RISK-BASED FACILITY MANAGEMENT APPROACH FOR BUILDING COMPONENTS USING A DISCRETE MARKOV PROCESS – PREDICTING CONDITION, RELIABILITY, AND REMAINING SERVICE LIFE

BY

MICHAEL N. GRUSSING

DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Civil Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2015

Urbana, Illinois

Doctoral Committee:

Professor Liang Y. Liu, Chair, Director of Research
Professor Khaled El-Rayes
Professor Nora El-Gohary
Professor Donald R. Uzarski

ABSTRACT

The U.S. building stock is large, diverse, and of critical importance to the economic and social well-being of the country. A proactive facility asset management approach is required to ensure these buildings support the purposes, functions, and missions for which they were built and continue to be used. For federal organizations, particularly those with large building portfolios, the goal is to deliver an acceptable level of performance while minimizing life cycle cost and risk. This research presents a framework that explicitly measures the risk and uncertainty associated with building conditions, and uses this framework to support better decisions for facility investment and resource allocation. The end result of this research provides a model for optimizing the selection and application of building work activities ranging from inspection to repair to replacement and recapitalization.

Realizing the importance of physical condition in the determination of a building's performance, a major objective of this research was to improve the statistical accuracy of building component condition prediction models by using a probabilistic approach. To do this, a discrete Markov chain model was proposed and developed. The result of this work is a robust process for developing Markov transition probabilities to model the condition degradation process using existing condition assessment data that has been acquired and continues to be collected for large portfolios of facilities. It solves the problems with data quality issues, effects from major repair interventions, and variable inspection observation times. It also provides a direct means of measuring uncertainty, reliability, and risk of component failure. Finally, it supports an unbiased process of determining expected service life for components by using the Markov chain model to compute the average number of time cycles to reach the failure state.

This probabilistic Markov chain prediction model provides a foundation towards a risk-based framework for facility management decision making. A Value of Inspection Information (VOII) model was developed by combining the probability distribution from the Markov prediction model with the decision tree logic from a value of information approach to calculate the benefit of inspection at a point in time using the last inspection results and the cost of component repair, replacement, and potential failure. In addition, the Markov prediction model was also applied to the work activity selection process, where the objective is the selection of the best activity to perform against a building component such that life cycle costs are minimized yet performance constraints are still satisfied. Traditionally these constraints have been condition based, but the proposed model also allows for risk based reliability

performance measures as well. Including risk more explicitly in the decision framework has the potential to change the selection optimization process.

The overall framework provides a logical approach that utilizes historic data to develop a more realistic model for building component condition and reliability. The approach analyzes component re-inspection information from large building assessment datasets (multiple inspections over time for a single component), to determine how past observed conditions correlate with future observed conditions to predict future reliability and service life. This model provides a stronger correlation to future condition and reliability estimates compared to an age-based deterministic model, and helps to counteract the situations where the recorded age of a component is not representative or expected design life is unknown. This allows a facility manager to proactively manage facility requirements using real-time risk-based metrics aligned with a data-driven probabilistic process.

To my son Teddy whose immense curiosity is my source of inspiration, and my wife Courtney whose patience and support made this work all possible.

ACKNOWLEDGEMENTS

This dissertation represents the culmination of a long journey for me, and there have been so many people who have helped me along the way. First and foremost, I want to acknowledge my family and friends who have provided such great support and encouragement over the last five years. To my parents especially, who have always given me everything a person could ever need to succeed, none of this would be possible without the foundation you have laid for me. And to my wife Courtney, who has been by me through this process step-by-step, I could not have gotten through the tough times without your positive outlook, encouragement and support.

I also want to thank my co-workers and colleagues whom I have had the privilege of working with over the years. This thesis is an extension of everything I have learned in my career at the US Army Corps of Engineers Construction Engineering Research Laboratory – experience I have gained in working with a great group of people all across ERDC-CERL, in the Engineering Processes branch especially, and with the Sustainment Management Systems team in particular. There are also so many visionary and dedicated people I have worked with at various agencies and organizations within the Army, the Navy, the Marine Corps, the Air Force, and NASA, just to name a few. It is their commitment to lifecycle asset management that has produced the invaluable dataset of facility information that made this study possible.

Finally, I would especially like to thank my committee for their support and guidance. To my advisor, Professor Liang Liu, who has been a wonderful coach throughout this process; it has been such a pleasure to work with you. You have given me freedom to explore and find my niche, while still providing the framework to guide me to this point, a delicate balancing act that you have achieved quite deftly. To Professors Khaled El-Rayes and Nora El-Gohary, I thank you for all for all your suggestions, feedback, and advice. You are truly experts in your fields, and your classes in optimization and data structures, respectively, helped to stimulate numerous ideas that have grown into prominent aspects of this thesis research. Last but not least, I would like to thank Dr. Donald Uzarski who has served numerous roles over my career, from supervisor, mentor, colleague, and now committee member. You are a pioneer in the science of facility asset management, and I am a fortunate to be able to work with such a passionate and driven researcher and engineer. You encouraged me to pursue this endeavor, and backed me up with your time and support all along the way. To all of my committee members, I hope this research is just the beginning of many future collaborations, as I look forward to working together further to advance the knowledge-base of construction management and life cycle asset management.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 - INTRODUCTION

1.1 Scale and Significance of the United States Buildings Portfolio

Buildings are constructed to provide support to their owners or occupants in a variety of purposes, functions, or missions. These missions may include, among many others, providing shelter for people or products, providing space to conduct production, maintenance, or health related operations, or providing an environment for education, training, or general assembly. From these missions have emerged different types of buildings (including residences, offices, hospitals, commercial retail, warehouses, factories, and schools) to support the general purpose for which they are built. In the case of the United States and other developed countries, the overall building stock has evolved over the course of decades, and in some cases, even centuries. New construction activities result in the increase in the building stock, and rehabilitation construction activities result in improvements to the current stock. In general though, investments in these construction activities are made with the intention that dividends will accrue through new capabilities or increased productivity, improved living conditions, and greater prosperity to the public (Aschauer, 1990). From an economic perspective, buildings may either directly facilitate the production of goods and services, or improve resource efficiency of that production. But from a social perspective, buildings can also serve to improve the quality of life of its occupants and users (Brand, 1995).

For many organizations, buildings represent a significant portion of their operations. In 2014, nonresidential construction spending for lodging, office, commercial, health care, educational, religious, public safety and manufacturing facilities was over $300 billion (United States Census Bureau, 2015). In 2013, operating costs totaled $21.5 billion (U.S. General Services Administration, 2015) for U.S. government owned building assets alone (a small portion of the total building stock). Furthermore, the U.S. building sector accounts for 41% of primary energy consumption, 44% more than the transportation sector (U.S. Department of Energy, 2015). The staggering magnitude of these resources and scale of the portfolio puts into perspective the significance of building structures to the economy and society. Today, new technologies in data science and business analytics are helping to find better ways to deliver more with less resources, and that is no less the case with building facility management. Much effort has been focused on delivering better and more efficient ways to construct these buildings; however, the investment in a particular building asset does not end with the completion of construction. A long tail of requirements for labor, equipment, material resources, and capital likely follows as one operates, maintains, renovates, and eventually demolishes a building (R.S. Means, 1996). As a result, organizations must also strive for new ways to operate, maintain, and rehabilitate the buildings that currently exist.

1.2 The Importance of Effective Facility Asset Management

Buildings require an initial capital investment during construction, as well as periodic capital infusions throughout their life cycle to modernize, otherwise they become obsolete and irrelevant to their users. Buildings also require continuous operating expenses, such as energy, water, and maintenance, throughout their life in service. Without proper funding and investment, buildings will degrade more quickly and obsolesce, thus resulting in adverse effects on performance. When this happens, a building becomes less efficient in supporting its primary mission. It costs more to operate, while generating less benefit to its owners or occupants.

Even with proper funding, responsible building management requires that one have a keen insight on what to fix, when to fix it, and the construction activities and techniques required to address these "fixes." This can include sustaining an existing facility, improving a deteriorated facility, upgrading a building to meet new user demands, energy efficiency requirements, etc., or even total replacement of a building. In order to make the most prudent decisions, a building manager must have a solid background of knowledge on the cost of the solution, as well as the impact that the solution will provide. The ideal scenario is to provide a solution that meets the building owner and building user requirements at the lowest total cost throughout its life cycle.

The effects of inadequate or poorly allocated funding has been well documented, especially for public infrastructure. The American Society of Civil Engineers (ASCE) reports on the state of America's infrastructure biannually and the overall grade in 2013 was D+, equaling "Poor" (American Society of Civil Engineers, 2013). As a developed economy with a developed infrastructure that has evolved over generations, the solution to improving this infrastructure will not be solved solely through the construction of new assets. It will also require a greater commitment to better sustainment, restoration, and modernization of the building assets that already exist. This is especially the case in an era of limited resources. Building facility managers are engaged in a struggle to reduce energy and materials dependency, as well as environmental impacts and greenhouse emissions. Due to these factors, a greater portion of construction spending in the US is shifting from the construction of new assets to the rehabilitation of existing asset (Laefer & Manke, 2008; Cohen, 2004). As this happens, the field of construction management has expended beyond just the construction phase to include the total life cycle of the structure (Dell'Isola & Kirk, 2003).

Asset management methodologies have been in place for decades for several infrastructure domains, including roads and pavements (U.S. Department of Transportation, 2015), railroads (Construction Engineering Research Laboratory, 2012), bridges (Abu Dabous & Alkass, 2008), and distribution pipelines (Simonoff, Restrepo, & Zimmerman, 2010). Responsible for overseeing one of the largest asset portfolios in the world, the Federal Highway Administration (FHWA) provides the following definition of asset management:

> “Asset management is a systematic process of maintaining, upgrading, and operating physical assets cost-effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision-making. Thus, asset management provides a framework for handling both short- and long-range planning.” (U.S. Department of Transportation, 1999)

Common among these asset classes discussed above is 1) their existence as part of a network, and 2) their continuous linear nature. This is important because failure or loss of performance in one small segment of the network can have a disproportionate and catastrophic effect on the entire system if the assets are not monitored and risk is not managed appropriately. This has led to a premium importance put on the risk management of these types of networked infrastructure. In addition, because of their linear nature, one portion or segment of the asset is generally similar to other segments in terms of its structure, design, materials, and performance requirements. This makes a consistent management approach across the segments of a linear asset type feasible. Finally, management of these linear asset types has taken an increased importance due to public safety concerns. In other words, risk management is critical for roads, bridges, railroads, and pipelines due to the potential public health consequences associated with a failure.

Asset management practices for building facilities have generally developed at a slower pace compared with the linear infrastructure classes listed above. A large part of this is due to the challenges of implementing a consistent management approach across the diverse domain of building assets. These challenges exist because a building is a vast array of integrated systems and components, with different construction disciplines typically responsible for each system (structural, electrical, plumbing, HVAC, etc.). While there are common systems across all buildings, the size, type, and configuration of these systems is usually unique from one building to the next. A large portfolio of buildings assets will typically contain a vast spectrum of building use types, construction types, and performance requirements for each. As a result, the complexity and uniqueness of building assets make the consistent management of each building difficult.

In addition, building asset management practices have evolved more slowly than their linear infrastructure counterpart due to their ownership profile. The infrastructure stock for roads, bridges, railroads, pipelines, etc., is usually owned by large entities such as federal, state, and local governments, as well as large companies such as utilities and railroads. These entities manage a large portion of capital intensive assets which are a major element of their core business. In some cases, asset and risk management practices for these infrastructure classes are mandated by law. Regardless, it usually makes economic sense to closely monitor and manage condition of these assets as a group since they represent such a huge capital investment. The stock of building assets, on the other hand, is owned by millions of different private citizens, businesses, corporations, and other organizations. Many of these buildings represent the sole infrastructure asset in an owner’s portfolio. Managing the condition, maintenance, and performance of that building is usually not the primary function or concern of that individual or business, thus sometimes leading to neglected sustainment for some buildings. For those individual building owners that do recognize the importance in protecting their long-term investment, their limited portfolio usually allows them to track building maintenance and repair needs without a formal enterprise asset management approach. Traditional building inspections alone, commissioned when needed, provide sufficient information to make prudent investment decisions.

Numerous influences, however, are currently evolving that are creating greater awareness of the need for structured building life cycle management similar to other civil infrastructure classes. One such influence is the rapid expansion of developing world economies, including the infrastructure to support them. The demand for basic commodities is increasing the costs for basic building materials such as concrete, steel, wood, and copper. As these material resources become more scarce and expensive, optimizing their allocation takes on greater importance and consequence. New building construction requires a significant amount of basic materials for construction of its foundation and superstructure. If an existing building is properly managed to be retrofitted or renovated to serve the same purpose, a large portion of those material requirements and expenses is averted. By the same reasoning, renovation and reuse can also help to divert construction waste materials away from landfills (Shami, 2008). Not surprisingly, the concept of sustainability has been a huge factor driving the need for improved building asset management.

Another factor affecting the need for building asset management is the scarcity of land available to build new construction, especially in urban areas. The practice of adaptive reuse of existing buildings has been gathering attention as a viable alternative to new construction (Shipley, Utz, & Parsons, 2006). Similarly, historic preservation policies (Pfaehler, 2009) have helped to make the demolition of older existing buildings to clear land space difficult. Because of these issues, the sustainment and rehabilitation of existing buildings has become a more significant aspect of the building construction market, and is being utilized as a more viable alternative to new construction for many inner-cities, cultural and historic districts, and even military bases.

As the lifespan of these structures gets extended out due to renovation, modernization, or adaptive reuse, the life cycle management of that structure becomes increasingly important. The heavy infrastructure systems discussed above, such as bridges, roads, and utilities, have design service lives ranging from 10 to 100 years, making life cycle management a necessity. Most building components or systems, however, have service lives ranging only from 5 to 35 years (Housing Association Property Mutual, 1995). If the maintenance and replacement of these components is neglected, the building can quickly become unfit for use, and further deterioration can make reuse of renovation a much less attractive option. Because traditionally not enough funding was devoted to maintenance and repair, owners are now accumulating an ever increasing maintenance deficit, which leads to premature failures and premature renewals, or buildings and systems that cannot be renewed at all (Smerkers, 2008). As a result, asset management principles for building facility assets are quickly being mandated and adopted, primarily with owners of large building asset portfolios such as local and state (Governmental Accounting Standards Board, 1999), and federal governments (Federal Register, 2004), as well as some large private corporations.

1.3 Motivation of this Research

A rapidly aging infrastructure and building stock in the United States and across the world jeopardizes the ability to support mission accomplishment, economic growth, and social well-being at the status quo. Moreover, rapidly expanding demands on some infrastructure will likewise make the status quo greatly inadequate in the near future. This requires two highly interrelated strategies:

1. Introduce new capabilities and capacities into the infrastructure stock to meet projected demand.

2. Adequately manage, maintain, improve, and renew the existing infrastructure stock to slow performance degradation and fill demand gaps.

Therefore, a decision support model is needed for planning facility improvement activities across a large portfolio of assets. This model must incorporate sound economic and financial metrics, asset life cycle performance changes, as well as risk and uncertainty considerations.

This research proposed a methodology that identifies optimal building investment strategies for maintenance, repair, and rehabilitation (MR&R) that maximize facility performance and minimize the negative impacts of owning/operating a facility. The model needs to consider all life cycle phases, varying condition states, and multiple stakeholders. It needs to consider all costs including external costs to the public (such as environmental) and users (such as risk and reliability uncertainty due to downtime and degraded performance). It will consider data collection methods to build this knowledge base that are both objective and repeatable but also cost efficient. And finally, it will provide powerful consequence analysis and visualization tools to facility managers.

When developing a life cycle approach to facility management, identifying and measuring the current state of facility performance is important, as is predicting the future expected state. This change in state occurs due to a number of complex factors. For example, physical condition changes over time due to the effects of gradual deterioration, intermittent damage, and even repairs. Likewise, the functional capability changes due to the effects of obsolescence and changing user requirements, as well as any restoration and modernization work accomplished.

Predicting the deterioration and future performance state of buildings, and specifically building components, has remained a difficult challenge. This is due partly to the complexity of building assets, and their many diverse component parts. It is also due to several factors affecting future building performance that are difficult to measure, identify, and predict, such as environmental factors, the amount of use and abuse it experiences, and the level of maintenance performed. Lastly, it is due to limited availability of historic datasets that contained meaningful performance indicators at a system or component level. Without these large-scale datasets, constructing a representative model of component performance and reliability over time in service has proven difficult.

However, facility condition assessment initiatives conducted on large facility portfolios across several federal installations are now producing the information necessary to support such an analysis. These standardized assessments result in a time-based quantitative condition metric at a component level.

This study uses data mining procedures on this large facility component database to explore and extract meaningful relationships between time in service and condition, reliability, and performance levels. This is a significant step towards the development of a comprehensive facility life cycle MR&R model that incorporates infrastructure economics (financial and performance metrics) with uncertainty (risk and reliability) for improved decision making.

1.4 Problem Definition

The purpose of this research is to identify new and improved approaches that build off existing capabilities and methods for the asset management of building facilities. The goal of facility asset management related to buildings is to determine the optimal application of work treatments such that the input costs is minimized, given constraints on resource availability and performance standards. This optimization can occur across all components of a system, all systems of a building, and all buildings in a facility portfolio. The ideal scenario is to provide a solution that meets the building owner and building user requirements at the lowest total cost throughout its life cycle. This requires accurate and up-to-date “knowledge” of the building and all of its constituent elements.

Buildings directly and indirectly contribute to the accomplishment of mission (public/non-profit organization) or generation of revenue (private/for-profit organization). The aging, obsolescence, and general deterioration of these buildings (and their systems and components) results in an elevated risk profile. Maintenance, repair and capital renewal activities all affect performance and risk. Many organizations have large portfolios of building assets that are interrelated in complex ways with each other, as well as other types of infrastructure such as transportation and communications systems.

As stated above, the overall goal is to minimize the total cost of ownership in facilities, which includes cost of operating, sustaining, restoring, and modernizing them. There is a limit to minimizing this cost though, as the facilities still need to meet a host of performance requirements over a certain time period, usually termed the facility life cycle. This requires restoration and modernization to continually balance the equation of changing performance capability versus performance requirements. Even with all of this, the facility has a finite life, and eventual demolition (and possibly new construction if its services are still needed) is imminent.

Thus, the performance capabilities and requirements are an important aspect of managing the facility. Facility performance is not a single entity, but depends on a number of issues, including safety, reliability, quality of life, mission support, efficiency, sustainability, etc. Each of these individual aspects depends on the condition and functional configuration to provide a level of performance, as well as the type of mission, use, and operational tempo which establishes the requirements for that level of performance. The probability of not meeting a performance requirement, and the consequence of that failure, determines facility risk.

The costs to operate, sustain, restore, and modernize a facility to meet all these performance requirements are not fixed. They depend greatly on the mission being performed, the type and size of facility, operational tempo, and prevailing local rates for energy, water, labor, materials, and equipment. But they also depend greatly on the current physical condition and current functional capability/configuration of the facility to meet performance requirements. Finally, they depend on what those performance requirements actually are, which can vary greatly. Therefore, the cost to operate and sustain to meet performance requirements is usually less in the near term if the facility is in a better condition and functional state. System, components, and equipment are generally newer, better maintained, and more efficient. However, maintaining a higher condition and functionality state over time to meet more stringent performance requirements also usually costs more over time.

The current physical condition will have arrived at such a state, from a past condition state, due to the effects of deterioration over time, as well as any sustainment work that was accomplished in that time. Likewise, the current functional capability will have arrived at such a state from a past state, due to the effects of obsolescence and changing user requirements, as well as any restoration and modernization work accomplished.

The result is that a small change in how the facility is managed and maintained can have a large impact on the cost of ownership, the condition and functionality trends, and the performance profiles. There is a myriad of options for operating, maintaining, and applying sustainment and modernization work at different times to different systems and components, and the key is finding the best application of options that minimize total cost and still meet performance requirements over the life cycle. The potential benefit is that tweaking certain aspects of the operations, maintenance, and recapitalization plan may result in drastically lower total costs with better performance, but this has to be done over a life cycle perspective.

1.5 Research Objectives

The primary objective of this research is to develop a probabilistic framework for the characterization of building component condition degradation over time based on actual inspection data derived from the large and growing dataset of inspection information collected via the Department of Defense's (DoD) Facility Condition Assessment Program. Once this model is developed, the approach will be incorporated into the following models and processes:

1. An approach for estimating expected component condition, reliability, performance, and service life over time.
2. An approach to optimize the timing for component inspections considering risk, using the condition degradation model developed in the research and applied to a value of information decision tree.
3. An approach to select the optimum type and year for component work activities based on the newly developed condition prediction model.

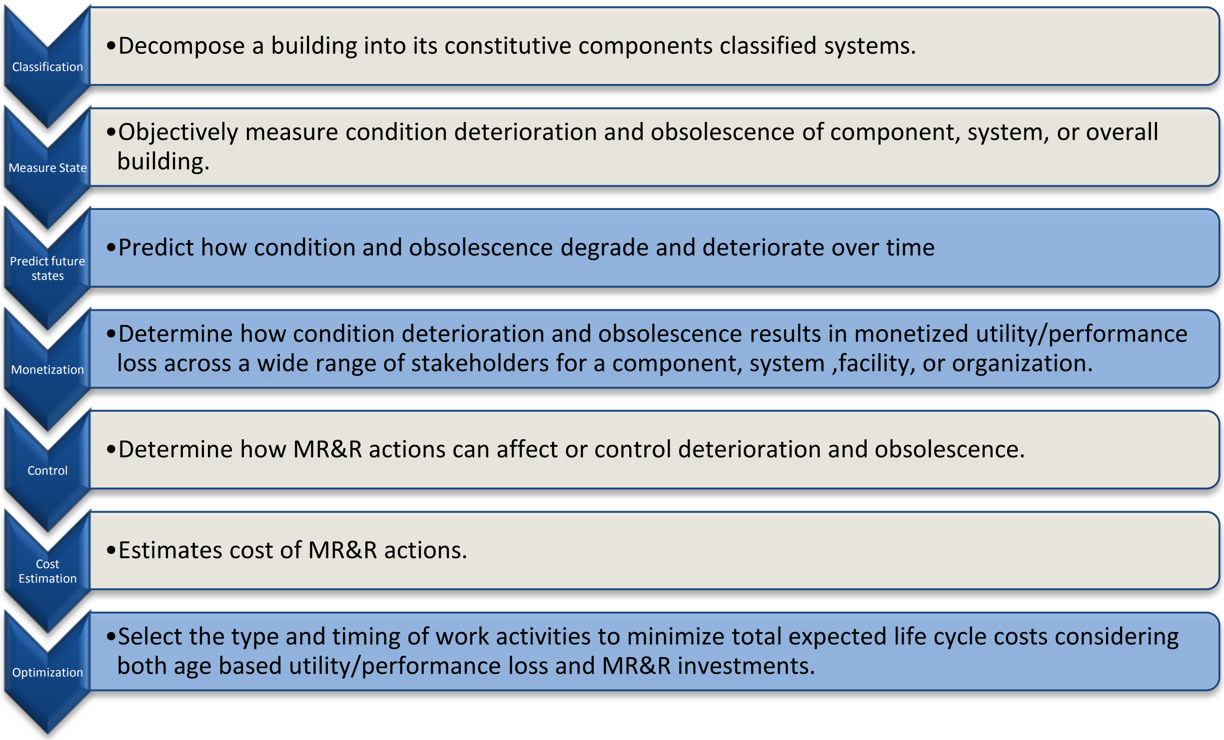
The result is an optimized multi-year facility work plan for a range of system and component level activities that considers various life cycle cost drivers, performance factors, as well as risk and uncertainty.

1.6 Research Methodology

To accomplish the proposed research goal, the ongoing model development has identified the following objectives, summarized in Figure 1. Highlighted areas of the figure represent the primary areas of research and development for this work.

- A model to decompose a building into its constitutive components, and classify those components into systems. (Classification)
- A standardized method(s) to objectively measure the condition deterioration and functional obsolescence of a component, system, or overall building. (Measure State)
- A model (or models) to predict how deterioration and functional obsolescence progress over time. (Predict future states)
- A model to determine how MR&R actions can affect or control deterioration and functional obsolescence. (Control)
- A method to determine how condition deterioration and functional obsolescence results in global performance loss for a system or building. (Monetization)

- A model that estimates the cost of work activities, life cycle operations, and performance loss and risk. (Life Cycle Cost Estimation)
- A method to select the type and timing of work activities which minimize total expected life cycle costs, subject to performance constraints. (Optimization)



- Decompose a building into its constitutive components classified systems.
- Objectively measure condition deterioration and obsolescence of component, system, or overall building.
- Predict how condition and obsolescence degrade and deteriorate over time
- Determine how condition deterioration and obsolescence results in monetized utility/performance loss across a wide range of stakeholders for a component, system ,facility, or organization.
- Determine how MR&R actions can affect or control deterioration and obsolescence.
- Estimates cost of MR&R actions.
- Select the type and timing of work activities to minimize total expected life cycle costs considering both age based utility/performance loss and MR&R investments.

Figure 1. Research Approach and Steps

As stated above, this research attempts to identify a process for determining and optimally selecting the MR&R actions which minimize facility stakeholder costs while maintaining facility performance. This analysis is conducted over several years of the building life cycle considering all pertinent factors that occur over that life cycle (such as deterioration, periodic inspections, or maintenance and corrective work treatments), in addition to the time value of money. Finally divestment (such as demolition) at the end of that time period is also an important consideration. The optimization is subject to certain constraints on resource availability (maximum annual budget available) as well as minimum acceptable performance levels (allowable condition state thresholds at any point during the analysis period).

1.7 Research Significance

This research provides several contributions to the body of knowledge for facility asset management and construction management. First, it builds on the past work done in condition assessment, condition prediction, and discrete Markov models to develop a probabilistic approach to building component condition state prediction, and proposes a novel process for developing discrete Markov Chain transition matrices for these building components using existing building assessment information. This methodology allows for variable observation intervals to estimate the transition probabilities and test the discrete Markov chain model. The development of the Markov chain process and transition matrices better predict condition state and condition index over time.

The research proposes a formal mathematical definition of failure to develop a reliability index for a building component using the same process. This is used to develop a risk-based framework that applies the Markov model for multi-year building component work activity selection and optimization of total cost of ownership. This framework uses both the condition index and reliability index as performance constraints in the optimization model. The framework is developed and illustrated for both a single component decision process, and whole building optimization. Finally, a process for risk-based component inspection scheduling is developed, using the Markov prediction model integrated with a value of information decision tree logic model. The result is an ability to calculate the value of an inspection at a certain point in time, given the cost of different work activity events and the results of past inspections. This provides a more effective way to allocate inspection resources and attention to the most critical components as a way of maximizing the return on inspection costs.

1.8 Report Organization

This report is organized into the following chapters:

- Chapter 1 provides an introduction to the motivation for this research, the scope and importance of building facilities, and the need for improved asset management approaches, as well as a discussion of the problem statement, and a summary of the proposed research objectives, and the significance of the research to the field of construction management.
- Chapter 2 provides a background of asset management practice and current approaches to building asset management, followed by a literature search of past and current research in condition assessment, condition prediction, and maintenance and repair optimization.
- Chapter 3 discusses the model framework and methodology, including a discussion of the data used to develop the transition probabilities, the approaches used to construct the transition

matrices, and the use of the model for service life estimation and reliability indexes, and verification and validation of results.

- Chapter 4 discusses the development of the value of inspection information model and presents an example case study for the optimization of inspection schedules for components.
- Chapter 5 discusses the development of a single component MR&R investment optimization decision analysis, including an example application that includes reliability performance factors and energy improvement alternatives.
- Chapter 6 presents the application of a whole building MR&R investment optimization approach that uses the above models to identify the optimal multi-year activity selection and considers the interactive effects of component condition on system and building level reliability.
- Chapter 7 concludes with a summary of the work and significant results, research contributions, and recommendations for future research related to several aspects of the study.

CHAPTER 2 – BACKGROUND AND LITERATURE REVIEW

2.1 Facility Asset Management - Current Approaches and State of Practice

Traditional building asset management functions have typically fallen under the purview of facility managers. Their roles have customarily included the administration of daily building operations, as well as the planning and scheduling of repair and renewal work. It is their responsibility to optimize expenditures and maximize the value of the assets over their life cycle. In this process, facility managers face many difficult decisions regarding how and when to repair their existing building stock in a cost effective way. In the past, facility managers have had limited tools, literature, or intelligent computer software to assist them in this decision-making process.

One significant step towards better facility management was the establishment of International Facility Management Association (IFMA), the professional association for facility managers, in 1980. IFMA classifies facility management responsibilities into several core competencies, including (International Facility Management Association, 2014):

- Communication, Emergency Preparedness and Business Continuity
- Environmental Stewardship and Sustainability
- Finance and Business
- Leadership and Strategy
- Operations and Maintenance
- Project Management and Quality
- Real Estate and Property Management
- Technology

Common among all the areas is that they involve mid- to long-range initiatives. Key to the building asset management philosophy is that building facility managers can perform construction related activities, including maintenance, repair, renovation, and modernization, at strategic times in an asset’s life cycle to sustain and improve condition and achieve an optimal level of performance. This requires targeted information be gathered and archived about the state and performance of the building and its constitutive systems and components. The typical means of gathering this information is through building assessments and inspections (Ewada, Zayed, & Alkass, 2010).

2.2 Building Ownership Profile and Importance of Stakeholder Perspective

The actual ownership of a building is one of the most important factors in how it will be managed from a life cycle perspective. The way in which the building supports the primary mission of the owner has a major influence on how that asset is viewed. Building ownership can be arranged in several categories, but the most basic categories are private sector building ownership and public sector building ownership.

The largest portion of the nation's building stock is comprised of private ownership, which includes residential homes or apartments, where a single family or individual owns or is responsible for only one property. There are also many businesses (both small and large) that own a limited number of industrial or commercial building properties, such as warehouse, office, and/or retail space. Finally, there are large corporations that may have a significant portfolio of building properties to be managed. It is for these large building portfolios that the adoption of enterprise wide asset management principles are most beneficial, since the scope of their assets and the significant amount of capital invested in them dictates a prudent management approach for their facilities.

Public building owners include federal, state, and local municipalities. These organizations typically have multiple building properties that are owned and managed, if not hundreds or thousands. These building assets represent a significant investment of tax payer dollars, and as a result, life cycle management may be a mandated requirement. Large federal building owners such as General Services Administration (GSA) and the Department of Defense (DoD) also have a quite diverse range of building types to be managed, which makes the consistency of the building asset management process a unique challenge.

For example, military installations are comprised of many of the same types of buildings, facilities, and infrastructure assets found in a small city, including houses, hospitals, schools, office buildings, factories, warehouses, and even airports, in addition to very specialized facilities that support the defense mission. These buildings are vital to the organization's mission, and serve an important purpose to housing troops, as well as for the day-to-day training, operations, and maintenance for the military. They also consume a large amount of resources, both during construction as well as operations, maintenance, and renewal. As these facilities operate in service and age, they require intermediate maintenance and repair actions, and eventually recapitalization to keep them functioning. When these actions are deferred, as has been the case with some DoD facilities, MR&R backlogs can rapidly accumulate. The last time the individual DoD services were polled by the Government Accountability Office (GAO) to estimate the MR&R backlogs for their facilities, the Army, Navy, and Air Force estimates were $20.4 billion, $27.8 billion, and $9.6 billion respectively (Government Accountability Office, 2008). These staggering numbers highlight the importance of life cycle asset management as a means to prioritize and manage these capital resource requirements appropriately.

While there are similarities and opportunities for “best business practices” to be adopted in building asset management, there are also substantial differences that exist between private sector and public sector building owners. While there are many large private sector facility owners such as Walmart, General Motors, and Boeing, the largest of these organization’s facility portfolio is usually no more than several hundred million square feet. By contrast, the Department of Defense (DoD), which is responsible for nearly 57% of federal facility assets, owns and operates over 276,000 buildings totaling nearly 2.2 billion gross square feet (GSF) and $585 billion in plant replacement value (PRV) (U.S. Department of Defense, 2014). This portfolio of assets spans a wide variety of facility types including maintenance, administrative and office space, housing, storage, and medical care. Thus, there is a significant difference in portfolio scope and management complexity, facility size, and facility type between federal and private sector interests.

In addition, there is an inherent difference in how federal and private sector businesses operate. Private sector assets can usually be linked to top line revenue production. This is difficult to do for federal facilities, since revenue is generally not generated from their operations. Instead, federal facilities support the production of more intangible services, such as national defense. Thus, it is difficult to communicate how potential failures in facilities affect the bottom line profits. Failures in federal facilities can have an impact on mission, but that impact is more difficult to monetize. However, since both private and federal businesses have operating expenses that they want to minimize, the common link is the need to develop asset management methods which seek a reduction in overall life cycle costs (including both operating expenses and capital expenditures). This can be done by proactive maintenance strategies that reduce unplanned and reactive breakdown maintenance, while extending the life of capital expenditures.

2.3 Building Asset Management Goals and Objectives

Infrastructure Asset Management is the discipline of managing decisions for sustainment, restoration, modernization, and eventual replacement across the life cycle for a portfolio of built assets. This requires that the building structure meets reasonable expectations for levels of service in a cost effective way (Salem, AbouRizk, & Ariaratnam, 2003). The first part of this requirement is achieved by defining an objective and measurable standard or level of service (LOS) for building performance, which may include minimum condition grades based on impact of asset failure. The building's LOS is controlled by sustainment (preservation) and restoration/modernization (capacity expansion based on strategic objectives). The second part of this requirement is to provide the required LOS using a minimum whole life (life cycle) cost approach.

Asset management decision support is thus made up of two critical but sometimes opposing goals: 1) the efficient allocation of resources through lowest sustainment, recapitalization, energy, and user costs, and 2) limiting the risk of failing to achieve the required level of service, through higher facility performance, better system reliability and availability, and lower rates of failure with less adverse consequences.

2.3.1 Allocation of scarce resources

As mentioned in the introduction, a large amount of resources is invested into a building. A building requires a significant investment commitment, not only when it is constructed or purchased, but also as it is put into service, maintained, renovated, and modernized. Investments in these building assets are made with the intention that dividends will accrue through new capabilities or increased productivity, improved living conditions, and greater prosperity to the public. Building construction essentially transforms liquid capital (and the material, labor, and equipment use purchased with this capital) into illiquid but physical capital assets that provide and support services (Grigg, 2010). For a large portfolio, this construction is usually accomplished over a long period of time, as the stock of building assets grows and evolves over generations. In the public realm, this capital comes from the issue of long-term bonds, or from direct appropriations by government. However, this investment represents a finite life that is tied to the physical asset. When they reach the end of this lifespan, some buildings are replaced as a whole, (if needed), while others are refurbished or replaced on a system or component basis as they wear out. In both cases, it requires additional capital to restore the performance and capability of the facility.

