdependency is the mission dependency between organizational missions. The interview consists of four questions; two questions address the intra-dependency and two questions address the interdependency. Figures 2 and 3 show the scoring matrices for this model.

- How long could the "functions" supported by your facility (functional element) be stopped without adverse impact to the mission?
- If your facility was no longer functional, could you continue performing your mission by using another facility, or by setting up temporary facilities?
- How long could the services provided by (named organizational subcomponent) be interrupted before impacting your mission readiness?
- How difficult would it be to replace or replicate the services provided by (named organizational subcomponent) with another provider from any source before impacting the command's mission readiness?

MISSION INTER-DEPENDENCY SCORE					
MD_B		Q3: Interruptability			
		Immediate (24/7)	Brief (min/hrs)	Short (<7days)	Prolonged (>7days)
Q4: Replaceability	Impossible	4.0	3.6	3.2	2.8
	Extremely Difficult	3.4	3.0	2.6	2.2
	Difficult	2.8	2.4	2.0	1.6
	Possible	2.2	1.8	1.4	1.0
MD_B = Mission Dependency Between Commands					

Figure 2 - Antelman-Dempsey Model for Intra-dependency Scoring (2003)

MISSION INTRA-DEPENDENCY SCORE					
MD_W		Q1: Interruptability			
		Immediate (24/7)	Brief (min/hrs)	Short (<7days)	Prolonged (>7days)
Q2: Relocateability	Impossible	4.0	3.6	3.2	2.8
	Extremely Difficult	3.4	3.0	2.6	2.2
	Difficult	2.8	2.4	2.0	1.6
	Possible	2.2	1.8	1.4	1.0
MD_W = Mission Dependency Within a Command's AoR					

Figure 3 - Antelman-Dempsey Model for Inter-dependency Scoring (2003)

The answers to these four questions are entered into the final Antelman-Dempsey MDI equation (3).

$$MDI = 26.54\left[MDI_{IN} + MDI_{BTW,AVG} + 0.1\ln\left(\mathrm{n}\right)\right] - 25.54 \quad (3)$$

Where MDI_{IN} is the MDI within a certain organization (intra-dependency), $MDI_{BTW,AVG}$ is the average MDI between organizations (interdependency) and n is the number of organizations evaluated. This method for determining criticality illustrates a blend between level-of-service driven importance and organizational-driven importance. The NAVFAC model illustrates an asset's criticality to a more localized mission, thus allowing for installations to prioritize their own assets, rather than having a standardized list prepared for them.

Folz and Nichols compared the Air Force and NAVFAC models to private sector models such as the Analytical Hierarchy Process presented by the American Society for Testing and Materials, which is applied by Booz Allen Hamilton (2014).

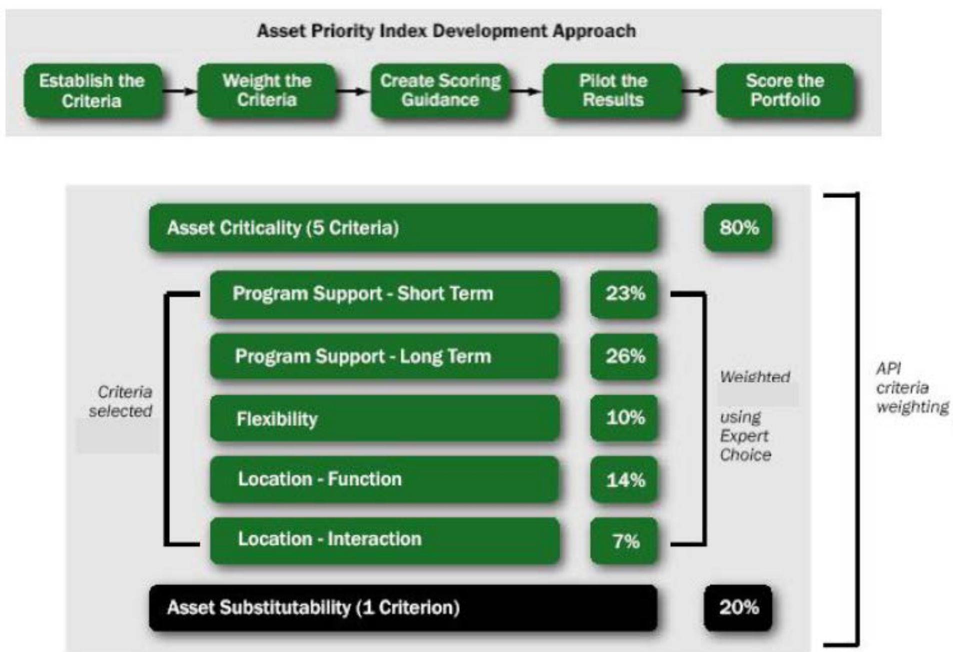


Figure 4 – Booz Allen Hamilton AHP model (Alvarado & Turner, 2007)

They concluded that a blend of methods would more accurately portray risk and foster a better representation of priority (Folz & Nichols, 2014). It can be concluded that the measurement of risk vis-à-vis the consequence of failure depends on the type and which level of the organization or stakeholder the risk pertains to. The analysis of varying levels of the Air Force's organizational structure and their associated risk associations is discussed further in section 2.7.

2.1.6 Industry Best Practices

Asset management has taken a strong foothold in industry where fixed assets provide substantial benefit to the accomplishment of missions. Over time, best practices have formed out of successes and failures and the study of asset management formed its own discipline. Standards and best practices emerged originally in areas that converted publically owned infrastructure into a privatized system. Practices formed to enhance the process and ensure newly privatized utilities capitalized on every possible investment. In Great Britain, the British Standards Institute (BSI) published the Publically Available Standard 55 (PAS-55) which outlines the standards best practices of the asset management discipline (US Army Corps of Engineers/IWR, 2013). The US Army Corps of Engineers acknowledges these best practices in its publication entitled: *Best Practices in Asset Management.* This publication summarizes the practices generated from the Institute of Asset Management, The Infrastructure Management Manual and Innovative Research from Delft University.

For compliance with PAS-55, the BSI requires an asset management policy to drive the process. Furthermore, they require established values to be incorporated with the entire cycle, a robust portfolio of assets and systems, performance and condition monitoring and continual improvement. Figure 5 illustrates the BSI model for asset management.

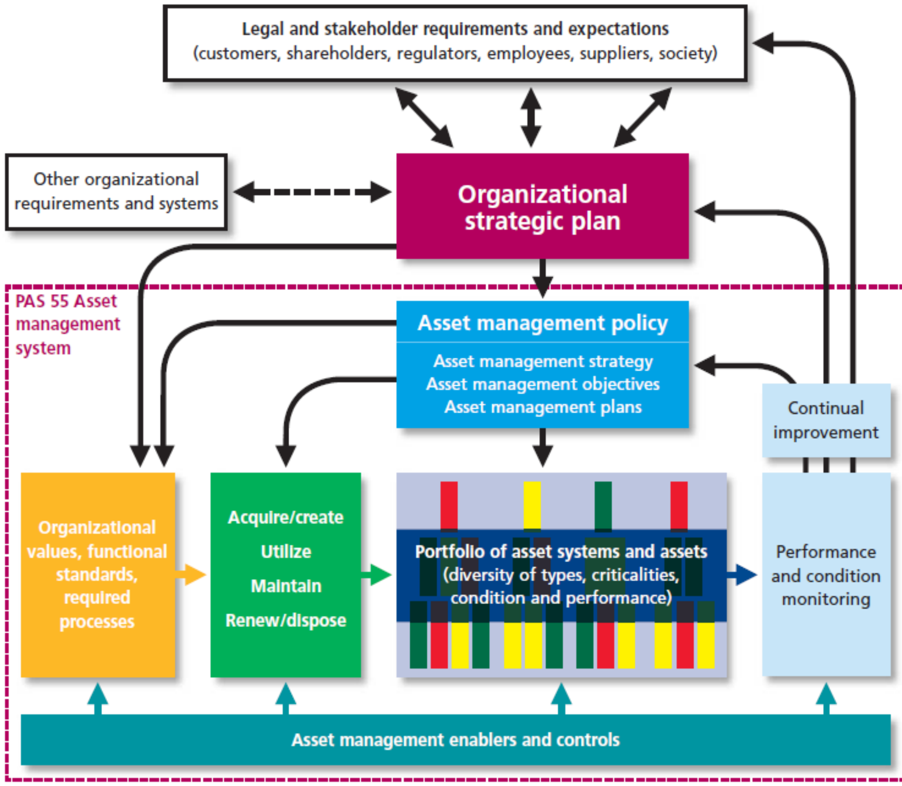


Figure 5 – BSI Model for Asset Management (BSI, 2004)

The United Kingdom-based Institute of Asset Management (IAM) led the development of the BSI's PAS in 2004 (US Army Corps of Engineers/IWR, 2013). The IAM's model is slightly more comprehensive than the BSI model but clearly state the best practices of level of service definition, performance measures, the use of an asset register and hierarchy, condition monitoring approaches and the definition of risk exposure. Of note, the IAM illustrates the use of lifespan-based condition assessment is appropriate for all infrastructure categories. This leads the conclusion that lifecycle-based condition assessment may be viable for organizations with limited resources. The US Army Corps of Engineers integrates these practices and standards into its own asset management model, summarized by budget justification, program management, planning, process repeatability and the link of assets to the nation via condition, mission and risk (US Army Corps of Engineers/IWR, 2013). The link between assets and the nation is illustrated in figure 6.

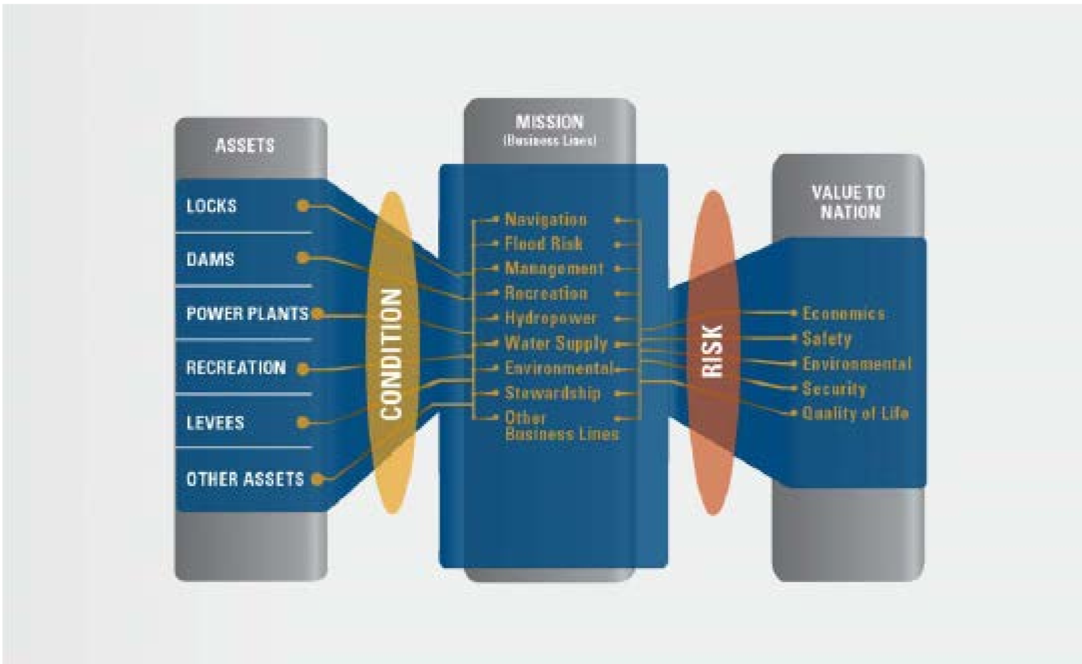


Figure 6 – US Army Corps of Engineers Asset Management Framework (2013)

The Army Corps of Engineers approach may be summarized by the definition of requirements, the development of lifecycle management strategies and the implementation or use of the information.

The National Research Council (2012) published a book that outlined the outcomes from investments in maintenance and repair for federal facilities. Among the council's findings was the importance of effective communication in asset management. Principally in communicating the value of a component or system to a mission, the cost of protecting its value and communicating mission loss, vulnerabilities and interdependencies.

Throughout the literature, several common themes were found. It was found that most organizations stress the importance of the approach. The approach is defined as an attainable, repeatable, planned and continuously improved upon plan. The second major finding was the stress of requirements in the process. Requirements or standards link levels of service to assets (whether the mission or the customer), integrate asset inventories and standardize the process of condition assessment and criticality indexing. The end-use of the information provided by asset management was stressed as important. Best uses for asset management include the formation of maintenance strategies, operational strategies, funding strategies and the basis for communication. Finally, the importance of buy-in was stressed in the literature. Buy-in from all levels of the organization is crucial to garner leadership support as well as lower-level craftsman support to work toward the established goals. The best practices found in the literature form a superb basis for the principles any asset management program should be based upon. The simplified asset management model is formed with these best practices in mind.

2.2 Air Force Asset Management

As previously mentioned, the US Air Force mandates asset management be implemented in its Policy Directive 32-10 (Headquarters, 2010):

> "Employ a sustainable asset management approach [which] integrates requirements to deliver installation support services needed for mission execution, provides the capability to advocate for resources, and then supports

> allocation of the necessary resources to provide, operate, maintain, and protect facilities, infrastructure, and installations required for effective mission support worldwide at their lowest life-cycle cost."

The service recently realigned the career field to enact an asset management mindset in its business processes (Culver, 2007). This realignment involved focus on building an accurate inventory, common levels of service, risk analysis, predictive maintenance capability and resource advocacy. The process of executing this approach is outlined in the Civil Engineer's Programming Plan for the Implementation of the Enterprise-Wide Civil Engineer Transformation. The process is broken into 6 steps (Headquarters, 2012c).

1) Asset visibility, data maintenance, and accountability

   Base: (Tactical & Operational)

   - Maintain accountability of entire asset inventory
   - Define mission priorities for each asset through local leadership & MAJCOM coordination
   - Assist in performing condition assessments

   MAJCOM: (Strategic)

   - Support installation data assessment updates
   - Identify/Advocate for new mission/emerging requirements

   FOA: (Strategic)

   - Standardize inventory process & data models
   - Execute centrally funded facility/infrastructure assessment data collection effort
   - Manage/guide recurring data updates

2) Requirements definition

   Base: (Tactical & Operational)

- Execute AMP/Sub-AMP Duties
- Sustain asset age, performance, condition & cost data to define, validate and score requirements

MAJCOM: (Strategic)

- Validate requirements/opportunities against mission needs

Forward Operating Agency (FOA): (Strategic)

- Apply levels of service to determine requirements and opportunities
- Utilize tools (e.g. SMS) to establish lifecycle requirements across enterprise
- Identify enterprise RE opportunities

3) Planning and investment strategy development
4) Program development-prioritization/allocation/advocacy
5) Project development / programming
6) Execute the program

It is clear that this process is largely driven by the need of higher levels to advocate for sustainment funding. At the core of steps one and two of this model lays the concept of Activity Management. Since realignment, Air Force Civil Engineering has used activity management as a driver towards common levels of service and standardized prioritization (Meeker et al., 2014c).

2.3 Activity Management Plans

The enterprise-wide civil engineer transformation calls for activity management as its engine to provide streamlined service to the various operational missions within the Air Force. Activity management is defined as "The coordinated management of activities of an organization to deliver on its objectives (IPWEA, 2011)." The activity management plan (AMP) is a fundamental tool for asset management and the core of the planning process, as it integrates infrastructure planning with the budgeting process. AMPs are designed to incorporate prioritization with condition and risk management. Similar to Duff's Level of Service model, the concept of activity management takes Civil Engineering activities and correlates them with their contribution to the mission. Figure 7 illustrates this as Duff's model adapted for Air Force Activity Management.

Figure 7 –Duff Model Adapted to Air Force Activity Management

The benefit to using this concept is the realization of effective communication of risk between engineers and leadership. Activity management allows engineers to clearly illustrate the contribution of certain engineering support functions to the accomplishment of the mission. To illustrate the connection, a sample activity might be to "provide water supply." In general, service levels within a water utility based activity would relate to quality, quantity, reliability, responsiveness, environmental acceptability and cost (IPWEA, 2011). Service levels are tracked using performance measures such as number of outages, asset age versus usable life and a direct condition scoring. The resulting values feed into a priority model that calculates priority based on risk. As previously mentioned, service levels act as targets for performance and key performance indicators are annotated within a specific activity. Projects are programmed to ensure levels of service are met and are prioritized in accordance with mission dependency, compliance or overall condition scoring. Figure 8 illustrates a typical Air Force civil engineering activity.

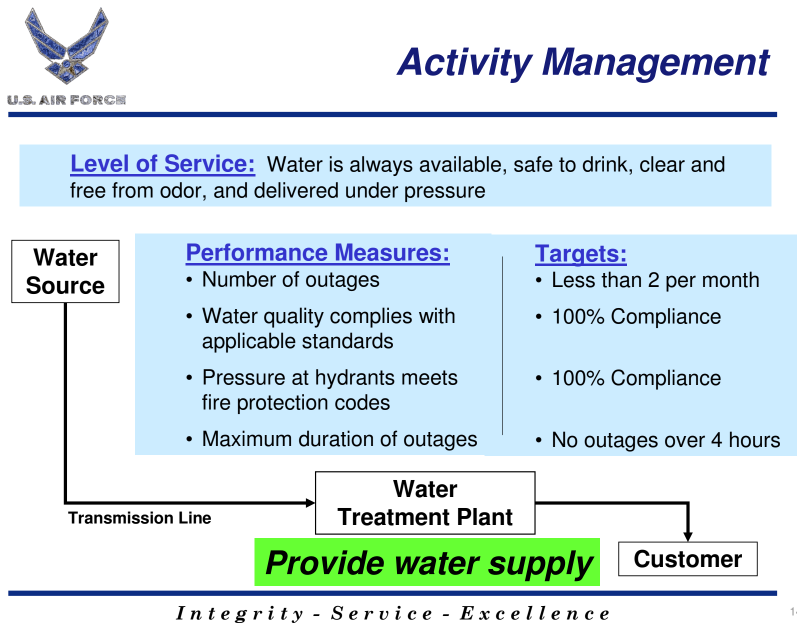


Figure 8 - Typical Air Force Civil Engineering Activity (Moore, 2008)

Standardized mission dependency associated with an asset's category code evens priorities from one infrastructure category or Air Force installation to another. Targets are usually set by either the installation, executive orders or by various other standards established in higher levels of the Air Force. The benefits of this method can be summarized by the ability of the model to level project priority across its entire portfolio. This cross-leveling concept is effective in multifaceted organizations such as those that require resources for both operational components (such as flying) and support components.