In addition to the capital investment that goes into construction or renovation, a building continues to consume resources during its use. Therefore, when weighing the different alternatives for an existing facility or a portfolio of buildings, it is important to consider all costs across the remaining life cycle. These include energy, water, waste, maintenance, and repair, as well as the larger construction activities. Because of these factors, the concept of sustainable development is becoming a more important issue, as embodied in recent initiatives such as Leadership in Energy and Environmental Design (LEED) standards (U.S. Green Building Council, 2012). While one of LEED's primary functions is to guide the design of new high performance and sustainable facilities, there are implications for existing buildings as well, since a continued shift towards renovation and adaptive reuse conserves land, basic materials, and landfill space. As a result, to acknowledge the fact that a substantial portion of the nation's building stock will continue to be represented by older existing buildings, the United State Green Building Council (USGBC) has published LEED criteria for existing buildings as well (Hicks, 2005). For existing buildings, optimal resource allocation requires timely maintenance and repair before more extensive damage and deterioration progresses to the point where replacement is the only option. It also requires implementing energy retrofits to improve building efficiencies where appropriate (Kollie, 2009). To accomplish all of these resource conserving initiatives ultimately requires an asset management program that tracks energy, water, and waste usage, condition trends, and maintenance and repair events over the full life cycle (Funk, 2010).

2.3.2 Management of infrastructure risk

The second aspect of building asset management is managing the risk associated with failing to achieve the required Level of Service discussed above. Since buildings are a complex collection of components arranged into systems, it is important to realize that buildings usually do not fail in a global sense, but their systems and components do fail. Building component failures result in risks associated with a building's life safety, unexpected downtime (system is unavailable or unreliable), or unexpected costly repairs (Government Accountability Office, 2006; Government Accountability Office, 2007).

As a result, there can be a unique level of service defined for each system or component of the building. In addition, there can be many functional aspects that make up a standard, each of which has a different bearing on risk, and each of which changes with time. These components include the need to respond to new requirements and increased capacity as demanded by building users and occupants, as well as the need to address deterioration, damage, and obsolescence that accumulates in building systems and components over their life cycle.

These aspects affect both the demand on the building (new requirements or increased capacities) and the capability to supply that demand (affected by component deterioration, damage, and obsolescence that accumulates during the life cycle). How often the system capability meets or exceeds this demand is one direct measure of reliability. Demand that can no longer be met, or is predicted to fall short at some point in the future, (in full or at some reduced rate) is an indicator of system failure. This probabilistic likelihood of system failure (or some degree of failure) is one of the fundamental bases for measuring infrastructure risk, along with the causal effect (consequence) of that failure (Staneff, Ibbs, & Bea, 1995). As a means of developing the concept of infrastructure risk for asset management, a number of terms are discussed below.

Potential infrastructure capacity is the potential capability of the building to produce output or provide a level of service, in the absence of reliability issues. All buildings are built to fulfill some purpose and meet some required level of service, and ideally, the potential capacity must match or exceed this requirement. If it does not, new capacity via modernization or new infrastructure footprints must be added. As a result, potential capacity usually changes very little in a building over time. Actual infrastructure capacity is the actual capacity of a facility asset at a specific point in time. Actual capacity may be lower than potential capacity due to partial or full unavailability of a system or systems for a number of factors. While potential capacity is fairly constant, actual capacity changes over time.

Infrastructure Reliability is the consistent production or expectation of similar results, or in the case of buildings, consistent actual capacity or level of service. This is a measure of the variability of actual capacity. An asset may be capable of producing at some capacity, and may achieve a high actual capacity on average, but if it is expected to operate at this level on a consistent basis (or provide that level on demand when needed), it needs to be highly reliable. There can be little variability in capacity and performance levels. This is typical of critical assets that operate continuously, so required reliability is related to infrastructure criticality.

Infrastructure Risk is exposure to the chance of injury or loss. This is the probability that infrastructure's actual capacity falls below some minimum required level of output or service, resulting in undesirable consequence, mainly due to reliability issues. If reliability is low, then the actual capacity can vary greatly from the ideal. To lower risk, one either needs to increase ideal capacity (overbuilt or redundant system) or increase reliability. Infrastructure Safety is the freedom from the occurrence or lowering of risk of injury, danger, or loss. This is a special case of infrastructure risk as discussed above. This is the probability of actual capacity falling below a lower safety threshold where injury consequences are likely. These consequences are usually more severe than the loss of output consequences.

Infrastructure Performance is the manner or efficiency in which an infrastructure asset fulfills its intended purpose to achieve required capacity. Two assets may be able to achieve the same capacity, but they may require completely different levels of resource input to make that happen. This may be due to different potential capacities, different reliability profiles, or different levels of manpower, materials, carbon emissions, energy usage, etc. The objective of asset management is to maximize performance given capacity requirements related to output or yield and reliability requirements related to risk.

In the definitions above, there are essentially two variables that affect infrastructure performance and risk. One is the potential capacity, which is based mostly on the initial built design and configuration, but could also be increased by modernization or adding additional footprint (or redundancy). The other is the reliability which decreases due to deterioration, obsolescence, etc., and can be improved by infrastructure repairs, component replacement, preventative maintenance, and even periodic inspections.

For existing buildings, much focus is set on the reliability aspect, since it is directly linked to risk, and can be improved by maintenance, repair, and even inspection activities if those support proactive MR&R decisions (Jido, Otazawa, & Kobayashi, 2008). However, a building's potential capacity is also an important issue when determining if a building renovation is a viable option. Therefore, both aspects should be considered as part of an effective asset management plan. In order to make inferences about building risk and reliability, facility information is needed to understand the condition and performance of the building, along with the user performance requirements (Sarja, 2006).

2.4 Traditional Facility Asset Management Steps

As mentioned previously, asset management principles have been used in the highway and other infrastructure domains for decades, and these principles have been applied to building facilities as well. As a result of this prior work, the basic framework for facility asset management has already been defined, and consists of a number of activities that can be broadly categorized into the following steps: 1) Inventory, 2) Needs Assessment, 3) Work Identification, 4) Work Activity Prioritization and Plan Optimization, and 5) Consequence/Trade-off Analysis.

2.4.1 Facility Asset Inventory

Before a facility manager can begin to manage a portfolio of buildings, he/she needs to understand what assets currently exist. This includes an itemized and accurate inventory of the buildings in a portfolio, with the key attribute information about those buildings. Within each building, a structured hierarchy describes the major systems and components, in addition to their material attributes, locations, expected service life and cost for replacing.

The building level inventory information describes the building facility assets owned by an organization. Essential for any building owner with a large portfolio of assets, this information is typically stored in a centralized “real property” database. For example, the Army, Navy, and Air Force all have real property databases cataloging their entire portfolio of building facilities (U.S. Department of Defense, 2010). Associated with each building is a facility record that includes a building’s name, number, location or address, point of contact information, number of floors, square foot area, etc. A building may also be classified into construction types and use types. There are several different types of facility use classifications (Construction Specifications Institute, 2013) depending on the type of organization owning the facilities. Asset worth is also usually tracked at the building level. This is the estimated value of the building, and there are many different means of arriving at this number, including book value, market value, current replacement value, appreciated historical value, value to owner, etc. The asset value is important data element in determining condition metrics, backlog estimates, and other information to support facility investment decisions.

While the building level inventory provides basic information about a building, it typically does not provide information about the systems and components of a building. Building component level inventory information becomes important when determining scope and schedule of building repairs and component replacements. This level of inventory can be thought of as a model constructed by the identification of systems and components that comprise the building. The building component inventory is typically organized into a hierarchy that first divides the facility into major building systems, and then into the individual components that make up those systems (Figure 2). To achieve consistent inventory information across different buildings, a classification scheme is used. There are several building component level classification systems that have been developed, including Masterformat (Construction Specifications Institute, 2012), Uniformat (Construction Specifications Institute, 2012), and Omniclass (Construction Specifications Institute, 2015) formats.

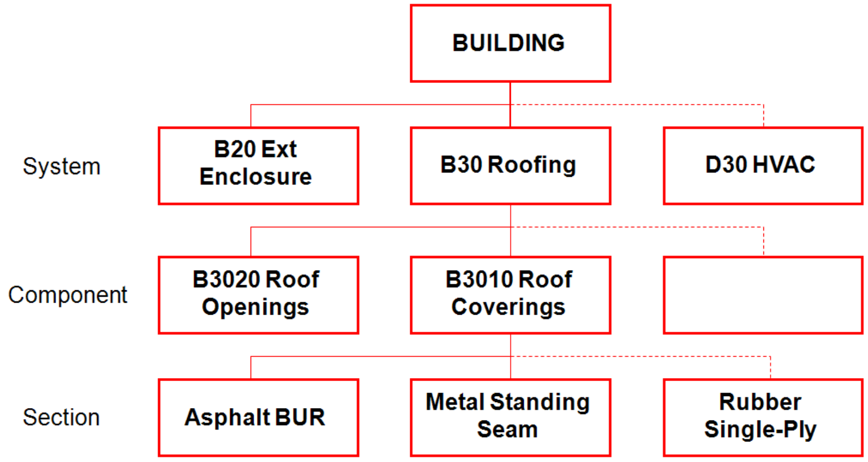


Figure 2. Example Uniformat Hierarchy

Associated with this component level inventory are attributes that define the characteristics of the components, including material type, equipment type, capacities, age, and location. For example, a window component may be made of metal, vinyl, or wood materials. The different material types have different responses to their environment over time, have different expected service lives, and require different work actions at various stages in their life cycle. There is also separate repair and replacement cost information related to labor, materials, and equipment associated with each component type. Therefore, the building component with its associated attribute information is one of the fundamental units for building life cycle asset management, condition assessment, and work identification.

In many cases, data collection is required to build a comprehensive component level inventory for a building, as shown in Table 1. This can be achieved by walking through the building and recording all pertinent elements, including quantities. If drawings are available, component inventory information and quantity take-offs may be used to construct the inventory model. Inventory components for a specific building type and size may also be estimated using models or templates. Finally, Building Information Models (discussed below) provide great promise to quickly provide component level inventory information based on the models created during design.

Table 1. Example Component Model with Replacement Costs

System	Component	Type	Qty	UM	Replace Cost ($)	Service Life(yr)
Electrical	Lighting Fixtures	Fluorescent Interior	425	EA	$144,840	30
Electrical	Generator Set	Gasoline 11.5-35 KW	1	EA	$2,418	25
Exterior	Exterior Door	Glass Personnel	6	EA	$17,410	40
Exterior	Exterior Window	Metal Casement	57	EA	$53,921	40
Interior	Interior Door	Metal Personnel	87	EA	$86,559	75
Plumbing	Waste Piping	Vinyl/Plastic	220	LF	$4,484	75
Plumbing	Piping	Copper 1"-2" Pipe	440	LF	$7,968	75
Structural	Slab	Concrete Foundation	13,000	SF	$82,680	100
Structural	Roof Deck	Metal	13,000	SF	$72,540	75
Roofing	Roof Drainage	Aluminum Gutter	617	LF	$12,574	25

2.4.2 Needs Assessment

Once the inventory of assets had been documented, the next step is to assess the asset inventory to identify needs for changes in maintenance policies, corrective repairs, major overhauls and renovations. The assessment essentially determines the state of the facility from condition, capacity, and performance standpoints, to determine if it meets user needs or where it falls short (Piper, 2004; Loy & Coleman, 2006). An objective, consistent, repeatable inspection is crucial to any building asset management process.

As discussed previously, a building is made up of interconnected parts and materials (components) to form systems, which perform one or more functions in an operating building. Those systems acting together, allow the building to support its overall mission or purpose. As with any physical asset, components generally deteriorate over time, causing adverse effects on system function. This results in physical condition loss over time due to age, use, damage, etc.

In addition, the design and capabilities of components, systems, and buildings as a whole generally improve over time due to new discoveries and technology. This causes existing building components to have a decreased value when compared to the state-of-the-art facility, and thus results in functional obsolescence loss. Since age is a strong indicator of obsolescence, an aging building and its constitutive components generally have decreased performance and user utility when compared to new construction. Actions can be taken, however, to slow, halt, or reverse this utility loss. These actions include maintenance, repair, and renovation. The effect of these actions on the future performance trajectory and associated utility state for a building depends on the nature and timing of the work performed. The overall goal of this objective is to provide a framework for the measurement of current performance states and prediction of future performance states.

There are several approaches for measuring current condition and performance states, including deficiency-based assessments (based on inspector recommended work deficiencies) and interval rating assessments (inspectors assign a numerical priority value based on condition). These approaches are sometimes limited by subjectivity and consistency. This proposed model builds upon work by the US Army Engineer Research and Development Center, which has developed an expert-based approach to compute a condition index (CI). The Condition Index has been used to measure and represent the physical condition of a road pavement section (Shahin & Kohn, 1979), while the expansion of this method resulted in a CI for building roof sections (Bailey, Brotherson, Tobiasson, Foltz, & Knehans, 1993) and generalized building component sections (Uzarski & Burley Jr, 1997). The condition index is a 0-100 scale, where a value of 100 represents a perfect (pristine) condition. The condition index is based on the observations from a condition assessment inspection performed using a standardized condition assessment process. To determine the quantitative CI, an inspector observes each building component and records the presence of distress mechanisms affecting operation and condition based on a set of guidelines. These observations result in a CI value calculated for each component at the time of the inspection. The condition index for a component, sub-system, system, or overall building is calculated by the weighted average of the element CI values of which it is composed. In addition to condition measurement, research by US Army Engineer Research and Development Center developed a method to calculate a functionality index (FI) on a 0-100 point scale which measures building capacity or capability (Grussing, Uzarski, & Marrano, 2009). Thus, functional obsolescence of an existing facility is defined as a loss of capability or capacity when compared to a new building. The FI calculation follows the same guidelines as those discussed above for the condition index.

2.4.2.1 Reasons for assessment

A building, like any physical asset, will deteriorate over time and with use. Building deterioration affects the performance, efficiency, reliability, and safety of the facility, occupant comfort and productivity levels, and the level of effort needed to restore the building back to acceptable standards. In addition to physical deterioration, buildings also suffer from obsolescence. When a building is new, it is designed and built to current requirements, current codes, and current technology and construction techniques. As the building ages though, requirements, codes, and technology will change but the building configuration will not. This adversely affects the building's inherent capability to serve its mission efficiently, contributing to obsolescence (Grussing, Uzarski, & Marrano, 2009).

As a building ages, deteriorates, and obsolesces, assessments are performed to measure the extent. The outcome of this assessment should provide information to building facility managers to help determine if the building meets requirements. As a result, the main reason to conduct an assessment is to understand building's current status, which helps support decisions about what types of sustainment, restoration, or modernization actions should be taken, if any, to improve performance, reliability, and risk. This primary reason for assessment supports several secondary motives for performing a building assessment, as discussed below.

Ensure proper construction, installation, or fabrication

Many times during the construction of a building, an inspection will be done to ensure that the construction meets specifications for quality and requirements for code (Illen & Iano, 2009). This can also occur after a building repair or renovation is performed. The purpose here is to identify initial defects that need to be corrected early on, when the construction staff is still on site or if the work is still under warranty.

Identify work, estimate budgets

One of the traditional reasons for conducting an inspection is to determine the requirements for building repair, or to provide a scope for renovation or modernization. Under this motivation, the inspector looks for deficiencies that should be corrected, as well as other areas that may warrant updating or improvement. The outcome of an assessment based solely on this motivation will typically be a scope of work for suggested repairs, a prioritization of individual work packages for different bid options, and an estimated construction cost to perform these activities (U.S. Navy, 1993). While this assessment can be highly customizable based on the desires of the building occupant or facility manager commissioning the assessment, this can also lead to subjectivity, inconsistency, and high costs across a large portfolio of assets. The information in the scope and costs that are provided are also date sensitive. If work is not performed on a building soon after this assessment is conducted, further deterioration and /or construction cost escalation may render the assessment information inaccurate (American Society of Civil Engineers, 1999).

As a result, an inspection that focuses solely on the scope and estimate of building work projects usually falls short of achieving asset management goals for large asset portfolios. It is better suited for smaller portfolios or individual buildings where a decision to renovate has already been made. In this case, a detailed assessment can provide critical information to the renovation planning process.

Identify failure or impending failure, measure reliability

A building assessment which focuses to identify failure or impending failure is usually driven by the need to ensure safety or continuity of building operations. Due to the critical nature of failure, inspections for certain buildings components may be mandated by regulatory requirements, such as requirements for elevator inspections, high pressure boiler inspections, and structural components, (Aktan & Farhey, 1997). An assessment of this nature directly targets one of the main goals of facility asset management namely, to limit and manage risk.

It is difficult to directly observe reliability of an asset. Reliability can be measured based on past history by determining what percentage of time that system or a similar system fails to meet requirements, and then extrapolate those data out for current and future times. However, infrastructure condition can be observed. This is usually done subjectively by following qualitative descriptors based on its appearance, operations, or apparent age (American Concrete Institute, 2008). These qualitative descriptors help to provide some consistency and develop a framework for communication of condition. Condition can also be measured more objectively through the identification of specific distresses, which are loosely associated with general failure modes. As the assessment of condition moves to a more symptom-focused, objective process, it can begin to serve as a proxy measurement for reliability. As a result, any condition assessment process needs to take these issues into account if reliability data are also a requirement.

Identify life cycle condition and performance characteristics

An assessment process that seeks to identify life cycle condition and performance characteristics for the existing building and its constitutive components is a critical aspect of any asset management methodology (Vanier, 2000). Here, work requirements are not a direct motive; instead the goal is to understand where the building and individual components are at in their life cycle, if they are performing as expected, and if this performance meets user requirements. To communicate these characteristics of the facility, an assessment of this nature typically results in the output of a number of facility metrics (Uzarski & Grussing, 2008). In this approach, condition assessment consists of translating inspection data into one or more meaningful condition metrics, which are then used to support the asset management decision making process. These metrics attempt to measure asset condition and reliability, remaining service life, functional capacities, and overall building performance. While this inspection focus does not generate building work requirements directly, these metrics can be used to quickly and objectively identify candidates for repair and improvement projects (Grussing and Marrano 2007).

2.4.2.2 Types and Levels of Assessment

Based on the motivations and reasons discussed previously, there are different types and levels of assessment that can be performed to target those motivations. These range from preliminary building assessments which cover a broad range to highly specialized inspections that focus on a specific component. As these assessments become more focused, the data collected, the level of expertise, and the cost associated with each increases.

Preliminary Assessments

Preliminary assessments are focused on capturing information about the facility as a whole. The focus is to determine the general condition of the facility, and its individual systems and components, but may also identify functionality, configuration, or obsolescence issues with the facility. These assessments may be performed by tenants, facility personnel, or general technicians. The results of this assessment may determine if and where a more detailed assessment should be performed.

Detailed Site Assessments

Detailed assessments are a more invasive survey of the building, to capture key life cycle characteristics of the main systems and components. The focus is to determine how the facility is performing and meets user requirements, as well as determining the fitness of use for continued service or renovation. These assessments are usually conducted by trained building technicians for a particular discipline (structural, mechanical, electrical), and may include a review of drawings, past work history, and maintenance documentation, external visual inspection, interviews with site personnel, and offline tests of equipment.

Specialty building assessments

Specialty building assessments are conducted to target specific aspects of the facility, either components, spaces, or certain performance attributes. They are usually conducted by highly specialized building consultants or engineers. These assessments may attempt to detect early fault conditions that can lead to equipment failures, unscheduled outages, or safety issues. They may entail non-destructive structural evaluations that are used when designing a building retrofit. These inspections may also include engineering evaluations that will identify space reconfiguration solutions for adaptive reuse. In all these instances, the information collected from these assessments directly supports the identification and design of repair and renovation work, if warranted.

Preventative and predictive maintenance inspections

These emerging assessment techniques are highly specialized technologies used to evaluate equipment condition. These techniques can include infrared, acoustic (partial discharge and airborne ultrasonic), corona detection, vibration analysis, sound level measurements, oil analysis and other specific online tests. While sophisticated, these methods can take years of experience and data collection to reach a high level of effectiveness (Levitt, 2003).

Condition Index Based Assessments

The concept of condition is not easily quantifiable the way explicit physical properties such as force, mass, and velocity are measured. Recent asset management approaches have attempted to measure condition by definition of a scale that correlates to varying degrees of qualitative condition descriptors, as shown. This Condition Index (CI) approach creates a link from the physical observations that can be made during an inspection process to the condition scale. These observations are termed “distresses.” A distress is an observable defect which adversely affects condition and can indicate potential failure modes for an asset. A finite list of distresses exists for each facility class. For a roof membrane component, as an example, distresses include blistering, cracking, potholes, rutting, and others. Each distress has a specific definition and visual cues that must exist. In addition, each distress has one or more levels of severity, which indicates how it affects an asset’s operational, mission, and life safety capabilities (Uzarski & Grussing, 2004).

During a distress survey condition assessment process, a trained building technician records the presence of all observable distresses present for an asset. That technician also indicates the severity and measures the amount of each distress. For each distress of a certain severity and quantity, a deduct value is applied. That deduct value directly relates the observed discrepancy to quantitative reduction in Condition Index. As an asset ages and deteriorates, its distresses accumulate, the severity and quantities increase, and the total Condition Index measure falls accordingly.

Technicians trained in the distress-based condition assessment process can expect a repeatable Condition Index value that reproduces the expert panel's judgment within ±5% (Uzarski & Burley Jr, 1997). The technicians are not asked to make subjective calls on the nature or urgency of a corrective repair, only to identify and record explicitly defined distress observations. This reduces the required expertise and cost of procuring inspection personnel, making condition assessments substantially more affordable.

2.4.3 Work Needs Identification

Work needs identification is one of the main tactical goals of building asset management planning (Halfawy, 2008), because as most building systems and components age, they have a decreased ability to meet main or tertiary functions, eventually reaching failure. These failures may be due to deterioration, damage, or obsolescence as discussed above. Unfortunately, performance specifications that explicitly define failure rarely exist. For example, a building component can continue to perform its function even after deterioration, but it may be at a lowered state of performance. Eventually however, this deterioration affects safety, energy efficiency, maintenance requirements, etc. It becomes riskier and more expensive to operate, maintain, or repair. In other words, a component may reach its economic service life well before the end of its technical service life. Eventually, progressive deterioration will ultimately reach unacceptable levels, beyond which further deterioration or structural behavior may be unpredictable, safety is compromised, or requirements are no longer met. At this stage, some remedial action becomes essential, although very few options may remain. Under this situation, the facility manager can no longer proactively manage the asset by selecting the best life cycle alternative. Instead, they are reacting to crises, and must choose from limited remaining options that are usually drastic and costly (Coberley, 2009).

The key to asset management and work needs identification in particular, in to understand the alternatives that exist for a building at a particular point in its life cycle, and choose the best treatment of alternatives to optimize performance, risk, and cost of ownership. This needs to happen within the context of 1) current state, 2) future states, and 3) if intervening actions (repairs) are conducted. This will help answer an all important question of facility management, “what is the risk of doing nothing, and how does that risk change by different infrastructure investment alternatives?”

2.4.3.1 Building Work Categories

Work related activities on a building can be categorized in many ways, based on the type, extent, cost, etc. The Office of Secretary of Defense for Installations and Environment has a detailed rules based categorization that groups work into the following types:

Sustainment

Building Sustainment involves the maintenance and repair activities necessary to keep an inventory of facilities in good working order, and includes regularly scheduled equipment adjustments and inspections, preventive maintenance tasks, and emergency response and service calls for minor repairs. It also includes major repairs or replacement of facility components that are expected to occur periodically throughout the life cycle of the facility. Examples of sustainment work for a building include regular roof replacement, refinishing of wall surfaces, repairing and replacement of building service systems (i.e. heating and cooling systems), replacing tile and carpeting, and similar types of work. It does not include environmental compliance costs, facility leases, or other tasks associated with facilities operations (such as custodial services, grounds services, waste disposal, and the provision of central utilities) (U.S. Department of Defense, 2014).

Restoration

This category involves the restoration of overall buildings to such a condition that it may be used for its designated purpose. Restoration includes repair or replacement work to restore facilities damaged by inadequate sustainment, excessive age, natural disaster, fire, accident, or other causes (U.S. Department of Defense, 2014). The Restoration category is usually associated with large scope building renovation and refurbishment projects, rather than the improvement or replacement of individual systems or components (typically sustainment).

Modernization

Modernization includes the alteration or replacement of facilities solely to implement new or higher standards, to accommodate new functions, or to replace building components that typically last more than 50 years (such as the framework or foundation) (U.S. Department of Defense, 2014). The modernization category is also typically associated with renovation projects, but focus is on meeting new user requirements and improved building technology, not necessarily on correcting damage and deterioration.

New Construction and Demolition

New construction is defined as a comprehensive action to completely replace an existing asset, potentially with different functionality or location. This includes construction that adds to an existing facility, or does not replace an existing facility that has reached its service life, or is beyond economical repair. New Construction results in growth in footprint in the real property inventory. Demolition results in the deconstruction and removal of all building contents from the site.

2.4.3.2 Considerations for building work

Determination for the type, timing, and extent of work to be performed on a building starts with a strategic look at the long-term needs of the building. For a large portfolio of buildings, this information is usually maintained in a real property master plan. For example, if the building is scheduled to be demolished, replaced, or removed from service in the near future, this will obviously have an effect on short term work to be accomplished in the building. In these situations, maintaining the long-term performance and value of the facility is not a driver, although ensuring safety and some minimum level of performance still may require corrective repairs.

If a building is expected to remain in service for an extended period of time (5-10 years or more), then it will need to be managed and maintained to a certain level of performance during that time span. As discussed above, assessments provide the information to determine building condition and performance, given deterioration, obsolescence, etc. The outcome of this assessment should provide information to building facility managers to help determine if the building meets owner and occupant requirements. As a result, the inspection methods employed determines how the work in a building ultimately gets generated.

Inspector Generated Work

Under this consideration, repair work on a building is a direct result of deficiencies identified and prioritized as part of a detailed inspection. Based on knowledge of a building's construction, applicable building codes, and guidance on requirements from the facility manager, an inspector or team of inspectors will recommend work activities and prioritize those work activities, and this forms the basis for developing the scope of work alternatives for a building. This method of determining works needs is essentially a decentralized approach. Inspectors and the standards they use to identify and prioritize work may be different across a large portfolio of buildings. As a result, this approach is reasonable for scoping out the work on a single building or small subset of buildings, particularly if those buildings have been marked for repair or renovation. It is less applicable, due to inconsistency and subjectivity, for a large portfolio of assets, especially if common standards are important (Hassanain, Froese, & Vanier, 2003).

Condition Generated Work

The Condition Index, as discussed above, is a tool for measuring the amount of performance lost due to condition degradation of the component over time from age, natural deterioration, damage, deferred maintenance, etc. The distress-based inspection process provides a condition scale that stretches across the wide array of building systems and component types for measuring this performance loss in a more objective and consistent way. Performance loss can come from a number of different mechanisms (distresses), each of which can be measured separately (via severity and density). The distress-based inspection process translates all these different mechanisms into a single metric.

This metric provides the common language for communicating condition across different buildings, systems, and components, each of which has different combinations of distresses, severities, densities, ages, and conditions. A Condition Index based inspection provides a framework for measuring condition by factoring in all the potential problems that could exist. And the resulting CI provides a way for decision makers to establish a threshold "standard" for the condition of those assets. While this approach attempts to take the subjectivity out of the inspection process discussed above, the subjectivity is shifted to the assignment of the standard condition level. It therefore becomes important for the decision makers establishing the standards to use for their assets to understand the CI scale and its relation to risk.

It is also important to understand that the CI measure (scale of 0-100) does not directly measure probability of failure, although it can serve as a proxy indicator in certain cases. As discussed above, for many building components, simply defining what constitutes a failure state can be ambiguous. For example, does a window fail when the vapor barrier is breached, it is no longer operable, a window pane breaks, or some other criteria? Obviously this failure state could have different meanings for different building uses or building occupants. So the CI metric provides a way of defining a quantitative failure state objectively and consistently. After an asset accumulates a sufficient number of distresses, its condition index drops below the failure threshold (set at a CI = 40 for most components). Whether it is functional or not, it has effectively failed. One can also envision the opposite situation where a piece of equipment stops working due to a minor event such as a circuit breaker tripping. While the component is currently not operational, if the fix is easy and inexpensive, it is not likely to be classified as failed.

Of course, the failure state is rarely the most efficient point to consider some corrective action in the first place. For many components, repair early in the life cycle can extend service life and avert expensive damage caused by accelerated deterioration. This is usually when degradation is readily apparent on an asset, but it has not yet proceeded to accelerate quickly to failure. If intermediate repair can be accomplished economically (not true for all component types) then the repair action should be considered. Thus, the CI standard determines what becomes the candidate work items. Some items may simply be allowed to run-to-failure, and these may have a lower standard applied to them.

In addition, the consequence of failure must be considered when setting the standard for a component. These consequences may fall into at least 3 categories: 1) safety/environmental consequences, 2) operational consequences, 3) aesthetic/quality of life consequences. If any of these consequences of failure are more adverse (unacceptable) than normal, that may lead to a higher standard threshold setting. For example, if the failure of some system or component results in a high safety risk, the standard should be set higher to compensate for that risk. In essence, a safety factor is applied to reduce the uncertainty of falling below a safety limit by maintaining the component at a higher condition and checking on it more frequently. Likewise, if the failure of a component affects mission operations, it is important to maintain at a higher condition for the same logic. Finally an aesthetic or quality of life requirement may lead to maintenance at a higher level, and thus a higher condition standard.

In these cases above, the standard (CI threshold) is increased to compensate for the more difficult task (increased probability) of not meeting the more stringent performance standards imposed. This number can be tailored based on building importance, system or component importance, and a number of other factors set by policy makers. There is not an industry standard, per se, published which says that HVAC, for example, needs to be maintained at a condition of 80 for example, because that will vary based on the factors discussed above. But the overall method of using a condition index approach provides a very structured and consistent process for work identification and generation.

2.4.3.3 Work Prioritization

In most large organizations, the cost of potential work candidates identified for a portfolio of buildings will far exceed what can actually be accomplished based on facility budgets. As a result, the work needs to be prioritized to determine what gets budgeted and what gets deferred. To ensure all stakeholders are represented, an objective and consistent prioritization process is critical to joining the priorities of the owner agency or organization with the local conditions at each building. This method for prioritizing this work can fall into two main categories.

Discretionary Intent

Traditionally, prioritization of work has been accomplished based on the discretionary intent of an individual person or group, and in many organizations this is still true. For example, in a traditional deficiency-based inspection process, an inspector will identify building deficiencies, and provide a criticality rating to these deficiencies. The criticality rating relates to how soon, in the inspector's opinion, the deficiency should be addressed and corrected, and typically ranges from 1 – immediate, to 5 – deferrable (U.S. Navy, 1993). This information, while subjective and sometimes inconsistent from one inspector to the next due to varying levels of experience and judgment, can be a primary factor in prioritizing work. Further along in the process, when work has been packaged into projects, scoped, and given a design estimate, individuals can determine, based on discretion and perception of its importance, what projects to fund in a particular year. Again, while this is a subjective approach to prioritizing building work needs, it allows individuals and stakeholders to have some control over the prioritization of repair work to be accomplished on the buildings for which they are responsible.

Multi-Criteria Optimization

Multi-criteria optimization uses building attributes and other metric data to determine the priority of work activities (Lounis & Vanier, 2000). This requires the development of a multi-criteria prioritization scheme. The development of a prioritization scheme starts with the definition of organizational objectives and the evaluation of how well a given component or its work action meets those objectives. This is done by specifying attributes of the building, component and work item which can be related to importance measures. For example, one objective is accomplishing the most cost effective work items. These work actions, when performed in a timely manner, can delay the occurrence of more costly repairs or failures. In this case, the main prioritization criterion is the calculated return on investment (ROI) metric. Another, sometimes competing objective, is repairing the most important component based on mission criticality. These are the assets that have the most significant effect on owner operations. Here, the different measures associated with building use type, building systems, and component importance weights are used as prioritization criteria. By assigning relative weights to the set of multi-criteria measures and objectives (either directly or through an analytical hierarchy process

(AHP) of pair-wise comparison) (Tesfamariam & Vanier, 2005), a consistent and objective importance score is calculated for each work activity or overall repair project, which can then be used to rank and establish the funding cut line based on anticipated budget levels.

2.4.4 Decision support and consequence analysis

A long-term maintenance, repair, and capital renewal plan for an organization can involve a portfolio of thousands of buildings all at varying condition states. With the numerous assets involved, optimizing a strategy that incorporates current user requirements, budget constraints, and future performance sustainment can be a difficult challenge. However, using a structured business process framework, and asset life cycle analysis, different investment decision scenarios can be explored, and consequences can be evaluated over a long-term horizon (Shohet & Perelstein, 2004).

One such automated consequence analysis tool is the IMPACT simulation model used in conjunction with the BUILDER Engineered Management System (BUILDER 2010). This model simulates the annual fiscal cycle of work planning, project creation, and work execution by projecting building, system, and component conditions into the future. Model inputs include the real property inventory information, condition information and deterioration trends, current work projects, budget projections, and user defined standards and prioritization schemes to initialize the model. The simulation then 1) generates work requirements based from projected conditions, user defined standards and policies 2) prioritizes work actions 3) assigns funding to highest priority work items using set budget resources 4) simulates the execution and completion of funded work 5) predicts the future condition of component assets based on work that is completed and deferred and 6) updates the component inventory database to reset the cycle for each year in the simulated budget plan (Grussing, Uzarski, & Marrano, 2006).

The end state of this process is a multi-year, prioritized list of work items, along with the expected costs and condition levels associated with that plan. This consequence analysis is a step towards the ultimate goal of building asset management – to provide tools and decision support information to help facility managers determine where, when, and how to implement building upgrades and repairs that offer adequate condition and performance at lowest life cycle costs. While the current IMPACT model, and the overall process discussed above, presents a good first step towards this goal, there are numerous avenues for research and improvement. Discussed in the next section are several challenges and technical gaps that prevent further refinement of building life cycle asset management methods to achieve better accuracy, efficiency, and effectiveness.

2.5 Existing Tools to Support the Facility Asset Management Process

Fortunately, there are several advances that are helping to make the data collection process, the analysis of information, and the reporting of that information more cost effective and streamlined. One of the most influencing factors affecting this is the wide spread use of computers that can archive and analyze large amounts of data quickly. There are several databases and systems that are making building asset management much more effective, including those listed below:

2.5.1 Computerized Maintenance Management Systems (CMMS)

Computerized Maintenance Management applications can manage work orders, trouble calls, equipment spare parts, inventories, and preventive maintenance schedules. Many programs also include features such as time recording, inventory control, and invoicing. These systems have become an increasingly important part of managing the day to day operations and activities of a building facility.

2.5.2 Sustainment Management Systems (SMS)

The Sustainment Management System (SMS) process (sometimes also referred to as Engineered Management Systems, or EMS) provides a condition index scale that stretches across the wide array of building systems and component types for measuring building performance loss in an objective and consistent way. Performance loss can come from a number of different mechanisms (distresses), each of which can be measured separately (via severity and density). The SMS inspection process takes all these different mechanisms and translates them into a single metric. This metric provides the common language for communicating condition across different buildings, systems, and components, each of which has different combinations of distresses, severities, densities, ages, and conditions. SMS provides a framework for measuring condition by factoring in all the potential problems that could exist, and the resulting CI provides a way for decision makers to establish a threshold "standard" for the condition of those assets used to generate work requirements/opportunities.

The Facility Condition Assessment (FCA) process that the SMS supports results in a better understanding of the physical condition and readiness of an installation’s buildings and the reliability of its systems and components. It also helps with the identification of work candidates for facility repair projects. It is a critical aspect of the shift towards a proactive versus reactive maintenance strategy. Instead of keeping facilities operational by relying primarily on corrective repairs (after a system or component has failed due to significant loss of function), it focuses on condition-based repairs which can be planned prior to failure. A condition-based approach can result in higher performing facilities at a lower life-cycle cost.

A condition-based facility repair strategy requires condition information that measures accumulated deterioration and loss of function be collected at a component level. Every component of a building has a primary function that it performs; this function is the reason that the component was constructed or installed in the building. It may also serve a number of secondary or tertiary functions. For example, for a door component, the primary function is to provide safe entry/egress of authorized movements while limiting unwanted movements of people (security), or other objects (water or moisture). The secondary functions would relate to aesthetics, and thermal and air control, among others.

Over the course of a building component's service life, it will likely experience a deterioration of its physical condition due to general aging, use in service, and exposure to a number of external or environmental factors. This condition deterioration is manifested in one or more distresses which adversely affect that component's current and future ability to perform its primary and/or secondary functions. These distresses include cracks, leaks, holes, corrosion, overheating, excessive vibration, animal/insect damage, as well as general deterioration or damage.

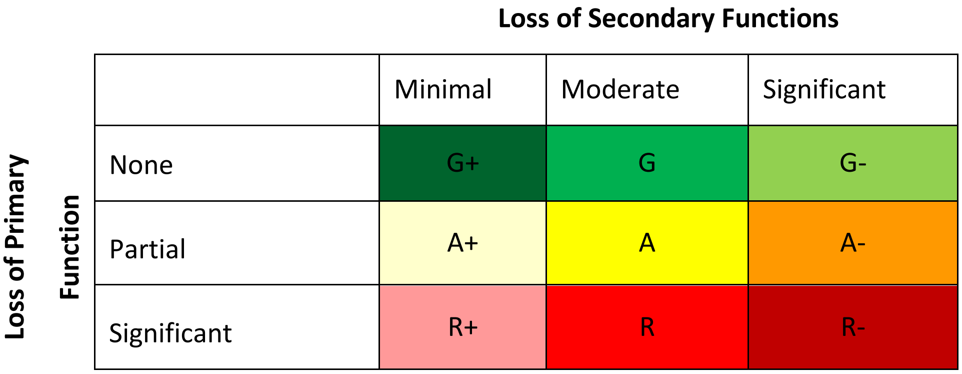
These distresses can be observed during a condition assessment process (inspection). The purpose of this condition assessment process is to measure (qualitatively and/or quantitatively) a component's ability to perform its required functions, considering the presence of accumulated distress.

There are two levels of the condition assessment process in BUILDER. The most detailed approach, the Distress Survey, involves the individual identification and recording of the type and nature of distresses observed for a component. The presence of these distresses recorded, in addition to the severity and density, results in a condition index metric which directly relates to the level of condition deterioration, and indirectly to the loss of function due to this deterioration.

A less labor intensive approach in terms of data recording (but not necessarily in terms of observation time), is the Direct Rating method, where a single qualitative rating is assigned to the component based on condition observations (taking all distresses into account). This also results in a condition index metric which relates to the level of deterioration and the loss of function. This abbreviated Direct Rating approach is often better suited to initial baseline assessments where the components are inventoried and data are initially loaded into BUILDER.

Both condition assessment methods discussed above require accurate and thorough physical observations during the assessment process. This sometimes may require an invasive (but non-destructive) look at the internal subcomponents of a component, if applicable (considering safety). It typically requires interviewing building occupants or maintainers to capture variations in component performance (versus what can currently be observed during an inspection). These assessments do not take the place of regulatory or specialized inspections, but may indicate the need for such. The intent of either assessment approach is to capture the current state of condition through the resulting Condition Index metric that reflects current and future potential loss of function. As a result, the abbreviated direct rating approach should accomplish the same result, although with more Condition Index variability due to a less rigorous data collection process, as the Distress Survey approach, provided the following guidelines (see Figure 3) are followed (in conjunction with the guidelines presented in the condition assessment manual:

1. Consider the primary function of the component and determine the level of loss of this function (if any) due to condition deterioration. This determines the GREEN, AMBER, RED nominal rating.
2. Consider the secondary functions of the component and determine the loss of these functions due to condition deterioration. This may result in a plus or minus adjustment from the nominal rating. A simplified rating matrix using this schema is shown in Figure 3.



Loss of Secondary Functions

		Minimal	Moderate	Significant
Loss of Primary Function	None	G+	G	G-
	Partial	A+	A	A-
	Significant	R+	R	R-

Figure 3. Direct Rating Guidelines related to Functional Loss

In the case of an exterior door component, considering the primary and secondary functions discussed above, examples of primary function loss for each level include:

- None – No loss of function, door provides a barrier to unwanted movements, while remaining fully operational.
- Partial – Noticeable deterioration to frame, surface, or weather stripping/seals which may allow partial movement when closed, and/or door is less than fully operational. Safety is not an issue.

- Significant – Deterioration to components of door assembly which allows significant potential for unwanted movement, and/or significant operational issues due to damage or misalignment of frame, door, or hardware, which may present a safety issue.

Likewise, considering secondary function loss for each level based on the chart above:

- Minimal – None/minimal loss of aesthetics or thermal/moisture control
- Moderate – Moderate loss of aesthetics due to faded paint or slight corrosion
- Significant – Significant loss of aesthetics and/or inability to control thermal/air movements

2.5.3 Sensors and Other Data Collection Devices

There are also several other technologies that are emerging that can help to improve the data collection process to feed these systems. One emerging technology is building sensors, which strategically placed, can provide a continuous stream of real time data about the operation of building components, and can even alert building professionals when in need of maintenance and repair. For example, in addition to the traditional sensors for security or emergency response, there are also sensors for condition monitoring, energy efficiency, and energy management. In addition, RFIDs are being used to tag components electronically, and store valuable component inventory information. Finally, where manual data collection is still necessary, during visual inspections for example, rugged and lightweight mobile devices are now available for the building inspector to carry with them on the job. In addition to allowing for electronic recording of pertinent building data, information can also be retrieved on site when needed.

2.5.4 Building Information Models (BIM)

With new computerized management systems and all the available information being generated, new challenges are presented as well, not the least of which is the need to integrate the different pieces of information together. For example, one challenge is the difficultly of linking different streams of building information, including real property, equipment and component inventory, space planning, condition assessments, work needs and work history, cost estimates, and GIS together to provide a comprehensive picture for asset management decisions. This may include the need to integrate separate infrastructure management systems or databases along with design systems or other management software.

The convergence of these different streams of building data, which spans all the life cycle phases, is currently being realized with the development of Building Information Models (BIM). In addition to providing a format for real time exchange of construction contract deliverables (Warranties, maintenance manuals, spare parts, special tools), it also provide a framework to store information for later exchange/retrieval (East & Brodt, 2007). This requires data standards for exchange of building information used by the facility maintenance and operations community.

BIM has been used for quite some time in dealing with complex construction projects (Sheppard, 2004) because it can integrate time and construction schedules as a 4th dimension into the 3 dimensional object oriented model of a building project, it allows construction managers to more easily see potential conflicts between crews, equipment, or materials during the construction process (McCuen, 2009). In addition, the detailed electronic information developed during the design and construction phase can have useful applications for the building owner as they operate, maintain, and possibly even renovate the building later on in the life cycle (East & Brodt, 2007). Because of the potential cost savings during the construction phase, and the multiple uses for the data during the building's life cycle phase, larger facility owners have begun to request a BIM as part of the deliverable during the turnover of a newly constructed building.

Because BIM is a newer technology, most existing buildings under consideration for renovation will likely not have BIM data available for use during design and construction planning. However, there have been recent applications where BIM data have been developed for an existing building as part of the building renovation project (Bandurowski, 2010). In addition, there are laser scan technologies that can generate a very quick and accurate 3D model of a building (Health Facilities Management, 2010), although this has limitations in identifying existing materials and internal hidden components or systems of the building.

With BIM in place for the renovation project, the construction management team, general contractor, and building owner can realize many of the beneficial advantages of BIM, namely improved communication and flow of information during the design, planning, and construction phase. Therefore, as selective demolition on the building begins and internal systems are uncovered, the initial model assumptions can be updated quickly based on real conditions and building configurations observed on the job site. This information is then available to all applicable members of the project delivery team, and job logic, construction schedules, resource demands, and material procurement charts can be updated rapidly if needed with less delays when assumptions change.

As mentioned previously, in addition to the benefits of BIM during the design and construction, the data also has advantages afterwards throughout the life cycle of a building. If pertinent building information is collected during the renovation of an existing building, that information will be of value for future renovation projects if saved in a BIM. It is therefore important that building owners especially be aware of the benefits of this type of information if they are considering requesting it as part of the building renovation project deliverable. For building owners interested in proactive life cycle management of their facility, BIM can deliver several advantages over traditional flat as-built drawings and operational/maintenance manuals for equipment. Having more accurate and current building information can help with better assessing needs and planning future building projects. With this information integrated with a facility asset management system, future repairs, renovations, or retrofits of individual systems or components of the building can be accomplished in a “just-in-time” matter as needed when they fail or become obsolete.

2.6 Building Facility Asset Management Challenges

One of the fundamental challenges to proactive life cycle building asset management is the emphasis placed on the design and new construction of building assets, without consideration of the other building life cycle phases. While proper design and construction are critical to the establishment of a high performing building, it is important to remember the attention to detail needed in the operations, maintenance, repair, and renovation phases. The academic research, course curriculum, and industry standardized practices devoted to building design and construction management have evolved into a vast body of knowledge over several generations, while the topics related to asset management, condition assessment, and building maintenance and repair are less developed and much more fragmented. However, as the country’s facilities and infrastructure continue to age, and land and materials become scarcer, adequate life cycle management is becoming just as critical as construction management for new facilities.

Current sustainability initiatives for facilities are beginning to highlight this importance. More attention, research, and education is being focused on long-term goals for both the natural and built environment. Buildings, like other forms of civil infrastructure, are a long-dated asset. However, building owners and managers may have a much shorter timeframe for goals and agendas. For example, in the private sector, decisions are sometimes driven by yearly (or sometimes quarterly) financial statements, while in the public sector, decisions are sometimes linked to election cycles. A good management program must strive to balance short term and long-term goals.

Facility Managers are responsible for executing short-term operational budgets as well as planning long-term investment strategies for the sustainment, restoration, and modernization of their real property assets. However, in many public works shops, there is often a lack of tools, personnel, and experience necessary to sufficiently analyze the infrastructure life cycle trends and then adequately communicate investment alternatives that balance mission readiness, reliability, and total life cycle cost. This difficult task is further complicated by inadequate, inaccurate, and subjective data with which to make decisions (Government Accountability Office, 2003; Government Accountability Office, 2008). Therefore, development of better decision making tools based on accurate and objective information is critical.

2.6.1 Cost of Collecting Building Information

The perceived cost of building asset management is yet another challenge to the process. Organizations want to undertake actions that add value to the bottom line. While implementing a long-term maintenance program provides immense value, it does not necessarily produce an immediate payback. In addition, effective asset management payoffs are difficult to quantify, while the costs and effort to implement are easily visible. Therefore, these programs are typically viewed as an expense rather than an investment. Likewise, data collection efforts to gather and assemble the information critical to a building asset management program are seen in a similar view, with skepticism that these programs can add value to an organization.

The effort of collecting and then maintaining the pertinent building information, including real property, building component inventory, condition assessment, and past work history can require extensive resources to accomplish. If this data collection effort is not targeted and cost effective, organizations will view these essential steps as a burden and unnecessary expense. The data collected needs to be translated into current and accurate information to support current decisions.

2.6.2 Balancing Needs of Different Stakeholders

One of the biggest challenges for facility managers is communicating their information to executive management. It is important that facility managers have a toolset of reporting metrics to which senior executives can easily relate. This allows managers to establish a tangible link between the buildings being managed and the organization’s primary mission. This is especially important in the public sector, because the portfolio is so large and diverse that it may be easy to assume that a single facility is not critically important. However, methods such as the Mission Dependency Index (MDI) can show otherwise. The MDI is a powerful tool because not only does it show that a particular facility is important or critical (Facility managers at lower levels generally know which assets are their most important), but it also provides a direct link to the missions it supports and the services it provides

(Antelman, Dempsey, & Brodt, 2008). This can be important when justifying or defending particular facility investments at higher levels.

This issue of establishing the conduit from facilities to mission underscores a much larger issue in facility management as well, and that is the communication link between local project execution and executive level strategic decision making. At the local level, facility managers deal with individual facilities, keeping these in working order for their tenants. At the executive level, decisions are made on the strategic direction and missions of the organization as a whole. Facilities are one factor in the production of goods or services that compete with many other factors. In many organizations, it is understood that there may be a communication gap between the facility managers that develop and execute work on facilities and the executive decision makers who appropriate the resources to complete the work. In the process, priorities get shifted without an understanding of how it affects operations at either end of the spectrum.

In an effort to meet the individual goals at each end of the spectrum, different management methods have been introduced. These include portfolio scale macro-level models and local facility level models. At the portfolio level, the main goal is to have a consistent process that is easy to apply to develop macro level budget allocation which looks out over several years. In this capacity, economic models, if well calibrated can adequately serve this purpose. However, macro-scale models cannot be used to direct resources down to individual facilities, systems, or components, as the regional and local facility managers are tasked to do, since they are not based on an actual physical facility inventory or condition assessment. In order to produce the information to support actionable work, inspections are required. This is traditionally accomplished via the process of identifying deficiencies to correct, and estimating the cost to do so. However, due to the detail required for these deficiency inspections, this is usually cost prohibitive to conduct a consistent assessment across the board at a local level, much less across an entire large agency or organization. To avoid wasting resources, these type of assessments should only be done when it is reasonably expected that a particular project will move forward to the execution phase. In addition, since further deterioration can change the scope of the work to be accomplished, these assessments should be conducted within one year of the commencement of work.

While the deficiency based inspection provides a precise cost estimate for an individual facility and directly supports execution of facility renovation, it does not support facility management in the two- to five-year planning horizon. This is where the communication gap between local execution and strategic planning exists. To bridge this chasm between economic models and deficiency-based project execution, the Sustainment Management System tools discussed previously have been developed to provide consistent planning metrics and processes for facilities. These tools are model-based, but these individual facilities models are based on actual system and component inventory for the facilities, and conditions based on physical observations. While this type of information requires more cost and effort than macro-level models to establish initially, once acquired the information can be re-used for several assessment cycles and provides a means of predicting future condition trends as well. The continuous tracking of condition life cycle also supports intermediate repair practices – the system can identify systems or components that are a prime target for repair or overhaul before catastrophic and expensive failures may occur, resulting in cost avoidance. In addition to supporting local MR&R planning by helping facility managers focus attention on critical issues, it also provides transparency, accountability, and feedback up the chain to the executive level to help make self-corrections in facility investment strategy.

Finally, the SMS tools also support a Knowledge-Based approach to inspection that improves on the traditional deficiency-based program, which is calendar based. In particular, under a knowledge-based inspection process, inspection frequency and level of detail can be adjusted based on current and projected condition states (Uzarski, Grussing, & Clayton, 2007). In other words, a knowledge-based approach can eliminate costly infrastructure inspection tasks that contribute little to risk management and mitigation, and better match resource investments to mission requirements. The criteria considered in developing appropriate inspection schedules include facility importance to mission, component criticality, time in service, remaining service life, current condition, deterioration rate, performance requirements, and reliability thresholds. A knowledge-based condition assessment plan is a critical intermediate step in the management program, because it enables facility managers to match strategic mission objectives to inspection frequency and level of detail. If the intermediate planning step is not taken, then the deficiency-based inspection process will typically only identify requirements once facilities or systems have already failed. This is the typical reactive maintenance that most organizations operate in today. This is costly, disruptive, and steers resources away from capital improvement and modernization which drives productivity towards unscheduled maintenance and repairs which is usually seen as a drain on operational resources. A run-to-failure mode may be perfectly applicable for certain types of facilities, systems, or components, but is extremely inefficient for many other kinds. The key is to develop an inspection and MR&R strategy that is mission focused and based on component criticality and condition life cycle. So while both economic facility modeling and deficiency based facility inspection both have their merits in the asset management continuum, the process is broken without a means to connect the two.

2.6.3. Understanding and Quantifying Returns on Facility Investments

Return on Investment (ROI) is a performance measure often used to communicate the efficiency of a monetary investment. In simple terms, it is the money gained (or lost) from an investment. This seemingly straightforward calculation is simply the return divided by the investment. In the financial industry, the investment may be called capital, principle, or a cost basis. In the realm of infrastructure asset/facility management, this investment is usually represented by the cost of construction, rehabilitation, renovation, or major repair of a facility (either part or whole) (Lemer, Building Public Works Infrastructure Management Systems for Achieving High Return on Public Assets, 1999). For infrastructure projects, the monetary value of this investment may not be known until after construction is completed. There is usually some uncertainty in the cost of construction, repair, etc., especially for future year activities due to changing scopes of work and the escalation of materials and labor. However, there are mechanisms to control this uncertainty and procedures to reasonably estimate the cost of an investment (Government Accountability Office, 2001).

While the investment portion of the ROI measure can be reasonably estimated, the determination of the other input for this calculation, namely the Return, can be considered problematic. In many cases, it is very difficult to determine the monetary gain for the investment in a facility (Gramlich, 1994). First, it is important to consider what a facility represents. In economic terms, the facility is real capital asset, and more specifically infrastructure capital. This real capital is a factor of production (in addition to land and labor) used to create goods and services. In the private sector, a factory may be built to produce goods to be consumed (purchased) on the open market to provide revenue for a company. If the company has no capacity to produce that good elsewhere, the value of that facility is directly tied to its revenue production. Now this revenue production cannot be individually attributable to the capital represented by the factory alone, since the factory may represent only a portion of all inputs needed in production. There are likely other factors involved in the production, such as raw materials, equipment, labor, and perhaps other dependent factories or facilities. However, unless redundancy and controls are built into the production process, the reduction of the functions provided by that factory, perhaps due to component failure, will likely result in loss of overall production capability, even if the other production factors remain intact. This makes it difficult to determine asset value from its risk of failure.

The return for public sector facilities is usually even more difficult. The value of these facilities is usually not directly tied to revenue generation. More often public sector facilities are a factor in the production of some civil or social service, which may be of intangible monetary value. This service usually extends beyond the boundaries of one person, group, or entity. It is amorphous and belongs to society as a whole. In addition, for a variety of reasons, the true cost of the services provided is often not known, or its true value to society is difficult to measure. Again, it takes more than just the facility to provide that public service. However, if the facility is rendered unusable, the quality of that service, and the efficiency with which is it produced, is degraded. Therefore, construction investments which maintain, improve, or expand the performance of the facility do produce some benefit or return (Gramlich, 1994). However, it is difficult to monetize what the benefit is to determine an accurate ROI for the construction activities being contemplated.

2.6.3.1 Work Activity Effects

One of the primary goals of an asset management plan is to identify recommended work requirements for building repairs and renovations. The key is to accomplish the right work at the right time so that the money spent has the maximum benefit on system and component service life, on building performance, and essentially on total cost of ownership (Farran & Zayed, 2009). When a component is replaced, it is generally assumed that its service life within that building is reset. However, when a building repair is performed, there is little formal knowledge of how that repair actually affects the life cycle. Without this information, the development of a truly comprehensive asset management system is elusive.

One would expect that MR&R activities would improve condition (either the current state or over time). And since Condition and Reliability are correlated, these activities should also improve reliability. But how does one measure this improvement? How does this affect the risk profile? If repair of a number of smaller failures can lower the probability of a group of detrimental consequences occurring, then this can directly result in cost avoidance if one can monetize these detrimental consequences. However, this is difficult because 1) estimating the cost of a failure consequence can be dubious, and 2) one would need to know the pre- and post-probability of failure (or failure propagation) for each repair action, which is difficult to estimate itself. However, collecting assessment data at a component failure mode level would provide some basis to make this analysis possible, at least in a broad sense.

2.6.3.2 Work Activity Cost Estimation

As building deficiencies are identified, a building owner obviously would like to know the cost to fix those deficiencies. However, cost estimates for construction projects are difficult to accurately estimate, and it is even more so with repair and renovation work. While methods have been developed to estimate and budget for building repairs and upgrades (Al-Mashta & Alkass, 2010), uncertainty in the preexisting conditions and configuration of the building can greatly affect cost variance during renovation. When renovation of an existing building is chosen as an alternative over purchase, lease, or construction of a new building, the deciding factor is usually cost. Therefore, a renovation project should generally cost less than a comparable new building. This is sometimes not the case, however, due to scope creep, change orders, and unplanned circumstances (Shipley, Utz, & Parsons, 2006). Added unplanned activities, increases in activity duration, and additional building components and materials being replaced can all adversely affect cost variance. Due to these uncertainties, conservative cost estimates during the project bid phase will help to alleviate some of the cost pressures later on during construction. It will also ensure that a project's overdraft financing requirements do not exceed available lines of credit due to changes in cash flow, namely higher outflows or expenses.

In addition, it is critical to be aware of any historical preservation constraints during the construction planning phase. Any renovation of a building that is part of the national historic register (Cyrenne, Fenton, & Warbanski, 2006) will likely cost more than a non-historic renovation. Since the renovation must conform to a certain architectural time period, there are limitations on the construction methods and types of materials used. For example, while the façade on a non-historical renovation may be more cost effective to remove and replace with new materials, a historic renovation may require that the existing façade be removed, the material refurbished, and then re-installed. This can result in more labor costs and longer activity durations. In addition to labor, material costs associated with historic renovation are typically higher due to the limited production and specialized nature of these items (Cyrenne, Fenton, & Warbanski, 2006). Despite all these challenges, cost estimates for building repair activities are still a critical part of the asset management process, and a number of different methods and models have been employed.

Economic Models

For government buildings, facility managers commonly receive their allotment of facility sustainment dollars based upon their facility inventory, regardless of mission priority or actual need. These economic estimates are based on facility square foot costs (U.S. Department of Defense, 2015). While easy to implement, they are broad and usually not applicable for a single facility.

Parametric models

The DoD Tri-Service Automated Cost Engineering System (TRACES) provides parametric models for building construction and repair (U.S. Army Corps of Engineers, 2014). Based on a specific building type, a parametric estimate is provided that varies by the size of the facility. These are mostly construction based cost estimates, but other efforts have explored parametric estimates for repairs (National Aeronautics and Space Administration, 2003), or restoration and modernization (Lufkin, 2005). At a component level, the BUILDER Sustainment Management System uses the Condition Index as an indicating variable for a parametric repair cost model, as discussed in more detail below.

Unit Price Models

The RS Means Group produces cost estimates for construction and installation of materials on a per unit basis (R.S. Means, 2014). Therefore, if one has specific knowledge of the quantity and type of a particular building component requiring replacement, this cost source can serve as a good basis for the estimate. If components are to be repaired versus replaced, RS Means also provides repair and renovation cost estimates, but the extent of the components listed is more limited.

Design Cost Estimate

One of the most accurate, yet expensive ways, to determine repair costs is to have a comprehensive building assessment followed by a renovation design to correct deficiencies. While this approach is the most accurate, it can also be cost prohibitive across a large portfolio of buildings.

Historic Basis

Facility managers can also estimate the cost for renovation or repairs based on experience or records of past work accomplished. This can provide an accurate estimate if a similar repair or renovation is being done. For example, the repair or replacement of similar components can be based on actual historical cost records for that location (Jrade & Alkass, 2007). Even building renovations can be based on past per square foot estimates, provided the scope and extent of the repairs is similar. If scopes are not similar, or if work horizon is too far out in the future, this method becomes much less reliable.

For global budgeting, programs for federal spending are built several years in advance, and are usually based on prior year spending levels. Individual facility requirements are rarely this regular, and can be difficult to predict without a robust assessment methodology. In general, federal agencies cannot carry over cost savings from year to year, even if those cost savings have a multi-year payback period. There is a need to establish more working capital funds based on non-appropriated and non-expiring dollars, so that facilities managers have the means of developing a more long-term and holistic MR&R strategy for facilities.

2.6.3.3 Facility Repair Costs

A critical part of facility asset management and work planning is work activity cost estimation. For the purposes of estimating the cost of performing a work treatment on a building element, the CSI Uniformat code can be used to directly link to RS Means Assemblies cost book (R.S. Means, 2014). For this development, a simple replacement cost model is used, where unit replacement costs for components, sub-systems, systems, and even buildings can be derived from RS Means, and multiplied by the total quantity for the building.

For component repair activities, the BUILDER Sustainment Management System uses a parametric model of component repair cost to estimate the corrective repair cost as a percentage of the total replacement cost based on the condition index value (U.S. Army Construction Engineering Research Laboratory, 2015). This parametric cost model assumes that as a building component's condition (represented by the condition index) deteriorates the cost of repair to restore full serviceability increases. Thus, when the condition index is very high (CI~100), there are minimal repairs to perform and repair cost is low. Likewise, a component condition index at or below the failure threshold (CI ~ 40) results in a repair cost estimate very near or even above the total replacement cost. At this point, repair is no longer an economically viable option. Between these two extremes, component repair cost is described by the parametric Equation 1:

$$UC_{repair} = UC_{replace} \times \left(\frac{100-CI}{100-CI_{term}}\right)^{N} \tag{1}$$

Where: UC_{repair} = estimated unit repair cost as a function of condition

$UC_{replace}$ = estimated unit replacement cost

CI = current predicted Condition Index

CI_{term} = designated Condition Index terminal value, usually 40

N = cost escalation factor

The unit replacement cost is based on component unit price information, such as RS Means, as discussed in the previous section. The condition index is based on the projected component condition at the time the repair is schedule to be performed, as shown in Figure 4. The parameter N is determined for a particular component by comparing the cost of a range of typical repair work actions at different life cycle points to the associated condition index values related to those work actions prior to the repair. The repair cost model also assumes a minimum service call cost with any work activity, to account for a technician making a site visit to initiate work.

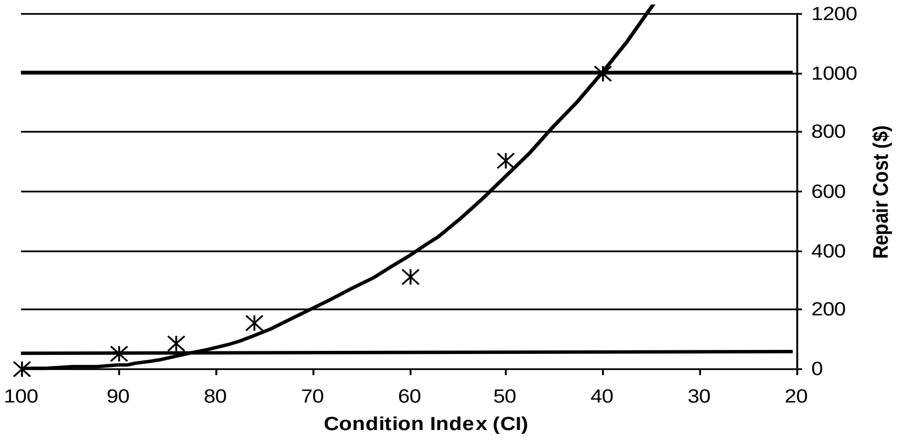


Figure 4. Unit Repair Cost ($) as a Function of Condition Index

2.6.3.4 Facility Operations Costs

Every facility, whether a single family home or a large government complex, has a cost of ownership associated with it. This cost extends well beyond the day when construction is completed and the facility is turned over for occupancy. A portion of this cost is related to maintenance, repair, and renewal expenses as the building's systems and components age and approach the end of their respective service life. Other costs may be incurred to remodel, reconfigure, or add new capabilities to a facility. Last but not least, there is the facility operating cost itself, which includes energy consumption. The individual responsible for managing that facility, whether that is a home owner or a building supervisor, can develop a plan to allocate a limited pool of resources to 1) ensure the facility meets occupant requirements and 2) minimize total cost of ownership, including all of the expenses discussed previously. If the facility is sufficiently large or complex, the facility manager may commission an assessment to identify opportunities to address one or both of these goals. To optimize resources, a prudent facility manager would consider both of these goals, and all of the cost of ownership components in a holistic sense before making a facility investment decision.

However, large facility owners, such as the U.S. Department of Defense (DoD), have unique challenges. In addition to being one of the largest facility managers in the world, it is also one of the largest energy consumers as it operates this vast array of facilities. (US Army activities alone represented 25% of all federal energy consumption in FY09). These facilities, and the system and components within them, have varying ages, conditions, and work requirements that are constantly changing as infrastructure deteriorates, new technologies or regulations emerge, and as mission priorities change. Due to the immense scope and dynamic operating environment, the effort of managing and directing the maintenance, repair, and rehabilitation resources (commonly referred to in the Department as Sustainment, Restoration, and Modernization, or SRM) for these facilities presents a unique challenge, both at the agency headquarters level and at the installation level with each Public Works Directorate.

Adding to this challenge, recent policies and executive orders have seen an increased focus on energy efficiency initiatives related to federal facilities. As a result, energy audits have become an increasingly effective tool for identifying areas for facility improvements. However, these audits have generally remained detached from the standard SRM investment decision making process, which is typically driven by aggregate cost models and condition-based inspections. As a result, facility managers and decision makers are not always presented with the whole picture, and are thus missing an opportunity to consider the total cost of ownership when planning facility repair and renewal. There is a synergy to be gained by fully integrating facility energy considerations with the facility life cycle SRM planning process. As a result, integration between standardized energy audits with other facility life cycle condition and performance metrics is needed. This holistic approach provides a more complete picture to decision makers on the “targets of opportunity” for facility repair and renewal, allowing them to better realize the total cost of ownership. Since activities related to facility repair ultimately affect both maintenance and repair costs and energy operations costs in the long-term, an integrated process can identify facility improvement projects with the most attractive total return on investment.

2.6.4 Estimating Facility Life cycle Characteristics

2.6.4.1 Component Service Life Estimation

The estimate of initial design service life is also a tremendous challenge for building asset management systems. Infrastructure systems typically involve large scale construction projects, and are hence capital intensive to build. Due to their large expense, they are designed and expected to remain in service at a high performance level for several decades or longer. In financial terms, these assets are classified as long-dated assets. Over the life cycle on a particular infrastructure asset, it will likely deteriorate, undergo changing user requirements, and generally become less efficient in its purpose when compared to new construction utilizing the state of the art technology and built to current requirements. In other words, portions of the building will converge to a failure end state.

Without intervening repair and renewal actions over the life cycle, its value to the owner or occupants will depreciate.

There are many ways of describing failure leading to end of service life, thus the definition of failure in a building can be ambiguous (Lemer, 1996). A building asset is made up of many systems and components, each of which can have more than one function to accomplish. If any one of these functions is no longer able to be performed due to a failure mode, the effects can range from insignificant and unnoticeable to catastrophic. However, these failure modes can also progress and compound over time, interacting with the performance of other functions so that unnoticeable failures can eventually result in catastrophic failures.

Obviously, one of the foremost goals of facility asset management is to prevent catastrophic failures from occurring, or at least predict them well ahead of time so that mitigation steps can be taken. These catastrophic failures are usually associated with health and safety issues, or abrupt loss of essential infrastructure capabilities. To protect against these expensive events, a number of checks (safety inspections) are put in place to identify characteristic signatures of a failing system. These are observable events that have been shown to be on the path to impending systematic failure. In other words, they are signature clues that may predict a larger failure. Since the key focus is to prevent global, catastrophic failure, these observations are usually linked to a number of smaller failures, which will need to accumulate before major impacts occur. Correcting a system that has reached the stage of "impending catastrophic failure" is expensive, both in terms of the cost of repairs and the cost of system downtime. This is rarely the most convenient or economical time for repair, and many times the only answer is total system replacement.

For the most part, in the realm of facility failure modes, catastrophic failures are the exception, not the rule. But while they are rare events, they usually draw the most public attention. However, as mentioned above, catastrophic failures are really just the culmination of other failure events that have compounded. In addition to resulting in large system failures, these child failure modes can also reduce total system performance and efficiency. Correcting these smaller failure modes before they propagate, can not only lead to a safer, more robust, longer life system, but it can also reduce life cycle operating costs. The return on maintenance and repair investment is usually many times higher when intervening at a lower level.

However, in order to make actionable decisions about MR&R investments (at a component level for example), one needs to have a list of the required functions and the consequential failure modes for each component. The effects of these failure modes need to be identified and documented. An objective inspection process then needs to be employed to check for and locate these failure modes on some periodic basis (Moubray, 1997). Over time, this database of information provides some information on the probability of one failure mode progressing to another, and what the consequence of that failure mode progression is. This directly supports the measurement of infrastructure risk, as discussed above.

To support this analysis requires a level of inspection below where traditional efforts are usually focused for most types of building assessments. This does not necessarily make the inspection more data intensive or more costly, but it makes the process more focused on specific observations about failure modes at a component level versus subjectively identified deficiencies at a more global level. The support of this type of analysis is fundamental to facility asset management.

2.6.4.2 Asset Condition Prediction

Facility management involves the optimal selection of activities such that life cycle costs are minimized over a certain time horizon, subject to meeting certain performance standards and requirements. The condition of facility, along with its systems and components, is an important factor in both the determination of life cycle costs related to maintenance, repair, and failure and performance. The measurement of the current condition and the prediction of future condition is thus a critical aspect of facility management process.

Condition is difficult to observe and measure directly because it is not a physical property like velocity and mass. It can have different meanings based on the reference point of the observer. These difficulties can be largely overcome by implementing a standardized condition assessment process, which attempts to remove much of the subjectivity in the process by identifying the indicators that can affect condition, such as distress mechanisms that can indicate loss of condition and performance. Despite this development, condition assessment inspection errors and biases are still bound to exist. Nevertheless, several different prediction models have been developed based on inspection data to project the expected condition of a component at a point in time.

2.6.4.2.1 Condition Prediction Methodologies

The results of these condition assessments are typically discrete condition measurements on an ordinal scale, which means that the numbers assigned do not indicate distance between ratings, but only relative ordering. These discrete ordinal measurements can also be obtained by discretizing a continuous performance scale. Figure 5 shows a generalized deterioration curve for what could be any building component. As time passes, quality or condition decreases due to friction, wear, UV exposure, fatigue, freeze-thaw cycles, and many other degradation mechanisms. For some asset types, these “distress” mechanisms interact and compound, accelerating condition deterioration over time. Eventually, condition transitions from one state to the next lower state (Madanat, Mishalani, & Wan Ibrahim, 1995), and this condition deterioration directly affects the performance of day-to-day facility operations. If performance drops below the threshold level, recapitalization, restoration, or repair becomes necessary. The cost of these actions increases substantially as condition further degrades, and if not performed, premature failure may result in unrealized asset service life for some or all of the building. Thus, a real penalty cost in terms of dollars exists for deferring work past a certain condition.