Asset and project prioritization is an important part of the AMP construct. Each asset must be given a condition score and relative importance. Once requirements are identified, this real property data outputs helpful information in prioritization. In order to effectively rank projects and assets, a risk-based approach should be implemented (National Research Council, 2012). As discussed in section 2.1.4, risk can be defined by equation 4 and summarized as the product of probability and severity.

$$Risk = Probability\ x\ Consequence \quad (4)$$

Condition assessment forms the probability portion of the equation. The Mission Dependency Index (MDI) defines the severity component of this equation. This index links an asset's performance to mission accomplishment and is elaborated upon in detail in section 2.3.2. The Air Force also uses a project's savings over its lifecycle to contribute to priority (Meeker et al., 2014a). By using a project's savings to investment ratio, this third factor can drive the priority of a project up if the condition score or MDI is low. Equation 5 defines how priority is calculated.

$$Score = PoF + CoF + CS \quad (5)$$

Where PoF is the probability of failure calculated by the condition index, CoF is the consequence of failure as determined by the MDI and CS is cost savings determined by a ratio of investment to savings over the project's lifecycle. Both PoF and CoF have maximum scores of 100 and CS has a maximum score of 10. Using this model, the score of a project will fall between 0 and 210 points.

2.3.1 Air Force Condition Assessment

The Air Force uses Utility Condition Indexing (UCI) in order to determine the condition of its utility assets. The value may be calculated in piecewise form or as a discrete asset.

UCIs for projects that have multiple parts or ancillary components are calculated using a weighted average. Equation 6 illustrates how the weighted UCI is calculated.

$$Weighted\ Avg\ UCI = \frac{(UCI_1 \times Cost_1) + (UCI_2 \times Cost_2) + \cdots}{Total\ Project\ Cost} \quad (6)$$

Each type of water infrastructure system has its own index. The quantity of outages, fire flow demand, remaining life and a direct condition score are used to model the overall health of water utility assets. Direct condition is a subjective rating that has 9 values ranging from totally unsalvageable to nearly brand new. Subjective ratings can be found in Section 3.3. Equation 7 represents the weighted condition indexing methodology for water distribution.

$$UCI_w = 3(outages) + 2(fire\ flow) + 3(remaining\ life) + 2(direct\ condition) \quad (7)$$

For components, devices and storage tanks, the equation is simplified to represent a weighted index consisting of subjective rating and remaining life. If not specific expected life is provided for a component, the condition index is reduced to simply a subjective rating. Equation 8 illustrates this index.

$$UCI_{w-c} = 6(direct\ condition) + 4(remaining\ life) \quad (8)$$

The resultant score for a water utility asset directly correlates to its probability of failure. If a brand-new asset has a UCI score of 100, it has a very low probability of failure. Conversely, old, worn-out assets nearing the end of their service life will have lower UCI scores and thus higher probabilities of failure. For utilities, the probability of failure is calculated by equation 9.

$$PoF = 2(100 - UCI_{tot}) \tag{9}$$

2.3.2 Air Force Asset Criticality

The Mission Dependency Index is a decision support tool for correlating an infrastructure asset's relevant importance to the mission (Grussing et al., 2010). By associating mission-dependency with a quantitative score, an importance factor is obtained for a given project's priority, forming the second portion of equation 2. The Air Force has a fixed reference of indices based on asset category code. At status quo, the consequence of failure is calculated by equation 10.

$$CoF = 0.6 \times MDI + 0.4 \times MAJCOM\_Priority \tag{10}$$

Where MAJCOM_Priority is the score each major functional command (MAJCOM) allots to a certain asset given its specific mission set.

2.3.3 Cost Savings

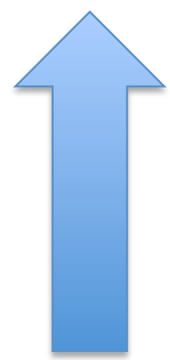
The final component to the Air Force's prioritization model is cost savings. This value is calculated with an equation that represents the ratio of cost savings after the project is complete to project investment. This component of the prioritization is weighted at 10% of the condition index and MDI, representing only a minor part of the formula. Equation 11 displays the equation for savings to investment ratio (SIR).

$$SIR = \frac{Lifecycle\ Savings}{Project\ Cost} \tag{11}$$

2.4 Air Force Activity Management Discussion

Activity management provides a method to communicate risk to mission from failed infrastructure. Through an assessment of condition and criticality, priority is placed upon those assets that need the most resources. Though this method has been recognized as effective at higher levels of Air Force organization, the lower levels have yet to realize its benefits. The complicated and subjective nature of indexing condition leads to inconsistent project scoring between installations. Furthermore, information that leads to condition information is scattered between several different offices in a Civil Engineer Squadron. This makes information difficult to aggregate for engineers directly tied to sustaining the utility system. In the literature, Vanier indicated that conflicting infrastructure management goals makes effective asset management difficult in a diverse organization (Vanier, 2001). His analysis revealed three key conflicting elements that engineers face in asset management; financial versus technical factors, conflicting planning horizons and the issue of network versus project. The balance between financial and technical factors is challenging in the Air Force, where the list of projects to be completed vastly outweighs the resources to fund them. Secondly, the difference in planning horizons is highlighted as another issue pertaining to administrative agendas at different levels of the organization. This could not be more applicable to the Air Force, where the various layers of organization exhibit various planning horizons. These inconsistent planning horizons lead to a disconnect between what the AMP is attempting to accomplish and what is important to lower levels. On a given installation, focus is placed upon what is directly in front of it, meaning they have a short planning horizon. At higher levels of the Air Force, their distance from the operational missions yields a more strategic approach, a longer planning horizon. From each level, the measured risk is the same (using the AMP). At lower levels, however the measured risk does not necessarily align with the realized risk. This misalignment of risk is illustrated in Table 1. Three levels of Air Force organization are presented, with samples for each. In each level of the organization, a planning horizon is presented. Finally, the driver for failure consequence is listed, meaning what is importance of the risk, answering the question posed in Section 2.1.4: What are the consequences of failure?

Table 1 - Illustration of various Air Force Levels and Planning Horizons

Level	Sample Organization	Planning Horizon	Failure Consequence Driver	Organizational Distance From Asset
Strategic	HAF, AFCEC, MAJCOMs	2-7+ years	Accomplishment of AF mission	
Operational	Operational Wing	2-5 years	Accomplishment of base's specific mission	
Tactical	Civil Engineer Squadron Utilities Shop	0-2 years	Level of service provided by system	

In summary, the AMP is a powerful tool, but is designed primarily for strategic requirements forecasting. While forecasting is invaluable to the Air Force, an improved, simplified approach to monitor the health and risk of a utilities infrastructure system at the installation level would improve short-term visibility and reduce outages. The framework exists for an effective installation support tool.

2.5 Literature Review Summary

Asset management has become commonplace in organizations with a diverse portfolio of infrastructure assets. This chapter highlighted some of the definitions for asset management and analyzed some of the important components that appear unanimously across them. Reviewing the literature provided insight into how the concept of risk, probability and consequence are inextricably linked in asset management. Best practices were identified and will be used to generate the Simplified Asset Management Model. The evaluation and discussion of risk pertaining to infrastructure is important, because risk-based methods are not only useful in resource-scarce organizations (National Research Council, 2012), they are required by Air Force standards (Headquarters, 2012c). After the analysis of the important components that formulate most corporate asset management models, a thorough review of the Air Force's own asset management model was conducted. This was done to reveal deficiencies and areas where the model may be improved or adapted differently. The AMP is a hugely useful tool for communicating risk across a broad portfolio of assets in a hugely diverse organization, but several limitations exist in its execution and application to lower levels of the organization. The varying degrees of separation between the lowest and highest levels of the Air Force mean that risk is not effectively communicated at lower levels or to different stakeholders on and Air Force installation. This provides the impetus to a simplified model that not only simplifies the founding processes of asset management, but also communicates risk to other stakeholders on an installation. The realization of a simplified model will benefit engineers at lower levels of the organization and be readily adaptable to the Air Force's already robust asset management program.

3.0 Model Development

Simplifying the Air Force's asset management model will focus on the first and second stages of their process, namely the stages of asset visibility and requirements definition. The model is not intended to replace the AMP or any part of the Air Force's asset management model, it is developed to make the process simpler for utilities engineers to harvest the data they already have to build a risk model catered to their level of management and planning horizon. Simplifying the preexisting model not only makes the asset management process easier to accomplish, it enhances the engineer's ability to schedule recurring work, preventative maintenance and build better response plans to outages. The model uses the AMP as a framework for how to build the model, and industry best practices are used recognizing the various limitations that exist on an Air Force installation. The following can summarize the goals of the simplified model:

1) Simplify the asset management process at the Air Force installation level

Make it easy for installation engineers and utilities shop foremen to develop a risk-based predictive model that uses the building blocks of the AMP to drive maintenance decisions, effectively harvest manpower, lower operating costs and communicate risk to mission, levels of service and the organization should various infrastructure fail. Realizing that every installation is at different stages in inventory accuracy and condition assessment, implement gap analysis tools to determine accuracy and resolution targets.

2) Reduce or eliminate unknowns in the system

Reducing the amount of unknown parameters in the utility system will lower the risk to the failure of unknown assets. Ideally, aggregating all available data about buried assets will uncover some relevant information to be used for condition assessment. Where data is unavailable, implement systematic processes to deduce information that can be used in the asset register.

3) Lower resolution of assets and systems to manageable levels

One of the greatest problems facing engineers is the task of indexing thousands of assets on an installation, including many hundred linear miles of pipeline. The concept of lowering resolution aggregates assets into zones. Risk is then calculated using an average lifespan and importance within that zone. Once risk among zones is defined, resolution may be increased by analyzing smaller zones or individual assets.

4) Design the model around existing asset management framework

Use the results of condition assessment and criticality to define models that are useful for communicating risk to installation leadership and may be used as a basis for programmers to program projects for longer-term sustainment or modernization.

5) Use best management practices to implement model

Using industry best management practices will provide proven steps to better-manage the utilities infrastructure. As stated in literature review, the manner in which asset management is conducted is as important as the data that formulates it.

3.1 SAMM Framework

Like most asset management models, the framework for SAMM is built on a data-centric inventory. The decision support that SAMM provides is drawn from an integrated data register. This register includes information pertaining to physical attributes, condition information and criticality from various perspectives. The information obtained from condition and criticality is fed into an equation that outputs a value pertaining to risk. Using various perspectives for criticality broadens the scope of the effects of assuming risk. Associating incomplete and completed work orders provides additional decision support and feedback illustrating where work is more frequently done in the system. The main goal of the model is to use information that already exists along with knowledge-based assessments to more effectively manage and utilize data. The first iteration of the model groups together collocated assets into zones. Condition and criticality are calculated for the zone as a whole. By aggregating the condition and criticality within a group of assets a rough approximation of risk may be calculated without collecting large amounts of data. Over time, the resolution of the risk model is increased through the calculation of risk within each zone. Below lists the core contents of the model.

Inventory – A comprehensive inventory audit of water system assets will be conducted using a systematic approach to gather information from as-built drawings, GIS maps and other relevant information that will lead to a more precise utility inventory. Collected information is used to reduce the amount of unknown attributes within the water system and feed information to calculate condition.

Condition – Condition assessment will determine which assets are at higher risk for failure than others. Non-invasive risk-based techniques will be used to minimize impact to the mission and make the most efficient use of existing data and manpower resources.

Importance – A criticality model is generated to present risk from the perspective of several different stakeholders relevant to the water system. Using components of Air Force mission dependency, associative service importance and finally internal criticality (importance within the utility system), the overall consequence of failure will change, leading to variances in risk levels to the Air Force mission, the installation's specific mission or the level of service provided by the utility system.

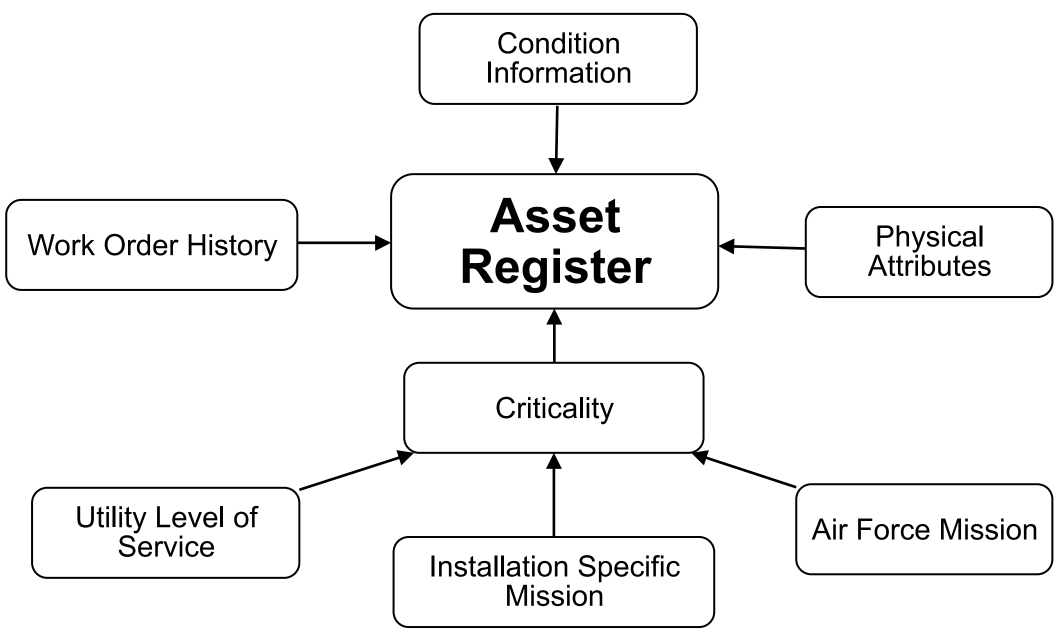


Figure 9 - SAMM Conceptual Model

3.2 Modified Risk Equation and Matrix

The results of the model are based on the Activity Management Plan's risk equation used to prioritize decisions at headquarters level. By instating a model similar to those used at higher levels, prioritization becomes simpler and more standardized across the organization. The equation obtains condition and criticality information that already exists, but may be scattered across several offices or databases or is missing. Consequence of failure will be determined in relation the Air Force mission (using the MDI), the installation's mission and the relative importance of the asset to the service provided by water distribution system. The level of risk is a function of condition and criticality and is first calculated for a zone of collocated water assets. There are three layers to the risk equation, each pertaining to the different consequences of failure. The formula for the risk equation is listed in general form below.

$$Risk_{1,2,3} = f(PoF, CoF_{1,2,3}) \quad (12)$$

Where risk is defined as a function of probability of failure and consequence of failure. The subscripts 1, 2 and 3 are used to represent the various consequences of failure to the Air Force mission, an installation's specific mission and the water system itself. A commonly used method for determining risk, which is used by the US Army and the US Air Force, is a risk matrix (Antelman et al., 2003; Folz & Nichols, 2014). The matrix follows the best practices for Operational Risk Management and charts the values of probability and consequence to form the final risk value (Headquarters USAF, 2013). The results of the risk equation are populated onto the risk chart in figure 10.

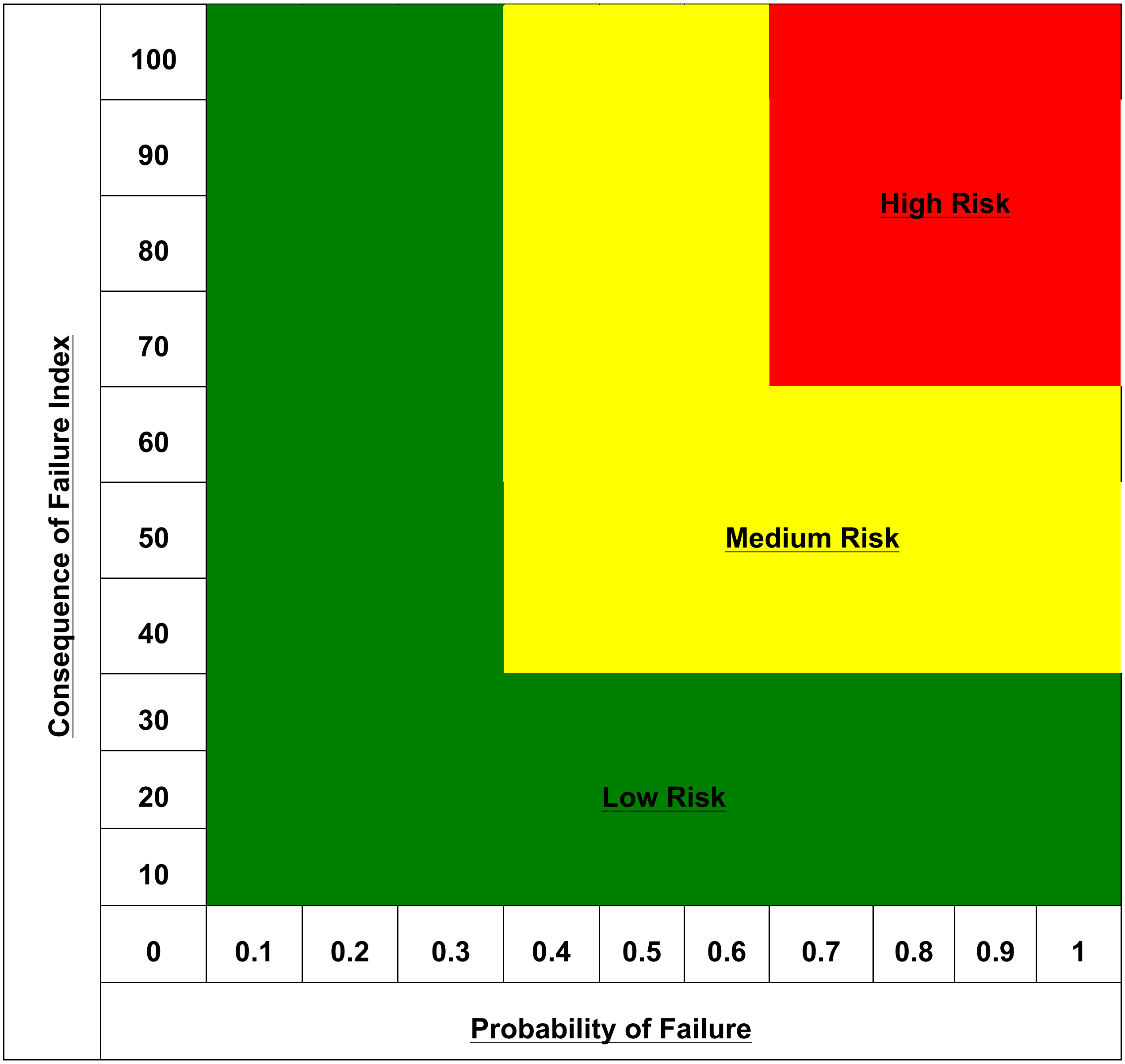


Figure 10 – Modified Risk Table

The form for the final risk equation will take the product of the probability of failure and the various consequences of failure to communicate the various risks associated with the asset. The final value of this risk is a number from 0-100. Equation 13 presents the final form for the SAMM risk equation.

$$Risk_n = PoF \times CoF_n \qquad (13)$$

Where n represents the stakeholder or failure consequence involved in determining risk. This may be the level of service-related consequence, specific mission failure consequence or total mission failure consequence.