If the life cycle deterioration curve in Figure 5 could be sufficiently established for any specific asset or component of an infrastructure, facility managers could easily determine condition at any point in time. They could then make the prudent decisions regarding when to do MR&R work. However, it is inconceivable to think that a single curve exists to adequately express the life cycle condition for a facility class or individual asset, because condition depends on unique localized factors, including climate, operational use, and levels of routine maintenance and corrective repairs. Therefore, depending on the course of MR&R actions over a life cycle, in addition to a number of other unpredictable events, the current and future condition states can be altered unexpectedly at any time. The result is that no single deterioration curve can be applied to a given asset with good confidence at the start of its life cycle. In fact, the true deterioration trajectory differs among individual building components of varying types.

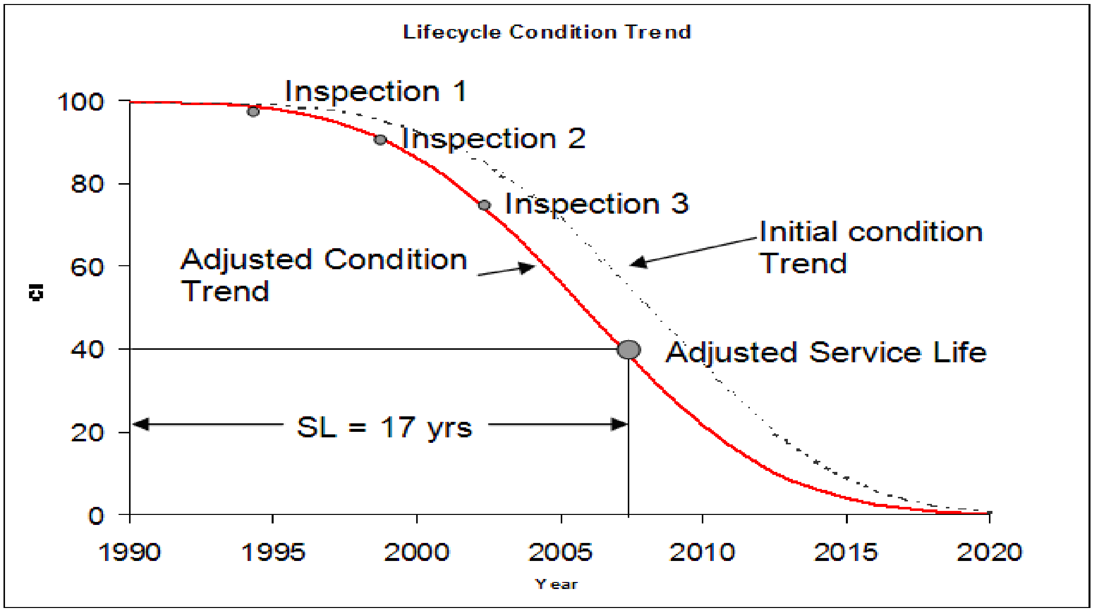


Figure 5. Example Condition Deterioration Curve

To account for the difficulty of predicting the service life and condition profile of a building component, the EMS tools discussed above strive to establish the accuracy and confidence of building life cycle deterioration curves through a standardized condition assessment methodology - the Condition Index approach and the resulting Condition Index metric. The Condition Index metric is a reliable gauge of an asset's local condition at a precise point in time. It can be used to compare expected conditions from an assumed life cycle curve illustrated in Figure 5 to actual measured conditions. This initial life cycle curve is adjusted using Condition Index data, defining a true, locally calibrated life cycle condition prediction trend for each asset (Grussing, Uzarski, & Marrano, 2006). This type of prediction approach falls under the age-based deterministic approach, described in more detail below.

2.6.4.2.2 Deterministic Models – Age-based approaches

Deterministic models describe a mathematical relationship between input and output parameters; this relationship can be of linear or non-linear type. Time linear and power law models have been applied for estimating the deterioration of water mains (Kleiner & Rajani, 2001) and pavements using neural network models (Lou, Gunaratne, Lu, & Dietrich, 2001), whereas exponential deterministic models have been applied for pipes (Wirahadikusumah, Abraham, & Iseley, 2001; Morcous, Rivard, & Hanna, 2002). Zhang and Damnjanovic used reliability functions to estimate pavement failure probabilities (Zhang & Damnjanovic, 2006).

Attempts to model building component condition using reliability related functions such as the Weibull cumulative probability distribution function have been studied. This is logical, because condition and reliability seem proportionally related. If one defines reliability as the probability of the asset performing at or above its minimum performance state over the course of a time interval, then a component with a CI of 90 is expected to have a higher probability of reliably performing than a component with a CI of 60, which has a higher chance of breakdown or failure before that time.

Using the Weibull function, the condition index for a given component is described as follows in Equation 2 (Grussing, Uzarski, & Marrano, 2006).

$$CI = A * \left(\frac{1}{CI_T}\right)^{-\left(\frac{t}{beta}\right)^{alpha}} \tag{2}$$

Where: CI = condition index (0-1)

A = initial condition (usually 1)

CI_T = Condition Index at failure (usually 0.37)

t = normalized age as a percentage of design service life

beta = service life adjustment parameter

alpha = condition degradation parameter

The Weibull probability function is based on expected component time to failure. Figure 6 shows the probability of a general component failure over time. From this analysis, the highest probability of failure is expected to occur between 2035 and 2040, which relates to the end of the component’s expected life. Figure 7 shows the inverse of the cumulative probability of component failure before a given year. Early in the life cycle there is a high probability of the component reliability performing, (the inverse of failure) which decreases as the component ages. Using this approach, minimum standards can be defined to set limits on the allowable reliability, hence signaling the need for corrective work.

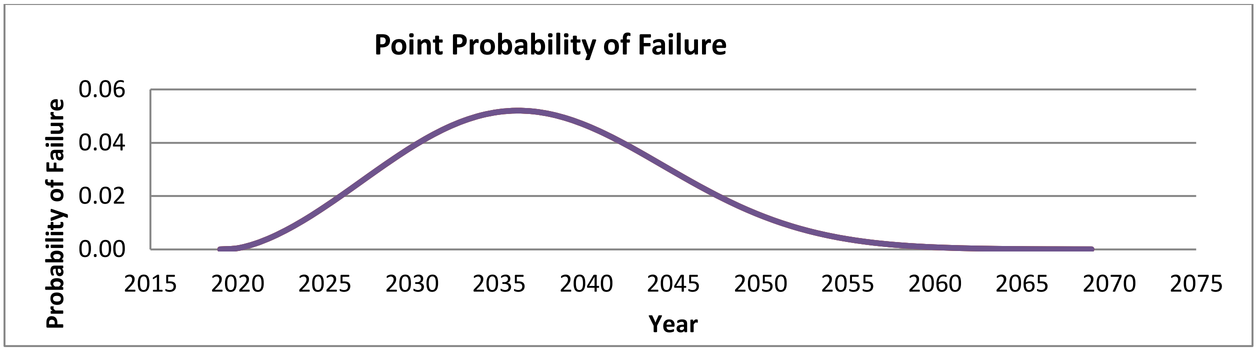


Figure 6. Component Probability of Failure versus Time

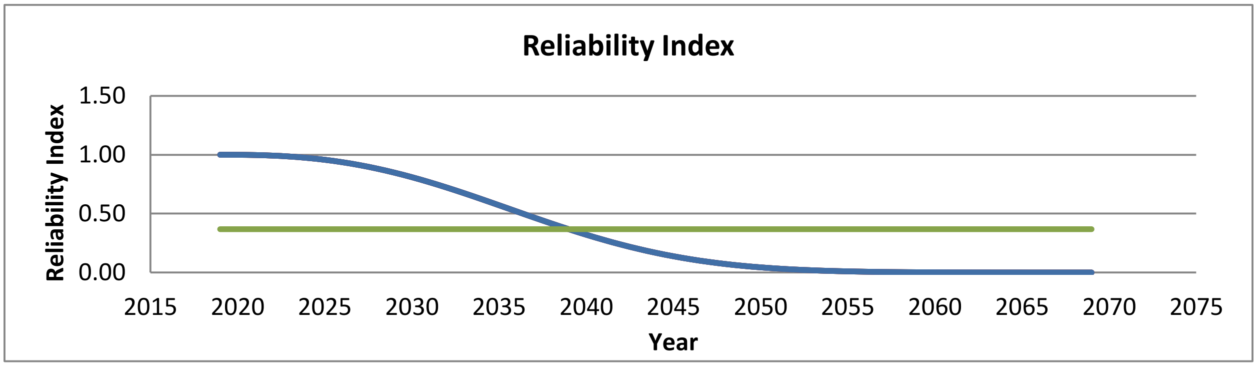


Figure 7. Component Reliability Index versus Time

There is an inherent assumption that the condition of an asset is directly related to its age, such that the older a component gets, the more accumulated deterioration and lower its expected condition. While this is generally true, age alone is not always the significant predictor of condition loss. There are several other factors that can affect a component's current condition, as well as the change in condition over time. To illustrate, Figure 8 shows the inspected component condition plotted against a component's age, pulling from a large subset of previously assessed BUILDER information for air conditioning units. Because of variations in the environmental exposure, use and abuse, and maintenance and repair received, simply plotting condition index versus relative age at the time of inspection results in almost no discernible pattern of condition over time, even for a specific type of building component. This data "noise" is due to the modeling challenges discussed above, in addition to the difficulty that may arise in many instances from an inspector attempting to ascertain the actual age of a component.

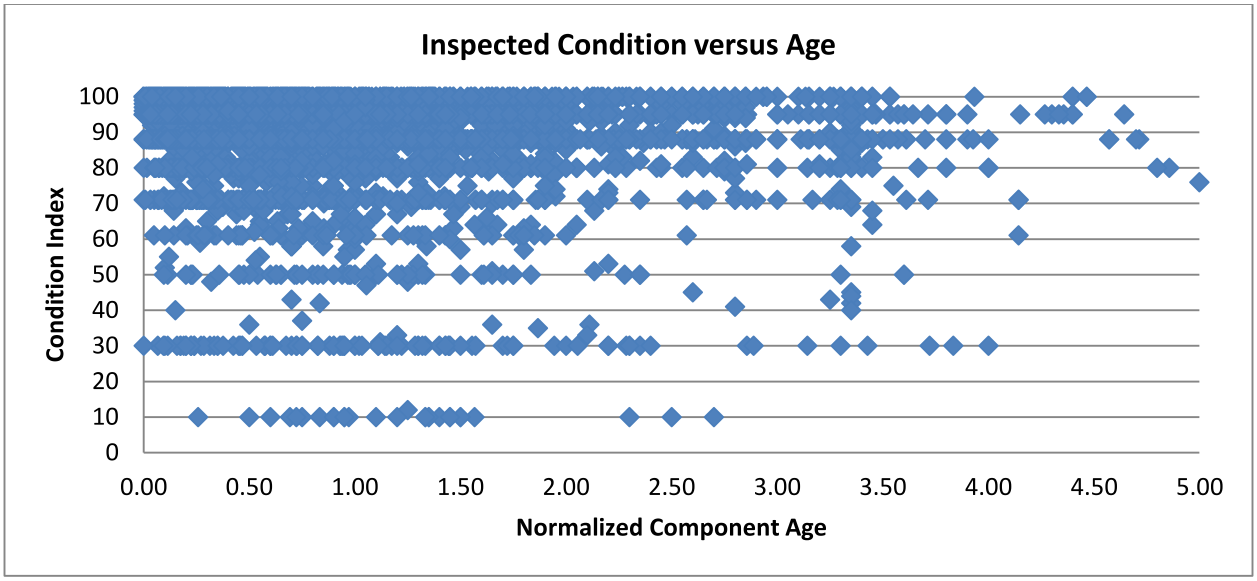


Figure 8. Condition index rating versus normalized age

However, if the data are broken down into discrete time-series ranges, and the percentage of components in each range that fall below a threshold CI is calculated, then the pattern as shown in Figure 9 below does emerge. This shows the probability of a building component (Air Conditioning Unit in this example) of a certain age range reaching a CI index threshold of 40, which was previously defined as a failure point. By using the polynomial trend line, with an R^2 value of 0.8, a mathematical relationship between age and failure probability (or probability of falling below the CI threshold limit) can be established.

The trend below can give a facility manager, whose job it is to keep all of its critical components operating at a standard of reliability, a means of understanding the probability of a failure event occurring. As a result, this analysis can help to identify and control unanticipated component failures that tend to lead to higher costs for unscheduled repairs and potential loss in building occupant productivity.

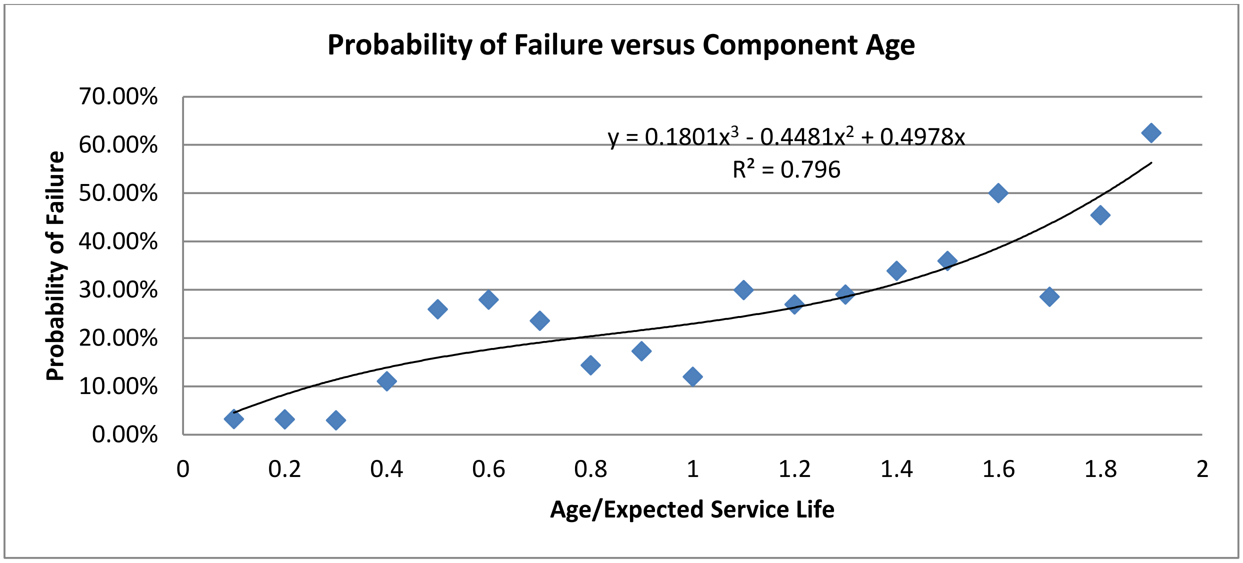


Figure 9. Historic Data Mining Probability of Failure versus Age

The limitation with the preliminary analysis in Figure 9 above is that it includes data for components that have undergone multiple repair activities that significantly affect the condition trajectory. This is because there are many components that have survived well past the expected service life; thus, they likely experienced one or more repair activities to improve condition and extend service life. This is a typical scenario, especially for organizations with primarily a reactive-based maintenance model, where components are kept operating as long as possible through unscheduled repairs, versus timely scheduled replacements. The inclusion of these data in the analysis above is problematic, however, because the Weibull reliability model assumes normal maintenance, but not corrective repairs which may improve condition and/or extend the life.

The primary purpose of a CI based inspection is to support a more proactive maintenance plan, by identifying component condition prior to failure. While an inspection will likely find some components that have failed, most that were inspected are in a non-failed state. Prior to the inspection, most components that did reach a limit state would be corrected through repair or replacement activities. As a result, the reliability curve above does not accurately depict the behavior of a typical component due to work altering the behavior.

The result of this is a higher percentage of components being in a better condition state relative to their age than what would be expected based on normal design life and the reliability models discussed above. This is further illustrated in Figure 10 below, which shows only a small percentage of components in the critical (red) CI range, even when their age is several times the expected life. In order to build a model which helps identify the best situations for the selection of certain component repair or replacement activities and their impact on condition and reliability, there first needs to be an understanding of a component's condition and reliability over time assuming simple deterioration with no work activities performed.

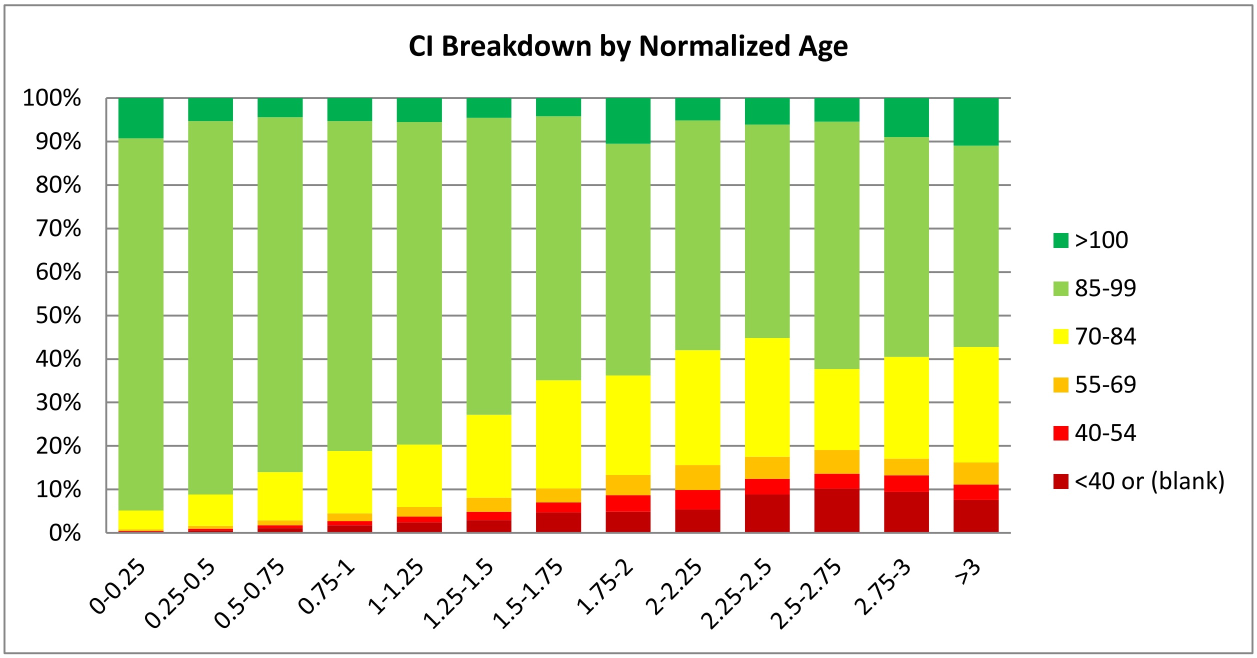


Figure 10. Breakdown of CI range probabilities for different normalized age ranges

As a result, to truly understand the condition versus age relationship under normal conditions, data associated with repairs needs to be filtered and removed. The difficulty is that very little data exist about when repairs were accomplished, and what the condition was before and after those repairs were performed, especially when looking at components that have been in service for several years with limited life cycle information associated to them.

The issues above point to some of the challenges and limitations of an age-based deterministic approach. In addition, some researchers have noted that the deterministic approach is often not applicable to complex asset systems when a mathematic relationship cannot be derived due to highly variable data (Edirisinghe, Setunge, & Zhang, 2015). Because of this, probabilistic (sometimes called stochastic) prediction models are discussed above, including the discrete Markov chain model in particular.

2.6.4.2.3 Stochastic Models – Discrete Markov Chain

A Markov process is a memoryless process, and depends only on the current, or last observed condition state to predict future states. It is based on the concept of probabilistic cumulative damage, which predicts change of condition over multiple transition periods (Bogdanoff, 1978). While other explanatory variables such as age, weather, maintenance, etc., can be taken into account, the incremental nature of the Markov model is more realistic because condition at a point in time is primarily a function of condition at a previous time (Madanat, Mishalani, & Wan Ibrahim, 1995). As a result, component age and expected service life is not a controlling factor of such an analysis, and thus provides an opportunity to improve on the limitations of the approaches discussed above.

Transition probabilities specify the likelihood that the condition of an infrastructure facility will change from one state to another in a unit time. Transitions are probabilistic in nature because infrastructure deterioration cannot be predicted with certainty due to unobserved explanatory variables, the presence of measurement errors, and inherent stochasticity of the deterioration process. The Markov process is the most prevalent used stochastic technique for highways, bridges, sewer pipes, and water pipes (Micevski, Kuczera, & Coombes, 2002).

Transition probabilities are obtained either from accumulated condition data or using expert judgment elicitation procedure (Morcous, 2006). Two methods are commonly used to generate transition probability matrices from condition data: regression-based optimization method and percentage prediction method. The regression based optimization method estimates transition probabilities by solving the nonlinear optimization problem that minimizes the sum of absolute differences between the regression curve that best fits the condition data and the conditions predicted using the Markov chain model.

Since the regression model is affected significantly by any prior maintenance actions, whose records are not readily available, the percentage prediction method is commonly used. Use of this method requires at least two consecutive records without any maintenance interventions, for a large number of components at different condition states, in order to generate reliable transition probabilities.

As discussed above, using age as the sole factor to derive a prediction models for condition deterioration based on physical inspection data is inappropriate. It is vital to consider the influencing factors. As a result, components are classified into groups of similar attributes. The purpose is to capture the fact that transition probabilities are a function of explanatory variables, so the population is segmented in order to develop transition matrices for each group.

The main advantage of the Markov model is its ability to reflect uncertainty, such as from initial conditions, applied stresses, assessment errors, and inherent uncertainty in the deterioration process (Lounis, 2000). These probabilistic models are also naturally computationally tractable for use with discrete variable optimization problems (Madanat, Mishalani, & Wan Ibrahim, 1995).

Markov Chains have been studied for applications against Storm Water Pipe Deterioration (Micevski, Kuczera, & Coombes, 2002), Waste Water Networks (Baik, Jeong, & Abraham, 2006), Pavement Deterioration (Ortiz-Garcia, Costello, & Snaith, 2006), Bridge Decks (Morcous, 2006), Bridge Elements (Agrawal, Kawaguchi, & Chen, 2010), and Underground pipelines (Sinha & Knight, 2004). All of these applications involve linear networks, which have many advantages over facility assets for condition prediction modeling. Building deterioration prediction presents a challenge due to the complexity associated with the hierarchical structure and number of building components (Edirisinghe, Setunge, & Zhang, 2015).

Edirisinghe et al proposes a Markov Chain model to study the parameters of the International Standards Organization (ISO) factor method, which attempts to determine the impact of a limited set of variables that affect deterioration and service life of building components (Edirisinghe, Setunge, & Zhang, 2015). That study is based on a small set of data using inspections performed at pre-defined and fixed times. Madanat et al, looking at generalized infrastructure transition probabilities also assumed a constant inspection period or observation interval that corresponds with the cycle time (Madanat, Mishalani, & Wan Ibrahim, 1995).

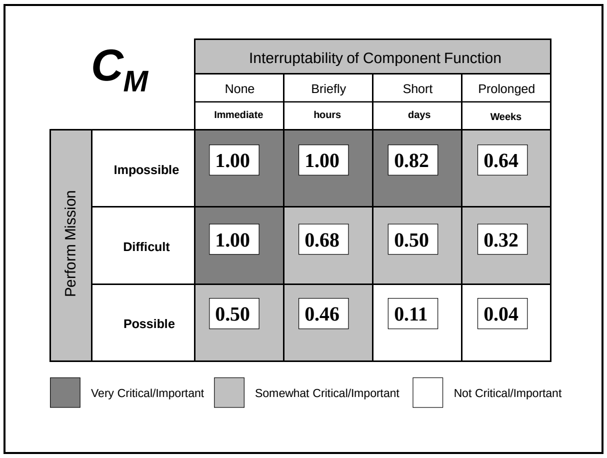
Most of these models are based on two important assumptions. One is the assumption of a constant inspection period, where inspections are performed at predefined and fixed time intervals. The other is the state independence assumption, where conditions depend only on the present condition and not past condition. Studies of the Markov model for bridge decks validated the state independence assumption is valid at a 95% confidence level, meaning the probability of any future state depends only on the present state and not the full inspection history. However, there are noted limitations with the assumption of a constant inspection period (Morcous, 2006).

This methodology below seeks to develop an approach which applies across a wide range of components of a building and uses variable observation data, although such capability would greatly enhance and improve building asset management systems that require condition and performance prediction. Furthermore, a major goal of this research is the extension of the Markov model for reliability and service life estimation for building components.

2.6.4.3 Component Importance Index

The component importance index is a measure used to determine the criticality of a component in regards to how it affects overall system and/or building performance. The index is a score ranging from 0 to 1, with higher values indicating higher criticality. It was developed using an expert elicitation process, where a panel of subject experts was presented with a range of component types and asked to determine how the interruption of each component's function affects a building's ability to perform mission, support occupant's quality of life, and adversely affect the operation or maintenance of other components (U.S. Army Construction Engineering Research Laboratory, 2015). This rating process was done for each of nine different building group types, realizing that some components may have a higher importance in certain buildings versus others. The criticality score was obtained by recording each rater's perceived impact of a component interruption as well as immediacy of that impact.

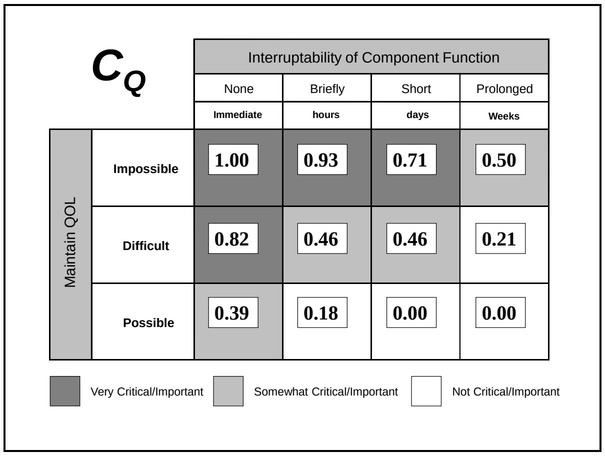
For example, if it was determined that interruption or failure of a particular component for an operational and training building would make mission performance difficult, and that adverse effect would transpire within hours of failure, referring to Figure 11, that component would receive a 0.68 mission criticality score. The same evaluation would subsequently be rated to obtain a quality of life (QOL) criticality score (Figure 12), as well as an operational and maintenance (O&M) effect score (Figure 13). These scores are aggregated based on the relative importance of mission, QOL, and O&M effects to obtain the overall criticality score for that facility type and component class (Table 2). This process is similar to development of the mission dependency index (Antelman, Dempsey, & Brodt, 2008) used to determine facility importance to mission.



C_M		Interruptability of Component Function			
		None	Briefly	Short	Prolonged
		Immediate	hours	days	Weeks
Perform Mission	Impossible	1.00	1.00	0.82	0.64
	Difficult	1.00	0.68	0.50	0.32
	Possible	0.50	0.46	0.11	0.04

■ Very Critical/Important ▨ Somewhat Critical/Important □ Not Critical/Important

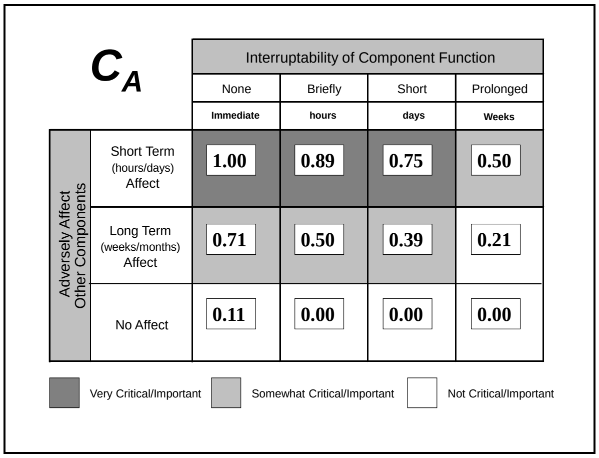
Figure 11.Component Criticality Matrix for Mission



C_Q		Interruptability of Component Function			
		None	Briefly	Short	Prolonged
		Immediate	hours	days	Weeks
Maintain QOL	Impossible	■ 1.00	■ 0.93	■ 0.71	▨ 0.50
	Difficult	■ 0.82	▨ 0.46	▨ 0.46	☐ 0.21
	Possible	▨ 0.39	☐ 0.18	☐ 0.00	☐ 0.00

■ Very Critical/Important ▨ Somewhat Critical/Important ☐ Not Critical/Important

Figure 12. Component Criticality Matrix for Quality of Life



C_A		Interruptability of Component Function			
		None	Briefly	Short	Prolonged
		Immediate	hours	days	Weeks
Adversely Affect Other Components	Short Term (hours/days) Affect	■ 1.00	■ 0.89	■ 0.75	▨ 0.50
	Long Term (weeks/months) Affect	▨ 0.71	▨ 0.50	▨ 0.39	☐ 0.21
	No Affect	☐ 0.11	☐ 0.00	☐ 0.00	☐ 0.00

■ Very Critical/Important ▨ Somewhat Critical/Important ☐ Not Critical/Important

Figure 13. Component Criticality Matrix for Adverse Effects on Condition

These component importance indexes can be used as a proxy for a consequence of failure analysis. For example, if the component was to reach a failure state, making interruption of its primary functions highly likely, and such an interruption would make the performance of key building functions difficult or impossible to perform, this would represent a very high impact. This is especially the case if the impact was immediate, since the correction of an unscheduled failure would likely not occur in advance. Therefore, for this research, if it is assumed the component importance index approximately relates to the probability the building will not perform as needed if component failure occurs. The condition importance indexes for several different building types is presented below (U.S. Army Construction Engineering Research Laboratory, 2015).

Table 2. Criticality Factors for Component Importance Index

	Criticality Values					
Component	**Admin.**	**Medical**	**Maintenance**	**Training**	**R&D**	**Storage**
B20 Exterior Envelope	0.30	0.42	0.26	0.32	0.32	0.21
Exterior Door	0.66	0.73	0.61	0.70	0.65	0.71
Exterior Wall	0.82	0.99	0.76	0.92	0.95	0.64
Exterior Window	0.51	0.64	0.37	0.75	0.45	0.20
B30 Roofing	0.32	0.52	0.26	0.32	0.36	0.24
Roof Surface	0.42	0.53	0.32	0.41	0.47	0.25
D20 Plumbing	0.45	0.62	0.40	0.53	0.55	0.33
Piping	0.64	0.88	0.55	0.79	0.84	0.31
Plumbing Fixtures	0.50	0.80	0.52	0.56	0.65	0.27
Water Heater	0.37	0.77	0.07	0.42	0.52	0.11
D30 HVAC	0.44	0.67	0.44	0.50	0.50	0.31
Air Handling/Ductwork	0.41	0.85	0.50	0.46	0.58	0.32
Cooling Unit/Plant	0.59	0.87	0.44	0.70	0.68	0.38
Heating Unit/Plant	0.68	0.87	0.54	0.67	0.74	0.35
D50 Electrical	0.48	0.71	0.56	0.57	0.53	0.48
Electrical Distribution	0.72	0.89	0.84	0.80	0.74	0.74
Lighting System	0.42	0.88	0.68	0.60	0.57	0.48

2.7 Activity Selection and Optimization

There are several numerical methods available for optimizing a solution to the problem stated above by selecting the appropriate type and timing of work actions to control performance state and deterioration. Lounis and Vanier use a dynamic programming formulation to optimize work activity selection for routine building maintenance (Lounis & Vanier, A Multiobjective and Stochastic System for Building Maintenance Management, 2000), but does not discuss higher level replacement activities. As a more robust method, Marseguerra et al provide a genetic algorithm approach to optimize repairs, but this approach was limited to transportation infrastructure assets, and not building systems and components (Marseguerra, Zio, & Podofillini, 2002).

Nonetheless, the genetic algorithm approach is promising for this research due to the complex and non-linear nature of this problem that stems from the interdependency of building systems and components. A genetic algorithm (Goldberg & Holland, 1988) is a search technique that mimics the processes of natural evolution to select an optimized solution set. El-Rayes et al applied a genetic algorithm approach for the optimal selection of sustainable building upgrades for interstate rest-area facilities (El-Rayes, Liu, & Abdallah, 2013). Where a large number of facilities is present, Hegazy et al applied a bi-level optimization approach to first optimize activities across a single facility, followed by a portfolio-level project selection (Hegazy, Elhakeem, Singh Ahluwalia, & Attalla, 2012).

2.8 Background and Literature Review Summary

While its application to buildings is still being refined and developed, civil infrastructure asset management principles are not new. They have been employed for many linear assets for decades. However, the building domain does present some challenges that make its adoption and implementation slower than the other civil assets. Fortunately, a number of factors are converging that make its application to buildings necessary and more appealing.

This chapter has identified many of the methods involved in current building life cycle asset management practice and the challenges that exist to continue improving building asset management. Some of these gaps have promising technologies and advances that are currently being developed to improve the quality, focus, and efficiency of building information to support decisions, and some require further research and development. The chapters that follow propose a methodology that builds on established tools and emerging technologies, while implementing a framework that improves the current state-of-the-art in building asset management in several areas, including performance measurement and prediction, total cost of ownership and risk considerations, and project and network level work optimization.

CHAPTER 3 –MARKOV MODEL DEVELOPMENT

Condition indexes have been developed to measure building component condition degradation due to age, use, and deterioration in support of asset management tasks related to work identification, planning, and prioritization. With the development of these indexes, a vast amount of condition index data have been collected for a wide range of components in buildings of varying type, use, and geographic location. For example, the U.S. Department of Defense has implemented a standardized condition assessment approach applied to thousands of Department-owned buildings, resulting in a vast Condition Index dataset that can support more in-depth study of building component condition and reliability. This thesis explores the existing condition data and develops a rigorous definition of the relationship between component condition, failure, and reliability. Presented is an approach to analyze the existing component condition datasets using Markov transition probabilities. This approach provides enhanced capabilities for predicting future condition trends by relying more heavily on past observed inspection results, and relying less on inputs traditionally prone to error, such as component age and expected service life. This chapter will also show how the proposed condition prediction methodology results in a reliability metric that conveys a component's probability of failure, providing a much needed measure for facility risk management.

3.1 Introduction

Measuring and predicting the deterioration and future condition state of these buildings, and specifically the building components that comprise them, is a critical piece of any asset management program. Recent condition assessment initiatives conducted on large facility portfolios, such as the Defense Department's, have greatly accelerated the amount of quantitative and temporal condition information available against the building component life cycle. While measuring the current condition state through these assessments is a critical step, it is also important for any life cycle model to be capable of predicting the expected change in condition state due to age, use, and deterioration. Past efforts have employed different models, such as including the Weibull cumulative probability distribution (Grussing, Uzarski, & Marrano, 2006) to predict an expected condition trend. However, these approaches involve the inherent assumption that the condition of an asset is directly related to its age. While it is generally true that the older a component becomes, the more accumulated deterioration and lower condition it is expected to be in. However, age alone is not always the significant predictor of condition loss. There are several other factors, including the operating environment, maintenance levels, and repair work accomplished, that can affect a component's rate of deterioration over time.

Due to the limitations of an age-based approach, this research examines a different methodology for condition prediction that is based on the Markov transition process. A Markov process is a memoryless process, and depends only on the current, or last observed condition state to predict future states. As a result, component age and expected service life is not a controlling factor of such an analysis, and thus provides an opportunity to improve on the limitations of the approaches discussed above.

As mentioned in Chapter 2, Markov Chains have been studied for various infrastructure applications. However, no approach has yet been developed which applies across the wide range of components of a building. Developing such capability would greatly enhance and improve building asset management processes that rely on condition prediction and reliability estimation for performance measurement. The methodology that follows in this chapter introduces the modified Markov process and model framework for predicting the condition state of a generalized building component at discrete points in time. Subsequent chapters of this thesis will illustrate how the results of this model can be used to more proactively plan intervening facility management activities such as component inspection, repair, replacement, and upgrades in order to better govern the condition and the reliability of operations of the components, systems, and building as a whole.

3.2 Research Approach and Methodology

The objective of this research is to develop a probabilistic framework and model for the characterization of building component condition degradation over time using actual inspection data derived from a large dataset of facility component life cycle information. This model will subsequently support improved facility asset management processes, such as the estimation of component condition, reliability, performance, and service life over time, the optimized timing of component inspections, and the selection of component work activities. While the central focus of this research is on building component condition prediction, it ultimately supports a broader goal to provide improved multi-year work planning analysis that considers various cost drivers and performance factors, as well as risk and uncertainty.

The traditional development of a probabilistic condition prediction model requires an ample amount of time-series condition information to develop the requisite probabilistic models. While several years of longitudinal time-series condition data do not currently exist, large datasets of paired condition data (two or more condition assessments separated by a minimum span of time) do exist. As an illustration, Figure 14 shows a range of observations over time represented by the x axis, for a number of similar component instances. While the number of observations for a single component across the x axis is limited and sparse, the number of components of which at least two condition measurements have occurred is vast. So while a long time-series of data do not exist, as the dashed line would indicate, this limitation is countered by a large cross section of components to be analyzed. As a result, the proposed Markov Model approach is to use the paired condition data to study the nature and probability of transitioning from one condition state to another, as a means of constructing a probabilistic-based deterioration model, similar to the dashed curve.

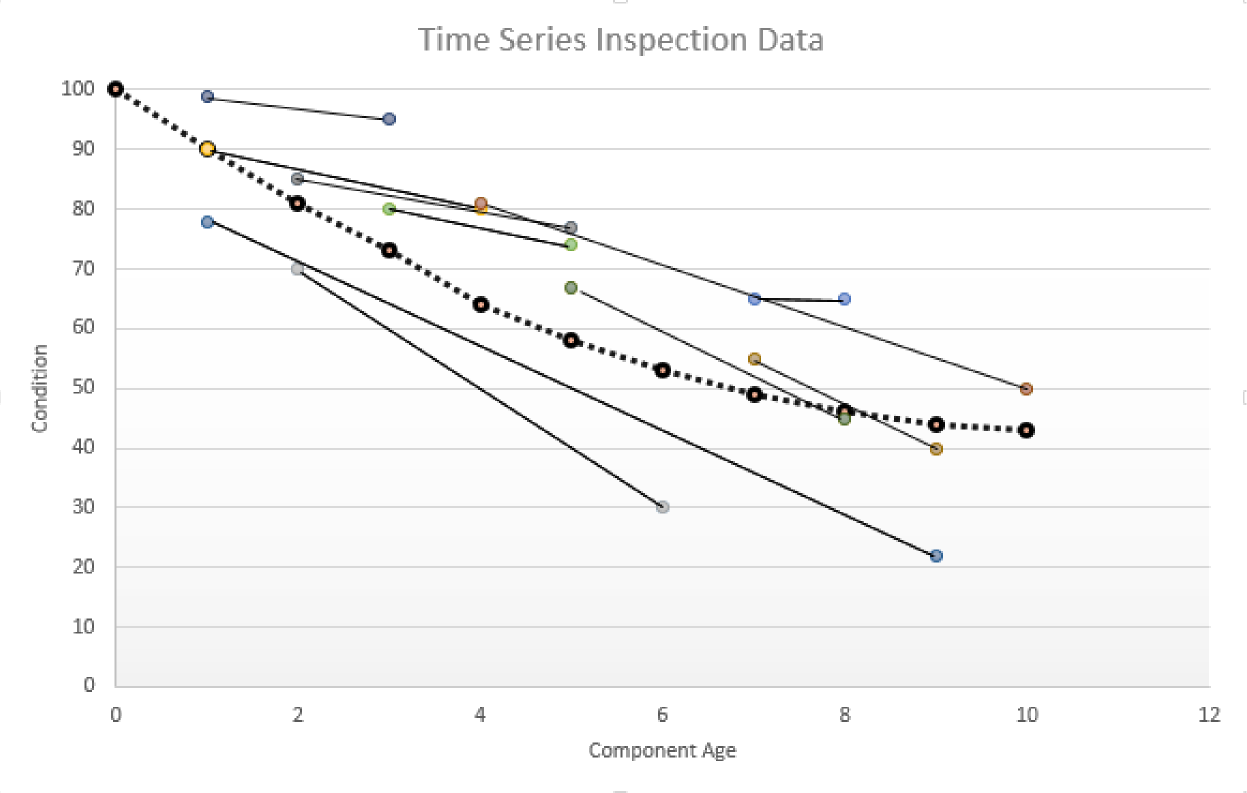


Figure 14. Example Time Series Component Inspection Data

3.3 Generalized Markov Model

A Markov process is a mathematical system that undergoes transitions from one state to another, such that the next state depends only on the current state and not on the sequence of events that preceded it. As a result, the process is referred to as memoryless, which is a unique property of a Markov system (Kemeny & Snell, 1960).

A Markov process can be modeled as a Markov chain, which is a sequence of random variables, X_i, that abide by the Markov property, namely that, given the present state, the future and past states are independent (Kemeny & Snell, 1960). Mathematically, this can be written as in Equation 3:

$$P(X_{n+1} = x \mid X_1 = x_1, X_2 = x_2, \ldots, X_n = x_n) = P(X_{n+1} = x \mid X_n = x_n) \tag{3}$$

The possible values of X_i form a countable set S called the state space of the chain. Markov chains are often represented by the transition matrix, M, from time t to time t+1, as shown in Equation 4 below:

$$M = \begin{bmatrix} P11 & P1j \\ Pi1 & Pij \end{bmatrix} \tag{4}$$

3.3.1 Discrete Markov Model

Using the above concepts, a generalized component condition model is defined such that a given building component can be in one of i condition states, Xi, which may correspond to the condition index rating scale described in Table 4 below. The probability of subsequently transitioning to condition state Xj at some point in time depends only on its last observed condition obtained from an inspection. If, for example, four primary condition states are defined (C1 – Excellent, C2 – Good, C3 – Fair, and C4 – Poor), then the expected state of the component at the next observation depends only on its most recent previously observed state. If the current condition state is unknown, but the component was observed to be in a good condition (state C2) at its last assessment, there exists some probability that it has remained in that good condition state, as well as probabilities of falling to fair and poor states respectively. Likewise, if the component condition was in a fair condition (state C3) initially, there are a different set of probabilities for remaining at fair, or falling to a poor state. Note that for the purposes of the current discussion, only components that undergo simple progressive deterioration with no repairs are considered, so the probability of the condition state improving is assumed to be zero. As such, if a component is initially in a poor condition state, this assumption provides no chance of improving to a fair or good condition state, so there is a 100% probability of remaining in the poor condition state. Due to these circumstances, the poor condition state is referred to as an absorbing state because once that state is entered, there is no chance of transitioning out of it without intervening activity, such as a component repair or replacement. Alternatively, the other states are referred to as transition states, since a component can transition in and out of those states.

While the four simplified condition states discussed above are used here as an example in developing the model, this is for illustrative purposes only. This research has identified seven condition interval ranges (presented below) that will be used as eventual condition states for analyzing the existing condition dataset. Under the four state example however, a transition Matrix M can be written comprised of elements P_{ij}, which represents the probability of condition transitioning from state i to state j. In addition to the generalized matrix, an actual set of probabilities is also provided as an example in Equation 5.

$$M = \begin{bmatrix} P11 & P12 & P13 & \\ 0 & P22 & P23 & \\ 0 & 0 & P33 & \\ 0 & 0 & 0 & Pij \end{bmatrix} = \begin{bmatrix} 0.80 & 0.15 & 0.05 & 0 \\ 0 & 0.70 & 0.25 & 0.05 \\ 0 & 0 & 0.50 & 0.50 \\ 0 & 0 & 0 & 1.00 \end{bmatrix} \quad (5)$$

As a result, if the condition state of the component at a certain point in time is known, and a transition matrix that describes the transition probabilities has been developed, then the probability of each condition state at the next observation can be calculated and used this to predict the component's condition. If for example, the last inspection determined the component was in good condition (state C2), and if there was 100% certainty in the accuracy of that observation, the condition state vector for that inspection observation can be represented as $[S]_o = [0, 1, 0, 0]$. Using the transition probability matrix, M above, the expected current condition state is then given as, $[S] = [S]_o \times [M]$, or as shown in Equation 6 below:

$$S = [\,0 \quad 1 \quad 0 \quad 0\,] \times \begin{bmatrix} 0.80 & 0.15 & 0.05 & 0 \\ 0 & 0.70 & 0.25 & 0.05 \\ 0 & 0 & 0.50 & 0.50 \\ 0 & 0 & 0 & 1.00 \end{bmatrix} = [\,0.00 \quad 0.70 \quad 0.25 \quad 0.05] \quad (6)$$

This example indicates there is a 70% probability of remaining in good condition, a 25% probability of falling to fair condition, and a 5% probability of dropping to a poor state.

3.3.2 Semi Markov Model

In a discrete Markov model process, the current predicted state depends only on the last observed state, and not the time since it entered that state or when the last observation was made. In reality for the purposes of this research, if two identical components were observed to be in the same condition state, but one observation occurred one time interval ago, and the other observation occurred two time intervals ago, one would expect more deterioration to take place over the course of two time intervals, and thus have a higher probability of a lowered condition state. In other words, the transition probabilities are not solely a function of the last observed state, but also the time since the last observation. This scenario is similar to a semi Markov process, which is not completely time independent like the discrete Markov model.

Thus, if M is the transition matrix that defines the transition probabilities for a single time interval, the following Equation 7 provides the transition matrix after n time intervals since the last observation:

$$M' = M^n \tag{7}$$

As a result, to predict the component's condition state over the course of multiple years, the above equation 7 is used to plot the expected probabilities as a function of n, or time since last observation. Using the example above, if S_o = [0 1 0 0] represented a good condition observation for an inspection occurring two time intervals prior, and M represents the transition probability over one time interval, one could calculate the current condition state which is 2 time intervals removed from the last inspection, to be given by [S_o x M] x M = S_o x M^2, or as shown in Equation 8:

$$S = [\,0 \quad 1 \quad 0 \quad 0\,] \times \begin{bmatrix} 0.64 & 0.23 & 0.10 & 0.03 \\ 0 & 0.49 & 0.30 & 0.21 \\ 0 & 0 & 0.25 & 0.75 \\ 0 & 0 & 0 & 1 \end{bmatrix} = [\,0 \quad 0.49 \quad 0.3 \quad 0.21\,] \tag{8}$$

As is evident here, with the semi-Markov model which takes time into account, there is a lower probability of the component remaining in a good condition state after two time cycles when compared to one, and thus a higher probability of declining to a worse condition state.

3.4 Transition Matrix Construction

From the above discussion, it is apparent that in order to use the Markov model to predict the component's condition state over time, a set of transition matrices is needed that represents the probabilities of going from condition i to condition j for a range of building components. Two methods are commonly used to generate transition probability matrices from condition data: the regression-based optimization method and percentage prediction method (Morcous, 2006). Since the regression method is affected significantly by any prior maintenance actions, whose records are not readily available, the percentage prediction method is utilized in this research by mining historic assessment data for building components. This requires that at least two inspections have been performed on a given component, and that those inspections are separated by a minimum interval of time, chosen as one year for this study. For the purposes of this discussion, the time between inspections is referred to as the observation interval, and the desired time interval of analysis (typically annual) as the cycle length.

In a simplified case for illustrating purposes, a situation is considered where the cycle length and observation interval coincide for all observation pairs. Here, the transition matrix is constructed by counting all the components of a particular subset (components of a common type for example) that experiences a condition transition from state i to state j, then dividing each by the count of components initially in state i. This provides each of the elements, P_{ij}, of the transition matrix M, which describes the probability of a transition from i to j after one cycle. Mathematically, this is expressed in Equation 9 as:

$$P_{ij} = N_{ij}/N_i \tag{9}$$

Where N_{ij} = count transitioning from i to j, and

N_i = total count initially in state i.

Of course, the cycle length and observation length for the building component data are not always the same, since components may not be inspected on an annual basis. Therefore, variations in observation intervals need to be taken into account, as well as other factors that affect the data. In the sections below, the data mining procedures and construction of the characteristic transition matrices using actual building assessment data are presented. Figure 15 below provides a flow chart for the process.

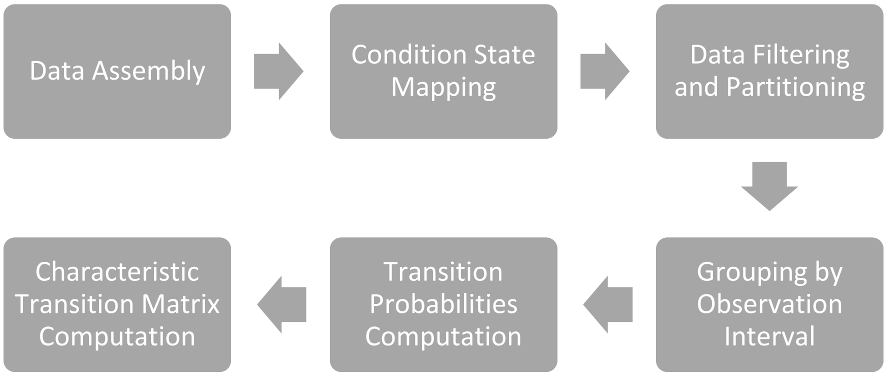


Figure 15. Flow Chart for Transition Matrix Construction

3.4.1 Component Data Representing a Fixed Observation Time Interval

In 2008, the U.S. Marine Corps (USMC) began service-wide implementation for a condition assessment program for their buildings using the BUILDER condition assessment methodology, which resulted in component inventory and condition rating data being collected for buildings and the constituent components spread across USMC military bases worldwide. In 2013, the Marines began the process of re-inspecting some of their buildings to reassess their current condition. These data provide a means of analyzing the condition state transition probabilities for a dataset containing pairs of ratings for nearly 33,000 individual components assessed approximately 5 years apart. Since the observation interval is constant across the components that were assessed, it provides a relatively straightforward means of constructing the transition matrices. However, since there is no guarantee that future inspections will occur at this same interval, and since it is necessary to incorporate these data into a more comprehensive dataset that includes other services, the more generalized scenario of mixed observation times must also be considered.

3.4.2 Component Data Representing a Variable Observation Time Interval

In addition to the USMC building data, with a common observation time of approximately 5 years, information for US Navy buildings was also available. While the U.S. Navy's (USN) inspection records do not go back as far as the USMC data, it represents a much larger dataset, with over 400,000 components having paired condition observation data. However, unlike the USMC, the USN observation interval is not consistent, instead varying from 1 to 5 years between inspections. To utilize this vast dataset of condition state information, a more generalized approach is needed for processing the transition probabilities, as discussed in the sections below. Some characteristics about the USMC and USN datasets are provided in Table 3 below.

Table 3. Dataset Characteristics

SERVICE	USMC	USN
#Component Pairs	33,329	402,692
Observation Interval	5 year	1-5 years
Average Observation Interval	5 years	2 years
% Same CI Range	35%	55%
% One CI Range Deterioration	29%	11%
% >1 CI Range Deterioration	26%	10%
% CI Improvement	10%	25%

3.4.3 Data Assembly, Filtering, and Partitioning

To assemble the data for analysis, the underlying BUILDER Structured Query Language (SQL) database is queried to create a dataset which lists each unique building component instance along with its pertinent inventory attribute data. This component inventory data is collected by assessors who identify the components that make up building, classifying each component based on its Uniformat component classification, such as an exterior door, roof covering, interior partition, etc. These assessors will also capture key attributes, such as the year installed, quantity, and specific material or component type if applicable.

After this component inventory information has been collected, a condition assessment is performed to capture the condition state each component. This is accomplished via the BUILDER SMS assessment methodology, using one of two types of inspection processes for measuring this condition, both of which result in a quantitative condition index score on a 0-100 scale that reflects the physical condition of the component at the time of the assessment. The distress survey approach discussed further in section 2.4.2.2 above is more detailed and labor intensive, but results in an inspection result that is more detailed and less subjective than the abbreviated direct rating approach. Currently, the vast majority of assessment data available for this study was collected using the direct rating approach due to time and budget constraints that were imposed. While the distress survey provides a more descriptive picture of the condition of a component asset, the direct rating approach is more than sufficient for accurately determining its general condition state, which is of greatest interest for this research.

Since inspections in BUILDER are performed against a specific component object, the previous and most recent inspection records were matched against each component's unique identifier. This allows for associating the inspection records for each component, showing the first and last inspection rating for each component instance, along with the date that each inspection occurred. This results in paired component observed condition state data at two discrete points in time. Since only a very small percentage of the components studied had more than two inspections, intermediate inspections were ignored in the data assembly step for this research. However, as additional inspections are performed in the future and multi-inspection series become available, it is recommended that each transition between any inspection and its next subsequent inspection for a component be treated as a separate data pair, as this will result in more data points for model development.

Next, since the resulting the condition index value that resulted from each rating assessment is a 0 to 100 continuous number, it was mapped to one of seven discrete ordinal condition states, shown below in Table 4. The discrete states were designed to bracket the inspection rating intervals associated with the BUILDER direct condition rating assessment. Appendix A provides a detailed description of the rating interval for this assessment process. The first three states below are associated with adequate states of condition (Green ratings per Appendix A), the next three states with a substandard rating (Amber ratings per Appendix A), and the final state reflecting an inadequate or very poor condition (combines the last three Red states per Appendix A). It was decided to combine the three Red direct condition rating intervals into a single discrete condition state because these rating bands simply represent varying degrees of a failed component in need of replacement. Furthermore, once a component condition is identified in any one of these states, it is generally considered failed and usually does not undergo any more inspections until a replacement occurs, so transitions among the three ratings are typically not observed. As a result, this last state is generally considered a component in a state of failure or impending failure, and thus state C7 denotes the absorbing state.

Table 4. Condition Index Rating Interval Ranges

CONDITION STATE	CONDITION RANGE	MID RANGE VALUE	DESCRIPTION
C1	>99	100	G+ rating; Minimal to no condition loss
C2	99-92	95	G rating; Slight condition loss
C3	92-85	88	G- rating; Minor Condition loss
C4	85-75	80	A+ rating; Noticeable Condition loss
C5	75-65	71	A rating; Significant condition loss
C6	65-50	61	A- rating; Major condition loss
C7	<=50	30	R rating; Severe condition loss; at or near failure

Table 5 shows a small example of the types of information available in the overall dataset used for analysis. Appendix B provides a larger subset of the overall dataset used, displaying all records related to Built-up Roofing Surface Components in Hot/Humid climate regions. This appendix represents a subset of over 1,000 component instances selected from more than 430,000 total instances in the dataset.

Table 5. Example Assembled Dataset

Component Identifier	783273	384832	954957	493054
Region	Hot-Humid	Hot-Humid	Hot-Humid	Hot-Humid
Building Number	124	325	675	998
Building Type	ADMIN	COMPANY HQ	WAREHOUSE	CLINIC
System	D30 HVAC	D30 HVAC	D30 HVAC	D30 HVAC
Sub-System	D3050 TERMINAL & PACKAGE UNITS	D3050 TERMINAL & PACKAGE UNITS	D3050 TERMINAL & PACKAGE UNITS	D3050 TERMINAL & PACKAGE UNITS
Component type	D3050175 - Rooftop A/C	D3050175 - Rooftop A/C	D3050175 - Rooftop A/C	D3050175 - Rooftop A/C
Description	ROOF TOP UNIT, SINGLE ZONE	ROOF TOP UNIT, SINGLE ZONE	ROOF TOP UNIT, SINGLE ZONE	ROOF TOP UNIT, SINGLE ZONE
Quantity/Units	2 EA	1 EA	4 EA	2 EA
Year Installed	1990	1984	2001	1995
Inspection Date 1	8/23/2010	8/31/2010	6/21/2010	8/23/2009
Inspection Rating 1	95	71	95	80
Inspection Range 1	2	4	2	4
Inspection Date 2	10/10/2014	9/13/2013	8/14/2011	10/10/2014
Inspection Rating 2	71	61	88	50
Inspection Range 2	5	6	3	7
Observation Interval	4	3	1	5

Once the raw dataset containing the component attribute information and its paired condition state and observation date information is assembled, the dataset is then filtered and partitioned to construct the transition matrix for a particular component attribute set.

For the purposes of this model development, it is necessary to test its predictive accuracy. This is done by partioning the paired observation data into two distinct sets. One set is called the training set and is used to develop the transition matrices based on the discussion below. The other set, called the testing set, is used to test the results of the analysis. The percentage of the total population used for training can vary, but was chosen as approximately 50% for this research. The effort of keeping these two datasets separate and independent ensures a robust model validation process, since the same data used to develop the model is not used to test the model. The process for how data were partitioned between the two sets is explained in further detail below in the model validation and verification section of this chapter.

In order to construct a model to describe simple progressive deterioration of a building component without any intervening work activity being applied, situations where major repairs or component replacements have affected the subsequent condition rating are excluded. However, the type, timing, or extent of any repairs performed against the component instance are not data elements currently collected or tracked in the dataset. While computerized maintenance management systems make the collection and association of these data possible, information is not available in a large scale to support the data model at this time. However, since it is assumed that a component's condition state cannot improve without these intervening repairs, the paired condition data are used to identify components whose subsequent condition index improved. This improvement is due to either a repair activity between the two inspections, or an error in one or both of the inspection ratings. Either situation is undesirable in the model, so a filter is applied on the change in observed condition to exclude these situations. In addition, components are filtered out when the installation date is more recent than the initial inspection date, indicating a component that was replaced between the two inspection observations.

Next, the filtered training dataset is partitioned based on specific component attributes. This is intended to capture the key explanatory variables that affect the transition probabilities. The analysis here partitions the dataset by the component type attribute based on the Uniformat level 3 classification (Charette & Marshall, 1999), since condition deterioration is assumed to manifest in different ways across components of different types. Other attributes could also be selected to partition the data, such as the component's age, the type and age of the building it belongs to, or its geographic location. Each partitioned dataset results in a separate Transition Matrix that applies only to the specific circumstances of the attributes with which it was created. Partitioning also results in a smaller dataset from which to create each matrix, which can adversely affect the robustness of the model. As a result, it is best to partition only as necessary to allow for sufficient data size and quality to develop the model.

Once the dataset has been filtered and partitioned to construct a single characteristic transition matrix (for each component type or other grouping one may want to define), it is next necessary to further group or partition the remaining training dataset by common observation intervals. This allows for separate treatment of observations taken one year apart versus five years apart, for example. To do this, the number of years between each of the two inspection dates is computed, then rounded to the nearest integer value.

3.4.4 Computing Transition Probabilities

Once the filtering, partitioning, and observation interval grouping has been performed, the transition probabilities can be computed for each observation interval group subset. Starting with one-year observation interval data and component classification B3010 Roof Coverings as an example, the following transition counts shown in Table 6 were computed using the CountIf function in Microsoft Excel. Each element of the matrix was determined by matching against the respective inspection 1 range value for each row and inspection 2 range value for each column, and counting all observation pairs that met that criteria. In addition to any applicable attribute filters, the counts in the Table 6 matrix were only performed against one-year observation interval data. The matrices associated with the other observation interval counts, while not shown here, were calculated the same way, but with their respective observation interval criteria applied in the CountIf function.

Table 6. Condition State Transition Counts for B3010 Roof Coverings, 1-year Observation Interval

		Inspection 2 State							
		C1	C2	C3	C4	C5	C6	C7	**Total**
Inspection 1 State	C1	698	33	3	2	0	0	0	**736**
	C2	0	728	31	10	1	3	0	**773**
	C3	0	0	971	26	5	3	2	**1007**
	C4	0	0	0	779	10	2	2	**793**
	C5	0	0	0	0	745	23	2	**770**
	C6	0	0	0	0	0	426	6	**432**
	C7	0	0	0	0	0	0	565	**565**
									5076

The transition counts were then converted to probabilities as shown in Table 7 using equation 9 to obtain the Markov transition matrix, which represents the probability of a component of the type "Roof Coverings" transitioning from condition state i to condition state j over a one-year interval assuming pure deterioration with no repair activities applied. While this is based only on the one year observation interval data, the same process is used to develop the transition matrix for each of the other observation intervals of interest.

Table 7. Condition State Transition Probabilities for B3010 Roof Coverings, 1-year Observation Interval

		Inspection 2 State						
	M_1	C1	C2	C3	C4	C5	C6	C7
Inspection1 State	C1	94.8%	4.5%	0.4%	0.3%	0.0%	0.0%	0.0%
	C2	0.0%	94.2%	4.0%	1.3%	0.1%	0.4%	0.0%
	C3	0.0%	0.0%	96.4%	2.6%	0.5%	0.3%	0.2%
	C4	0.0%	0.0%	0.0%	98.2%	1.3%	0.3%	0.3%
	C5	0.0%	0.0%	0.0%	0.0%	96.8%	3.0%	0.3%
	C6	0.0%	0.0%	0.0%	0.0%	0.0%	98.6%	1.4%
	C7	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%

3.4.5 Normalizing to Single Cycle Transition Matrix using Hidden Markov Approach

Next, the characteristic transition matrix that corresponds to the desired one year cycle time interval is obtained by using inspection data across all observation intervals. This is necessary because the effective transition matrix and the observation data used to construct it is different for each observation interval. Since individual matrices for each interval are not desired, these must be reconciled into a single matrix that describes the characteristic deterioration for that component group.

To accomplish this, a hidden Markov approach is used that assumes hidden state transitions still occur in the intermediate years between inspections. As a result, transition probabilities are assumed the same in each cycle (homogenous), and the n-cycle transition matrix is linked to the one year observation cycle matrix by Equation 10.

$$M_n = M_1^{(Lo/Ld)} \tag{10}$$

Where L_d = desired cycle length (1 year)

L_o = actual observation interval

Figure 16 illustrates the process to calculate the one year characteristic deterioration matrix using multiple interval observation data. First, the observed transition matrix counts are computed similar to Table 6 above, but for each of the observation intervals of interest. This also allows for the calculation of the initial state vector for each observation interval, and the total number of observations for each interval.

Next, since a one-year characteristic transition matrix is desired, the one-year observation interval transition count matrix is used to calculate the one-year characteristic transition probability matrix M_1. These values are only temporary initialization values, as the elements in this matrix will be adjusted to incorporate the additional observation data beyond the one-year interval. However, the M_1 matrix is used to calculate the values for each M_n matrix that represents the deterioration probability matrix for an n-year cycle time by using equation 10 above.

Using the M_n matrix multiplied by the vector representing the number of components in each initial condition state for each observation interval, the predicted transition count matrix for each observation interval, P_n, is calculated. From this, an error matrix, E_n, is computed for each observation interval, where each element of the matrix is the difference squared between the observed and predicted element value.

Using Microsoft Excel Solver, the error between the observed and predicted matrices is minimized by adjusting the elements in the one-year characteristic deterioration probability matrix, M_1, in order to satisfy the minimum objective function given by Equation 11:

$$\text{Min} \sum \{ \sum E_n \times (\sum O_n / \sum O) \} \tag{11}$$

The value $\sum E_n$ represents the sum of the squared error for each element for observation interval n, and $\sum O_n/\sum O$ represents the weight for each observation interval, determined as the number of n-interval observations over total number of observations. The result of this Solver optimization is a characteristic matrix, M_1, with a one-year cycle time that best fits the observed inspection data across all observation intervals.

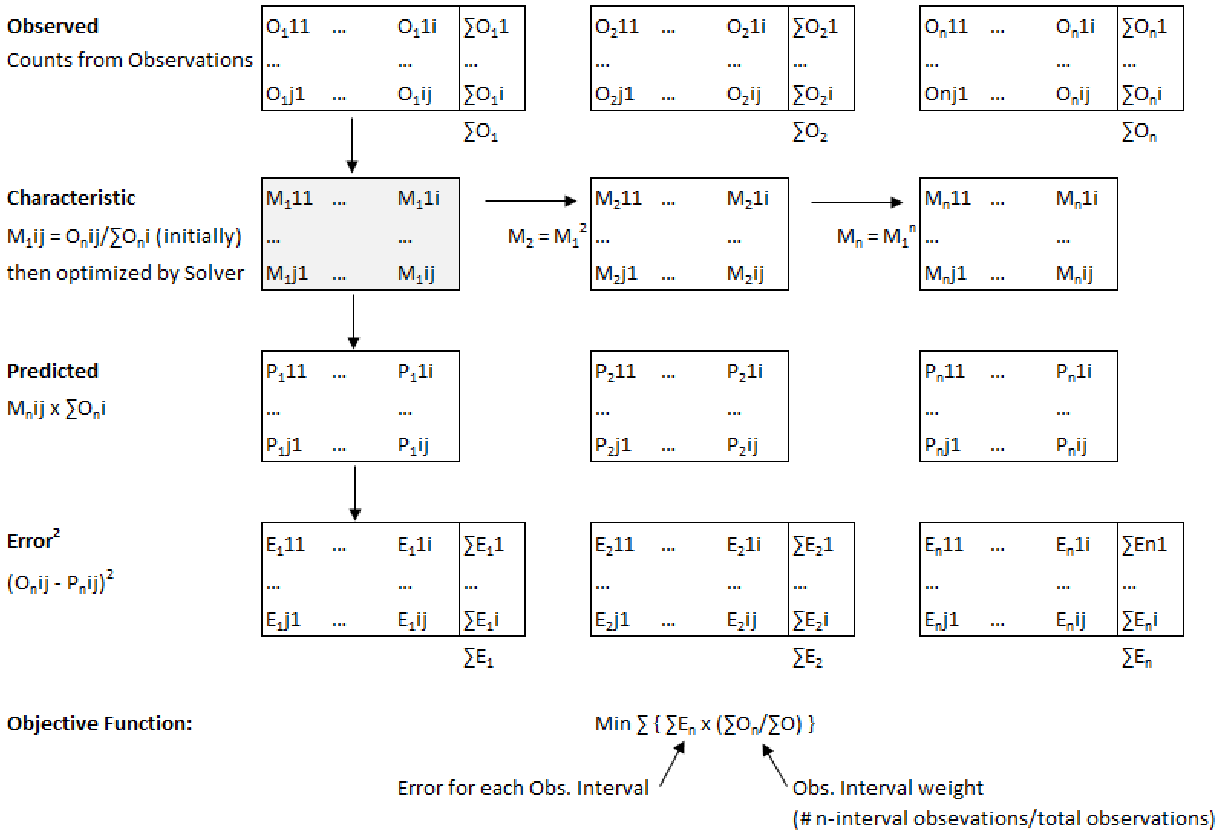


Figure 16. Illustration of single cycle deterioration matrix calculation

3.5 Deterioration Transition Matrices

Using the above process allows for the construction of the characteristic deterioration transition matrix for a particular component type or attribute grouping. The transition matrix for the B3010 Roof Coverings component data is shown in Table 8. In addition, characteristic transition matrices are provided in the Appendix section for a wide range of components (Appendix C), specific component types (Appendix D), and regional climate zones (Appendix E).

Table 8. Deterioration Transition Matrix for B3010 Roof Coverings

B3010					Subsequent State			
		C1	C2	C3	C4	C5	C6	C7
initial state	C1	0.692	0.133	0.114	0.014	0.023	0.01	0.014
	C2	0	0.813	0.11	0.034	0.019	0.013	0.011
	C3	0	0	0.858	0.082	0.027	0.014	0.019
	C4	0	0	0	0.83	0.102	0.043	0.025
	C5	0	0	0	0	0.862	0.1	0.038
	C6	0	0	0	0	0	0.91	0.09
	C7	0	0	0	0	0	0	1

Using Table 8, if a component was previously assessed with a condition rating in the C2 range, then one would expect an 81% chance of remaining in that range, and an 11% chance of deteriorating to the next lower range after 1 year. As a result, given an initial assessment and no intermediate repairs, the probability of a transition to a lower condition state can be projected. The transition matrix above does not explicitly specify what the future condition rating for a component will be or predict precisely when a transition to a lower condition state will occur. However, it can be used to construct an expected deterioration curve over time, as explained in the sections below.

3.6 Repair Transition Matrices

In addition to analyzing the behavior of pure component deterioration, another desire is to evaluate the data under conditions of an intermediate repair event. These component data points are identified by the pairwise records where a condition rating increase occurred between the previous and subsequent inspections. This allows for 1) a determination of the probability of a repair activity given the initial condition rating, and 2) an analysis of the effect of the repair activity, measured by the change in condition between the two inspection ratings.

Table 9 shows the probability of improving to subsequently higher condition levels, given the initial condition rating is higher than the subsequent rating. The same process discussed above to determine the deterioration transition matrix is used to determine the repair transition matrix, with two exceptions. One, the counts are only performed on components whose subsequent condition was higher than the initial condition. Two, the C1 condition state was combined with the C2 condition state, since this is the condition for a like-new component, and repairs from this condition state are not likely.

The method here presents a way to measure the effect of a repair activity against a component, but it does not distinguish what type of repair activity that might be. This level of distinction would require integrated data from a computerized maintenance management system (CMMS). For example, one component may undergo a substantial overhaul, while another component may undergo a minor corrective repair that results in minimal condition increase. While this method does not differentiate between the two, it does provide a way to model the effect of generalized component repair based on observed data. Appendix F lists the repair transition matrix for a wide range of building components analyzed using this approach.