3.3 Probability of Failure

Probability of failure is designed to determine the probability an asset will fail based upon certain parameters such as condition and age. As mentioned earlier, condition assessment seeks to measure an asset's readiness to perform its designated task (Grigg, 2006). Simplified condition assessments may be used in organizations with limited resources to provide a notional probability of failure. Among the several methods the NRC notes for condition assessments, the use of the service life models presents the most useful tool for adapting the information that an organization already has to obtain a probability of failure (National Research Council, 2012). Of note, the use of the Weibull model presents an opportunity to adapt a tool that is already in use in other sustainment management systems. The BUILDER SMS uses the Weibull distribution to predict the component-section condition index in facilities (Marrano, 2006). The adaptation of such a distribution function would simplify the process for engineers to determine a probability of failure using only a condition score and the known age of the asset. The goal of the simplified model is to simplify the condition assessment process using pre-existing data and knowledge of the system retained by utility engineers to obtain a probability that may be measured across the utilities portfolio evenly. Using the pre-existing data of installation date, a table of expected lifespans for various types of materials and a subjective condition rating, a notional probability of failure may be obtained. Thus, the simplified probability of failure can be conceptualized by equation 14.

$$PoF = f(\overline{CD}, \overline{L}) \tag{14}$$

Where CD is a subjective condition degradation score and L is the mean ratio of age over expected life. For the probability function, advanced degradation and age should both yield higher probabilities of failure but should never exceed a probability of 1. Applying both variables to a Weibull Cumulative Distribution Function outputs a notional probability for a given condition degradation and life ratio. This formula allows engineers to estimate the approximate probability of failure is for a given condition and age, or simply review the adjusted lifecycle of an already-degraded asset. The general-form Weibull formula is presented in equation 15.

$$f(x) = 1 - e^{\left(-\frac{x}{\lambda}\right)^{k}} \tag{15}$$

Where λ is the scaling parameter and k is the shape parameter. For the purposes of this analysis, the shape parameter is set to 5 to shape the function to a curve that most appropriately portrays assets failure probability over time. The Weibull condition degradation model uses the Air Force's AMP condition index score as a baseline to formulate a condition degradation coefficient. This coefficient represents the scaling parameter that alters the distribution. As condition degrades, the probability of failure increases with a given age. Equation 16 displays the simplified formula for calculating the probability of failure, which is used in the database along with lifecycle tables to generate the notional probability of failure. Table 2 illustrates the AMP condition rating structure and the improved condition degradation coefficients. Figure 11 displays the distribution for all condition ratings in table 2.

$$PoF = 1 - e^{\left(-\frac{L}{CD}\right)^{k}} \tag{16}$$

Table 2 - Condition assessment rating structure

Rating	**Direct Condition Rating**	**Condition Score**	**Improved CD**
Red (-)	Overall component-section on degradation is total. Few, if any subcomponents salvageable.	5.5	0.01
Red	Severe serviceability or reliability reduction to the component such that it is barely able to perform. Most subcomponents are severely degraded.	6.0	0.1
Red (+)	Significant serviceability or reliability reduction in component-section or "sample." A majority of subcomponents are severely degraded and others may have varying degrees of degradation.	6.5	0.3
Amber (-)	Component-section or sample has significant serviceability or reliability loss. Most subcomponents may suffer from moderate degradation or a few major (critical) subcomponents may suffer from severe degradation.	7.0	0.5
Amber	Component-section or sample serviceability or reliability is definitely impaired. Some but not a majority. Major (critical) subcomponents may suffer from moderate deterioration with perhaps many minor (non-critical) subcomponents suffering from severe deterioration	7.5	0.7
Amber (+)	Component-section or sample serviceability or reliability is degraded but adequate. A very few major (critical) subcomponents may suffer from moderate deterioration with perhaps a few minor (non-critical) subcomponents suffering from severe deterioration	8.0	0.8
Green (-)	Slight or no serviceability or reliability reduction overall to the component. Some, but not all, minor (non-critical) subcomponents may suffer from minor degradation or more than one major (critical) subcomponent may suffer from slight degradation	8.5	0.9
Green	No component section or sample serviceability or reliability reduction. Some, but not all, minor (non-critical) subcomponents may suffer from slight degradation or few major (critical) subcomponents may suffer from slight degradation. Component section greater than one year old.	9.0	1
Green (+)	Entire component free of observable or known distress. Component section is less than one year old.	9.5	1.25

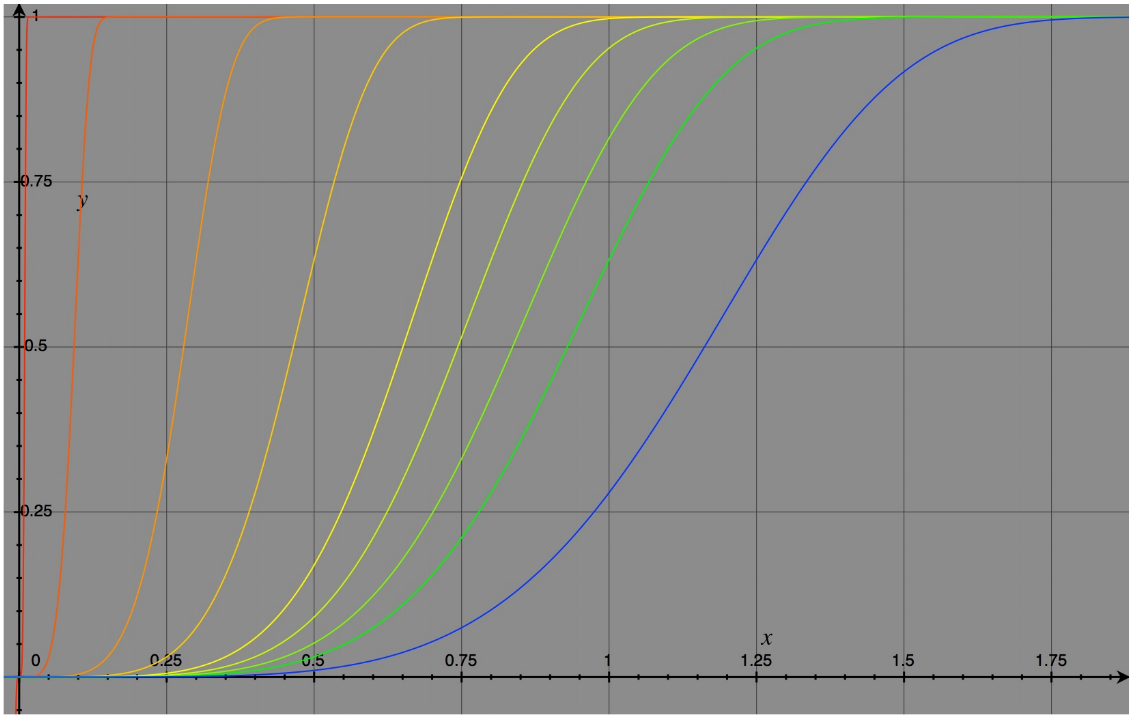


Figure 11 – Weibull distribution for all condition degradation coefficients

3.4 Consequence of Failure

The consequence of failure forms the severity component to the risk formula and associates a criticality to the asset (Grigg, 2012). Simplifying the severity portion of risk is challenging, as there is no empirical method to determine the importance of an asset or group of assets. Much research has been conducted to enact solutions that more effectively align criticality to missions or levels of service. In multilayered organizations such as the Air Force, the communication of risk is difficult at different levels when all are using a strategic model for criticality. At status quo, the Air Force assigns an MDI based upon an asset's category code (type). This metric is designed to evaluate what "an asset brings to the performance of the mission as determined by the governing agency (Federal Real Property Council, 2004)." This method makes no considerations for an installation's specific mission. Assets and projects are not prioritized in accordance with installation-specific risk, but the risk associated with the highest level of mission accomplishment. It can be concluded that the use of the MDI represents the communication of strategic risk, which is effective in the prioritization of projects across a wide portfolio of asset types and missions but is less effective in tactical decision support. The simplified model seeks to communicate risk at lower organizational levels and adapt a "bottom-up" approach to the communication of risk. As presented in the literature review, Table 3 represents the various organizational levels of the Air Force and what drives the consequence of failure for that particular level. Failure consequence is hierarchal, that is from the lowest level the driver of failure consequence supports the next level of the mission. As the levels increase to the strategic level, the failure consequence must be flattened across many infrastructure categories and a variety of other support functions. Thus, the paradox of establishing failure consequence is illustrated and illustrates the impetus to communicating various levels of risk. Table 3 also presents the tools that are formed at lower levels to communicate risk.

Table 3 - Organizational Levels of the US Air Force and Drivers of Failure Consequence

Level	**Sample Organization**	**Planning Horizon**	**Failure Consequence Driver**	**CoF Tool**
Strategic	HAF, AFCEC, MAJCOMs	2-7+ years	Accomplishment of **AF mission**	Mission Dependency Index
Operational	Operational Wing	2-5 years	Accomplishment of **base's specific mission**	Service Association Index
Tactical	Civil Engineer Squadron, Utilities Shop	0-2 years	**Level of service** provided by system	System Criticality Index

In order to exact a standardized risk communication tool, all values that communicate consequence of failure must be normalized to the same interval. For the MDI, the adjudicated value is renormalized to redistribute the range of possible values from 1-100. Currently MDI values range from 25 to 99, redistributing them will allow an even comparison of risk compared to other criticality values. This data is manipulated using equation 17.

$$MDIn = 1.338 * MDI - 32.446 \qquad (17)$$

The second and third components use facility criticality association and importance within the system to communicate risk to different layers.

3.4.1 Service Association Index

The Service Association Index (SAI) is designed to communicate risk to an installation's leadership using the pre-existing critical infrastructure program (CIP). The CIP portrays the installation's most important facilities and other infrastructure to the accomplishment of their specific mission (Office of Management and Budget, 2004). Using an association to the critical facilities on the installation will benefit the communication of risk to critical facilities should water infrastructure assets fail. Association should be done using corporate knowledge of the system and should take into account all assets that contribute to delivery of water to that particular facility. With assets that support more than one facility on the critical facilities list, the highest value calculated will be used to form the SAI for that particular asset. In example, a water main may be the sole source of potable water on and installation and services all of the facilities. This water main will be score a very high service association index due to its support of critical facilities, but branches from that water main may receive lower scores since they might service lower priority facilities. In determining values for SAI, the general form function listed in equation 18 correlates an importance based on facility "x" of "n" facilities in the CIP plan.

$$SAI = \frac{-99(x-n)}{n-1} + 1 \quad (18)$$

This tool not only assists in the communication of risk to installation leadership, it also forms a model of what consists of the installation's most important utility assets. Furthermore, it can be beneficial in the portrayal of implications to the mission of failed water assets.

3.4.2 System Criticality Index

The communication of risk at the lowest level of the organization benefits the decisions made by utilities engineers. Engineers at the tactical level are presented with the challenge of where to focus preventative maintenance efforts and send craftsmen to repair a myriad of water assets, thus the tool must align with the levels of service they are striving to meet every day. The system criticality index seeks to identify which assets contribute most to the levels of service provided by the water system. The organization of lowest tier in the system may be simplified to that of a public or private water utility, where levels of service are largely customer and revenue focused and importance may be associated in a hierarchal sense, where the most important water assets are those of higher diameter, serving more customers than lesser-important assets such as water connections or lower-diameter water mains. In order to determine importance among assets at this level, an AHP determines interruptability, redundancy, relationship to infrastructure and level of customer support to communicate risk to degraded levels of service (Sterling et al., 2009). Through the systematic prioritization of level-of-service prioritized assets, the communication of risk may be conducted at the final level, thus completing the enterprise-wide risk communication tool. Table 4 illustrates the AHP questionnaire with equation 19 illustrating how the answers to those questions are turned into an SCI.

Table 4 – System Criticality Index Analytical Hierarchy Process

Criteria	**Questions**	**Answers**
1. Interruptability	How significant is the impact to the delivery of water if the asset fails?	0 – Not Significant 1 – Slightly Significant 2 – Significant 3 – Very Significant
2. Redundancy	How many redundancies exist that provide the same or similar levels of service to customers?	0 – More than 3 1 – 2 2 – 1 3 – No redundancies
3. Relationship to Infrastructure	To what extent does the asset support the distribution infrastructure	0 – Very Little or not at all 1 – Minor support 2 – Major Role 3 – Critical Role
4. Customer Satisfaction Support	To what extent does the asset enable better customer interface or satisfaction?	0 – Very low likelihood of complaint 1 – Low likelihood of complaint 2 – High Likelihood of complaint 3 – Very high likelihood of complaint

$$SCI = 8.25(q1 + q2 + q3 + q4) + 1 \qquad (19)$$

3.5 Work Order Association

Work orders are important data points for asset management at several levels of the organization. Work orders not only tie in maintenance investments into the decision process of repair or replacement but also provide other valuable system-level information for engineers and installation leaders. From the utilities engineer perspective, populating a map with complete and non-complete work orders aids in the communication of weak or failing points in the system and allows schedulers to more effectively plan preventative maintenance efforts. Associating location to work orders enables engineers to more readily integrate multi-disciplinary renewal projects. If a water main break work order exists under a road scheduled for renewal, these two projects may be combined into one project that will yield benefit for both the roadways and the water system. At the more operational (installation leadership) level, population of work orders on a map illustrates to leaders where they need to advocate for sustainment funding. Additional operational benefit exists in the illustration of interdependencies between the operational mission and infrastructure. An example of this would be the population of water main break work orders on a map that exist under high priority access roads. This communication tool would benefit the operational mission in the long-term by effectively communicating how closely linked infrastructure is to the successful accomplishment of the mission. Finally from a strategic level, the frequency of work orders and overall backlog of work orders would aid in resource allocation for a particular installation. If the installation has a long backlog of incomplete work orders, this communicates to the higher levels of the organization one of several messages:

- There are manpower limitations on the installation
- The work order review process does not effectively eliminate unnecessary work orders
- Additional resources must be allocated to that installation to reduce the amount of work orders on backlog

Possible methods of implementation for this process include work order geo-tagging and manual GPS entry of backlogged work orders. The most integrated approach to populating maps with work orders would be to incorporate a required field of specific location on the work order entry process. By making the step of work order location compulsory on work orders, facility managers and operations planners would enter geographic information in the first step of the work order review process. Another approach to incorporating geographical information in the work order process takes a retroactive approach to the process. Beginning with the backlog of work orders, a utility systems craftsman would manually link work orders to GPS coordinates using equipment that would feed the information to the register.

3.6 Risk Model Summary

The basis of the risk model is to provide additional layers of decision support information that yield benefit to more layers of the organization. The tool uses the core concepts of asset management to yield risk-based information to the strategic, operational and tactical levels of the multi-layered Air Force. Using a standardized probability of failure across levels ensures that condition is fairly measured at all three levels. For establishing criticality, the consequence of failure is realigned and normalized to meet the goals of the strategic, operational and tactical levels of the Air Force. By using pre-existing tools and pre-existing information the model can provide comprehensive support to the decisions made by engineers, installation planners, installation leadership and higher headquarters decision makers. An added benefit of the development of this model is the realization of the misalignment of risk communication in an organization such as the Air Force. The layered nature of the strategic, operational and tactical visions, missions and goals point to using a standardized criticality index across the board. In theory since all layers of the organization work for the highest level, criticality should be measured in accordance with strategic vision. In reality, the comparison of strategic priorities and more operational priorities can illustrate to leadership at all levels where work should be focused and optimized to enhance support to the mission and levels of service at different planning horizons. The next logical steps of model development include conceptual illustration of the data structure and the manner in which the model should be built. Determining values for this model can be a difficult task to accomplish for thousands of assets, thus the manner in which the model is implemented is just as important as the information that is collected to communicate risk.