Table 9. Repair Transition Matrix for B3010 Roof Coverings

B3010		Subsequent Observation					
		C2+	C3	C4	C5	C6	C7
Initial Observation	C2+	1	0	0	0	0	0
	C3	0.4258	0.5733	0	0	0	0
	C4	0	0.4109	0.5891	0	0	0
	C5	0.0439	0.1055	0.1343	0.7142	0	0
	C6	0.0344	0.0868	0.0485	0.1175	0.7094	0
	C7	0.0247	0.0582	0.0714	0.0662	0.0888	0.6874

3.7 Reliability Index Using Confidence Intervals

Once the characteristic Markov deterioration matrix has been derived, this can be used to predict future expected condition, reliability, and service life over time. Assuming the component is in condition state C1 at the time of its installation, then its condition vector is given by $S_0 = [\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ ]$. Estimation of the condition state at a point t years past the install year is given in Equation 12 as:

$$S_t = S_0 \text{ x } M^t \qquad (12)$$

If an inspection was recently performed at year t_o and resulted in observed condition profile S_o, then current expected condition state S is easily updated using Equation 13:

$$S_t = S_o \text{ x } M^{(t\text{-}to)} \qquad (13)$$

S_t represents the vector of probabilities for each condition state. If each condition state is assigned a representative Condition index value, as given in column 3 of Table 4 shown previously, and this is defined as vector CI_{value}, then the expected Condition Index, CI_t, can be computed at any point in time given in Equation 14 as:

$$CI_t = S_t \times CI_{value} \tag{14}$$

In addition, a reliability index, RI, is defined as the probability of condition index or condition state above a set threshold limit over a predefined period of time, typically one year. For this study, condition state C7 is defined as the threshold limit, which represents a Red condition assessment rating, and a failed state. Further, a limit vector, L, is defined with the value of 0 for any condition state that is a limit state, and a value of 1 for any state that is a non-failed state. For this study, this vector is shown in Equation 15 as:

$$L = [\ 1\ 1\ 1\ 1\ 1\ 1\ 0\ ]^T \tag{15}$$

Then, the reliability index, RI_t, at a point in time is calculated in Equation 16 as,

$$RI_t = S_t \times M \times L \tag{16}$$

Table 10 shows the example calculations for Condition index and Reliability index at discrete points in time using the characteristic deterioration matrix given in Table 8 above. Column C_n represents the probability of the component being in that state at the time in years given for each row. In addition, the value after the state indicates the representative condition index associated with that state, from Table 4. This is used to calculate the projected condition index. For example, the projected CI at year 5 is: CI(5) = 0.094x100 + 0.42x95 + 0.282x88 + 0.084x80 + 0.061x71 + 0.033x61 + 0.025x30 = 87.7

The RI represents the probability that the component remains in a non-failed state (all states except C7 in this example). For year 5, the calculation for projected RI is: RI(5) = 0.094 + 0.42 + 0.282 + 0.084 + 0.061 + 0.033 + 0.025 = 97.5

Table 10. Example calculation of condition index and reliability index

Time	C1/100	C2/95	C3/88	C4/80	C5/71	C6/61	C7/30	CI	RI
0	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0	100.0
1	62.3%	25.6%	8.0%	1.5%	1.4%	0.7%	0.5%	96.5	99.5
2	38.9%	38.2%	14.8%	3.1%	2.7%	1.4%	0.9%	93.7	99.1
3	24.2%	43.2%	20.4%	4.8%	3.9%	2.0%	1.4%	91.5	98.6
4	15.1%	43.8%	24.8%	6.6%	5.1%	2.7%	1.9%	89.5	98.1
5	9.4%	42.0%	28.2%	8.4%	6.1%	3.3%	2.5%	87.7	97.5
6	5.9%	39.0%	30.6%	10.1%	7.2%	4.1%	3.1%	86.1	96.9
7	3.7%	35.5%	32.3%	11.8%	8.1%	4.8%	3.9%	84.4	96.1
8	2.3%	31.9%	33.2%	13.3%	9.1%	5.6%	4.7%	82.8	95.3
9	1.4%	28.3%	33.6%	14.7%	9.9%	6.4%	5.6%	81.2	94.4
10	0.9%	25.0%	33.5%	16.0%	10.8%	7.3%	6.5%	79.6	93.5

In addition, Figure 17 shows a plot of these values as time varies. From this graph, it can be shown that the expected condition index over time closely follows an exponential decay function (denoted by the dotted line C_p in Figure 17), and the reliability index closely follows a Weibull cumulative probability distribution function (denoted by dotted line R_p in Figure 17). The exponential decay parameter, d, for the condition index decay model, and the Weibull function parameters alpha and beta for the reliability index model, are listed for a wide range of components in Appendix G.

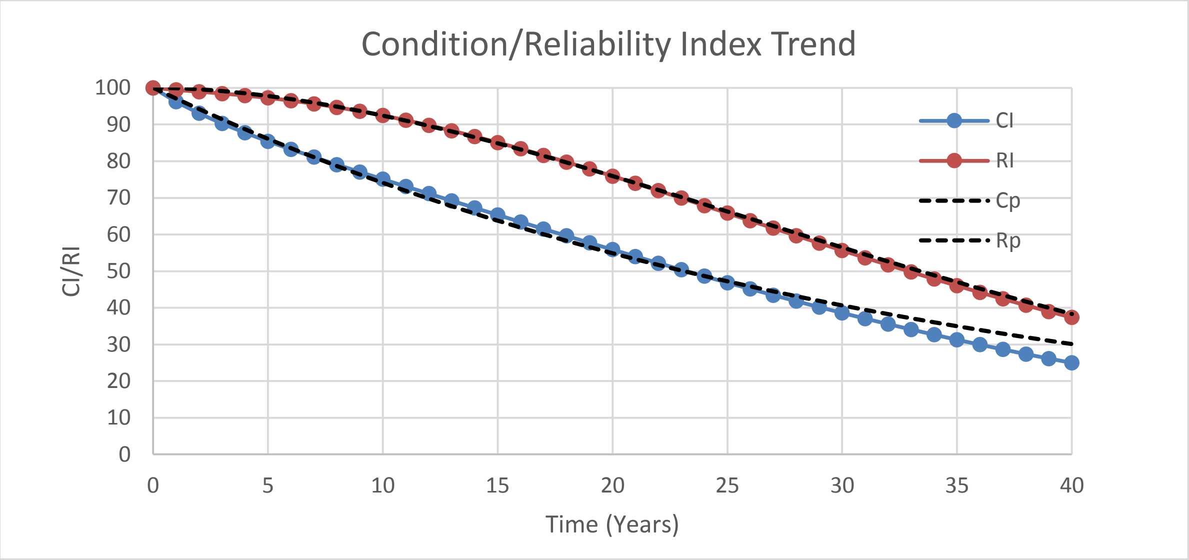


Figure 17. Condition/Reliability Index Trend

3.8 Service Life Estimation using Hitting Time

Finally, the expected service life of a given component can be computed using the characteristic deterioration matrix. Craig and Sendi describe the steps (summarized in Appendix H for reference) to directly calculate the "hitting time" for a transition matrix, which is the average time for transition to the absorption state (Craig & Sendi, 2002). In addition to this approach, a Monte Carlo simulation approach can be used to simulate the life cycle deterioration and determine expected service life. The later approach was adopted in this research using a large sample pool comprised of 10,000 virtual components to generate life cycle condition profiles for each component type. The Monte Carlo approach provides a close approximation to the hitting time calculation for average service life, and also allows for the calculation of standard deviation.

The resulting average expected service life and standard deviation values for several building component types computed using the Monte Carlo approach are shown in Table 11 (a full table of values is contained in Appendix I). The advantages of using the probability based Markov deterioration matrix is that expected service life values can be obtained in an unbiased way, using observed condition assessment information, even if actual failure (average time to failure) data do not exist.

Table 11. Expected Service Life by Component Type

Component Type	Service Life (years)	Standard Deviation (Years)
B2010 Exterior Walls	37.1	21.9
B2020 Exterior Windows	27.2	15.9
B2030 Exterior Doors	37.2	20.1
B3010 Roofing Coverings	25.8	16.4
D2010 Plumbing Fixtures	38.0	21.0
D3020 Heating Equipment	50.2	30.9
D3030 Cooling Equipment	43.2	24.0
D3040 HVAC Distribution Equipment	29.8	19.5
D3050 HVAC Terminal and Packaged Units	49.4	27.4
D5010 Electrical Distribution Equipment	48.6	26.3

3.9 – Verification and Validation

This section discusses the process for verifying and validating the Markov model to ensure the predicted results sufficiently match observed results. Verification ensures that the underlying model conforms to the mathematical and statistical assumptions. Validation determines how well the proposed model predicts actual observed data.

As mentioned above, the paired component condition data were partitioned into a training set used for model parameter estimation, and a testing set, used for this process of model validation. The separation of the full population of variable observation data (the USN dataset for the purposes of this research) into the two discrete datasets was done by assigning each observation pair a random number between 0 and 1. Since the percentage of testing data was chosen to be approximately 50% of the population total, any paired component condition record with its randomly assigned index less than 0.5 was placed in the testing set, and any record with its index 0.5 or greater was placed in the training dataset. Using this independent testing dataset, a number of approaches are presented to ensure the model displays true predictability. These approaches include categorical frequency analysis, pairwise condition state analysis, pairwise condition index analysis, and a comparison to the deterministic time-based Weibull cumulative probability distribution function.

3.9.1 Categorical Frequency Analysis

The Markov Model is a way to describe the component deterioration process that occurs when transitioning through a sequence of progressive condition states. As a result, given a condition state observed by an inspection, and the time since that inspection, the probability that the component currently exists in each of those states can be computed. In the paired condition set, the first inspection represents that initial observation from which a future condition state probability vector can be computed, and the second inspection represents an actual observed state measured at that subsequent point in time.

The predictive accuracy of the Markov Model was verified by using the component data previously partitioned for testing. This was used to compare the number of components predicted in each condition state using the Markov model at the time of the second inspection versus the actual observed number for condition rating from the second inspection (see Table 12). Using this comparison, one can measure the one-way goodness of fit of this categorical data by calculating the Pearson Chi Squared statistic, to test the hypothesis that the observed sample data distribution is consistent with the distribution derived from the Markov prediction model. For this test, a significance level of 0.05 was established, corresponding to a 95% confidence level, and six degrees of freedom were assumed, corresponding to the seven condition categories. The Chi Squared test statistic can be computed by Equation 17:

$$X^2 = \sum (O_i - P_i)^2 / P_i \tag{17}$$

This results in an X^2 test statistic of 1.446, which is associated with a P-value of 0.96, indicating a high probability of observing a sample statistic as extreme as the test statistic. Since the P-value is much greater than the significance level of 0.05, the hypothesis that the Markov model sufficiently predicts the condition distribution is accepted.

Table 12. Model Validation, Predicted versus Observed

State	Predicted, P_i	Observed, O_i	Difference
C1	1125	1143	18
C2	2290	2327	37
C3	2983	2969	-14
C4	2197	2207	10
C5	1962	1955	-7
C6	1778	1758	-20
C7	3000	2976	-24

The analysis above considers the resulting condition state counts and frequencies for all initial condition states. In addition, a two-way categorical analysis that also considers the initial condition state that the final condition state came from can also be evaluated. This can be represented as a two dimensional matrix of the difference between the predicted and observed counts for each condition state, as shown in Table 13 below.

Table 13. Two-way Categorical Analysis Differences in Predicted Versus Observed

Diff^2	1	2	3	4	5	6	7
1	322.2	28.24	148.6	6.602	2.211	1.166	0.201
2	0	1811	664.2	63.83	11.85	8.252	6.14
3	0	0	584.8	182	23.1	6.132	11.63
4	0	0	0	822.4	294.9	52.51	18.14
5	0	0	0	0	406.8	214.6	30.48
6	0	0	0	0	0	70.21	70.21
7	0	0	0	0	0	0	0

Here, the calculation of the Chi Squared statistic uses the same equation 17, except it includes all elements in the two-way matrix. The calculation for each element of this matrix is shown in Table 14 below. Summing all elements of this matrix gives the Chi squared statistic for this test, which is 8.11. However, since there are more degrees of freedom in this analysis, 21, versus the one-way analysis, the corresponding P-value for this situation is 0.995. Since the P-value is much greater than the significance level of 0.05, the hypothesis that the Markov model sufficiently predicts the condition distribution under this more complex scenario is accepted.

Table 14. Chi-Squared Goodness of Fit for Two-Way Categorical Analysis

Diff^2/Pred	1	2	3	4	5	6	7	Sum
1	0.286	0.057	0.29	0.055	0.017	0.015	0.002	0.722
2	0	1.008	1.28	0.322	0.098	0.094	0.073	2.876
3	0	0	0.3	0.485	0.14	0.062	0.091	1.078
4	0	0	0	0.547	0.799	0.265	0.136	1.746
5	0	0	0	0	0.346	0.746	0.211	1.303
6	0	0	0	0	0	0.068	0.316	0.384
7	0	0	0	0	0	0	0	0
							Chi^2	8.109

3.9.2 Pairwise Condition State Analysis

The previous analysis considered aggregated counts of the condition state across all the test observations. As a result, this tested how well the model as a whole matched observed behavior, but does not measure the predictability for an individual component. To validate how well the model performs, a pairwise analysis of each component observation is needed. This pairwise comparison can be performed using either the condition states, or the associated condition index.

3.9.2.1 Point prediction validation using condition state

For each individual observation of the test dataset, the difference between the observed and predicted condition states was calculated. If the observed and predicted states were the same, this difference is reported as zero, while positive values represent a predicted condition higher than observed, and negative values a predicted condition state less than observed. Table 15 below shows the results of comparing the predicted versus observed condition states on a component by component basis, and Table 16 shows the same comparison, but with breakouts for each observation interval.

Table 15. Condition State Point Prediction Accuracy for Markov Model

Pred-Obs	Count	%
6	0	0%
5	0	0%
4	0	0%
3	0	0%
2	67	0%
1	720	5%
0	11165	73%
-1	1868	12%
-2	710	5%
-3	437	3%
-4	263	2%
-5	103	1%
-6	2	0%
Total	15335	

Table 16. Condition State Point Prediction Accuracy by Observation Interval for Markov Model

Pred-Obs	1	Year	2	Years	3	Years	4	Years	5	Years
6	0	0%	0	0%	0	0%	0	0%	0	0%
5	0	0%	0	0%	0	0%	0	0%	0	0%
4	0	0%	0	0%	0	0%	0	0%	0	0%
3	0	0%	0	0%	0	0%	0	0%	0	0%
2	0	0%	0	0%	0	0%	67	2%	0	0%
1	0	0%	139	4%	91	3%	472	15%	18	28%
0	4166	94%	2608	80%	1597	49%	1639	51%	8	13%
-1	185	4%	297	9%	813	25%	547	17%	16	25%
-2	39	1%	100	3%	329	10%	233	7%	9	14%
-3	15	0%	64	2%	228	7%	115	4%	10	16%
-4	5	0%	25	1%	114	4%	115	4%	3	5%
-5	4	0%	18	1%	81	2%	0	0%	0	0%
-6	1	0%	0	0%	0	0%	0	0%	0	0%
Total	4415		3251		3253		3188		64	

As a whole, the Markov model predicted the observed condition state at the time of the second inspection accurately more than 73 percent of the time, and was within plus or minus one of the true condition state more than 90 percent of the time. Considering the stochastic nature of the deterioration process for building components, a predictability this high is considered significant.

Looking at the results broken out by observation interval, it is clear, as one would expect, that the highest predictability occurs when the observation interval is smaller, indicating a shorter time since the last inspection. In fact, the Markov Model accurately predicts the component state 94% of the time after only one year, but this accuracy falls as the observation increases. This result, while expected, is important, and the ability to quantitatively measure the loss of prediction accuracy over time is a key feature of knowledge-based inspection scheduling, to be discussed in the subsequent chapter.

Finally, an R squared coefficient of determination was calculated for the condition state pairwise comparison, resulting in a value of 0.714, which is considered good for the type of behavior this model attempts to predict.

3.9.2.2 Point Prediction Validation using condition index

Table 17 below shows the results of comparing the predicted versus observed condition index values on a component by component basis, and Table 18 shows the same comparison, but with breakouts for each observation interval. The ranges indicate how many condition index points the predicted value was off from the observed value.

Table 17. Condition Index Point Prediction Accuracy for Markov Model

Pred-Obs (Mid)	Lower	Upper	Count	%
90	75	100	35	0%
60	50	75	203	1%
40	35	50	192	1%
30	25	35	178	1%
20	15	25	852	6%
10	5	15	844	6%
0	-5	5	7438	49%
-10	-15	-5	4662	30%
-20	-25	-15	931	6%
-30	-35	-25	0	0%
-40	-50	-35	0	0%
-60	-75	-50	0	0%
-90	-100	-75	0	0%
		Total	15335	

Table 18. Condition Index Point Prediction Accuracy by Observation Interval for Markov Model

Mid	Lower	Upper	1	Year	2	Years	3	Years	4	Years	5	Years
90	75	100	2	0%	5	0%	19	1%	9	0%	0	0%
60	50	75	7	0%	24	1%	101	3%	68	2%	3	5%
40	35	50	14	0%	31	1%	68	2%	69	2%	9	14%
30	25	35	8	0%	23	1%	96	3%	50	2%	1	2%
20	15	25	115	3%	119	4%	304	9%	254	8%	8	13%
10	5	15	149	3%	100	3%	295	9%	290	9%	9	14%
0	-5	5	3848	87%	474	15%	948	29%	1142	36%	16	25%
-10	-15	-5	0	0%	2236	69%	1294	40%	1114	35%	18	28%
-20	-25	-15	272	6%	239	7%	128	4%	192	6%	0	0%
-30	-35	-25	0	0%	0	0%	0	0%	0	0%	0	0%
-40	-50	-35	0	0%	0	0%	0	0%	0	0%	0	0%
-60	-75	-50	0	0%	0	0%	0	0%	0	0%	0	0%
-90	-100	-75	0	0%	0	0%	0	0%	0	0%	0	0%
		Total	4415		3251		3253		3188		64	

The Markov model predicted the condition index at the time of the second inspection to be within plus or minus 5 points of observed more than 49 percent of the time, and was within plus or minus 15 points of observed more than 84 percent of the time. While this is still significant considering the stochastic nature of the component deterioration process, it is somewhat less accurate than the prediction of the condition state.

Looking at the results broken out by observation interval, again it is clear that the highest predictability occurs when the observation interval is smaller, indicating a shorter time since the last inspection. After one year, the Markov Model accurately predicts the component index within 5 points 87% of the time, but this accuracy falls as the observation increases. Finally, an R squared coefficient of determination was calculated for the condition index pairwise comparison, resulting in a value of 0.686, which is considered adequate for the type of behavior this model attempts to predict, but less than the prediction of the condition state.

3.9.3 Comparison to Weibull Deterministic Model

Finally, the same analysis performed above was also performed using the deterministic Weibull model to predict component condition behavior. To estimate the condition index at the time of the second inspection, based on the inspection results from the first inspection, the following Equations 18 and 19 were used (Grussing, Uzarski, & Marrano, 2006).

$$CI_2 = \left(\frac{100}{CI_T}\right)^{-\left(\frac{t_2}{DL\times\beta}\right)^{\alpha}} \tag{18}$$

Where CI$_2$ = predicted Condition Index at the time of the second inspection

CI$_T$ = terminal condition index at component failure, usually 40

t$_2$ = age in years of the component at the time of the second inspection

DL = component expected design life

α = deterioration parameter that varies by component, and

β = service life adjustment factor given by Equation 19 below:

$$\beta = t_1/(DL \times \left(-\log_{\frac{100}{CI_T}} CI_1\right)^{\frac{1}{\alpha}}) \tag{19}$$

Where t$_1$ = age of the component in years at the time of the first inspection

CI$_1$ = resulting CI from the first inspection.

Table 19 shows the categorical frequency analysis, comparing the Weibull model predictions to the observed values. It is evident that the Weibull model does not follow the underlying statistical distribution of the observed data. This is not surprising, considering the Weibull approach is deterministic, not a probabilistic approach.

Table 19. Goodness of Fit Categorical Analysis for Weibull Deterministic Model

State	Predicted, P_i	Observed, O_i	Difference
C1	2465	1143	1322
C2	1742	2327	-585
C3	2019	2969	-950
C4	2938	2207	731
C5	1886	1955	-69
C6	1361	1758	-397
C7	2924	2976	-52

Table 20 shows the results of the pairwise point prediction between the Weibull predicted condition index at the time of the second inspection, and observed condition index from the second inspection, and Table 21 shows the results broken out for each observation interval. In addition Table 22 and Table 23 show the same results, except this time comparing the observed versus predicted condition states, where the predicted condition states for the Weibull model were mapped from the predicted condition index values using Table 4.

Table 20. Condition State Point Prediction Accuracy for Weibull Model

Pred-Obs	Count	%
6	0	0%
5	0	0%
4	1	0%
3	0	0%
2	134	1%
1	2949	19%
0	9295	61%
-1	1308	9%
-2	881	6%
-3	358	2%
-4	199	1%
-5	114	1%
-6	96	1%
Total	15335	

Table 21. Condition State Point Prediction Accuracy by Observation Interval for Weibull Model

Pred-Obs	1	Year	2	Years	3	Years	4	Years	5	Years
6	0	0%	0	0%	0	0%	0	0%	0	0%
5	0	0%	0	0%	0	0%	0	0%	0	0%
4	0	0%	1	0%	0	0%	0	0%	0	0%
3	0	0%	0	0%	0	0%	0	0%	0	0%
2	0	0%	0	0%	20	1%	110	3%	4	6%
1	229	5%	1017	31%	828	25%	861	27%	14	22%
0	4038	91%	1877	58%	1127	35%	1103	35%	15	23%
-1	85	2%	186	6%	581	18%	430	13%	9	14%
-2	38	1%	88	3%	358	11%	385	12%	9	14%
-3	15	0%	49	2%	144	4%	133	4%	10	16%
-4	5	0%	16	0%	101	3%	73	2%	3	5%
-5	4	0%	12	0%	47	1%	51	2%	0	0%
-6	1	0%	5	0%	47	1%	42	1%	0	0%
Total	4415		3251		3253		3188		64	

Table 22. Condition Index Point Prediction Accuracy for Markov Model

Mid	Lower	Upper		
90	75	100	45	0%
60	50	75	190	1%
40	35	50	283	2%
30	25	35	371	2%
20	15	25	534	3%
10	5	15	1474	10%
0	-5	5	8898	58%
-10	-15	-5	3311	22%
-20	-25	-15	222	1%
-30	-35	-25	5	0%
-40	-50	-35	2	0%
-60	-75	-50	0	0%
-90	-100	-75	0	0%
Total			15335	

Table 23. Condition State Point Prediction Accuracy by Observation Interval for Weibull Model

Mid	Lower	Upper	1	Year	2	Years	3	Years	4	Years	5	Years
90	75	100	2	0%	6	0%	21	1%	16	1%	0	0%
60	50	75	8	0%	21	1%	93	3%	64	2%	4	6%
40	35	50	16	0%	35	1%	104	3%	119	4%	8	13%
30	25	35	12	0%	32	1%	170	5%	151	5%	4	6%
20	15	25	31	1%	72	2%	229	7%	187	6%	8	13%
10	5	15	112	3%	164	5%	560	17%	617	19%	11	17%
0	-5	5	4070	92%	1733	53%	1129	35%	821	26%	10	16%
-10	-15	-5	161	4%	1181	36%	913	28%	1035	32%	14	22%
-20	-25	-15	3	0%	4	0%	31	1%	177	6%	5	8%
-30	-35	-25	0	0%	2	0%	3	0%	0	0%	0	0%
-40	-50	-35	0	0%	1	0%	0	0%	1	0%	0	0%
-60	-75	-50	0	0%	0	0%	0	0%	0	0%	0	0%
-90	-100	-75	0	0%	0	0%	0	0%	0	0%	0	0%
		Total	4415		3251		3253		3188		64	

The r squared coefficient of determination of the Weibull condition state prediction was 0.635, and the r squared for the Weibull condition index prediction was 0.672. These results show that the Weibull model is a decent point predictor of condition, particularly with the condition index.

3.9.4 Discussion of Results

Appendix J contains Markov Model data validation statistics across a large range of components, and Table 24 shows the results of the Markov approach discussed above applied specifically to B3010 building roof covering components. In order to determine any sensitivity to grouping methods, three different group levels were analyzed. The highest level, with the most data points but the least amount of detail is at the component type level. The next level down separates the component by its material type categories, resulting in more detail but less data points. Finally, the lowest level represents a further breakdown of the asphalt built-up roofing components by geographic location, leading to the most detail but least number of points to construct the deterioration model.

Table 24. Summary of Results for B3010 Roof Coverings

			State Prediction Accuracy		
Group Description	**# Data Points**	**Service Life (Years)**	**Exact Match**	**Plus/Minus 1 State**	**R²**
D3010 Roof Coverings	14,171	25.8	71%	89%	0.69
Built-up Roof	3,464	20.1	70%	91%	0.74
Hot-Dry Region	803	21.0	63%	92%	0.66
Hot-Humid Region	776	17.0	71%	90%	0.76
Marine Region	325	12.0	69%	89%	0.61
Single Ply Roof	1,154	30.1	76%	90%	0.75

Table 24 also shows the estimated service life for each component group classification, including variations by region. These regional climate groupings are based on the Building America Climate Zones (U.S. Department of Energy, 2014), and the climate region map is contained in Appendix K. Based on these regional groupings, the model predicts as expected the roof surfaces in marine and humid regions to have lower service lives than in dry regions. It also predicts a longer service life for single ply versus built-up roof surfaces.

The accuracy values indicate that specifying the material type leads to slightly better point prediction accuracy, while further specifying by regional variations results in mixed results but generally reduces validated accuracy. As a result, while more detail may be expected to produce better prediction accuracy, further partitioning also results in less data to build and test the model. This puts a limitation on the degree of partitioning that can be implemented. It is expected that as more inspections are performed over time, there will be more data to develop and test the model, especially for sub-partioned data sets.

In addition, it should also be noted that the categorical frequency analysis requires a sufficiently large testing dataset because of the nature of the Chi Squared test statistic. Since the difference between predicted and observed for each category grouping count is divided by the predicted amount, and since some transition probabilities can be relatively low, a smaller testing population size may result in a low predicted counts near or at zero for some transition categories. Very low predicted counts (less than five) greatly affect the Chi Squared calculation, and a zero predicted count leads to a division by zero error. This was the primary reason the testing percentage was selected to be so high (50%), since lower testing populations greatly increase the chance of near zero category counts. Again, further inspections will provide more condition data for which to overcome this issue.

Finally, additional inspection data will provide further opportunities to validate the assumptions of the discrete Markov model. One of the fundamental assumptions is that the model is stationary, meaning the transition probabilities for a unit of time do not change based on the age of the component or observation time between inspections. However, once a substantial number of components have three or more inspections recorded, the same validation tests can be repeated against these separate sets of observed conditions to verify assumptions and model behavior.

3.10 Summary of Markov Model Development

From a probabilistic standpoint, the Markov prediction approach matches the overall statistical distribution of the observed condition state, as shown in the categorical frequency analysis. This confirms that as a whole, the Markov approach does a very good job of representing the deterioration behavior of a typical or average component, much better than the deterministic Weibull model.

Predicting the exact behavior of an individual component is a much more difficult process, but the Markov approach still performs remarkably well considering the stochastic nature of the behavior. The prediction of an individual condition state is noticeably better than the Weibull model, and prediction of the condition index is marginally better. As expected, the accuracy of point prediction in both approaches is very good when the observation interval is short, but degrades substantially as the time since the last inspection observation increases.

The true improvement in the Markov approach is the fact that it results in a distribution of the condition state probabilities, while the deterministic model does not. This probability distribution can be used to measure risk and uncertainty, which will be of critical importance in the applying the Markov approach to practical applications in building asset management, as is illustrated in the chapters below.

CHAPTER 4 –INSPECTION ACTIVITY OPTIMIZATION MODEL

Component condition is a fundamental factor involved in a building's life cycle cost, performance, and operational risk. Proactive facility asset management requires an understanding of the current and future expected condition of the components that comprise a building. The primary means of obtaining this information about building component condition state is through an inspection process, which is usually performed by an individual inspector using visual observations at a discrete point in time. Since condition generally changes due to deterioration over time, as was explored in detail in Chapter 3, uncertainty about the current condition state increases as time passes since the last inspection was performed. Ultimately, this necessitates a re-inspection to again capture the most recent observations about condition state. Of particular interest to facility managers is determining the optimal time to inspect or re-inspect the components of a building. Historically building inspections have typically been conducted on a fixed frequency, but this calendar-based approach does not always provide the best value balanced against risk when budgets are constrained and inspection resources are limited. As a result, knowledge-based approaches based on a flexible frequency and data driven inspection scheduling methodology that rely on specific knowledge about the condition and risk profile of the component have been studied and developed (Uzarski, Grussing, & Clayton, 2007). The methodology presented in this chapter expands on this knowledge-based approach by quantifying the value that an inspection will provide to a decision maker at a certain point in time, given a component's last inspection information, the time since the last inspection, the cost of work activity alternatives, and the value that the work activities provide.

4.1 Background

The US Department of Defense (DoD) has adopted as a policy, a standardized facilities assessment program in order to objectively and consistently assess the condition and performance of their building facilities. The information gathered under this program has been collected and recorded into a life cycle facility asset management application called BUILDER Sustainment Management System (SMS). This web-based application serves as an enterprise knowledge base for archiving key characteristics and the condition state of the DoD's large facilities portfolio as a means of both ensuring adequate mission support and supporting better investment decisions (Grussing, Life Cycle Asset Management Methodologies for Buildings, 2013). This knowledge base is organized in a hierarchical data structure, with building assets aligned with the Department's real property records representing the top level, followed by building systems and eventually individual component instances at the lowest level. These individual component instances form the building blocks of a larger working facility, and as the facility ages and deteriorates over time, it is these components that degrade and eventually fail adversely affecting building performance unless repair or replacement activities are performed. Much of the effort of the public works organizations at the individual military bases, and a large portion of the maintenance, repair, and recapitalization expenses that go towards the sustainment, restoration, and modernization of military buildings, is focused on attending to these individual component instances. As a result, there is significant value in better understanding the characteristics of these components, and more importantly their current and future condition state.

Information in BUILDER is primarily collected at the component level. This information collected by trained architects and engineering (A/E) professionals is both qualitative and quantitative, and can be characterized as either static inventory or transient inspection information. The inventory information describes the type, age, and quantity of each component that is identified, along with geographic location and specific building in that it exists. In addition, each component is classified using the Uniformat classification system (Charette & Marshall, 1999), which provides a consistent way of grouping similar component types together for condition analysis, cost estimating, or other asset management purposes. This inventory information is used to label the characteristic attributes of each component, and is similar to building information model (BIM) data that may be assembled for newly constructed buildings.

Along with the component inventory information that is collected, each component's physical condition is assessed, resulting in the collection of condition information. These inspections can be conducted via various methods, each with a different level of detail and accuracy. One such method, the distress survey procedure, provides a record of the type of distresses present, their severity levels, and their quantities. The distress survey inspection process for building components follows the same process previously developed for pavements (Shahin, Cation, & Broten, Micro PAVER Concept and Development Airport Pavement Management System, 1987), railroad tracks (Uzarski, 1993) and roofing systems (Bailey, Brotherson, Tobiasson, & Knehans, Roofer: an engineered management system for bituminous built-up roofs, 1989). This procedure is objective, repeatable, and provides the most accurate picture of component condition, but is also relatively time consuming to perform.

As a result, an abbreviated inspection method called the direct rating procedure allows for the visual evaluation of the component as a whole against a set of nine different rating criteria (Table 25). Less detail and accuracy result from the direct rating approach, but it is also less time consuming and expensive to perform. To determine the condition state, an inspector rates each building component based on guidelines similar to those provided in the Table 25 below. Each rating is associated with a numerical CI value, which assigns that value to the component at the time of the inspection (Uzarski & Grussing, 2004).

Table 25. Inspector Guidelines for Condition Index Determination

Rating	CI Value	Rating Definition
Green (+)	100	Entire component free of observable distresses. Like new condition.
Green	95	No serviceability or reliability reduction. Slight degradation but non-critical. No work other than routine maintenance.
Green (-)	88	Slight or no serviceability or reliability reduction. Some noticeable degradation but non-critical. No work other than routine maintenance.
Amber (+)	79	Serviceability or reliability is degraded, but still adequate. Moderate deterioration but non-critical. Minor repairs needed.
Amber	68	Serviceability or reliability is noticeably impaired. Moderate deterioration or damage requires corrective repairs.
Amber (-)	60	Significant serviceability or reliability loss. Significant degradation or damage requires major rehabilitation or overhaul.
Red (+)	50	Significant serviceability or reliability. Repairs are not feasible and replacement is needed.
Red	25	Severe serviceability or reliability reduction may result in loss of use or safety. Immediate replacement warranted.
Red (-)	10	Complete degradation and loss of serviceability. May result in damage to surrounding components. Replace immediately.

Therefore, regardless of the method, this assessment results in a condition index (CI) score (Uzarski & Burley Jr, 1997), which measures the condition of each component at the time of the assessment. Over the course of several years, building assessments have occurred across hundreds of locations worldwide, collecting data for more than 45,000 buildings containing collectively over 1.5 million individual building component instances. Chapter 3 illustrated how this information can be used as the basis for constructing component deterioration models using a discrete Markov transition process. It also discussed how recent component inspection information is used to update the prediction of condition.

These periodic component assessments ultimately support facility investment decisions for scheduled work activities such as repairs or replacements. While in general, the information from these inspections bring value to the facility managers tasked with operating and maintaining the buildings they are performed against, this inspection value varies based on a number of factors. These factors include but are not limited to the time since the last inspection was performed, the condition rating of the last inspection, the consequence of any failure that may occur, and the opportunities for life extending repairs. As a result, while many types of building inspections are conducted on a fixed frequency, this calendar based approach does not necessarily consider all these factors and thus does not provide the best value balanced against risk when inspection resources are limited.

The National Research Council identified this issue in a recent report on federal facility investments, by noting federal agencies should avoid the collection of data that serves no immediate purpose, requiring any data collection effort should provide a clearly defined benefit to offset the cost of collecting it (National Research Council, 2012). This report went further to recommend the use of a knowledge-based approach to condition assessment. Such an approach adjusts inspection frequency and assessment detail given information about the component lifecycle, as a means of optimizing inspection resources (Uzarski, Grussing, & Clayton, 2007). That work identified numerous purposes for an inspection depending on the lifecycle characteristics, and then recommended tailored inspection frequencies and levels of detail to target these purposes. It has broad coverage across a wide range of inspection considerations and uses rules-based logic to determine inspection requirements. The methodology presented in this chapter builds on this knowledge-based approach but limits its focuses to two of the key inspection purposes cited in the previous work. The first inspection focus of this research is to determine component condition in support of end-of-life replacement, and the second focus is to support the timing of opportunistic service life extending corrective repair work. This is done by evaluating condition state an uncertainty at key points in a component's lifecycle in order to quantify the value that an inspection can provide to support each work decision.

4.2 Objective

The objective of this chapter is to present a methodology to calculate the value that building component inspection information provides in support of the work planning decision process. This approach considers the time since the last inspection occurred, the expected condition state of the component, and the costs and benefits of a range of component work alternatives. This chapter will illustrate how the approach can be used to assist in planning the type and timing of inspections to optimize their value.

As mentioned above, this approach focuses on two key inspection purposes. The first purpose is associated with mitigating the risk of component failure that results in unexpected downtime and costly unplanned or unscheduled reactive work activities. The second purpose is related to identifying the ideal time for corrective repair actions to maximize the opportunity for extending service life and minimizing the penalty of deferring repair activities beyond this point.

4.3 Methodology

4.3.1 Analysis Considerations

Facility managers are responsible for managing the work activities against the components of facilities. As a result, information about what type of work is needed and when is of critical importance. This requires an understanding of the condition of the component, as well as knowledge about how that condition will change or degrade over time. A condition assessment can identify a component's observed condition state at that point in time, and a prediction model, such as described in Chapter 3 can estimate the expected change in condition over time. However, uncertainty in the true condition of the component still remains after each of these processes, especially as the time since the last inspection increases.

The methodology described in this chapter takes these uncertainties into account to determine when is the best recommended time to perform a component inspection in order to maximize the value that the data acquired provides for the decision making process. This value is derived from the difference between the expected net value of the decision one would make not having the information available, and the value of the right decision one would make if the information was available. Understanding that inspections have a cost to the facility manager or owner, the goal is to collect the most relevant data at the right time to help support the best decision.

As an illustrative example, a facility manager may be concerned about the condition of the roof surface component on a particular building. Faced with developing an annual work plan for the next fiscal year, he or she is concerned with the decision about whether to repair the roof, replace the roof, or defer any work into the future. If the facility manager was seriously considering making such an expenditure, an inspection would likely be performed to determine the nature of any problems that exist prior to making a decision. However, when managing a large portfolio with hundreds of buildings and thousands of components, it is usually cost prohibitive to inspect each item in every year prior to developing the work plan. As a result, it becomes necessary to determine which components should be inspected in any given year to maximize the value that the inspection provides in informing the annual work planning process for component repair and replacement alternatives. Therefore, considering any generalized component, the facility manager would like to know whether an inspection is of value at the current point in time, as well as which component inspections provide the best value. To do this, a framework is proposed below based on the concept of the value of information.

4.3.2 Value of Inspection Information (VOII)

The Value of Information (VOI) is the amount a decision maker would be willing to pay to obtain that information prior to making a decision (Lindey, 1985). Applied to the context of facility management, the information one is seeking to obtain is the condition state of a building component, and the decision being made is what type of work activity to apply against that component to improve or maintain its condition. As a result, a Value of Inspection Information (VOII) model is proposed, which is applied against a building component with a finite life and a continuously degrading condition. The goal of a facility manager to maintain an acceptable condition by applying repair or replacement work activities at strategic times in the component's lifecycle to extend or renew it. The model makes the assumptions that these options are presented to the facility manager at the beginning of a work execution cycle, usually annually, and the objective is to maximize the expected net value over that cycle. In addition to the estimated cost of the repair or replacement work activities that a facility manager may decide to perform, this net value also includes the potential cost of failure that results from component downtime and costly unscheduled reactionary work, as well as the benefit of added or renewed service life from any work.

4.3.3 Calculating probability values using Discrete Markov Model

Even prior to any decision about whether to inspect or not, some information about the component being analyzed is likely to exist. If the component was inspected previously, the time since that inspection (number of years) and result of that previous inspection is available. Even if an inspection has not been performed previously, an estimate of the year that the component was constructed or installed is generally available, at which time the component can be assumed to have been in new or excellent condition. As a result, the model requires an estimate of the component's condition for at least one prior point in time. This condition can be expressed as a discrete condition state, or as a probability distribution across a range of condition states, as was presented in Chapter 3. The seven discrete condition states used in that development are applicable for the VOII model as well, but are collapsed and presented as four condition states (Table 26) in the VOII model development discussed below for purposes of brevity. Once the methodology is explained, a case study considering the seven condition states that align with the development from Chapter 3 will be presented

Table 26. Abbreviated Set of Condition States for VOII Development

State	Description
C1	Excellent
C2	Good
C3	Fair
…	…
C7	Poor - Failed

Using these condition states, it is assumed that the single cycle transition probabilities between the condition states in Table 26 above is given by transition matrix M, with example values contained in Table 27.

Table 27. Example Transition Matrix for VOII Development

M	C1	C2	C3	C7
C1	0.75	0.20	0.05	0.00
C2	0.00	0.85	0.10	0.05
C3	0.00	0.00	0.50	0.50
C7	0.00	0.00	0.00	1.00

Given the observed condition state, S_o, from the last inspection, and the time since the last observation, t_o, the current expected condition state S_t (at the beginning of the current annual work cycle) is given by Equation 20:

$$S_t = S_o \text{ x } M^{to} \tag{20}$$

Since the objective is to support decisions over the course of the full annual work cycle (typically aligned with the calendar or fiscal year), the model is ultimately concerned not just with the current estimated condition state at the beginning of the current annual work cycle, but also the estimated condition state S_{t+1}, at the end of the work cycle, given by Equation 21:

$$S_{t+1} = S_t \text{ x } M \tag{21}$$

The probability that the component will remain in a non-failed condition state over the course of a year (in the example above, any state other than the Poor/Failed state), is given as the sum of the non-failed state probabilities. As stated in section 3.7, this is referred to as the component reliability, or the probability that the component meets performance requirements over a certain period of time. The complement of the reliability is the probability of failure (in the case presented here, degradation to condition state C7) prior to the end of the annual work planning decision cycle. For the example above, this the probability of being in a C_1, C_2, or C_3 state, as shown on Equation 22.

$$RI = P(C_1)+P(C_2)+P(C_3) = 1 - P(\text{Failure}) \tag{22}$$

In addition to the condition, information about the relative cost of the pertinent work activities applicable for the component is required. In the example of the roof surface component discussed above, the facility manager will likely have information on the cost of the roof replacement, provided that activity is planned and scheduled. However, the facility manager also faces the risk of unplanned or reactionary work, due to an unexpected failure that requires immediate reactionary attention after annual work plan decisions have been made. In this situation, the cost of a component replacement can be difficult to estimate but is usually much higher, sometimes more than double the planned activity cost. This increased cost is due to unplanned facility downtime as well as the cost of expediting labor, materials, and equipment to complete the work.

Finally, in order to make a consistent comparison of decision alternatives, the VOII framework must also consider the value of the component at the end of the work planning cycle, generally one year from the present year of analysis. The notion of component value can have various meanings, but this framework adopts an interpretation where value is a function of the replacement cost of the component and its expected remaining service. For example, a component that was just installed or replaced and now exists in excellent (new or like new) condition state is expected to have nearly its full design life remaining. Conversely, if the component is in a poor condition state, it has effectively reached the end of its useful life. Table 28 shows as an example the remaining service life associated with each of the four condition states in Table 26.

Table 28. Example Time to Failure Estimate for VOII development

State	Remaining Service Life
C1	10 years
C2	5 years
C3	2 years
C7	0 years

The remaining service life (RSL) is defined here as the average number of cycles (years) that it is expected to take for a component in its current condition state to transition or deteriorate to the absorption state (failed or poor state). The RSL is a function of the current condition state vector and its characteristic Markov transition matrix. The estimated remaining service life can be derived directly from the Markov transition matrix using the approach presented in Appendix H, or based on a Monte Carlo simulation, as discussed in section 3.8 above.

Given the expected condition state (represented by the probability of each discrete state) at the end of the annual work planning cycle, and the average time to failure from each state as given above, the expected remaining service life (RSL) at the end of the work planning cycle is calculated as shown in Equation 23.

$$RSL = \sum P(C_i) \times RSL(C_i) \qquad (23)$$

Dividing the expected remaining service life by the total expected component design life (which is also the time it takes to transition from the excellent state to the poor or failed state) gives the percentage of useful service life remaining for the component asset. Multiplying this percentage by the component replacement value provides a measure of the current value of the component. This is represented in Equation 24 below:

$$\text{Component value} = \text{Replacement value} \times RSL/DL \qquad (24)$$

This value generally decreases over time with degradation, but can increase if work is performed. Replacement activities reset the component's service life, effectively restoring the remaining useful life back to its original design life. Repair activities also restore a component's useful life, but not necessarily back to its full design life. For example, if a repair is performed that improves the condition from fair to good, based on Table 28, one would expect service life to increase from two to five years. This service life extension has a real monetary value, since the eventual investment required to renew or recapitalize the component through replacement activities can be deferred. Alternatively, if that repair represented the best economic option, but was not performed, a penalty cost results from the lost opportunity from that work activity. It is the intent of the VOII framework developed here to capture the value of any potential opportunities that a component inspection can help to identify.

Based on the considerations presented above, the facility manager needs to make a determination about whether to include a particular component renewal or replacement activity on the annual work plan or not. The facility manager would also like to know if component repair at some lower cost is a feasible option, but practically speaking, that option would only be considered immediately after an inspection is done. This is because one needs to have accurate and recent knowledge of the extent of any accumulated damage that the repairs will address. Figure 18 below shows the value of an inspection information decision tree, which implements the concepts developed above.

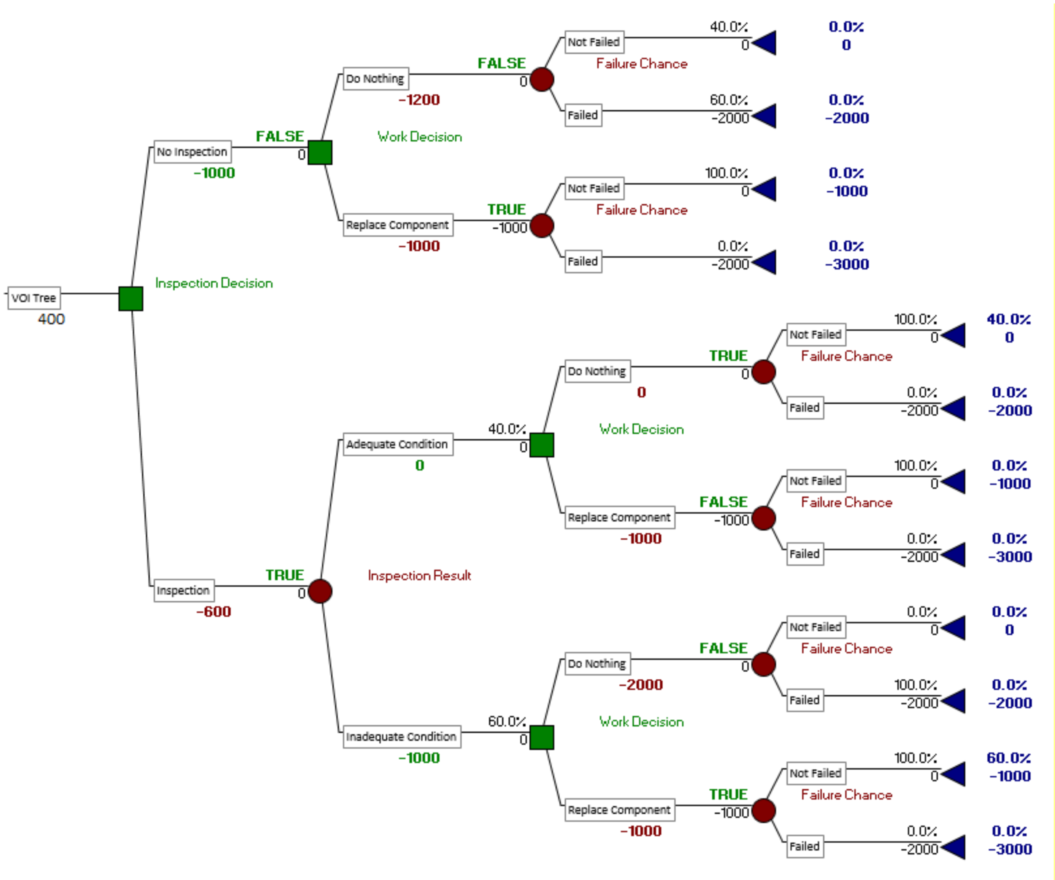


Figure 18. VOII Decision Tree

4.3.4 Model Definition - No Inspection Branch

The top branch of the tree represents the situation where an inspection is not performed, and the annual work planning decisions are made based on the current known condition of the component from the last inspection. In addition, the costs for planned component replacement, unplanned replacement, and corrective repair are provided in Table 29 below, along with the impact of those work activities. Note that the repair activity is only available if the inspection option is chosen.

Table 29. Example Activities for VOII Development

Action	Cost	Effect
Planned Replacement	$100k	Restore to Excellent condition (C4), reset service life
Unplanned Replacement	$200k	Restore to Excellent condition (C4), reset service life
Repair	$25k	Restore to Good condition, extend service life

In this example, if the decision is made not to perform an inspection, the facility manager has two options. The first option is to do no work, and run the risk that it fails and requires an unplanned replacement. Otherwise, one can preemptively plan for its replacement based on its age and/or projected condition. If the first option is chosen, to defer any work into the next planning cycle or longer, one of two chance events could occur. The first chance event is that the component does not fail before the end of the current planning cycle, of which there is no failure cost incurred due to unplanned replacement. The probability of this event is the same as the component's current reliability, which is the probability of no failures within the next year, given no work is performed. The other chance event is that the component does fail, at which time a cost of $200k is incurred due to unplanned replacement work. The probability of this event is the complement of the reliability.

Choosing the second option for scheduled replacement at a cost of $100k will assure the component meets all performance requirements and does not fail, at least through the end of the annual planning cycle, if not longer. Thus, the only possible event for the replacement option is that the component does not fail, and the complement of this event, the probability of failure before the end of the next work planning cycle, is assumed to be zero.

For each of the chance events, the model considers the costs, as well as the component value based on its expected condition and remaining useful life at the end of the work planning cycle. If the component is replaced, either by scheduled or unscheduled work activity, the result is a return to the excellent condition state, which also results in a remaining useful life of 10 years based on the example in Table 28 above. If no work is performed, the expected condition state is estimated based on the Markov transition matrix equation.

If for example the time since the last inspection was five years ago, and the result of that inspection was a condition of Good (state C_2), using Equation 20, shown previously, the current estimated condition state, S_t, at the beginning of the work cycle is shown in Table 30.

Table 30. Current Estimated Condition State for Example VOII Development

Condition State	Probability
C1	0.000
C2	0.444
C3	0.118
C7	0.438

Note that Table 30 shows some chance of failure at the beginning of the work planning cycle. However, the model assumes that if a replacement activity is selected, it will occur prior to any potential failure and not incur the unscheduled replacement penalty. Likewise, the expected condition state at the end of the annual work cycle, along with the associated reliability and expected remaining service life, is given for each work activity alternative and chance event, as shown in Table 31.

Table 31. End of Year Estimated Condition for Chance Events for No Inspection Branch

Work Decision	Chance Event	C1	C2	C3	C7	Reliability	RSL
No Work	No Fail	0.00	0.38	0.10	0.52	0.48	1.99
	Fail	1.00	0.00	0.00	0.00	1.00	10.00
Replace	No Fail	1.00	0.00	0.00	0.00	1.00	10.00
	Fail	1.00	0.00	0.00	0.00	1.00	10.00

The information in Table 31 is used to determine the probability and expected net value of each event. The probability that the component does not fail in the next year, given no work is performed, is the same as its reliability from Table 31. The probability of failure is the complement of the non-failure event. This model explicitly assumes a work decision of replacement results in 100% probability of non-failure. The expected net value of each event is the difference in component value against any work costs (scheduled or unscheduled) incurred. Again, the component value is the product of replacement value and the ratio of remaining service life to total service life. As a result, the component value at the end of the work planning cycle for each event is provided in Table 32 below.

Table 32. Expected Net Value of Chance Events for No Inspection Branch

Work Decision	Chance Event	Event Probability	Work Activities	Work Costs ($k)	Exp. Comp Value ($k)	Exp. Net Value ($k)
No Work	No Fail	0.48	Nothing	$ -	$ 20.93	$ 20.93
	Fail	0.52	Unscheduled Replace	$ 200	$ 100.00	$ (100.00)
Replace	No Fail	1.00	Scheduled Replace	$ 100	$ 100.00	$ -
	Fail	0.00	Sch. & Unsch. Replace	$ 300	$ 100.00	$ (200.00)

Finally, the expected value of each decision is given by summing the product of expected net value of each event by the estimated probability of each event. The expected net value of each decision in the tree is shown in Table 33 below. It is assumed that the facility manager will select the option with the maximum net value. As a result, for this example, considering no inspection is performed, the best option is to include the component replacement on the upcoming annual work plan. The net value of this decision is zero cost, meaning the cost of the replacement is balanced out by the value of the component after replacement has occurred.

Table 33. Expected Net Value of No Inspection Branch Decisions

Work Decision	Exp. Net Value ($k)
No Work	0.48 x $20.93 + 0.52 x -$100 = -$41.90
Replace	1.00 x $0 + 0.00 x -$200 = $0

4.3.5 Model Definition - Inspection Branch

The bottom branch of the decision tree considers the case where an inspection is performed to gather more recent information about the condition of the component. After this information is performed, the facility manager then makes a decision based on the new information available. The same work alternatives for scheduled component replacement or work deferral are still applicable options to the facility manager, as is the option for component repair. It is assumed that component repair returns the component to a good condition unless the result of the inspection is a poor condition rating. In that situation, the only work option available is component replacement.

The same methods as above are used to calculate the occurrence probability, cost, value, and expected net value of each event (failure or no failure) for each work alternative (deferral, repair, or replacement). However, this set of calculations has to be performed for each possible condition state that the inspection could return. The result is that there will be an optimal work decision (highest expected net value) for each inspection rating. This allows the facility manager to tailor the work plan based on the results of the inspection. The best work alternative for each condition state has an optimal expected net value. Also, the probability of an inspection returning each of the 4 condition ratings can be given by the current condition state of the component, as shown in Table 30 above. Note however that this assumes the inspection provides perfect information, or identifies the true component condition with 100% accuracy. This is not always the case, and a procedure is presented below to adjust for cases of imperfect inspection information. Regardless, the estimated condition state, reliability, and RSL for each chance event in the inspection scenario are provided in Table 34 below.

Table 34. End of Year Estimated Condition for Chance Events for Inspection Branch

Inspection Result	Work Decision	Chance Event	C1	C2	C3	C7	Reliability	RSL
Excellent	No Work	No Fail	0.75	0.20	0.05	0	1	8.6
		Fail	1.00	0	0	0	1	10
	Repair	No Fail	0	1.00	0	0	1	5
		Fail	1.00	0	0	0	1	10
	Replace	No Fail	1.00	0	0	0	1	10
		Fail	1.00	0	0	0	1	10
Good	No Work	No Fail	0	0.85	0.1	0.05	0.95	4.45
		Fail	1.00	0	0	0	1	10
	Repair	No Fail	0	1.00	0	0	1	5
		Fail	1.00	0	0	0	1	10
	Replace	No Fail	1.00	0	0	0	1	10
		Fail	1.00	0	0	0	1	10
Fair	No Work	No Fail	0	0	0.50	0.50	0.50	1.00
		Fail	1.00	0	0	0	1	10
	Repair	No Fail	0	1.00	0	0	1	5
		Fail	1.00	0	0	0	1	10
	Replace	No Fail	1.00	0	0	0	1	10
		Fail	1.00	0	0	0	1	10
Poor	No Work	No Fail	0	0	0	1.00	0	0
		Fail	1.00	0	0	0	1	10
	Repair	No Fail	0	0	0	1.00	0	0
		Fail	1.00	0	0	0	1	10
	Replace	No Fail	1.00	0	0	0	1	10
		Fail	1.00	0	0	0	1	10

In addition, the net component value of each event is calculated in Table 35 below, based on results from Table 34.

Table 35. Expected Net Value of Chance Events for Inspection Branch

Inspection Result	Work Decision	Chance Event	Prob	Cost	Value	Exp Net Value
Excellent	No Work	No Fail	1.00	$ -	$ 86.00	$ 86.00
		Fail	0	$ 200.00	$ 100.00	$ (100.00)
	Repair	No Fail	0.95	$ 25.00	$ 50.00	$ 25.00
		Fail	0.05	$ 225.00	$ 100.00	$ (125.00)
	Replace	No Fail	1.00	$ 100.00	$ 100.00	$ -
		Fail	0	$ 300.00	$ 100.00	$ (200.00)
Good	No Work	No Fail	0.95	$ -	$ 44.50	$ 44.50
		Fail	0.05	$ 200.00	$ 100.00	$ (100.00)
	Repair	No Fail	0.95	$ 25.00	$ 50.00	$ 25.00
		Fail	0.05	$ 225.00	$ 100.00	$ (125.00)
	Replace	No Fail	1.00	$ 100.00	$ 100.00	$ -
		Fail	0	$ 300.00	$ 100.00	$ (200.00)
Fair	No Work	No Fail	0.50	$ -	$ 10.00	$ 10.00
		Fail	0.50	$ 200.00	$ 100.00	$ 100.00)
	Repair	No Fail	0.95	$ 25.00	$ 50.00	$ 25.00
		Fail	0.05	$ 225.00	$ 100.00	$ (125.00)
	Replace	No Fail	1.00	$ 100.00	$ 100.00	$ -
		Fail	0	$ 300.00	$ 100.00	$ (200.00)
Poor	No Work	No Fail	0	$ -	$ -	$ -
		Fail	1.00	$ 200.00	$ 100.00	$ (100.00)
	Repair	No Fail	0	$ 25.00	$ -	$ (25.00)
		Fail	1.00	$ 225.00	$ 100.00	$ (125.00)
	Replace	No Fail	1.00	$ 100.00	$ 100.00	$ -
		Fail	0	$ 300.00	$ 100.00	$ (200.00)

The optimum work decision, maximum expected net value, for each inspection result is provided in Table 36.

Table 36. Optimum Work Decision for each Inspection Result

Inspection Result	Result Prob	Optimum Decision	Exp Net Value
Excellent	0.000	No Work	$ 86.00
Good	0.444	No Work	$ 37.28
Fair	0.118	Repair	$ 17.50
Poor	0.438	Replace	$ -

Overall, the expected net value of the bottom branch, which assumes an inspection is performed, is given by summing the product of the probability of each condition rating, $P(R_i)$ multiplied by the expected net value of the best work alternative for each rating, $ENV(R_i)$, shown in Equation 25 as:

$$ENV_{no\ Insp} = \sum P(R_i) \times ENV(R_i) \qquad (25)$$

For the example provided above, this results in an expected net value of \$18.6k. The value of the inspection information in this example is the difference between the expected net value if the information is available (inspection is performed) and the expected net value if the information was not collected (inspection not performed), shown in Equation 26 as:

$$VOII = ENV_{insp} - ENV_{no\ insp} \qquad (26)$$

If this value exceeds the cost of acquiring this information (the cost of performing the inspection), then the inspection does provide a net benefit in improved decision making. One can also use the model presented above to see the value of a component's inspection as a function of time and last inspection result, as shown in Figure 19. Here, it is evident that if the last inspection observed a result of good, then maximum value of the next inspection occurs if it is performed two years after the last inspection. Any sooner than this, and the inspection is of less value, due to the proximity to the last inspection. Any longer than this, and the decision maker may miss out on opportunity costs that component repairs may provide. Of course, this optimal time between inspections will vary depending on the type of component, its expected design life, the costs of planned and unplanned replacements and corrective repair, and the condition at the time of the last inspection.

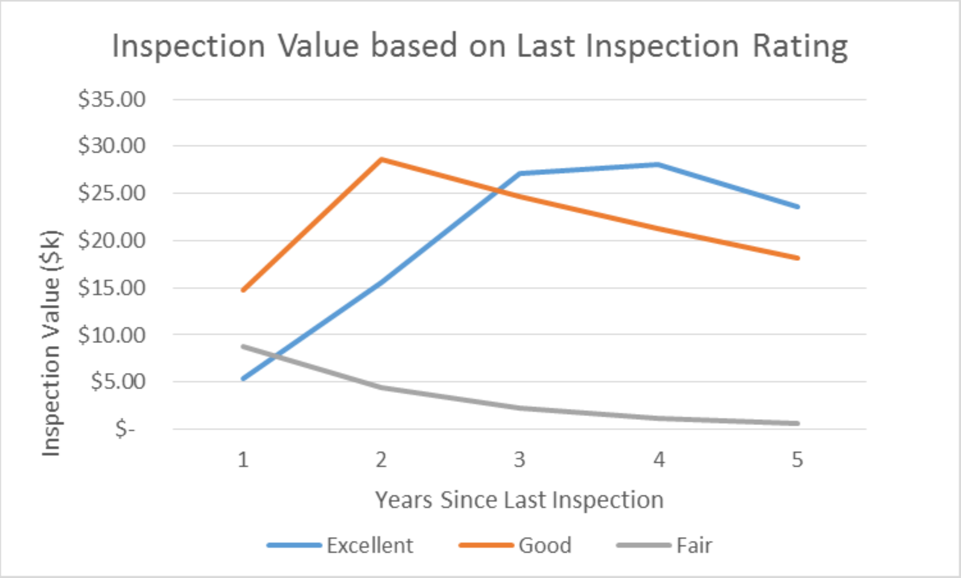


Figure 19. Present Inspection Value as a function of Last Inspection Rating and Time since Inspection

4.3.6 Value of Imperfect Information

Finally, the value of an inspection will vary depending on the accuracy of the inspection process. The development above assumed a perfect inspection process for illustrative purposes. This means that the inspection result always returns the true condition of the component. This is usually not the case, as there is always the possibility of inspection error.

The calculation of probabilities for the bottom branch of the decision tree representing the availability of current inspection information depends on the accuracy of the inspection result, because it is based on conditional probability. Under the assumption of perfect information resulting in 100% accuracy (as in the simple example above), then a poor condition state where the component faces impending failure will always be rated as such by the inspector, and a good condition state will always get an acceptable rating. However, in reality, this perfect information scenario rarely exists, and there exists some probability (hopefully small) that a component in one condition state may receive an inspection rating that indicates a different state. For example, Table 37 below, shows the probability that a component of a certain rating is actually rated as such, which is defined by inspection accuracy matrix M_A.

Table 37. Inspection Accuracy Matrix, M_A

		Actual	
Observed	M_A	Acceptable	Unacceptable
	Acceptable	0.8	0.1
	Unacceptable	0.2	0.9

This example indicates that when the actual condition is acceptable, 20% of the time it is rated incorrectly as unacceptable, and when the actual condition is Unacceptable, 10% of the time it is rated as acceptable. Using this more realistic assumption of imperfect inspection information, and the current estimated condition vector as calculated above, one can calculate the probability of a given inspection result if an inspection is performed by Equation 26:

$$R_I = M_A \times S^T = \begin{bmatrix} 0.8 & 0.1 \\ 0.2 & 0.9 \end{bmatrix} \times [0.51 \quad 0.49]^T = \begin{bmatrix} 0.46 \\ 0.54 \end{bmatrix} \tag{26}$$

The conditional probability theorem can then be used to calculate the revised expected current condition state vector based on the new information for each inspection result. For example, the probability of being in a condition state S_i given condition rating R_j is calculated by Equation 27 as:

$$P(S_i|R_j) = \frac{P(R_j \mid S_i) \times P(S_i)}{P(R_j)} \tag{27}$$

This calculation is performed for each combination of current rating and observed state, using the numbers in the examples above, and organized in Table 38 below.

Table 38. Expected Condition States using Bayesian Revision

		Current State	
Observed Rating		Acceptable	Unacceptable
	Acceptable	$P(S_1\|R_1) = 0.89$	$P(S_1\|R_2) = 0.11$
	Unacceptable	$P(S_2\|R_1) = 0.19$	$P(S_2\|R_2) = 0.81$

These adjusted condition rating probabilities based on inspection accuracy are then used in place of the probability values in the process described above to model the effect of some level of inspection imprecision. This will be illustrated further in the case study to follow.

4.4 Case Study

The methodology presented above is applied to a detailed case study with actual data that illustrates the use of this approach for determining the optimal time for an inspection based on the value of information it provides. Using RS Means Maintenance and Repair cost book, the costs for a number of component activities, are determined for a 600 V switchgear unit (Table 39). These include the costs discussed above for component replacement or repair, as well as the cost for multiple inspection methods. Note the repair cost can vary significantly based on the nature of the corrective work needed. This model assumes a typical repair activity with a constant level of effort and cost. While the repair cost is fixed, the effect of the repair activity as manifested in the post-repair condition will vary based on the pre-repair condition and the repair transition matrix to be applied. The model also assumes that unscheduled work costs two times the amount the same schedule work activity would cost.

Table 39. Applicable Decision Alternatives and Events

Event	Type	Cost
Component Replace (Scheduled)	Work	$3,295
Component Replace (Unscheduled)	Work	$6,590
Component Repair	Work	$487
Component Inspection (Distress)	Inspection	$84
Component Inspection (Direct)	Inspection	$42

For this case study, the seven discrete condition states originally presented in Chapter 3 for the Markov model development are used, with upper, lower, and mid-point values for each state as shown in Table 40 below.

Table 40. Discrete Condition States

State	Upper	Lower	Mid
C1	100	99	100
C2	99	92	95
C3	92	85	88
C4	85	74	80
C5	74	64	71
C6	64	55	61
C7	55	0	30

Related to these seven condition states, the transition matrix for the pure deterioration, which is associated with the option for no work, is shown in Table 41, developed from the methodology in Chapter 3 using actual data for the switchgear component. In addition, the transition matrix for the repair alternative is shown in Table 42, which is based on the assumption that a repair from states C1-C5 restore the component to a C2 (good) condition at the end of the work cycle. It also assumes repair from state C6 is assumed purely stop gap measure, and thus keeps the component at that state but does not improve it, while repair from failed state C7 has no improvement to a non-failed state. Finally, Table 43 represents the transition matrix if a replacement work activity is selected, which resets any component's condition back to the C1, or excellent condition. Depending on the work activity decision being evaluated in the decision tree, the respective matrix is applied to the current expected condition state vector, S_t, to determine the end of year condition state probabilities after any work has been accomplished. For example, to evaluate the year end condition state, S_{t+1}, if a repair is done, given the current condition state, S_t, and a repair matrix M_{repair}, Equation 28 is used:

$$S_{t+1} = S_t \times [M_{Repair}] \qquad (28)$$

Table 41. Pure Deterioration Transition Matrix for D5010 Electrical Distribution Switchgear

Do Nothing	1	2	3	4	5	6	7
1	0.72	0.13	0.08	0.03	0.02	0.00	0.01
2	0.00	0.82	0.11	0.04	0.01	0.01	0.01
3	0.00	0.00	0.89	0.07	0.02	0.01	0.01
4	0.00	0.00	0.00	0.89	0.08	0.02	0.01
5	0.00	0.00	0.00	0.00	0.87	0.12	0.01
6	0.00	0.00	0.00	0.00	0.00	0.95	0.05
7	0.00	0.00	0.00	0.00	0.00	0.00	1.00

Table 42. Repair Transition Matrix for D5010 Electrical Distribution Switchgear

Repair	1	2	3	4	5	6	7
1	0	1	0	0	0	0	0
2	0	1	0	0	0	0	0
3	0	1	0	0	0	0	0
4	0	1	0	0	0	0	0
5	0	1	0	0	0	0	0
6	0	0	0	0	0	1	0
7	0	0	0	0	0	0	1

Table 43. Replace Transition Matrix for D5010 Electrical Distribution Switchgear

Replace	1	2	3	4	5	6	7
1	1	0	0	0	0	0	0
2	1	0	0	0	0	0	0
3	1	0	0	0	0	0	0
4	1	0	0	0	0	0	0
5	1	0	0	0	0	0	0
6	1	0	0	0	0	0	0
7	1	0	0	0	0	0	0

Finally, Table 44 and Table 45 below list the inspection accuracy matrix for two different types of component inspections, representing different levels of detail and associated accuracy. This is used to incorporate the assumption of imperfect information, as discussed above. While it is expected that these accuracy matrices will vary by a number of factors, including component type, the research to further develop these values has not yet been conducted. In lieu of this research, the following assumptions have been adopted to develop the accuracy matrices for the distress survey inspection (Table 44) and the direct rating inspection (Table 45). These assumptions are based, in part, on the research conducted to develop the condition indexes (Uzarski & Burley Jr, 1997).

1. Inspection errors (error = CI inspection – CI actual) are random and normally distributed
2. The inspection error level does not vary significantly by condition level or component type.
3. For distress surveys, inspection error level is +-5 points with a 95% confidence interval.

4. For direct ratings, inspection error level is +-10 points at 95% confidence interval.

Table 44 represents the accuracy matrix for a distress survey process, which is a more detailed inspection process than the direct rating process represented by Table 45. Since the distress survey process is more detailed, the assumed accuracy bands associated with this inspection type are more narrowly defined. While multiple branches of the VOII model may be added to consider additional inspection types, for brevity only the direct rating inspection type is considered in the results below.

Table 44. Distress Survey Inspection Accuracy Matrix

Rated/Actual	C1	C2	C3	C4	C5	C6	C7
C1	85%	10%	4%	1%	0%	0%	0%
C2	5%	85%	5%	4%	1%	0%	0%
C3	2%	5%	85%	5%	2%	1%	0%
C4	1%	2%	4%	85%	4%	3%	1%
C5	0%	1%	2%	5%	85%	5%	2%
C6	0%	0%	1%	4%	5%	85%	5%
C7	0%	0%	0%	1%	4%	10%	85%

Table 45. Direct Rating Inspection Accuracy Matrix

Rated/Actual	C1	C2	C3	C4	C5	C6	C7
C1	70%	20%	9%	1%	0%	0%	0%
C2	15%	70%	10%	4%	1%	0%	0%
C3	4%	10%	70%	10%	5%	1%	0%
C4	1%	4%	10%	70%	10%	4%	1%
C5	0%	1%	4%	10%	70%	10%	5%
C6	0%	0%	1%	4%	10%	70%	15%
C7	0%	0%	0%	1%	9%	20%	70%

Figure 20 shows the resulting VOII decision tree constructed using the Precision Tree add-in module (Palisade Corporation, 2015) for Microsoft Excel. Because of the number of work alternatives and the number of condition states, this decision tree is quite large, but Figure 20 shows an exploded view of a portion of this tree.