4.0 Data Model Development

This chapter discusses the development of a data model that uses the information obtained in chapter 3 and effectively portrays it to various levels. This represents the development of a physical model of infrastructure risk that links graphical features to values calculated from a database. The goals of this data model can be summarized by the following:

- Present a structure that outlines how data is collected and manipulated to portray risk
- Define user inputs and application outputs
- Define layers of the data model
- Define sources of data and structure of database
- Provide user-focused physical GIS model

The model is developed for use in a Geographic Information System (GIS). GIS presents the logical platform to manipulate data due to its prevalence in today's evolving asset management community and universal state of adoption in the Air Force. GIS is ideal due to its robust capability to use spatial relationships as a way to manage, coordinate and analyze data (Baird, 2011). In the Air Force, the use of GIS is through GeoBASE, a program that integrates the capabilities of war fighting, operational support and infrastructure (Tinsley, 2005). "GeoBASE has become increasingly important as an operational and strategic decision-making tool (Tinsley, 2005)." Thus, the platform is set for the development of the data model.

4.1 Data Model Definitions

A GIS data model is defined as the process to describing and representing parts of the real world in a computer system (Maguire & Grisé, 2001). Maguire and Grisé developed a conceptual framework for the development of a GIS data model in their 2001 exposé on data model development. It is important to note that interconnection from the real world to people is defined by the integrity and strength of the GIS data model and the operational manipulation of geospatial information. Figure 12 illustrates this concept.

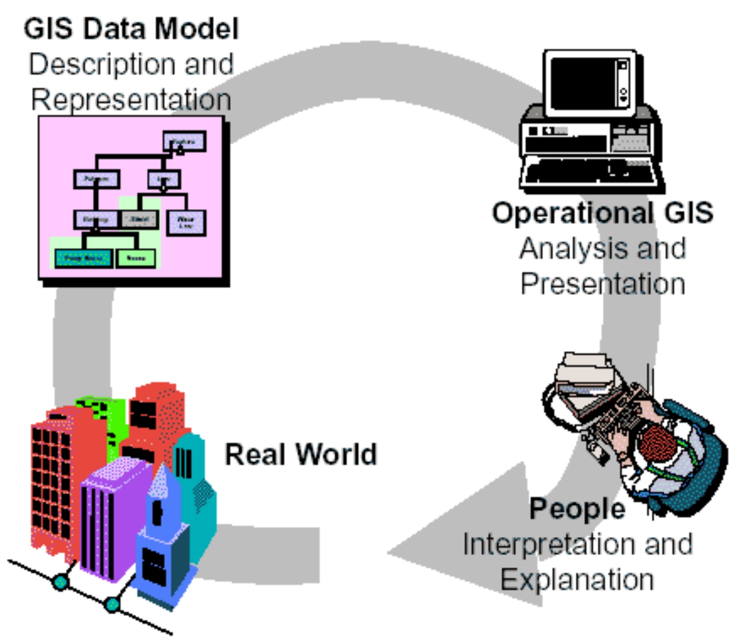


Figure 12 – Data Models in the portrayal of real world information (Maguire & Grisé, 2001)

The data modeling process established by the same authors takes reality, as defined in this case by the assets that form a water distribution system, forms a conceptual model that illustrates the basis of what the end state is. The next step of conducting a logical model turns the conceptual model into relationships or formulae that result in the end-state but without any application architecture. These stages of conceptual and logical model definition were covered in chapters 2 and 3, literature review and model development. The physical model may be oriented towards user or developer, and consists of the necessary building blocks to formulate a geospatial representation of the real world. Figure 13 presents the data modeling process from Maguire and Grisé.

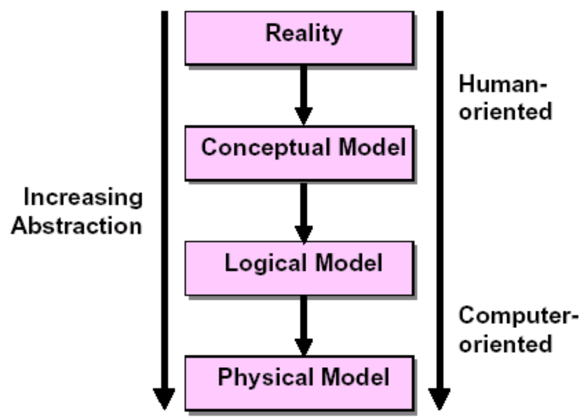


Figure 13 – Maguire & Grisé GIS Data Modeling Process (Maguire & Grisé, 2001)

Maguire and Grisé continue to define a user-focused data model as the description of the system independent of specific details of the particular application (2001). Thus, the user-focused physical model is based on definition of inputs and outputs, establishment of data layers and a graphical representation of the model concept. In this context, users are defined as either cartographers responsible for outputting maps, engineers responsible for data input or any other relevant user of the module.

4.1.1 Application Definitions

It is first prudent to define what inputs and outputs are generally desired of the physical data model. User inputs are defined in this context as the inputs to the application from the user that are required to obtain an output from the program. User inputs and application outputs are listed and briefly described below:

User data inputs: Inputs that engineers and cartographers must input into the application to obtain values for criticality

- Service Association Information: Defined as which assets directly support facilities on the critical infrastructure program priority list. Analysis must be conducted by the utilities engineer and cartographer to ensure these inputs are accurate and represent which are the most important assets for critical facilities.

- System Criticality Index: Utilities engineer answers 4 questions pertaining to system-driven importance.

- Condition score: Utilities engineer subjectively scores the condition of the asset using table 2.

- Optional manual-entry work order field: Fields to populate work order points on the map, must include information on work order number, type, category, priority and whether or not the work order was completed.

Application-based user inputs: Inputs the users of the application will enter to obtain outputs from the module

- Level of risk calculated: User must define which level of risk to be calculated by the module (strategic, operational, tactical).

Module Outputs: Listed below are the desired outputs of the module resulting from user input.

- Risk Value: Color coordinated value of risk (green, amber, red) pertaining to a specified organizational level (level of risk input). Risks calculated at different levels are color coordinated differently to portray the variance in risk between organizational levels.
- Work order information: The module outputs a point (represented as a color coded dot) on the map that contains information such as work order location, type, urgency and a brief description. This information should be readily available as a hover-over-activated text box.

4.2 Application Structure

The SAMM module is constructed of various data layers that all perform different functions to achieve the goal of a simple interface to calculate risk. Listed below are the layers incorporated in the physical data model and definitions for each.

Client layer: The client layer consists of a GIS module user interface that has prompts users for inputs that will affect the calculation of risk. The client layer consists of two panes for different user types. For the user interested in obtaining information pertaining to risk (i.e.-those who wish to see the results of the module), the pane consists of a prompt for which levels of risk should be calculated. The other pane is designed for entry to the database layer, to be used by the engineer. This layer permits the input of all user data inputs described above.

Application Layer: The application layer obtains attributes from a unified database and calculates risk values; this is where the components of risk are calculated (PoF, CoF, Risk) and determines criteria for low, medium and high-risk assets. This layer must also query work order location information from the work order database in stored in another system. Finally, this layer must contain the lookup tables and query scripts for normalizing criticality values such as the MDI, the critical facilities list and the expected lifespan of a material.

Database layer: This layer is the core of the SAMM process as it contains all of the information necessary to calculate risk. The contents of this database are explained in detail below.

4.3 Database structure

The successful collection and manipulation of data drives the success of water utilities (Oxenford et al., 2012). The goal of the database is to aggregate standardized and relevant information that may be used by the SAMM module to calculate risk. The collection of this information is explained further in section 4.3. Relevant data is information that can be directly used to generate values for condition and criticality. The application layer will use this database to generate a geospatial representation of risk. The core of the database contents revolves around information that should be readily available to those close to the system. The following is obtained for assets and input into the database.

- Real Property Unique Identifier
- Description
- Type
- Material
- Install year

- Status (active/abandoned)
- Diameter
- Length
- Depth
- Coordinates

4.4 Sources of Data

Data already exists for much of the system but is spread across multiple platforms, media and offices within a Civil Engineer Squadron. The data model integrates data from all possible existing sources along with new information garnered from condition assessment and failure consequence analysis. Figure 14 illustrates the diversity of data associated with assets.

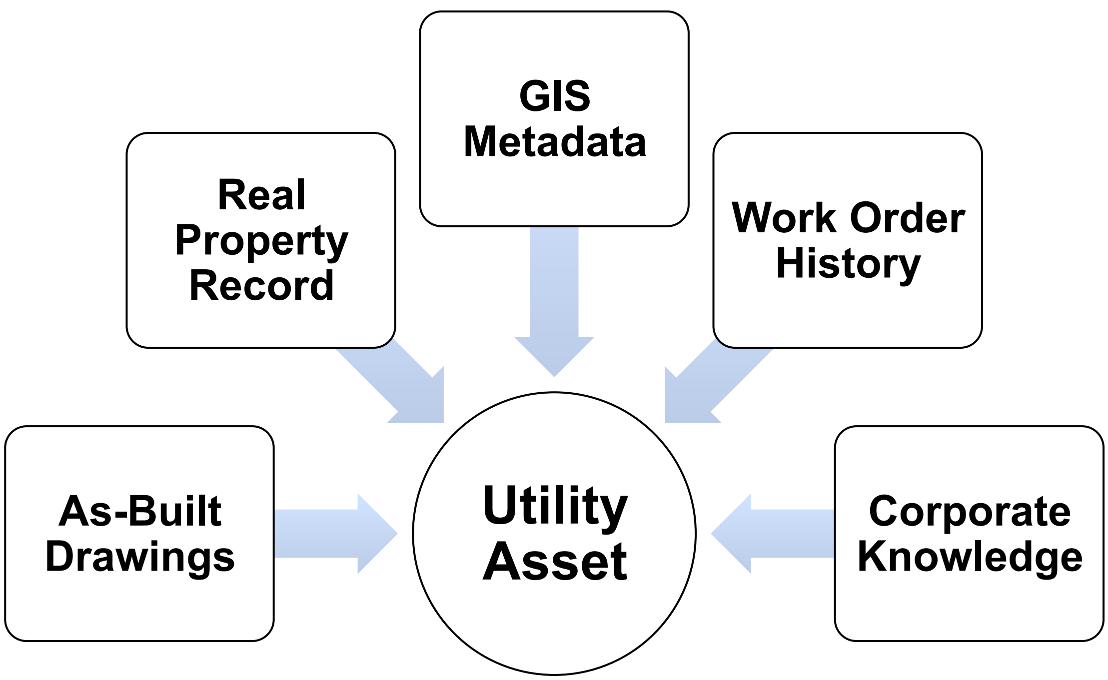


Figure 14 – Sources of Asset Data

4.5 User-Focused Data Model Illustration

The user-focused data model illustrates what the SAMM module accomplishes. Using pre-existing information, information is fed into a database. The application layer calculates risk based on the values stored in the database. The client layer allows users to generate values for risk based on selected operational level, or fill gaps that may exist in the database. By integrating all possible data points, the effective communication of risk is achieved.

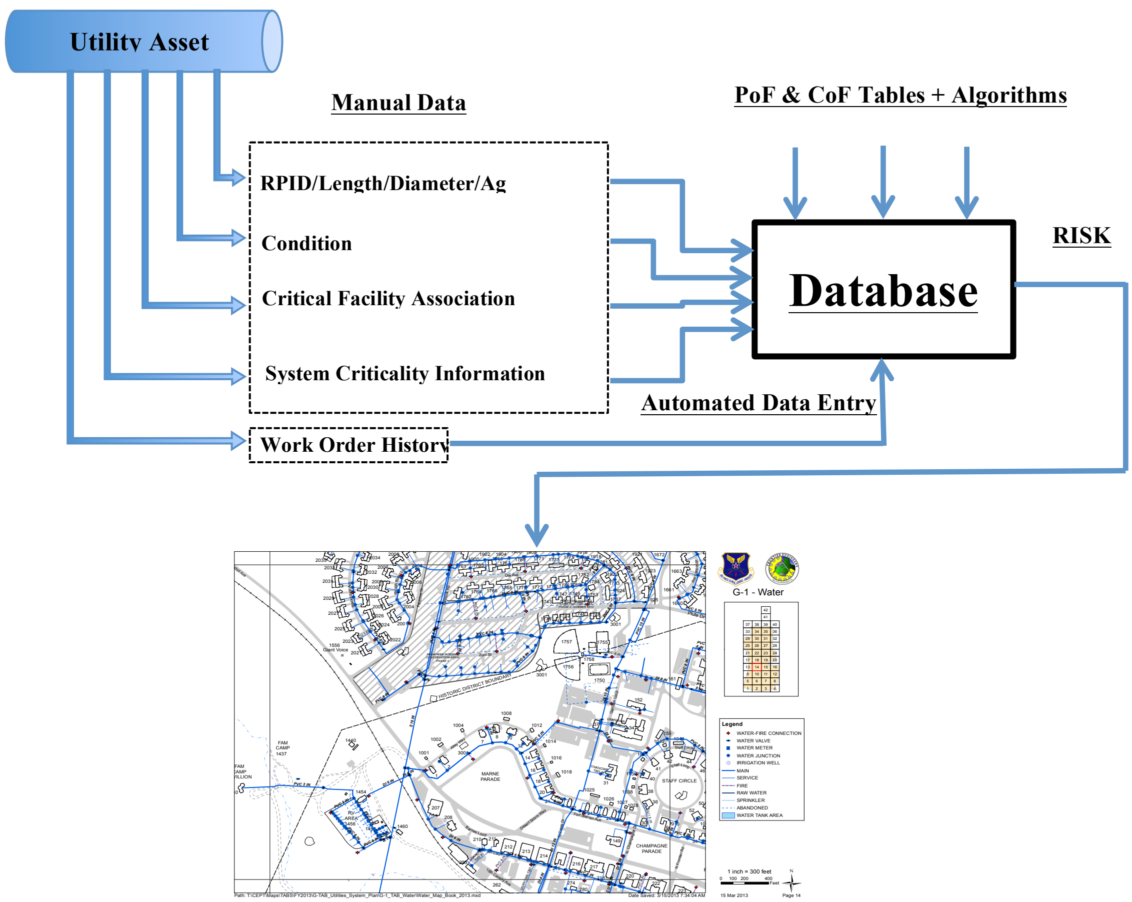


Figure 15 – Conceptual Physical Data Model

4.6 Data Model Summary

In summary, the data model is intended to illustrate how to use and process the information collected by SAMM. The development of this data model into a user-friendly GIS based application would enable the use by craftsmen, engineers and leaders to communicate risk, channel maintenance efforts and bolster infrastructure visibility.

5.0 Implementation Strategy

This chapter covers the strategy in which SAMM should be executed to maximize the benefits that the model is designed to provide. A standardized and documented process for inspection that provides accurate and repeatable results is one of the cornerstones of asset management (Gordon & Shore, 1998). As previously mentioned, the model is designed to capitalize on both pre-existing information and corporate knowledge of the system to guide preventative maintenance efforts and communicate infrastructure risk at various levels in the organization. Like the risk model, the implementation model is founded on simplicity; ensuring engineers have a manner in which to approach a problem of such vast magnitude. The strategy begins by identifying and filling information gaps in an iterative manner. Hierarchal iteration facilitates the evaluation of risk within a hierarchal tier and manages the amount of information collected at one single time.

5.1 Strategy Requirements and Process Diagram

The requirement exists for engineers to maintain an accurate and detailed inventory of infrastructure assets (Headquarters USAF, 2012c). With industry best management practices in mind, a strategy is designed to take the typical CES from possessing limited knowledge of their water system to possessing the capabilities presented by SAMM. The key to implementing the strategy effectively is through the use of linear segmentation, hierarchal relationships and the use of iteration to build data over time. The end state of the process eliminates issues presented by poor continuity through the conversion of “corporate knowledge” to documented data. The overall process is illustrated in Figure 16 for how installations should plan and implement SAMM.

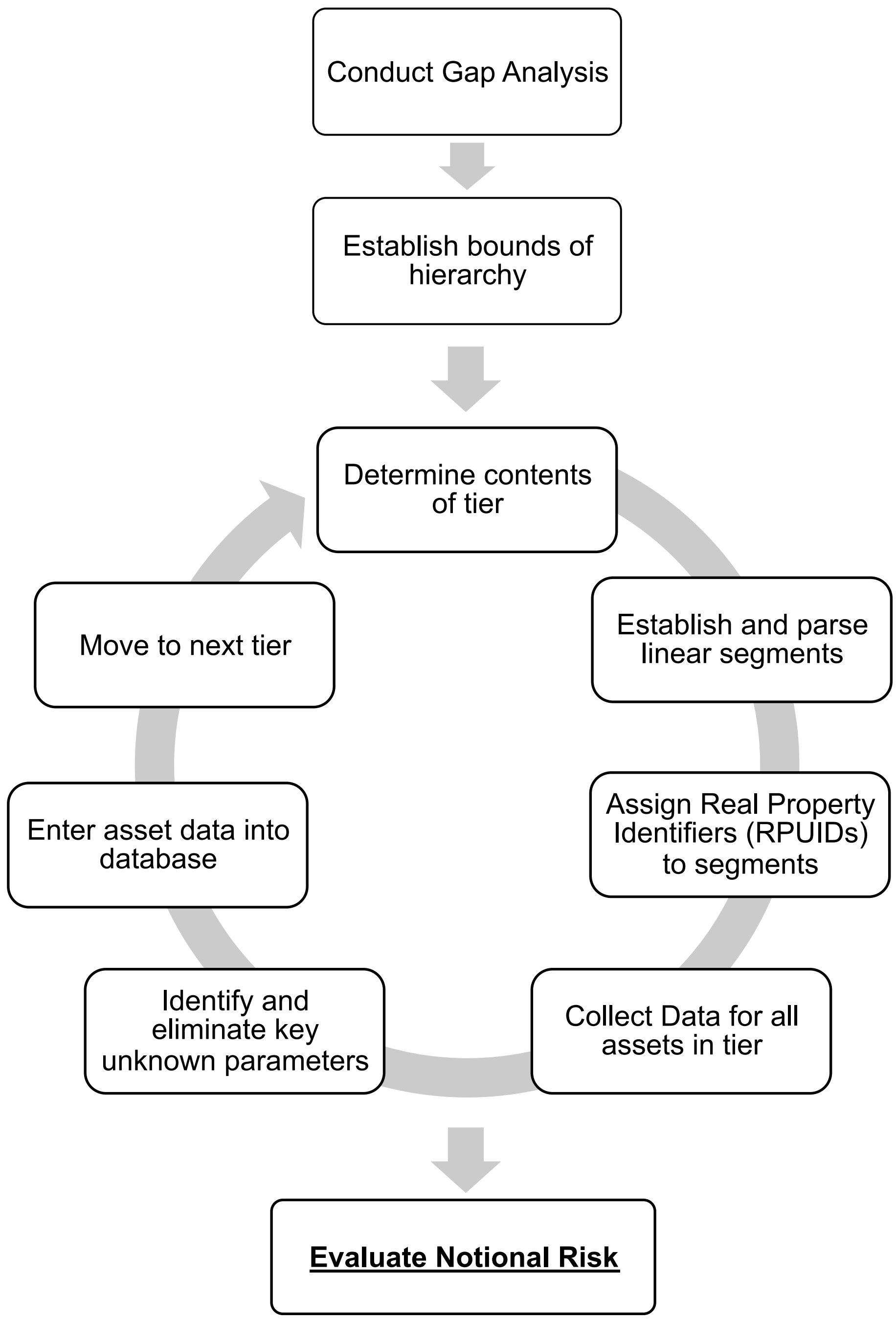


Figure 16 – SAMM Implementation Strategy Process Diagram

1) Gap analysis to establish current state and set goals

- The gap analysis tool is required of strategic planners by the Air Force (Headquarters USAF, 2012c). The adaptation of gap analysis tools at lower levels will aid in the development of targets and improvement steps along the SAMM process.

2) Establish bounds of hierarchy

- The bounds of the hierarchy are necessary to establish the scope of each iteration of the SAMM cycle. Bounds may be based on diameter and the amount of hierarchal tiers will depend on the level of detail deemed appropriate by the installation

3) Conduct iterative hierarchy process

- The iterative hierarchy process is designed to bring the level of information collected at one time to manageable levels. Engineers are able to aggregate data for one tier and calculate risk or continue to the next tier.

4) Evaluate notional risk

- Notional risk may be calculated at the completion of each tier or at the completion of the entire hierarchy.

5.2 Gap Analysis

The Program Action Directive for the Civil Engineer Transformation identifies the use of tools such as the gap analysis to aid in setting targets for the adaptation of the enterprise-wide asset management model (Headquarters USAF, 2012b). A gap analysis is a methodology to improve performance based on existing performance and potential performance (Langford & Franck, 2009). The strategic level uses the gap analysis to aid in the development of planning and investment strategy. At the tactical level, the gap analysis tool is adapted to identify performance gaps in the accuracy of the asset inventory, facilitate the creation of the hierarchy and communicate the outputs of SAMM. The tool is also helpful for establishing the scope that encompasses the collection and presentation of data. The accuracy and abundance of information used as inputs for SAMM will vary from installation to installation. Scope should then be established first to ensure the correct amount of work is directed towards inventorying the water distribution system. By cataloguing an organization's current state and setting targets, steps may be taken to improve every aspect of the register's performance. Table 5 illustrates the adaptation of the gap analysis tool to the implementation of the SAMM. The analysis is broken down into three focus areas that SAMM seeks to improve. Inventory accuracy (and efficacy), the utilities hierarchy and the evaluation and communication of risk.

Table 5 - Gap Analysis for Setting Scope and Performance Targets Within SAMM

	Current Performance	**Key Improvement Steps**	**Desired Performance**
Inventory Accuracy	• xx% inventory accuracy • xx unknown values • xx% data aggregated into one database	• Collect known data • Locate/validate utility locations • Document data and edits to maps	• 100% inventory accuracy • 0 Unknown values • 100% data collection
Utilities Hierarchy	• 0 Hierarchy Tiers • 0% Linear segmentation • 0% RPUID assignment	• Determine tier contents • Determine nodes • Assign or adapt naming convention	• 5 Hierarchy tiers • 100% linear segmentation implemented with RPUIDs assigned
Risk Evaluation	• 0% condition indexed • 0% criticality determined	• Conduct condition assessments • Conduct criticality assessments	• 100% condition assessed, ready to restart process • Criticality calculated at 3 levels, ready to restart process

5.3 Iterative Hierarchy Process

The iterative hierarchy process evaluates each tier within a utilities hierarchy as a whole. The EPA and IPWEA both call for hierarchal methods to developing asset registers (EPA, 2006; IPWEA, 2011). Most installations have many miles of distribution pipeline as well as thousands of valves, connections and other assets. The process is designed to simplify that process to the fullest extent possible by only evaluating risk for assets belonging to one particular tier. This process begins with the assets at the highest level of the hierarchy; those assets with the greatest number of dependent assets (or child assets) are evaluated first. Once risk is evaluated at the highest level, the next lowest level is evaluated. This process iterates until the model renders itself to the lowest level of detail desired.

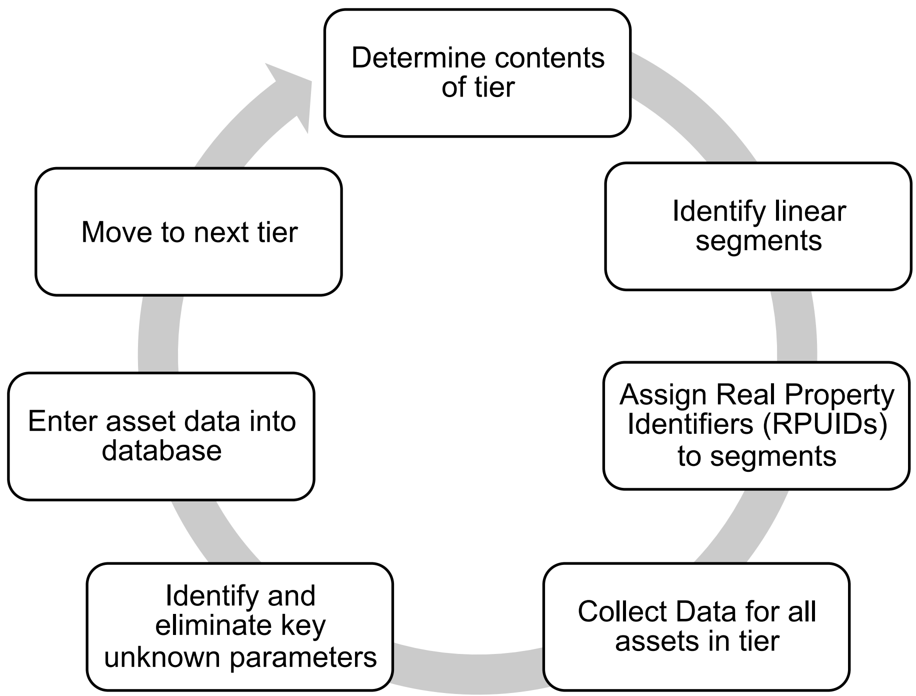


Figure 17 – Iterative Hierarchy Cycle

1) Determine Contents of Tier: Engineers decide which assets reside in a particular tier.

2) Identify Linear Segments: Using linear segmentation guidance, divide infrastructure into logical segments between nodes or logical break points.

3) Assign Real Property Unique Identifiers to segments: Each segment must be accounted for using the pre-existing naming convention already practiced at the installation

4) Collect data for all assets within tier: For each asset within the tier, aggregate all information pertaining to installation date, material, use and

5) Identify and eliminate unknown parameters such as installation year, diameter and material

6) Enter all relevant data for each segment into database

7) Move to next tier

5.3.1 The Utilities Hierarchy

Hierarchies are often useful in building inventory databases, as they incorporate importance with other key information (Oxenford et al., 2012). Using this method engineers may determine which assets are more important to the delivery of water to critical facilities providing valuable data that form the elements of the lower criticality indices. The Air Force's unique and diverse ownership of utilities on different installations means hierarchy levels and boundaries must be adjusted for each installation. The general form of the hierarchy is illustrated below and illustrated in Figure 18:

- Highest tier should consist of main distribution where other assets depend on its performance (ie-12" water main with nodes that lead to most connections on the installation). This tier contains assets of critical importance to the entire distribution system.

- Middle tiers should include assets that support a smaller number of facilities, for instance a street connection or water main of lower diameter.

- Lowest tiers should include assets that are of lower importance to the distribution system itself, cost less money, require less maintenance and/or are readily replaceable. An example of a lower tier would be check valves, control valves or fixtures.

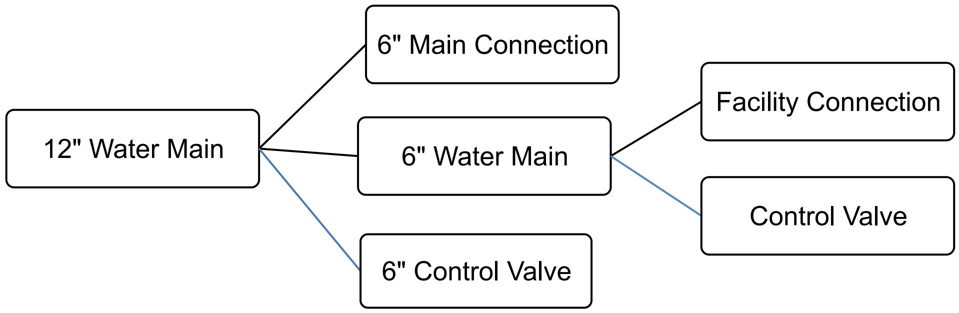


Figure 18 – Sample Utilities Hierarchy

5.3.2 Linear Segmentation

Currently, a common practice at Air Force installations is to consider the entire utility network as one facility. AFCEC has procedures in place for linear segmentation (Meeker et al., 2014b). Segmenting linear infrastructure is critical to this process as it allows the engineer to calculate risk for segments within the system rather than calculating risk for the system as a whole. Linear infrastructure is defined in Department of Defense Instruction 4165.14 as “A facility whose function requires that it traverse land (e.g., runway, road, rail line, pipeline, fence, pavement, electrical distribution line). Linear segmentation is largely beneficial to asset accountability and is a common business best management practice (Office of the Under Secretary of Defense, 2005).

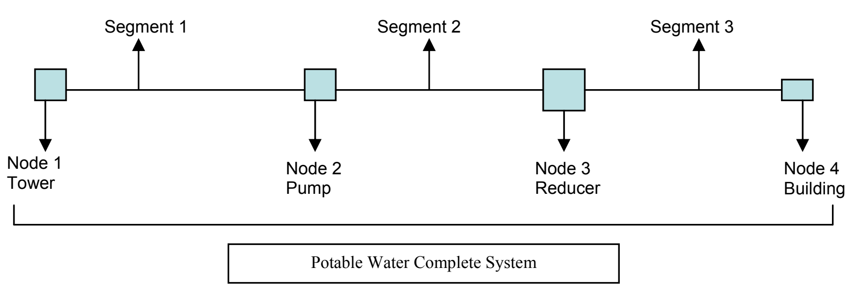


Figure 19 – Linear Segmentation Sample (Office of the Under Secretary of Defense, 2005)

5.3 Best Practices for Implementation

It is important to finally incorporate best industry practices into the implementation strategy. In keeping with the best practices outlined in the literature review, the recommended practices include 4 essential keys to success.

1) The Approach: Ensure the approach to the problem is attainable by setting hierarchal levels appropriately and collecting a nominal amount of information. Ensure the process is repeatable and continuous feedback is given to improve each iteration of the cycle. Finally, the plan must be documented, published and issued to every member of the team.

2) Set Standards: Integrate program into daily duties and routines. Teach the process to all new craftsmen and ensure they know there is a standard for 100% information accuracy. Standardize to the best extent possible the manner in which subjective condition ratings are issued.

3) Document Everything: Ensure knowledge-based information evolves to documented data that may be used to calculate risk. Collect easiest, most accessible data first, identify gaps and ensure they are eventually filled

4) Obtain buy-in from all levels: From leadership to craftsman, every member of the team must understand and support the process, its reasoning and its eventual outcome.

Over time and perhaps many iterations of the SAMM cycle, data gaps will be filled and more information may be gleaned on the utility system, which will enable engineers to make more informed decisions.

6.0 Model Validation - Case Study

This chapter discusses a case study in which both phases of research were tested to determine feasibility and efficacy. It was found that fundamentally the ideas presented would greatly benefit engineers at the installation level, but not without some improvements to communication and continuity. Francis E. Warren Air Force base was selected as a case study due to the author's own experience with the harsh environment that engineers and infrastructure are subjected. The difficult nuclear support mission along with the relatively challenging climate all contribute to the difficulty realized in sustaining infrastructure.

6.1 Case Study Background

Francis E. Warren Air Force Base (FE Warren AFB) is the United States Air Force's oldest continually active military installation and has been active since 1867 (US Environmental Protection Agency, n.d.). The base was originally constructed with the purpose of protecting rail workers along the frontier section of the transcontinental railroad. Since that time, the installation has seen many changes, expansions and a handover from the US Army to the US Air Force in 1947. The installation presents a unique case study pertaining to water infrastructure management due to its unique mission and challenges the base faces day to day. Engineers on the installation are forced to take a "worst first" approach to sustainment, giving all of their attention to what is already broken. The manner in which the installation's utilities are managed is in stark contrast to how standards set-forth at the headquarters level dictate how infrastructure should be managed. The issues surrounding this problem stem from a variety of manpower and engineering challenges that prevent a more risk-based approach to managing the installation's utility systems. The infrastructure has a widely varied age, with some distribution installed before the Second World War. Inaccurate utility maps mean that craftsmen tasked with isolating leaks are often ineffective at closing supply to sections within the network. Furthermore, these inaccurate maps mean that the utilities are at risk of being unintentionally excavated during a construction project leading to unintentional outages and expense. These challenges are exacerbated by a high turnover of manpower. Most military tours at the installation are no longer than 4 years. This means that much of the corporate, undocumented knowledge of the system leaves with the craftsman that moves to his or her next assignment. Finally, there is a shortage of money to invest in a solution. The squadron is forced to focus on immediately emergent needs, and is given little time to do any planning.

6.2 Case Study Approach

The case study was conducted to validate the simplified model's risk matrix and implementation strategy. The goal was to reveal the shortcomings of the currently applied model for activity management and test the applicability of the Simplified Asset Management Model. First, the validation of "the problem" was reviewed with engineers. After a discussion of the problem, the simplified asset management model was presented to three different offices in the 90th Civil Engineer Squadron. First, from a commander's perspective, the interview with the 90th Civil Engineer Squadron Commander validated the leadership's buy-in and overall attitude toward tactical infrastructure management decisions. To obtain a breadth of input, discussions were also facilitated in two separate offices that would both play pivotal roles in carrying-out the model. Engineers in the Utility Systems Element and the Geointegration Element were interviewed. For each guided discussion, topics formed around the topics of key issue identification, model presentation, efficacy validation and obstacle identification. Each level provided insightful and experience-based input to what issues lie in the current day-to-day operations as well as the potential obstacles that might exist should such a model be adapted in a civil engineer squadron.

6.3 Results

6.3.1 Civil Engineer Squadron Commander

The commander of the squadron was interviewed first to garner insight into his own perspective of the squadron's awareness of the utility system and determine the need for an installation-focused asset management tool. He believed that the squadron's utility specialists did not possess much knowledge of the water system and thought the simplified model would bring fidelity to their inaccurate records. Furthermore, he believed the simplified model would aid in the prioritization of preventative maintenance efforts and act as an effective communication tool to other leadership on the installation. The commander felt that the adaptation of such a model would enhance communication among flights and elements within the squadron and would be a good method to aggregate data into one commonly accessible location. He believed that the best feasible method to begin the process of aggregating data would be through a contract, as his concerns of accomplishing the first iterations of the implementation strategy can be summarized by limitations of manpower and resources. Overall, the response was positive and reflects that Civil Engineer leadership recognizes the need for increased visibility of utility assets and a more standardized approach to channeling preventative maintenance.

6.3.2 Utility Systems Engineers and Craftsmen

A majority of the time spend at the installation was with the Utility Systems engineers and craftsmen. Prior to visiting, an engineer was asked to randomly select a water asset from the inventory. They were asked to collect as much data as they could in a relatively short period of time. This was requested to test how long it would take to collect data on any particular asset, should the implementation strategy be conducted and data gaps identified and filled. It was found that the engineer was able to collect limited information about water assets including diameter, use, year installed and general location, but that limited information was not available for all assets. It was noted that the collection of information for assets with unknown attributes could take hours, since the information is scattered across several offices within the squadron. The discussion approach was similar to that of the commander, with more technically specific question that provided insight into details of the operations of the element. The engineers had a similarly positive response to the presentation of the model. They also believed that the model would enhance their ability to prioritize preventative maintenance and enhance communication between their office and others within the squadron. They also believed that populating work orders on the map would enhance their ability to communicate potential weak points or focus areas to leadership. These engineers echoed the commander's concern for time availability and other resources. They also noted communication barriers and the information disparity as obstacles to success. Finally, they believed that the whole process would require methodical planning and feedback in order to be successful.

The discussion with utility engineers brought forth several findings that are specific to this installation but may be specific to other installations with similar structure and limitations. It was found that engineers treat the utility system as one facility with one real property unique identifier (RPUID), rather than as linear segments and individual assets. The process of linear segmentation was discussed and the engineers agreed it would be value-added to segment the infrastructure to better the asset management process. It was also found that there was much knowledge and information that would benefit the model's adaptation that was retained by the engineers themselves. This "corporate knowledge" exists with only the engineers with experience. For instance, several non-commissioned officers presented an anecdote of abandon-in-place pipelines that remained under pressure due to shutoff valve location. They provided the location of the issue and explained what and why the problem existed. After asking them if any of this information was documented, they responded to the negative. As discussions of the model carried on in front of a valve location map, the engineers pointed out that the map itself was "at best 80% accurate." Thus, the accuracy in the data the engineers possess may limit their ability to develop the model. When discussing the implementation strategy, the engineers provided input to better its execution. They pointed out that using a diameter-based hierarchy would be the simplest and most effective way to determine the higher-tier assets in the system. They believed that using several different diameter "brackets" would facilitate the creation of a nominal amount of hierarchal tiers that could individually be assessed and audited. The presentation of work order association provided the most consequential validation of the model's potential. The discussion of work order association led to the craftsmen implementing the concept during the interview, using various color markers to indicate the area where work orders where scheduled, in work and completed.

This visit was certainly the most educational and provided a very honest and informative perspective on utility management on the installation. They reinforced the notion that engineers are forced to make due with the information they have at hand, and that the need very much exists for methods that improve utility management.

6.3.3 Geointegration Technician

The Geointegration office was interviewed to assess the technical feasibility of the simplified model. Similar to the other discussions, an outline of the model and its implementation strategy was presented and the technical feasibility was discussed. In this interview, questions focused primarily on geographic information systems, which are widely used by the Air Force for a myriad of different purposes (Tinsley, 2005). Esri® ArcGIS is the Air Force's common platform for geographic information systems. The software was discussed as applied to the installation and it was found that module addition is supported, along with all other features in ArcGIS. The Geointegration technician also believed that the adaptation of such a model would benefit the squadron through enhanced communication and decision support. His concerns echoed those of the engineers interviewed previously, summarized by limitations of time, money and manpower. He believed that the main obstacles in the way of such a model can be summarized by the communication barriers that seem to exist in the squadron and the lack of continuity between one engineer and the next.

6.4 Case Study Findings and Conclusions

Carrying out this case study was very educational in characterizing some of the difficulties that a typical civil engineer squadron possesses. The discussions reinforced the existence of various problems that SAMM seeks to solve and validated it as a potential solution to installation asset management. It was found all levels agreed that the need for improvement exists and the model fits the need appropriately. All engineers responded positively and believed the model would enhance communication between offices, data accuracy, work order prioritization and facilitate the communication of infrastructure-related topics to other squadrons on the base. It was also found that all engineers shared the same sentiments on limitations and obstacles. Summarized by the availability of manpower, resource allocation and the commitment of time, engineers were apprehensive about agreeing the process was in fact simple and implementable. This is due to many factors at various levels, but generally stems from reductions in manpower and resources, meaning every engineer is responsible for more than before and is given less to accomplish his or her job.

The results of the case study lead the conclusion that the model could be effective in reducing or eliminating problems with data accuracy and disparity, improving communication and improving the prioritization of short term work with some caveats. These caveats include the vast limitations that exist in the lower levels of the Air Force such as the time available to dedicate to the model, which stems directly from reductions and limitations in manpower. As the Air Force reduces its footprint, the responsibilities of the engineer remain the same, thus the specific workload of each engineer increases commensurate with the reductions in manpower available to accomplish the work. It was found that in general, engineers were overtaxed and overwhelmed with the amount of work they must do every day. An example of this was illustrated in the discussion with the GIS technician who, in the middle of interview, had to take a technical support call, which fell outside his normal duty description. He was acting as three separate people that day, fulfilling the role of his primary duty and two other duties normally assigned to others. This clearly illustrates that in lower levels of the Air Force, Engineers are forced to divert and segment their time throughout the workday to accomplish many tasks, some of which may be unrelated to one another.

The case study was educational in communicating the viewpoints of engineers at different levels of a civil engineer squadron. Feasibility was most optimistic at the command-level, with more hesitation at the utility craftsman level. The final conclusion from the case study is that the model would be very beneficial to the squadron, but would require careful planning and total buy in from different offices and leadership levels within the squadron. The only way to successfully execute the simplified model would be through a unified effort.

7.0 Comparative Case Study

The research has led to proposed solutions that simplify the process of asset management at lower levels of the Air Force. The previous case study validates the model's feasibility, but many obstacles stand in the way of its successful implementation. Best practices were kept in mind and drove many of the fundamental concepts that form the simplified model. It was found that even with best practices in mind, engineers possessed some apprehension to the ability to conduct assessments, assign criticality and built the accuracy of their asset register over time. These conclusions lead to the assertion that compared to fee-based public utilities; defense-based asset management is inherently more difficult due to a lack of continuity driven by rapid personnel turnover, an absence of integration and other institutional factors. Obstacles such as these drive the need to conduct a comparative analysis of the differences between asset management the defense industry and the public works industry. One of the more substantial conclusions of the literature review was that the asset management process is driven by several factors, chief among which is the calculated allocation of resources. Asset management fundamentally drives at making smarter, more founded decisions for sustainment and investment. However, the need exists to compare and contrast the processes and idiosyncrasies of a fee-based public utility and a defense organization such as the Air Force. It is obvious that many differences exist between these two types of organizations, however the need for asset management remains the same. The City of Fort Collins Utilities provides an effective comparison due to its highly developed asset management program. Understanding and characterizing how this program compares to the Air Force's program provides valuable insight into how the Air Force's program may be improved to optimize its performance in the future. Furthermore, the study aids in the characterization of why defense-based asset management appears to be a more difficult and complicated process to master. This chapter studies the impetus to asset management and the various roles that the mission, revenue and integration play in asset management programs of the Fort Collins, Colorado Utilities (FCU) and the United States Air Force.

7.1 The Impetus to Asset Management

Fundamentally, asset management is driven by the need for long-term infrastructure visibility (US Army Corps of Engineers/IWR, 2013). It exists to provide a manner in which organizations may make smarter decisions about where to channel funding, when to invest in maintenance versus capital and how to plan for the future. The Air Force uses asset management to integrate investment decisions from drivers such as **mission impact, facility condition, safety deficiencies, military judgment, quality-of-life, policy directives, laws, executive orders and Congressional interest items** (Headquarters, 2012c). Conversely, FCU's asset management program is driven by **aging infrastructure**, a need for **more defensible budgets and rates**, **regulatory and legislative changes**, and **workforce transitions** (Parton, Conner, Kumar, & Heart, 2011). It is clear that from these two definitions that the need exists for asset management, but is driven by different factors. Both definitions allude to aging infrastructure and policy but that is where their similarities end. The Air Force incorporates the execution of the mission, safety, quality of life and judgment into its definition. It is clear that the Air Force seeks to take the most holistic approach possible, and prioritizes mission accomplishment above all other drivers to asset management. Conversely, FCU alludes to budget and rate defense and workforce transitions to drive their process. Their approach seeks to define asset management at its most fundamental level, with the incorporation of the need for a standardized process to be in place as the workforce cycles.

7.2 The Role of the Mission in Asset Management

In both cases, the mission is paramount to the existence of asset management, whether explicitly stated or implied. The mission itself and the relationship to infrastructure is where the difference exists. In the case of FCU, the mission *is the customer or end user*: "Provide exceptional services for an exceptional community (City of Fort Collins, 2013)." In the case of the Air Force, the mission is also the customer, but the customer is not necessarily the end user. The mission of the Air Force is to "Fly, Fight, and Win… In Air, Space, and Cyberspace (Headquarters USAF, 2012a)." In both cases, the customer provides the basis for planning via population growth or mission expansion, but there lies a correlation in the case of FCU that is harder to draw in the case of the Air Force. In the case of FCU, the correlation exists between the managed assets and the end user or mission. FCU's water assets enable the accomplishment of their mission to provide exceptional services. In the case of the Air Force, water assets support the accomplishment of the mission. To that end, the term "mission" means the overall mission of the entire Air Force. The contribution of a particular water asset may be somewhat low to the strategic mission when compared to the more focused mission of a specific Air Force installation. Between Air Force installations, there may be variances in the amount an asset contributes to their specific missions. In the case of the Air Force, the mission drives asset management, but the different levels of the mission make correlating criticality difficult.

7.3 The Role of Fees in Asset Management

Perhaps the most obvious financial difference between the FCU organization and the Air Force is the presence of revenue. FCU's revenue is chiefly driven by user fees, which enables the utility to have a general notion of what to expect in future years. The asset management process they use drives at justifying the rates they set for customers and the budgets they plan for future years. FCU can be seen a "self-sufficient entity" which collects user fees, builds its own budget and prioritizes projects in accordance with their mission, vision and values. The Air Force, on the other hand, does not collect user fees. The process in which the Air Force allocates resources to infrastructure is vastly different, and is initially allocated by Congress, which is divided within the Department of Defense, and further divided amongst the needs of the Air Force. The Air Force's asset management program drives at carefully justifying the amount of resources allocated to infrastructure, but the amount they receive is variable, unpredictable and competes with other needs of the Air Force, such as operations or weapons systems. This complicates the process of project prioritization and the use of the MDI keeps priorities evenly balanced across the organization. It can be seen here that the two organizations compared obtain and use money very differently, and that has a specific impact in the manner in which they define their programs. The Air Force's definition is much more holistic and accounts for factors that aren't noted by FCU. The need for complete justification exists across the scope of the Air Force's interests (e.g. mission, personnel safety and morale).

7.4 The Role of Integration

Integration is becoming commonplace among organizations that practice asset management (US Environmental Protection Agency, 2009). Integration plays an important role in the decision support that asset management provides as it ties the needs of various arms of the organization into one commonly viewable platform. Integration via data is commonly referred to as one of the most important components of an asset management program (Grigg, 2010). FCU has taken strides in the previous years to integrate data and manipulate it to provide effective risk communication that aids in where to channel resources for maintenance and sustainment. The result of integrating data can be seen in Figure 20, which presents a snapshot of FCU's pipeline risk assessment tool.

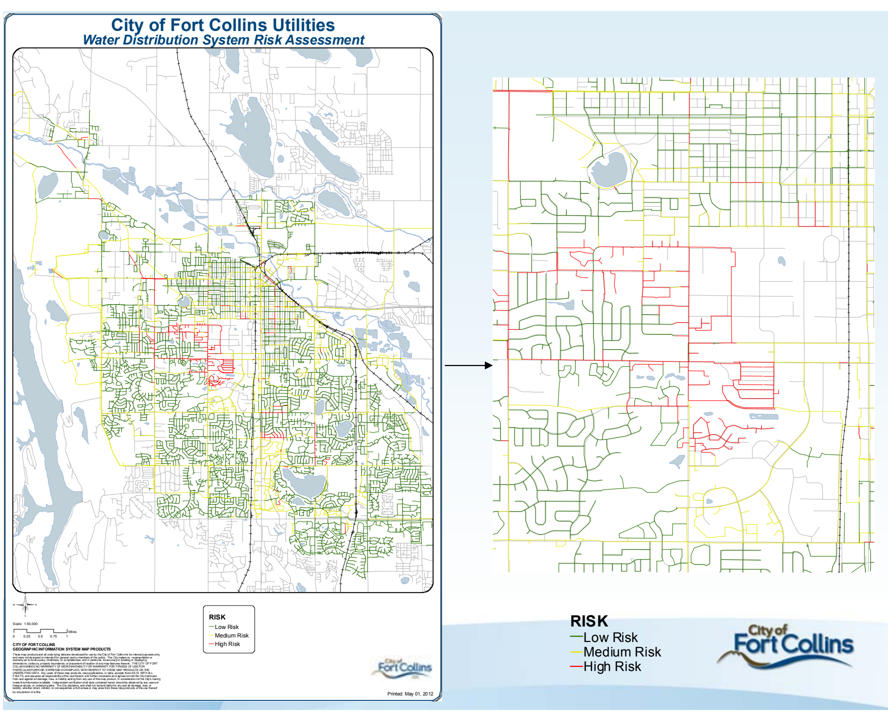


Figure 20 – City of Fort Collins Water Distribution Risk Assessment Tool (Parton, 2012)

This integration enables decision support using graphical features to represent relative risk to the delivery of water to customers. The Air Force, on the other hand, does not posses a single, integrated system that collects data and manipulates it to enable decision support (Harnly & Sitzabee, 2013). This is driven by the vast differences in different infrastructure systems across the Air Force's portfolio. The adaptation of an integrated, multi-sector asset management system would be difficult to implement, but very beneficial in the long-term.

7.5 Conclusions

This comparison leads to many conclusions about factors that vary between a public utility and a defense organization. The high level of uncertainty exhibited by engineers at the installation level is due to factors that are not present in FCU, such as the lack of an integrated data platform and high personnel turnover, complicated by the retention of undocumented corporate knowledge. FCU is fortunate to only have one mission and focus area, thus leading to a totally integrated asset management program; moreover they do not have a constantly rotating workforce. Conversely, the Air Force's diversity, disparity and size make the implementation of an integrated platform a challenging problem. Furthermore, it can be concluded that the financial basis of the organization plays an important role in how decisions are prioritized and resources are allocated. The final conclusion is that of similarity. Through all the differences between these organizations, the fundamentals hold true. No matter the driver for asset management, the target remains the same: make each dollar more effective.

8.0 Conclusion

The United States Air Force has practiced asset management since 2007 (Harnly, 2012). Since its inception, it has evolved to meet the needs of resource advocacy and other interests. This research was conducted in response to certain findings that indicate the Air Force primarily uses asset management as a strategic tool and has limitations at the tactical level. The realization of these inconsistencies led to the development of a tactically focused asset management model that captures the intent of risk-based asset management but uses the information to drive tactical decisions. The model consisted of the mathematical framework, a user-focused data model and a strategy to implement the process at a level commensurate with the amount of available time and manpower realized by the typical Civil Engineer Squadron. The model in its entirety was presented to various levels of the 90th Civil Engineer Squadron at FE Warren Air Force Base and it was found to be universally well-received. Engineers believed in the possibility of improved decision support tools through an overall improvement in the manner in which the program was conducted. The most consequential indicator of acceptance was the immediate adaptation of work order placement on a wall-mounted valve map. Utilities craftsmen immediately found this to be useful to indicate recurring weak points and before conclusion of the meeting were planning on adapting a pen-and-ink process. The case study not only validated the model, but also uncovered some communication barriers that exist in the Squadron. It was found that there exists an absence of clear communication channels between the offices responsible for geointegration, future project programming and utilities craftsmen.

Engineers believed that these barriers were hindering their ability to most-effectively accomplish their day-to-day duties. These barriers may or may not exist at other installations, but the documentation of them leaves other installations with anecdotes that aid in the development of their own asset management plans. The research concludes with several findings, limitations and areas where research may be focused to better the practice of asset management in the Air Force in the future.

8.1 Findings

The research led to several findings identified by the author and the substantiation of findings identified by others. The first and most consequential finding was the realization of the need for improved infrastructure management at the lowest levels of the Air Force. During the case study, engineers agreed that their processes required improvement and several issues hindered their ability to make informed infrastructure management decisions. First, the disparity and inaccuracy of data led the challenge of exactly where an asset is and how it relates to the network. The communication barriers between offices within the squadron worsen the problem. It was found that one office had a map of the utility network printed in 2011 supporting their preventative maintenance efforts, while another office utilized current maps. Furthermore, issues pertaining to continuity mean that data and relevant information is usually not recorded, but retained as “corporate knowledge” by individual engineers. The process of turning this corporate knowledge into recorded information would greatly benefit the engineers’ ability to make tactical decisions.

The next key finding is the process of recording data and information is made difficult by absence of an integrated data platform. In the absence of readily available tools (i.e. integrated maintenance management systems) that enable engineers to document information, score condition and index criticality makes asset management extremely difficult at the lowest level. This finding supplements the findings of Harnly's analysis of the Air Force's Strategic Asset Management program. She states "Air Force efforts should align the data and Maintenance Management Systems (MMS) required for strategic level asset management with the data and MMS required for tactical level asset management (Harnly & Sitzabee, 2013)." Furthermore, it should be noted that information (i.e. physical information, condition information, criticality) should be aggregated and stored in one location to facilitate data manipulation.

The absence of integration and robust data along with the barriers that exist at tactical levels leads the subsequent finding. Given the undeveloped environment, engineers are forced to make due with the limited time, manpower and monetary resources they have. This leads to the "worst first" approach to infrastructure management. The research and analysis seeks to develop a model that can improve the situation keeping limitations in mind.

Finally, the research reveals that when compared to other urgent mission areas, water infrastructure receives a relatively low priority in the Air Force's daily operations. This finding is realized in the absence of integrated MMS, disparity of data and tactical decision support tools offered to engineers. Water infrastructure will continue to be relevant to mission accomplishment and an ever-aging system but recognition of its importance in management within the Air Force has yet to be seen.

8.2 Limitations of Research

The research was conducted to provide engineers at lower levels of the Air Force potential solutions to the problems they realize. This research was intended to use best practices in the industry and align with the inherent limitations the Air Force realizes across the enterprise (e.g. reduced defense spending). Several limitations prevented this research from developing further and should be noted to identify areas where research in this field may be improved or developed further.

Communication, realized in one of the consequential findings preventing successful asset management, was also realized as a barrier to research. It was found that the Author's distance from the operational Air Force made it challenging to pull busy engineers from their daily duties. This resulted in the somewhat limited-scope case study.

A further limitation existed in the development of methods and concepts that readily align with the Air Force's asset management program. The recent reorganization of the career field and its evolving processes make the eventual amalgamation of this model with the corporate model variable.

A limitation also exists in the scope of research. The scope of research was defined by the time allotted to it, and thus represents the study of one Air Force installation. The development of perspectives across a larger cross section would greatly improve the overall feasibility of the model and provide useful feedback to better its components.

8.3 Further Research

Areas for further research exist in the technical development of the components of the risk model. Specifically, the empirical determination of the parameters used in the Weibull-based probability of failure tool would lead to a more robust correlation between condition, age and failure probability. This research would use statistical methods and recorded data to better resolve the information.

The development of a GIS-based application of the user-focused physical model presented in chapter 4 would greatly benefit the research. This application would effectively enable the model and allow sharing and testing at different Air Force installations.

8.4 Summary

This research can be concluded with an example of the complexity of enterprise-wide asset management. There exists a myriad of factors that require careful analysis before investment is made. Comparing the importance of one installation's mission to another or one major command to another is a daunting challenge for strategic planners. Water infrastructure may contribute differently to the successful accomplishment of the mission at installation A than it does at installation B. Thus, the dynamic nature of the Air Force's mission and the complexities within its organization make the solution to the problem a challenging one. The enabling of tactical asset management and its integration with strategic asset management will certainly yield great benefit to engineers at every level of the Air Force.

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Appendix 1: Scholarly Article submitted to The Air and Space Power Journal

FORGING TACTICAL ASSET MANAGEMENT SOLUTIONS FOR AIR FORCE-OWNED WATER UTILITY ASSETS

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Water utility infrastructures to support operations and buildings are not only important to Air Force installations but also expensive to maintain and repair. While the Air Force strategic asset management structure focuses on mid-to long-term planning for budget allocation, at the installation level many issues confront the effectiveness of this program. Problems arise from asset inventory to condition assessments and failure consequence assessment. With inaccurate asset inventories, data disparities and uncertain information on system condition, installations are forced to take a "worst first" approach to maintenance operations. Reductions in force size and spending provide the impetus to create a simplified method for asset management. To solve this complex problem, an investigation of approaches to utility asset management has been conducted with emphasis on the Air Force's existing activity management framework. Using pre-existing information and new methods, a model was developed to bolster the efficacy of pre-existing resources. Knowledge-based condition assessments and value-added criticality assessments allow utility engineers to calculate infrastructure risk for their own planning horizons, rather than strategic planning horizons. By laying the groundwork for how utility infrastructure can be better managed, conclusions about

feasible approaches are made considering the Air Force's monetary and manpower constraints. The research concludes with an analysis of the roles of key factors in the process of asset management as practiced by the defense industry and fee-based public utilities. The implications of this research primarily benefit multi-layered organizations that currently use a top-down approach to asset management. By aiding the ability for lower levels to aggregate data and determine priority, improved levels of service, more effective mission support and reduced outages may be realized.

The Problem: ***Strategic*** Asset Management for ***Tactical*** Decisions

The mission of the Air Force has evolved and fluctuated with the many roles it has played in national defense in the past 67 years. The importance of infrastructure sustainment via asset management has been made a focus area for leaders in the past 10 years. Since its introduction, the successful execution of asset management has been made difficult due to the layered nature of the Air Force's organization. The strategic level has led the charge for asset management through the need for strategic sustainment funding justification. The very nature of the strategic planning horizon that asset management supports leads to the core of the problem. Asset management seeks to enable smarter and more informed decisions for infrastructure investment through the careful prioritization of requirements. Prioritization is a function of risk, which is a function of condition and criticality. Currently, the Air Force uses one prioritization tool to determine how valuable an asset is to the accomplishment of the overall Air Force mission. This Mission Dependency Index is a function of an asset's category code, and may be adjusted slightly by each functional command to improve scoring. The inherent problem with this methodology is the strategic nature of the failure consequence metric: “To Fly, Fight and Win … in Air, Space, and Cyberspace.” The many specific missions of individual Air Force installations together enable the accomplishment of the strategic mission, but there exists a need for an improved and simplified method for engineers at the installation level to calculate risk to their own planning horizons. The misalignment of the strategic-versus-tactical asset management has driven issues leading to poor installation-level management. The issues that characterize the difficulties in maintaining strategic asset management can be summarized by their constant state of flux. Over time, the turnover of military personnel has created a myriad of record discontinuities, inaccurate utility maps and data gaps[1]. Furthermore, the evolution and buildup of installations has created an atmosphere conducive to execute repairs expeditiously, in lieu of taking steps to prioritize and document. Figure 1 illustrates what was found to be the core of the problem, disparate and unreliable information.

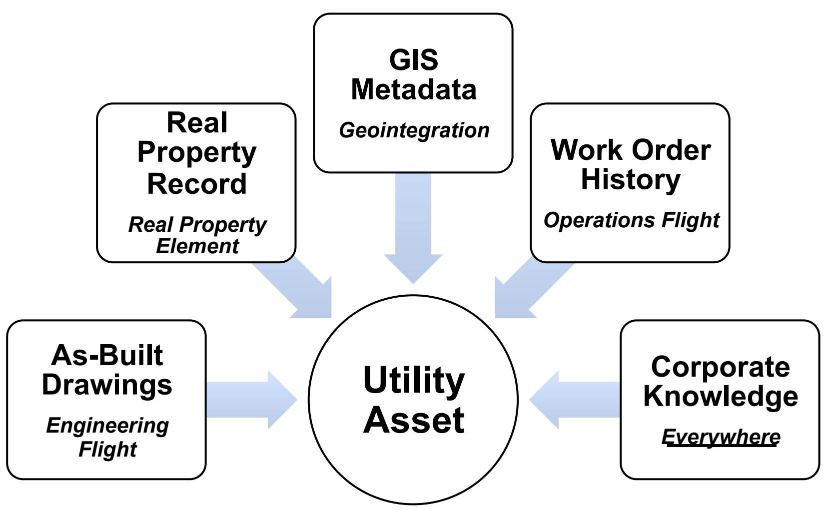

Figure 1 – Sources of Asset Information

In the absence of accurate records, how can the utility engineer know where to channel preventative maintenance efforts? How will engineers communicate the implications to the installation's mission should the infrastructure fail? The absence of reliable records has made installation-level asset management a cumbersome task. Not only is the record disparity an issue, the lack of a structured and centralized data system means that engineers do not have the tools they need to collect information and support their decisions. This leads to engineers simply reacting to main breaks and adapting a "worst first" approach to infrastructure management. Instead of making decisions to prevent failure, decisions are made to react to failure.

The Importance of Tactical Asset Management Tools For Water Infrastructure

The need for a simplified asset management model stems from the varying degrees between Operational, Tactical and Strategic asset management in a layered organization such as the US Air Force. At each level, the elements that make up the asset management process are varied with the different planning horizons. Gordon and Shore (1998) indicated three planning horizons that demonstrate the difficulty in asset management decision-making: Tactical, operational and strategic[2]. The structure of the US Air Force can be broken down into these levels and as the Air Force's Enterprise asset management model illustrates, great focus is placed on the strategic level. These three levels coincide with planning varied horizons and with these different planning horizons comes a variance in the type and quality of information that is used to make decisions. The following can summarize the differences in the three levels:

1. Each level has different levels of service

2. Each level has different consequences of failure
3. Each level has different amount of system knowledge
4. Each level has different planning horizons
5. Each level has different missions (but all form the highest level)

Though the Air Force has a hierarchal organizational structure, the inherent complexity in adapting a strategically focused asset management model in a tactical environment provides the impetus to the simplified model. This need is clearly illustrated through comparison with public utilities sector. A fee-based public utility uses asset management to address aging infrastructure, regulatory and legislative changes and workforce transitions[3]. In a defense organization, water utilities provide ancillary support functions that enhance the mission, but do not directly contribute to it. The lack of a clear link between the organization's mission and its asset management program along with the lack of fee-generated revenues complicates the problem of asset management further. The simplified model is designed to provide useful decision support information for engineers at the lowest level about condition, potential failure and more effectively link mission criticality to levels of service.

While the concepts and conclusions of this research are applicable to Air Force-wide adaptation with slight variance between infrastructure categories, water infrastructure provides a challenging and useful exercise to research possible solutions. Most of water infrastructure is buried and out of sight, meaning the direct monitoring of condition state is not usually practical. Measuring criticality is also a difficult challenge, as the levels of service provided by water utilities do not directly contribute to the accomplishment of the Air Force mission. Furthermore, the relatively harsh environment in which water infrastructure operates advances its decay. Finally, the integrated management of water utilities is one of the final infrastructure categories that do not possess its own maintenance management system (MMS) in the Air Force. Thus, the research of methods to simplify the process may benefit the adoption of integrated technology in the future.

The Solution is *Simplicity*

After discussing asset management in various flights at a sample installation, it was found that engineers required the ability to simplify the process to collect and record information. Furthermore, they required a tool that would be useful in communicating risk to their own planning horizon, rather than the strategic planning horizon of the Air Force as a whole. Simplifying the process for engineers at the installation level provided a method to obtain more accurate and reliable information pertaining to utility condition and priority. The research was conducted to provide installations with a tool kit they may use if they do not have a complete register of their utilities inventory including their asset's condition or importance. It was found that a Simplified Asset Management Model (SAMM) would best fit the installation's need by maximizing the use of pre-existing information and manpower. Not only was it important to develop the mathematical approach to priority, but also develop a strategy for implementation. To develop the solution, status quo was established and SAMM was developed to remedy the issues identified. SAMM was generated with feasibility and efficacy in the forefront of development. The model's priority algorithm must be simple enough for engineers to use every day, the data structure robust enough to collect all the pertinent information and the criticality indices relevant to the engineer themselves.

Model Development

The basis of SAMM is the effective calculation of risk to additional audiences. The tool uses the core concepts of asset management to yield risk-based information to the strategic, operational and tactical levels of the layered Air Force. Using a standardized probability of failure across levels ensures that condition is fairly measured at all three levels. For establishing criticality, the consequence of failure is realigned and normalized to meet the goals of the strategic, operational and tactical levels of the Air Force. By using pre-existing tools and pre-existing information the model can provide comprehensive support to the decisions made by engineers, installation planners, installation leadership and higher headquarters decision makers. An added benefit of the development of this model is the realization of the misalignment of risk communication in an organization such as the Air Force. The layered nature of the strategic, operational and tactical visions, missions and goals point to using a standardized criticality index across the board. In theory since all layers of the organization work for the highest level, criticality should be measured in accordance with strategic vision. In reality, the comparison of strategic priorities and more operational priorities can illustrate to leadership at all levels where work should be focused and optimized to enhance support to the mission and levels of service at different planning horizons. The model was developed using the following process:

1. Define core principles of asset management

2. Garner a clear delineation between strategic and tactical asset management

3. Analyze the currently implemented strategic asset management model

4. Adapt best industry practices for organizations with resource limitations

5. Formulate lifecycle-based condition assessment model based on reliability modeling tools

6. Align criticality indexes to various stakeholders relevant to water infrastructure

7. Develop methodology for engineers to collect information about the utility system in an iterative manner

Simple **Condition Assessments**

Condition assessment is designed to determine a notional probability of failure for an asset. The goal of the simplified model is to simplify the condition assessment process using pre-existing data and knowledge of the system retained by utility engineers to obtain a probability that may be measured across the utilities portfolio evenly. Among the several methods for condition assessments, the use of the service life models presents the most useful tool for adapting the information that an organization already has to obtain a probability of failure[4]. Of note, the use of the Weibull model presents an opportunity to adapt a tool that is already in use in other sustainment management systems. The BUILDER SMS uses the Weibull distribution to predict the component-section condition index in facilities[5]. SAMM uses the pre-existing Air Force Activity Management Plan Direct Condition Rating table and adjusts the condition score to fit a

Weibull Cumulative Distribution Function. This function outputs a notional probability of failure given an asset's age and subjective condition. The result is the ability to index condition rapidly given a subjective rating and a known value for age. The results of this condition methodology are presented in Figure 2. Note that for different condition indices, the slope of the function varies.

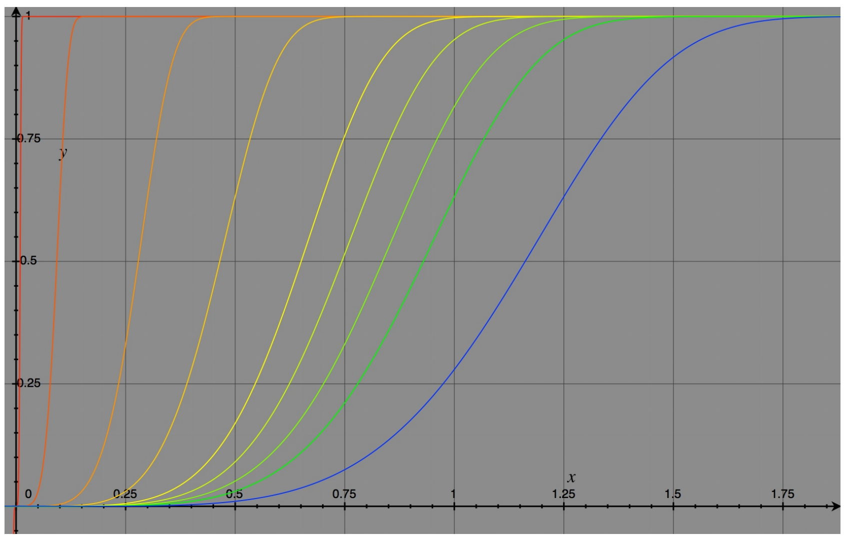

Figure 2 – Weibull distribution for all condition degradation coefficients

Simple and *<u>Relevant</u>* Failure Consequence

Not only is SAMM designed to simplify the asset management process for engineers; it is designed to provide more relevant information. After analysis of the various planning horizons at different levels of the Air Force, it was concluded that a variety of failure consequence indices would enable the communication of risk at various levels. Thus, using two new failure consequence methods along with the existing Mission Dependency Index (MDI), the engineer may calculate failure consequence to not only the Air Force mission, but also the installation's mission and the customers that the water system supports (such as military family housing, irrigation, etc.). The service association index (SAI) uses an installation's Critical Infrastructure Program (CIP) priority list to generate a relationship between infrastructure and the most important facilities on an installation. The System Criticality Index (SCI) uses an analytical hierarchy process (AHP) to determine interruptability, redundancy, relationship to infrastructure and level of customer support[6]. Table 1 presents the three indices used by SAMM to generate more relevant priorities through consequence of failure (CoF).

Table 1 - Organizational Levels of the US Air Force and Failure Consequence Tools

Level	Sample Organization	Planning Horizon	Failure Consequence Driver	CoF Tool
Strategic	HAF, AFCEC, MAJCOMs	2-7+ years	Accomplishment of **AF mission**	Mission Dependency Index (normalized)
Operational	Operational Wing	2-5 years	Accomplishment of **installation's specific mission**	Service Association Index
Tactical	Civil Engineer Squadron, Utilities Shop	0-2 years	**Level of service** provided by system	System Criticality Index

Work Order *Visibility*

Work orders not only tie in maintenance investments into the decision process of repair or replacement but also provide other valuable system-level information for engineers and installation leaders. From the utilities engineer perspective, populating a map with complete and non-complete work orders aids in the communication of weak or failing points in the system and allows schedulers to more effectively plan preventative maintenance efforts. Associating location to work orders enables engineers to more readily integrate multi-disciplinary renewal projects. If a water main break work order exists under a road scheduled for renewal, these two projects may be combined into one project that will yield benefit for both the roadways and the water system. At the more operational (installation leadership) level, population of work orders on a map illustrates to leaders where they need to advocate for sustainment funding. Additional operational benefit exists in the illustration of interdependencies between the operational mission and infrastructure. Finally from a strategic level, the frequency of work orders and overall backlog of work orders would aid in resource allocation for a particular installation. The most integrated approach to populating maps with work orders would be to incorporate a required field of specific location on the work order entry process. By making the step of work order location compulsory on work orders, facility managers and operations planners would enter geographic information in the first step of the work order review process.

An Implementation *Strategy*

A standardized and documented process for inspection that provides accurate and repeatable results is one of the cornerstones of asset management[2]. As previously mentioned, the model is designed to capitalize on both pre-existing information and corporate knowledge of the system. Like the risk model, the implementation model is founded on simplicity; ensuring engineers have a feasible manner in which to approach a problem of such vast magnitude. The strategy begins by identifying and filling information gaps in an iterative manner. Hierarchal iteration facilitates the evaluation of risk within a hierarchal tier and manages the amount of information collected at one single time. The key to implementing the strategy effectively is through the use of linear segmentation, hierarchal relationships and the use of iteration to build data over time. The end state of the process eliminates issues presented by poor continuity through the conversion of “corporate knowledge” to documented data. The overall process is illustrated in Figure 3 for how installations should plan and implement SAMM.

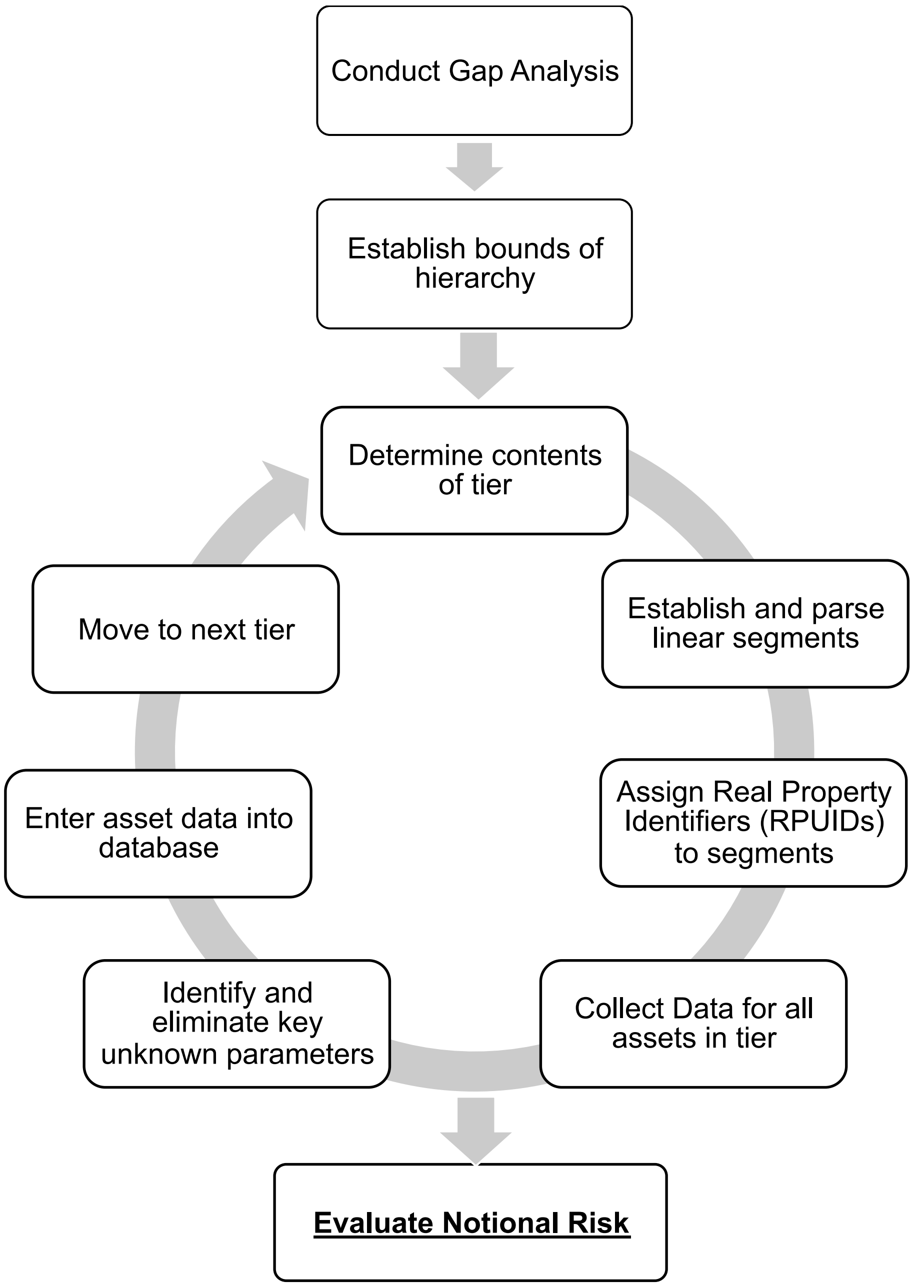

Figure 3 – SAMM Implementation Strategy Process Diagram

SAMM Validation: FE Warren AFB

A theory-confirming case study was conducted to validate SAMM's risk matrix and implementation strategy. The goal was to reveal the shortcomings of the currently applied model for activity management and test the applicability of the proposed SAMM. First, the validation of "the problem" was reviewed with engineers. The problem was defined as a lack of communication between flights, a lack of information about the utility system and the methods in place to enact repair. This problem was validated with every engineer interviewed. The simplified asset management model was then presented as a solution to the problem to three different offices in the 90th Civil Engineer Squadron. First, from a commander's perspective, the interview with the 90th Civil Engineer Squadron Commander validated the leadership's buy-in and overall attitude toward tactical infrastructure management decisions. To obtain a breadth of input, discussions were also facilitated in two separate offices that would both play pivotal roles in carrying-out the model. Engineers in the Utility Systems Element and the Geointegration Element were interviewed. For each guided discussion, topics formed around the topics of key issue identification, model presentation, efficacy validation and obstacle identification. Each level provided insightful and experience-based input to what issues lie in the current day-to-day operations as well as the potential obstacles that might exist should such a model be adapted in a civil engineer squadron.

FE Warren AFB: An Ideal Test Site

Francis E. Warren Air Force Base (FE Warren AFB) is the United States Air Force's oldest continually active military installation since 1867[7]. The base was originally constructed with the purpose of protecting rail workers along the frontier section of the transcontinental railroad. Since that time, the installation has seen many changes, expansions and a handover from the US Army to the US Air Force in 1947. The installation presents a unique case study pertaining to water infrastructure management due to its unique mission and challenges the base faces day to day. Engineers on the installation are forced to take a "worst first" approach to sustainment, giving all of their attention to what is already broken. The manner in which the installation's utilities are managed is in stark contrast to how standards set-forth at the headquarters level dictate how infrastructure should be managed. The issues surrounding this problem stem from a variety of manpower and engineering challenges that prevent a more risk-based approach to managing the installation's utility systems. The infrastructure has a widely varied age, with some distribution installed before the Second World War. Inaccurate utility maps mean that craftsmen tasked with isolating leaks are often ineffective at closing supply to sections within the network. Furthermore, these inaccurate maps mean that the utilities are at risk of being unintentionally excavated during a construction project leading to unintentional outages and expense. These challenges are exacerbated by a high turnover of manpower. Most military tours at the installation are no longer than 4 years. This means that much of the corporate, undocumented knowledge of the system leaves with the craftsman that moves to his or her next assignment. Finally, there is a shortage of money to invest in a solution. The squadron is forced to focus on immediately emergent needs, and is given little time to do any planning.

Case Study Results

Carrying out this case study was very educational in characterizing some of the difficulties that a typical civil engineer squadron possesses. The discussions reinforced the existence of various problems that SAMM seeks to solve and validated it as a potential solution to installation asset management. It was found all levels agreed that the need exists and the model fits the need appropriately. All engineers responded positively and believed the model would enhance communication between offices, data accuracy, work order prioritization and facilitate the communication of infrastructure-related topics to other squadrons on the base. It was also found that all engineers shared the same sentiments on limitations and obstacles. Summarized by the availability of manpower, resource allocation and the commitment of time, engineers were apprehensive about agreeing the process was in fact simple and implementable. This is due to many factors at various levels, but generally stems from reductions in manpower and resources, meaning every engineer is responsible for more than before and is given less to accomplish his or her job.

The results of the case study lead the conclusion that the model could be effective with some caveats. These caveats include the vast limitations that exist in the lower levels of the Air Force such as the time available to dedicate to the model, which stems directly from reductions and limitations in manpower. As the Air Force reduces its footprint, the responsibilities of the engineer remain the same, thus the specific workload of each engineer increases commensurate with the reductions in manpower available to accomplish the work. It was found that in general, engineers were overtaxed and overwhelmed with the amount of work they must do every day. An example of this was illustrated in the discussion with the GIS technician who, in the middle of interview, had to take a technical support call, which fell outside his normal duty description. He was acting as three separate people that day, fulfilling the role of his primary duty and two other duties normally assigned to others. This clearly illustrates that in lower levels of the Air Force, Engineers are forced to divert and segment their time throughout the workday to accomplish many tasks, some of which may be unrelated to one another. Feasibility was most optimistic at the command-level, with more hesitation at the utility craftsman level. The final conclusion from the case study is that the model would be very beneficial to the squadron, but would require careful planning and total buy in from different offices and leadership levels within the squadron. The only way to successfully execute the simplified model would be through a unified effort.

Research to Analysis: Comparison with the Public Utility Sector

The research led to proposed solutions that simplify the process of asset management in a tactical environment. The previous case study validates the model's feasibility, however many obstacles stand in the way of its successful implementation. Best practices were kept in mind and drove many of the fundamental concepts that form the simplified model. It was found that even with best practices in mind, engineers possessed some apprehension to the ability to conduct assessments, assign criticality and built the accuracy of their asset register over time. These conclusions lead to the assertion that compared to fee-based public utilities; defense-based asset management is inherently more difficult due to a lack of continuity driven by rapid personnel turnover, an absence of integration and other institutional factors. Obstacles such as these drive the need to conduct a comparative analysis of the differences between asset management the defense industry and the public works industry. One of the more substantial conclusions of research was that asset management is driven by several factors, chief among which is the calculated allocation of resources. Asset management fundamentally drives at making smarter, more founded decisions for sustainment and investment. However, the need exists to compare and contrast the processes and idiosyncrasies of a fee-based public utility and a defense organization such as the Air Force. It is obvious that many differences exist between these two types of organizations, however the need for asset management remains the same. The City of Fort Collins Utilities provides an effective comparison due to its highly developed asset management program. Understanding and characterizing how this program compares to the Air Force's program provides valuable insight into how the Air Force's program may be improved to optimize its performance in the future. Furthermore, the study aids in the characterization of why defense-based asset management appears to be a more difficult and complicated process to master.

The *Impetus* to Asset Management

Fundamentally, asset management is driven by the need for long-term infrastructure visibility[8]. It exists to provide a manner in which organizations may make smarter decisions about where to channel funding, when to invest in maintenance versus capital and how to plan for the future. The Air Force uses asset management to integrate investment decisions from drivers such as **mission impact, facility condition, safety deficiencies, military judgment, quality-of-life, policy directives, laws, executive orders and Congressional interest items**[9]. Conversely, FCU's asset management program is driven by **aging infrastructure**, a need for **more defensible budgets and rates**, **regulatory and legislative changes**, and **workforce transitions**[3]. It is clear that these two definitions characterize the need for asset management, but different factors drive it. Both definitions allude to aging infrastructure and policy but that is where their similarities end. The Air Force incorporates the execution of the mission, safety, quality of life and judgment into its definition. It is clear that the Air Force seeks to take the most holistic approach possible, and prioritizes mission accomplishment above all other drivers to asset management. Conversely, FCU alludes to budget and rate defense and workforce transitions to drive their process. Their approach seeks to define asset management at its most fundamental level, with the incorporation of the need for a standardized process to be in place as the workforce cycles. This is a key delineation as it characterizes the need for standardization in its definition, a key limitation in the Air Force's program.

The Role of the Mission

In both cases, the mission is paramount to the existence of asset management, whether explicitly stated or implied. The mission itself and the relationship to infrastructure is where the difference exists. In the case of FCU, the mission *is the customer or end user*: "Provide exceptional services for an exceptional community (City of Fort Collins, 2013)." In the case of the Air Force, the mission is also the customer, but the customer is not necessarily the end user. The mission of the Air Force is to "Fly, Fight, and Win… In Air, Space, and Cyberspace[11]." In both cases, the customer provides the basis for planning via population growth or mission expansion, but there lies a correlation in the case of FCU that is harder to draw in the case of the Air Force. In the case of FCU, the correlation exists between the managed assets and the end user or mission. FCU's water assets enable the accomplishment of their mission to provide exceptional services. In the case of the Air Force, water assets support the accomplishment of the mission. To that end, the term "mission" means the overall mission of the entire Air Force. The contribution of a particular water asset may be somewhat low to the strategic mission when compared to the more focused mission of a specific Air Force installation. Between Air Force installations, there may be variances in the amount an asset contributes to their specific missions. In the case of the Air Force, the mission drives asset management, but the different levels of the mission make accurately correlating criticality very difficult.

Fees and Revenue as a *Fuel* For Asset Management

Perhaps the most obvious financial difference between the FCU organization and the Air Force is the presence of revenue. FCU's revenue is chiefly driven by user fees, which enables the utility to have a general notion of what to expect in future years. The asset management process they use drives at justifying the rates they set for customers and the budgets they plan for future years. FCU can be seen a "self-sufficient entity" which collects user fees, builds its own budget and prioritizes projects in accordance with their mission, vision and values. The Air Force, on the other hand, does not collect user fees. The process in which the Air Force allocates resources to infrastructure is vastly different, and is initially allocated by Congress, which is divided within the Department of Defense, and further divided amongst the needs of the Air Force. The Air Force's asset management program drives at carefully justifying the amount of resources allocated to infrastructure, but the amount they receive is variable, unpredictable and competes with other needs of the Air Force, such as wartime operations or weapons systems. This complicates the process of project prioritization and the use of the MDI keeps priorities evenly balanced across the organization. It can be seen here that the two organizations compared obtain and use money very differently, and that has a specific impact in the manner in which they define and execute their programs.

Integration as the *Engine* for Asset Management

Integration is becoming commonplace among organizations that practice asset management[12]. Integration plays an important role in the decision support that asset management provides as it ties the needs of various arms of the organization into one commonly viewable platform. Integration via data is commonly referred to as one of the most important components of an asset management program[13]. FCU has taken strides in the previous years to integrate data and manipulate it to provide effective risk communication that aids in where to channel resources for maintenance and sustainment. The result of integrating data can be seen in Figure 4, which presents a snapshot of FCU's pipeline risk assessment tool.

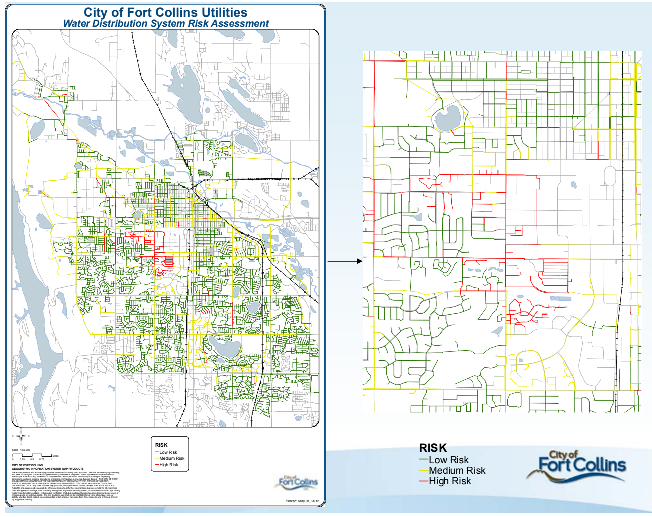

Figure 4 – City of Fort Collins Water Distribution Risk Assessment Tool[14]

This integration enables decision support using graphical features to represent relative risk to the delivery of water to customers. The Air Force, on the other hand, does not posses a single, integrated system that collects data and manipulates it to enable decision support[15]. This is driven by the vast differences in different infrastructure systems across the Air Force's portfolio. The adaptation of an integrated, multi-sector asset management system would be very beneficial in the long-term.

Key Research Findings

The research led to several findings identified by the author and the substantiation of findings identified by others. The first and most consequential finding was the realization of the need for improved infrastructure management at the lowest levels of the Air Force. During the case study at FE Warren AFB, engineers agreed that their processes required improvement and several issues hindered their ability to make informed infrastructure management decisions. The first and foremost issue was in the disparity and inaccuracy of data. This led the challenge of exactly where an asset is located and how it relates to the network. The communication barriers between offices within the squadron worsen the problem. It was found that one office had a map of the utility network printed in 2011 supporting their preventative maintenance efforts, while another office utilized current maps. Furthermore, issues pertaining to continuity mean that data and relevant information is usually not recorded, but retained as “corporate knowledge” by individual engineers.

The next key finding is the process of recording data and information is made difficult by absence of an integrated data platform. In the absence of readily available tools (i.e. integrated maintenance management systems) that enable engineers to document information, score condition and index criticality makes asset management extremely difficult at the lowest level. This finding supplements the findings of Harnly’s analysis of the Air Force’s Strategic Asset Management program. She states “Air Force efforts should align the data and Maintenance Management Systems (MMS) required for strategic level asset management with the data and MMS required for tactical level asset management[15].” Furthermore, it should be noted that information (i.e. physical information, condition information, criticality) should be aggregated and stored in one location to facilitate data manipulation.

The absence of integration and robust data along with the barriers that exist at tactical levels leads the subsequent finding. Given the undeveloped environment, engineers are forced to make due with the limited time, manpower and monetary resources they have. This leads to the “worst first” approach to infrastructure management.

Finally, the research reveals that when compared to other urgent mission areas, water infrastructure receives a relatively low priority in the Air Force's daily operations. This finding is realized in the absence of integrated MMS, disparity of data and tactical decision support tools offered to engineers. Water infrastructure will continue to be relevant to mission accomplishment and an ever-aging system but recognition of its importance in management within the Air Force has yet to be seen.

Way Ahead: *A Unified Effort*

The state of asset management in the Air Force is in constant evolution. Generally, the trend has been positive for solutions to be integrated Air Force-wide that enable more effective decision support. Continued growth and development in Air Force asset management will require a unified effort towards a solution. This unified effort should stress education at every level of the organization, teaching the principles of asset management to the youngest Airmen as well as those with the most experience. By informing the workforce of the Air Force's direction, innovative ideas will be introduced from all facets of Air Force Civil Engineering. Not only should the unified effort stress education, but also the systematic and programmatic approach to the problem. By obtaining leadership buy-in, engineers will take a systematic approach to set targets and report results. Using an integrated approach, failure consequence communication should be improved to portray risk to more than just one stakeholder. By improving the efficacy and perspective of the priority model, engineers may be able to better-predict how infrastructure will impact its surroundings in the future. It is simply through unity that will measure the success or failure of the future of Air Force asset management.

Future Research

The research presents several opportunities for further study to improve SAMM and develop alternative solutions to tactical asset management. A comprehensive test of SAMM would indicate areas where condition indices might be tweaked, further simplified or altered altogether. This test would take an installation with disparate records and data through the process, measuring the level of accuracy over time to indicate how the condition improves. Validation of the failure consequence indices would also present an opportunity for future research. Accomplishing a "failure consequence audit" would see researchers conduct a survey of key assets to assess the variance between each index. Ultimately, this research may lead to a method that effectively captures multi-faceted failure consequence in one simple index. Finally, the greatest opportunity for future research would be to broaden the scope of the case study from one installation to many. This case study would use a standard approach to garner the attitudes at a diverse set of installations to develop an optimized model that would better suit the Air Force's tactical need. Enabling tactical asset management and integration with strategic asset management will certainly yield great benefit to engineers at every level of the Air Force in the future.

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Captain Gregory (MS, Colorado State University) is on an Air Force Institute of Technology/Civilian Institutions assignment, earning an MS in Civil Engineering at Colorado State University. In previous assignments, his work in nuclear missile facilities engineering led him to synch over $4.5 million in missile facilities infrastructure projects. His work as energy manager for FE Warren AFB led to the identification of over $1 million in cost-saving energy projects. As Executive Officer for the 577th Expeditionary Prime BEEF Group in Afghanistan, he led battlefield circulations, group-wide reorganization efforts and authored essential historical documents that documented the Air Force's first Expeditionary Prime BEEF Group. Following his degree, Captain Gregory will teach asset management at the Civil Engineer School at Wright Patterson AFB, Ohio.

Appendix 2: List of Acronyms in Order of Appearance

SAMM ....Simplified Asset Management Model
AMP .... Activity Management Plan
FES ....Fire Emergency Services
MMS.. Maintenance Management System
GASB ....Governmental Accounting Standards Board
BSI ....British Standards Institute
EPA ....Environmental Protection Agency
IWR ....Institute of Water Resources
FCI ....Facility Condition Index
LoS.. Level of Service
ISO .... International Standards Organization
NRC .... National Research Council
MDI..Mission Dependency Index
NAVFAC..Naval Facilities
AHP.. Analytical Hierarchy Process
PAS-55..Publically Available Standard 55
IAM.. The Institute of Asset Management
IPWEA.. Institute of Public Works Engineering Australia
PoF.. Probability of Failure
CoF ....Consequence of Failure
CS ....Cost Savings
UCI .... Utility Condition Index
MAJCOM.. Major Command
SIR .... Savings to Investment Ratio
AFCEC .... Air Force Civil Engineer Center
HAF ....Headquarters US Air Force
GIS .... Geographic Information System
SMS ....Sustainment Management System
CD .... Condition Degradation
CIP .... Critical Infrastructure Program

SAI .... Service Association Index
SCI .... System Criticality Index
CES .... Civil Engineer Squadron
AFB .... Air Force Base
RPUID .... Real Property Unique Identifier
FCU .... Fort Collins Utilities
BEEF .... Base Engineer Emergency Force