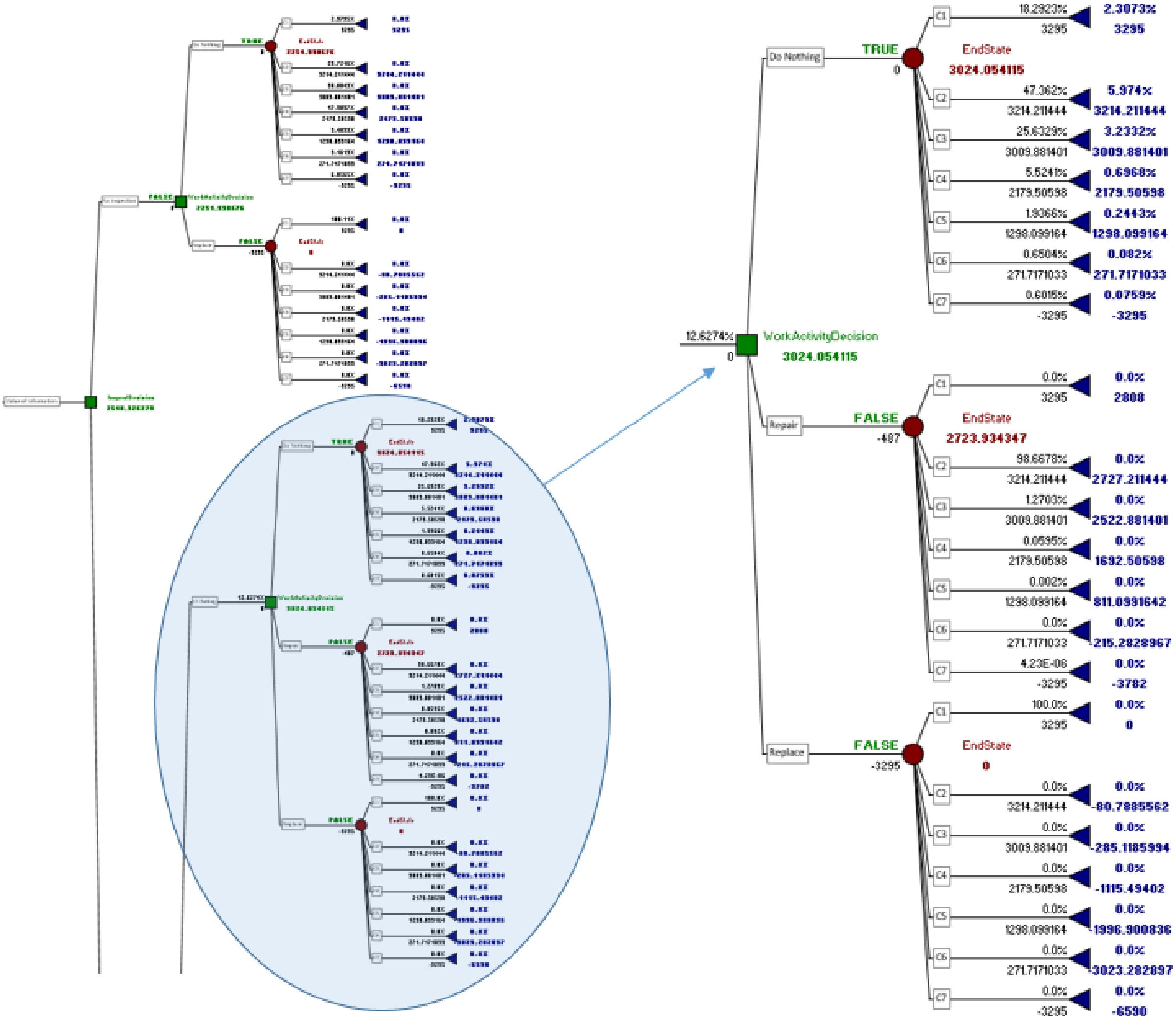


Figure 20. VOII Decision Tree for Case Study Example

Table 46 shows the value of inspection information for a direct rating inspection approach, varying both the time since the last inspection and the result of the last inspection, for a direct survey inspection. The highlighted values indicate the years in which the inspection value is greater than the estimated inspection costs. Note that while the inspection value is generally higher as the time since the last inspection increases, this does not mean that one should delay an inspection in order for its value to rise. It simply means the cost difference between the “No Inspection” versus “Inspection” alternative is higher in those circumstances. If one elects for inactivity beyond the point where inspection is of economic value, then deferring each year results in a higher cost of operations.

Table 46. Two-way sensitivity of Direct Rating Inspection Value

		Time Since Inspection: (Years)							
Direct		1	2	3	4	5	6	7	8
Last Inspection Result: (CI)	50	$51.08	$29.68	$23.79	$18.95	$14.54	$10.52	$7.73	$6.73
	55	$51.08	$29.68	$23.79	$18.95	$14.54	$10.52	$7.73	$6.73
	60	$351.99	$434.33	$514.08	$591.25	$665.84	$719.24	$649.47	$582.58
	65	$60.06	$94.82	$141.67	$192.90	$247.56	$304.86	$364.09	$424.65
	70	$60.06	$94.82	$141.67	$192.90	$247.56	$304.86	$364.09	$424.65
	75	$66.20	$73.76	$94.96	$120.06	$148.89	$181.19	$216.71	$255.14
	80	$66.20	$73.76	$94.96	$120.06	$148.89	$181.19	$216.71	$255.14
	85	$66.20	$73.76	$94.96	$120.06	$148.89	$181.19	$216.71	$255.14
	90	$2.23	$8.11	$23.20	$44.64	$67.88	$93.03	$120.14	$149.22
	95	$6.12	$16.86	$28.97	$43.07	$60.72	$81.17	$103.43	$127.56
	100	$9.24	$19.54	$31.00	$43.81	$58.99	$77.11	$97.79	$120.34

To illustrate the calculation of the inspection information values in Table 46, a 4-year period since the last inspection is assumed, which was a direct survey assessment that resulted in a CI of 95 (condition state C2). Since the direct survey does not result in a perfect determination of condition state, the expected actual condition state at the time of the inspection observation is given in Equation 29 by:

$$S_o = [0, 1, 0, 0, 0, 0, 0] \times [M_{Direct}] = [0.15, 0.70, 0.10, 0.04, 0.01, 0, 0] \qquad (29)$$

And the current expected condition state now assuming pure deterioration (refer to Table 41 for $M_{Deterioration}$) over 4 years is given in Equation 30 as:

$$S_t = S_o \times [M_{Deterioration}]^4 = [0.04, 0.36, 0.29, 0.16, 0.08, 0.05, 0.03] \qquad (30)$$

To determine the value of the "No Inspection" decision, the expected value of either performing no work on the component or replacing the component is calculated and the best value among the two options is chosen. Note that the repair work option is not considered for the No Inspection branch, since it is assumed that alternative is only applicable if an inspection has been performed to determine the scope of the repair work. For the "Do Nothing" work alternative, the expected condition state at the end of the analysis year is given in Equation 31 by:

$$S_{t+1} = S_t \times [M_{Deterioration}] = [0.03, 0.30, 0.30, 0.18, 0.09, 0.06, 0.04] \qquad (31)$$

Summing the probability of the non-failed condition states results in a reliability index, RI, of 0.96. The expected remaining service life for each condition state can be calculated from the $M_{deterioration}$ matrix using the steps provided in Appendix H, with results shown in below in Table 47.

Table 47. Effective Age and Remaining Service Life by Condition State

State	Effective Age	RSL
C1	0	40.4
C2	0.5	39.9
C3	1.8	38.6
C4	7.6	32.8
C5	12.8	27.6
C6	18.6	21.8
C7	40.4	0.0

Summing the product of the probability and remaining service life for each state gives the expected remaining service life for the component at the end of the work cycle, which results in 34.5 years. Since no work is performed, there is no work cost associated with this option, but with a 4% probability of failure, the expected cost of failure is given in Equation 32 as:

$$P(\text{failure}) \times (\text{Cost}_{URpl} - \text{Cost}_{SRpl}) = 0.04 \times \$(6{,}590 - 3{,}295) = \$122 \quad (32)$$

Finally, the value of the component at the end of the work cycle, based on its percentage of remaining service life from its expected condition state, is given in Equation 33 as:

$$\text{Value} = \text{RSL/DL} \times \text{Schedule Replacement Cost} = 34.5/40.4 \times \$3{,}295 = \$2{,}814 \quad (33)$$

From this, the expected net value of the “No Work” option is \$2,814 - \$122, or \$2,692.

For the “Replace” work alternative, the expected condition state at the end of the analysis year is given in Equation 34 by:

$$S_{t+1} = S_t \times [M_{Replace}] = [1, 0, 0, 0, 0, 0, 0] \quad (34)$$

This results in a reliability index of 1.00, and a remaining service life that is fully restored back to the expected design life of 40.4 years. Under this scenario, there is no risk of failure, but the cost of the schedule replacement work activity is \$3,295 from Table 39. Similarly, the component value is given in Equation 35 by:

$$\text{Value} = \text{RSL/DL} \times \text{Schedule Replacement Cost} = 40.4/40.4 \times \$3{,}295 = \$3{,}295 \quad (35)$$

From this, the expected net value of the “Replacement” option is \$3,295 - \$3,295 or \$0. This will always be the case for replacement as the model is defined, since the value of the component after replacement balances the cost of that replacement activity. Since the “No Work” Option has a higher expected net value, it is assumed that given no inspection is performed at the beginning of the work planning cycle, the facility manager should select this option, and not include the component on the annual work plan.

This value is then compared against the lower half of the decision tree, which models the scenario where newly acquired inspection information is available. The result of this inspection can be one of seven condition state values, each of which has a given probability of occurring based on the current expected condition prior to the inspection, and the accuracy of the inspection type to be performed. The probabilities, along with the associated value of the best work option for each rating are summarized in Table 48.

Table 48. Rating Probability and Expected Value for Inspection Decision Branch

Rating	Probability	Best Option	Work Cost	Value	Net Value
C1	12.6	Do Nothing	\$ -	\$ 3,135	\$ 3,135
C2	27.9	Do Nothing	\$ -	\$ 3,128	\$ 3,128
C3	25.1	Do Nothing	\$ -	\$ 3,017	\$ 3,017
C4	16.3	Do Nothing	\$ -	\$ 2,652	\$ 2,652
C5	8.9	Repair	\$ 487	\$ 2,730	\$ 2,243
C6	5.3	Repair	\$ 487	\$ 1,994	\$ 1,507
C7	3.9	Replace	\$ 3,295	\$ 3,295	\$ -

It is important to note that repair options are considered in this portion of the analysis. Multiplying the probability of each rating by its associated net value results in an overall expected value of \$2,511 for the “Inspection” decision. This is \$260 greater than the value of the “No Inspection” decision, so this particular set of component characteristics results in a value of inspection information of \$260. This corresponds to the value in Table 46 where the row is 95 (CI of last inspection) and column is 4 (years since last inspection).

Table 49 shows the resulting value of information if a distress survey is considered. It uses the same set of calculations presented above, except uses the distress survey accuracy matrix (Table 44) to calculate the expected rating probabilities. As noted above, the distress survey is assumed to be more accurate in identifying the actual condition state of the component, and thus the value that it provides a decision maker is ultimately greater. This can be weighed against the cost of a distress survey, which is usually greater than the direct rating approach due to the time and detail involved in such process. If field experience shows that for this component, the time and cost required for a distress survey is approximately two times that required for a direct rating inspection, the highlighted values in Table 49 show the situations where distress approach is economically feasible based on the parameters specified. The optimal inspection type selection is not fixed, but likely to change as inspection costs and accuracies change associated with each method vary. For example, a distress survey approach on certain components with many subcomponents may take four to five times as long as a direct rating approach, while other components may take much less time. However given the relative cost of each, optimal inspection strategies can be evaluated.

Table 49. Two-way sensitivity of Distress Survey Inspection Value

		Time Since Inspection: (Years)							
Distress		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Last Inspection Result: (CI)	**50**	$18.17	$10.20	$5.29	$4.87	$4.49	$4.14	$3.83	$3.54
	55	$18.17	$10.20	$5.29	$4.87	$4.49	$4.14	$3.83	$3.54
	60	$305.74	$418.37	$526.69	$630.79	$730.78	$826.78	$918.95	$1,000.08
	65	$82.67	$136.86	$197.90	$264.33	$334.91	$408.57	$484.40	$561.64
	70	$82.67	$136.86	$197.90	$264.33	$334.91	$408.57	$484.40	$561.64
	75	$111.68	$140.68	$173.61	$210.44	$251.07	$295.28	$342.82	$393.38
	80	$111.68	$140.68	$173.61	$210.44	$251.07	$295.28	$342.82	$393.38
	85	$111.68	$140.68	$173.61	$210.44	$251.07	$295.28	$342.82	$393.38
	90	$11.27	$34.65	$61.32	$90.19	$121.21	$154.44	$189.94	$227.69
	95	$14.47	$34.96	$58.05	$83.62	$111.14	$140.71	$172.38	$206.17
	100	$16.41	$34.24	$55.82	$79.29	$104.65	$132.02	$161.47	$193.05

Finally, Table 50 shows the decision that results in the highest return on value considering either no inspection, direct rating, or distress survey options.

Table 50. Optimal Inspection Decision for Example Scenario

		Time Since Inspection: (Years)							
		1	2	3	4	5	6	7	8
Last Inspection Result: (CI)	<=59	Direct	None	None	None	None	None	None	None
	60-64	Direct	Direct	Direct	Direct	Distress	Distress	Distress	Distress
	65-74	Direct	Distress	Distress	Distress	Distress	Distress	Distress	Distress
	75-89	Distress	Distress	Distress	Distress	Distress	Distress	Distress	Distress
	90-94	None	None	None	Distress	Distress	Distress	Distress	Distress
	95-99	None	None	None	Direct	Distress	Distress	Distress	Distress
	100	None	None	None	Direct	Distress	Distress	Distress	Distress

4.5 Summary of Inspection Activity Optimization

The methodology described in this chapter presents a new process to estimate the value of a component inspection in determining the optimum inspection observation timing and schedule. These inspections are typically performed to help support facility management decisions, such as the type and timing of work to apply for a building component. Once an inspection is performed, a deterioration model like the one presented in Chapter 3 can be used to project future condition loss over time. However, these models have limitations as the uncertainty about the actual condition increases as the time passes since the last inspection. Recurring inspections can help to decrease this uncertainty, but considering inspections require time and resources that may be limited, it is necessary to choose the most economic or optimal time to perform that next inspection.

As a result, a method is proposed for selecting and scheduling the inspection of components by maximizing the value that the inspection provides a facility decision maker. The Value of Inspection Information approach presented here uses the condition prediction model and component reliability profiles based on the Markov approach developed in Chapter 3 applied using a Value of Information decision tree to derive this quantitative inspection value. The model uses the expected component condition state and cost of various work alternatives to consider the expected net value for a range of options, in cases where the inspection information is collected, as well as when it is not. The approach helps to screen for situations where an inspection is most likely to identify a risk or component failure or an opportunity for repair work. Applied to a real life case study, the results indicate that there is indeed an optimal time since the last inspection that maximizes inspection value, allowing for better allocation of scarce resources. In addition, varying inspection types with different levels of detail and accuracy can be analyzed, allowing for a selection of the best type of inspection to perform given the component's current lifecycle profile.

An important feature of this methodology is that an actual cost to conduct the inspection is not necessary to perform the analysis. Instead, the VOII model provides the value that an inspection is expected to offer, regardless of inspection cost. Once this value is calculated, it can be compared to the actual inspection cost to determine if an inspection would provide positive net value. From an inspection cost perspective, it is important to note that the type of inspection considered in this chapter is not a detailed or specialty assessment intended to provide a fundable scope of work for any repairs necessary. Instead, the inspection is a condition index-based assessment that provides a determination of condition state and can support a rough scoping estimate for repairs. While the former may better support work estimate preparation and eventual work execution, the latter is usually less expensive to perform and better supports the work planning process, which is the focus of this research.

CHAPTER 5 – SINGLE COMPONENT WORK ACTIVITY OPTIMIZATION MODEL

A key part of facility asset management is an understanding of what activities to perform against the components of a building at a particular point in time. A comprehensive analysis should consider the current and future condition and performance states, in addition to the costs required to operate, maintain, and repair or replace building systems and components at the end of their respective service life. The chapters above presented approaches for predicting future condition trends based on the current measured state, and acquiring inspection information to maximize the value of determining those condition states. Using that background, this chapter presents an approach for modeling the attributes, activities, and effects for a building component, as a means of optimizing total life cycle cost and performance. The process arranges the pertinent characteristics of a component as an attribute vector, which is acted upon by a matrix which contains information about the applicable component work activities and their effect on the attributes. Selection of a particular activity, or set of activities, to apply to the component has the result of transforming the initial attribute vector into a resultant vector. This resultant vector reflects the expected post-activity state and configuration of the component. This process can be replicated several times over the course of a planning time horizon to simulate the passage of time and study the long-term effects of different work scenarios. The methodology is applied against a case study at the end of this chapter, upon which the results related to the optimized work activity type and timing for different component and facility configurations will be discussed.

5.1 Background

The U.S. Department of Defense owns and operates over 2.2 billion square feet of building facilities that support training, housing, operations, and other missions. These buildings represent a large, diverse, and aging portfolio of facilities, but despite their age are mostly functional and operational. Keeping these buildings in a functional and operational state as continuous deterioration occurs requires maintenance, repair, and replacement (MR&R) of the building components on a periodic basis. In the current fiscal operating environment however, where budgets and resources for MR&R work are continuously under pressure, it is critical that the allocation of these resources attempts to maximize long-term value, while still assuring facilities and components are reliable in the near term.

This requires a number of interrelated but sometimes competing strategies to achieve. First, facility managers must seek a solution that attains adequate long-term condition targets. These targets are typically based on condition or work backlog metrics. Second, facility managers are always under pressure to reduce continuous operating costs, such as the costs of energy that a building will consume. Third, even with a long-term focus on condition, the facility and its components must remain reliable in the near term in order to support its ongoing mission. All these objectives must be achieved at the best value to the owner, resulting in the lowest ownership cost.

Current asset management tactics have focused on achieving these goals through rule-based approaches. For example, a rule-based approach may have a pre-established rule or standard to replace a component when its age surpasses its design life, or consider repair when its projected condition falls below a minimum standard. These rules are typically applied at a discrete point in time and in a linear fashion. For example, in determining what work to perform in a facility over a ten year analysis period, that time horizon would be divided into ten one-year periods and the rules for which work activities to consider, and priorities for that work, are then evaluated in each year independently. This process is a significant improvement over an ad hoc approach where work is determined reactively without a set of underlying rules. However, the linear nature of this approach makes it more difficult to distinguish work that appears of value in the near term, but may provide questionable long-term value. It is also difficult to evaluate the comprehensive risk and opportunities from a set of decisions that span the entire analysis period.

In the example above, due to the risks of component failure, as well as the opportunity for repairs that may extend useful service life, a component may be triggered for a work activity well before its actual failure point in order to mitigate the risk and lost opportunity that may result in a future year. Instead of establishing condition standards solely based on notional condition standards to mitigate these risks, reliability-based standards can be established where risk is inherently considered. In addition, by using a non-linear work selection process that looks across multiple years, the true optimal work year and activity type can be identified.

The probabilistic deterioration model and resulting reliability index metric presented in Chapter 3 provides a means of incorporating risk in the decision making process, and implementing these improvements. Using this data-driven statistical model coupled with a non-linear optimization work selection process, the methodology presented in this chapter is shown to better achieve the goals discussed above for near and long-term performance and overall cost.

5.2 Objective

The objective of this chapter is to present a method for the optimized selection of component work activities for the life cycle of a building component, such that a minimum total cost of operations is achieved given constraints on component performance related to condition and reliability measures. The measures for expected condition and reliability are based specifically on the methodology developed in Chapter 3, applied to a risk-based work planning approach. In this chapter, individual components are treated separately, such that the performance of one component does not affect the condition or reliability of another associated component. As a result, components are assumed independent and any potential interactions are currently ignored, but will be considered in the next chapter.

While past approaches have considered replacement of the component "in-kind" (with one of similar type, size, efficiency, or configuration), this model also incorporates options for additional work alternatives, such as replacement not "in-kind." The motivation for this is to consider potential recurring operational cost savings, such as energy, that can be realized by replacing with a different, better, or more efficient component. Thus, the objective is to analyze a more comprehensive set of options available to a facility decision maker for component sustainment, restoration, or modernization in order to achieve the optimal component's life cycle profile.

5.3 Methodology - Model formulation

As stated in the objective section above, this model considers the building component as a singular entity that supports a system and/or overall operation in a building facility. By focusing on a single component versus multiple components, the issue of the relative importance of each component in a building, as well as the non-linear complexities that arise from the interaction among components, is minimized. While these are important issues to explore further, this simplification allows one to establish the logic that occurs at an elemental level.

A general component has a number of characteristics that describes its type, configuration, and state. The characteristics are both static and temporal in nature; that is, some of these characteristics change little if at all over the course of the component's service life, while others may change drastically over time due to aging, degradation, or the application of work activities. The characteristics that describe the pertinent aspects of the component needed for asset management decisions can be modeled as a vector, C, which is comprised of sub-vectors related to basic properties, type specific attributes, and transient state metrics, as shown in Table 51 below.

Table 51. Component Characteristic Vector

Characteristic	Value	Sub-vector Type
AssetID	BLR1	Basic Properties
Asset Type	Boiler	
Replace Cost	$100,000	
Design Life	20 years	Specific Component Attributes
Year Installed	2000	
Size	1,000 MBH	
Efficiency	80%	
Hours of Operation	1,500	
Age	15 years	Performance State Metrics
Remaining Life	5 years	
Condition Index	62	
Reliability Index	71	

A given component can undergo one or more events over the course of its life cycle, and these events affect the characteristics of the component, including its performance state. Each of these activities has additional attributes that relate to the time, duration, and cost of a given activity, as well as the activity effect on the individual component characteristics. As a result, an activity matrix A is defined that is used to model the activities to be applied to a component at a point in time. Table 52 below shows an example activity matrix with three general classes of activities: Operation, Repair, and Replacement.

Table 52. Component Activity Matrix

Activity Type	Operate	Repair	Replace
Activity Code	0	1	2
New AssetID	BLR1	BLR1	BLR1
New Type	Boiler	Boiler	Boiler
New Size	1000 MBH	1000 MBH	1000 MBH
Ne Efficiency	80%	80%	90%
New Hours Operation	1500	1500	1500
New Replace Cost	$100,000	$100,000	$100,000
New Design Life	15 years	15 years	15 years
New Year Installed	2000	2000	2015
New Age	15	15	0
New RSL	14	17	20
New Condition	90	95	100
New Reliability	84	90	100

The cells within each column of the table above contain the information that is used to model how the component characteristics change, if at all, as each activity is performed or applied. The effect of applying activity matrix A to initial component characteristic vector C is a resultant vector R that represents the expected value of characteristics at the end of the time interval of analysis. This process can be replicated multiple times, with the resultant vector R_i from the first time cycle becoming the characteristic vector C_{i+1} for the start of the next time cycle, as a means to determine the optimal selection of activities to achieve some desired state over a multi-year time horizon. As such, the generalized activity model is given in Equation 36 below:

$$C_i \text{ x } A = R_i = C_{i+1} \tag{36}$$

5.3.1 Objective Function

After defining a general data framework, the objective function for this work selection model is defined. As stated above, the objective is to minimize the total expected life cycle cost of the component over the analysis period, including all applicable costs which can be estimated. This analysis considers the following component related costs: Operations, Maintenance, Repairs, Replacements, and Upgrades.

5.3.1.1 Operations

Component operations costs are related to the costs to operate the facility that can be attributed to the component being analyzed. In this study, the primary operations costs are energy costs. For actively consuming energy components, such as boilers or chillers, costs can be estimated directly based on the average amount of energy they consume in a specified time period, typically annually. Likewise, these energy estimates are based on the type and efficiency of the component, either for the current configuration or a different optimal configuration is that is being considered.

In addition to active energy consuming components, there are passive components that affect energy usage for the facility but do not actively consume energy. These include such components as roofs, walls, doors, and windows that provide a thermal barrier between the interior space and outside climate. Numerous energy calculators have been developed (International Building Performance Simulation Association, 2014) for a range of building components, taking attributes as inputs for the component as well as the building as a whole, and producing energy usages estimates. These calculators allow the estimation of the expected energy savings if the component was replaced with a more energy efficient alternative.

5.3.1.2 Maintenance

Maintenance refers to the costs to maintain facility components to sustain an acceptable performance level. Maintenance sustains a component at its current condition level, and may help to slow deterioration, but does not generally improve condition state. Annual maintenance costs for components can be obtained from industry data sources, such as RS Means, or by mining data from a Computerized Maintenance Management System (CMMS) to determine the costs for scheduled maintenance. The cost of component maintenance varies by type, age, or condition of the component. In this study, it is assumed that the components receive the appropriate levels of maintenance as recommended, but the decision about whether to perform maintenance and the type of maintenance is not considered in this analysis.

5.3.1.3 Repair

Component repair is the activity of restoring lost condition to a component that has undergone degradation in order to meet a defined performance standard. Repair activities restore some or all of the condition lost over time due to deterioration of the component, which usually also results in an extension of the component's service life. Repair costs can be derived from completed tasks for work orders and trouble tickets for corrective repairs found in the CMMS database. The cost of repair depends on the nature of the work performed, but in general depends on the type of component. RS Means Maintenance and Repair cost data (R.S. Means, 2014) includes costs for many types of common building component repair activities.

5.3.1.4 Replacement

Component replacement costs are a result of component replacement, overhaul, or reconditioning to a like new state. Component replacement may be in-kind, using a similar component type, configuration, or performance standard level. However, replacement may also involve the installation of a component that is substantially different than the original (see upgrade below). This may be required to meet a higher demand or obtain better energy efficiency. Data supporting a component replacement cost model can be derived from industry sources such as RS Means unit cost and assemblies price book, as well as documentation from past building renovation projects. Since replacement results in removal of the existing component, its costs depend primarily on the component type, size, and configuration, but are assumed to be generally independent of the age and condition of the component being replaced.

5.3.1.5 Upgrade

Upgrade costs are associated with replacement of a component to a capacity, efficiency, or standard that exceeds the level of the existing component. For example, replacing a standard efficiency boiler component with a high efficiency boiler is an upgrade activity that usually has a higher cost compared to a standard replacement in-kind. This additional cost may result in better facility performance or lower operational costs, which can make the higher initial costs warranted in the long run. For this analysis, a 10% premium for component upgrade is assumed over the standard replacement cost from RS Means.

Recent emphasis on sustainability and adaptive reuse of existing buildings has begun to place an added emphasis on non-condition related problems as well, such as functional obsolescence and energy inefficiencies in buildings. Like the condition-based problems, there is a myriad of detection and diagnostic techniques for identifying, measuring, and addressing the issues related to mission and operational efficiency, but these alone do not provide all the tools needed to develop improved long-term facility investment strategies. This is because the solution to an optimized set of maintenance, repair, and replacement activities cannot occur by treating building condition, functionality, and energy efficiency as orthogonal stove-piped metrics, since in reality they are tightly coupled. Instead, an integrated framework is needed that considers all costs of building ownership, including operations and energy costs, maintenance and repair costs, recapitalization costs, and even user costs related to mission and risk.

5.3.1.6 Bringing Costs to Current Net Present Value (NPV) Dollars

In order to provide comparable values over the course of the analysis period, all future projected costs are calculated based on current value dollars using the general inflation rate and any applicable escalation rates for construction (work activities) or energy (operations cost). This is done using Equation 37 below:

$$\text{FutureCost}_b = \text{Current Cost}_a \times (1 + I + E)^{(b-a)} \tag{37}$$

Where FutureCost_b is the future cost of work item in year b, CurrentCost_a is the current cost of the work item in year a, I is the inflation rate, and E is the escalation rate. These costs are then converted to net present value based on the set discount rate to reflect the time value of money, using equation 23 below:

$$\text{NPV}_a = \text{FutureCost}_b \times (1 - D)^{(b-a)} \tag{38}$$

Where NPV_a is the net present value based on the current year a, and D is the discount rate reflecting time value of money.

5.3.2 Constraints

Performance constraints are modeled to ensure that any optimized set of work alternatives still results in condition and reliability measures that are at or above acceptable predefined standards. As illustrated in the previous chapters, condition assessment information is used to determine the current condition and reliability states at a point in time. However, since deterioration results in a loss of condition over time that results in lower reliability and eventual failure, a condition and reliability prediction approach, as discussed in Chapter 3, is critical to project the current expected CI and RI measures for each year of the analysis. In addition, these expected values need to be updated to reflect any work activities that may be selected for application on the component.

5.3.2.1 Estimating Condition Index

As shown in Chapter 3, if a component was previously inspected at some point in the past and no work has been performed since, the current expected condition can be estimated given the result of the last inspection and the time since that inspection was performed. This is done using the Markov condition deterioration model to compute the current expected condition state and associated probability of failure. Transition matrices have been developed for various component types by analyzing past inspection results to determine the probability of transitioning between each set of states. In addition to transition matrices for deterioration, transition matrices for other work activities such as component repair or replacement can also be defined. These matrices can be applied in a successive chain in order to estimate the condition state at the current point in time based on past work performed. For example, if a component repair was performed in year 1, no work performed in year 2, and a replacement performed in year 3, then estimated condition state at the end of year 3 would be given by Equation 39:

$$C_3 = C_0 \times M_{repair} \times M_{deterioration} \times M_{replace} \tag{39}$$

Where C_3 is the condition state at end of year 3, C_0 is state at end of year 0, and M_x are the transition matrices for that component's repair, deterioration, and replacement work actions, respectively. Development of transition matrices for component deterioration as discussed in depth in Chapter 3, and Chapter 4 provided the matrices for deterioration, repair, and replace activity alternatives in Table 41, Table 42, and Table 43, respectively.

5.3.2.2 Estimating Reliability Index

Section 3.7 presented the component reliability index, defined as the probability of the component remaining in a non-failed condition state over the work analysis cycle, typically one year. As a result, the reliability index for any year of the analysis is calculated by multiplying the expected condition state vector Ci, at the beginning of that year by the Markov transition matrix M, and then summing the probabilities associated with non-failed states from the resulting vector.

5.3.3 Decision Variables

For this analysis, each decision that a facility manager is likely to encounter is identified and coded as a discretized value. Table 53 shows the typical work activity decisions for a generalized component, along with several optional work activity decisions. In each analysis simulation year, one of these work activities is selected, and the choice affects current and future year characteristics such as condition and reliability.

Table 53. Work Activity Codes

Work Alternative Code	Description
0	Do Nothing
1	Repair Component
2	Replace Component with current configuration
3 (optional)	Replace Component with optimized configuration a
4 (optional)	Replace Component with optimized configuration b
… (optional)	Replace Component with optimized configuration n

If work activity code 0-Do Nothing is selected, then no work activity cost is incurred and the component experiences normal deterioration as modeled in the pure deterioration transition matrix. If work activity code 1-Repair is selected, then the Repair transition Matrix is applied which generally improves condition as well as reliability. If work activity code 2 through n is selected, replacement is performed and the replacement transition matrix is applied to estimate current CI and RI. In addition, the component’s year installed and age is updated. If work activity code 3 or greater is selected, if applicable, key characteristics of the component are updated to reflect a replacement with a different configuration. For example, this may be used to select the replacement of a normal efficiency boiler with a high efficiency boiler.

5.3.4 Optimization Approach

The optimization step attempts to find the best mixture of component work activities, represented by the optimal work decision for each year. For this study, the component model, complete with the activity cost estimates and the projected condition and reliability, is formulated in Microsoft Excel. An add-in to Excel called Evolver (Palisade Corporation, 2015) was then used to specify the fitness function based on total life cycle cost of ownership, the constraints based on projected condition and reliability, and the decision variables as presented in Table 53. Then, an optimization is performed which generates a number of trial solutions (work decisions for each year) and uses a genetic algorithm approach to continually improve results of each trial. Using the genetic algorithm approach, each solution set is treated like an independent "organism" that can generate or produce other organisms with some similar traits or characteristics. Through a number of evolutionary steps, the algorithm evaluates which solutions are the best to survive to the next generation, while also occasionally trying “mutations,” or completely new solutions to guard against settling on a local minimum.

Using this approach, the optimization goal as defined above is to find the minimum total life cycle cost, which is specified in the model definition. This life cycle cost is the sum of all present value operations, repair, replacement, and upgrade costs attributed to the component over the period of analysis. The decision variables are represented by the adjustable cell ranges, which are configured to accept integer values between 0 and 3 for each year of the analysis. Finally, both the condition index and reliability index constraints are specified, which requires the estimated CI and RI to be above the minimum preset standards, either at the end of the analysis or the end of each yearly cycle. These standards apply as long as the building is active. If the analysis year is beyond the divestiture year of the facility, then these standards are relaxed to zero, reflecting that the component requirements are no longer needed if the building is demolished, for example. If applicable, additional constraints, such as yearly budgetary constraints, could also be included.

5.4 Case Study

To further illustrate this component optimization model, a case study is presented which applies the methodology above to a typical decision faced by a facility manager. In this example, the building roof surface component is considered, and the objective is to determine the type and timing of work applications to perform against this roof across the lifespan of the building.

5.4.1 Global, Site and Building-Specific Variables

Table 54 below summarizes the global variables used in the case study analysis, including the discount rate, inflation rate, and pertinent escalation rates for roof construction and building energy costs. A maximum time horizon is also specified, which determines the length of the analysis period.

Table 54. Global Variables

Analysis Variable	Value
Time Horizon	40 years
Discount Rate	3%
Inflation Rate	2%
Construction Escalation	2%
Energy Escalation	3%

Table 55 summarizes site specific characteristics based on building location. This includes such variables as heating and cooling degree days, solar load, and local energy costs.

Table 55. Site Variables

Analysis Variable	Value
State	IL
City	Peoria
HDD	6331.5 Annual deg F -day
CDD	882 Annual deg F -day
Solar Load	1304.5 Annual Ave Btu/ft2 per day
Electricity, Summer	$0.10 /KWh
Electricity, Winter	$0.10 /KWh
Fuel	$1.00 /Therm

Table 56 summarizes the building characteristics, including the building type, sources for heating or cooling, as well as the efficiency of the heating or cooling systems. Also included here is a building divest year, which indicates when the building is anticipated to be replaced, demolished, or otherwise removed from service. Once the building has reached this divestiture point, it is assumed that any components of that building are no longer needed to perform as they otherwise would under active service requirements. This affects the type and timing of the activities one would consider performing against the components of that building.

Table 56. Building Characteristics

Analysis Variable	Value
Building Type	Old Office
Heating Source	Fuel
Efficiency, Cooling (COP)	2.00
Efficiency, Heating	70%
Facility Divest Year	2050

5.4.2 Component-Specific Variables

Table 57 shows the characteristics for the example roof surface component being analyzed. This includes such information as the current type of component, the year it was installed or last replaced, information about the most recent inspection performed, as well as expected design life and work activity costs. It also shows detailed attributes about the component that affect operational requirements, such as energy costs. This table lists this information for both the current configuration, and any other configurations to be considered if replaced (not "in-kind").

Table 57. Component Characteristics

Analysis Variable	Current Configuration	Optimal Configuration
Section Name	Section A	Same
System Type	B3010 Roof Coverings	Same
Component Type	Low Slope Roof	Same
Component Subtype	Built-up Roof (BUR)	Same
Comp Year Installed	2000	Varies
Last Inspection Date	1/1/2012	Varies
Last Inspection CI	92	Varies
Component Quantity	100,000	Same
Replacement Cost	$7.61/ft2	$8.37/ft2
Repair Cost	$3.97/ft2	$3.97/ft2
Min CI Standard	50/100	Same
Min RI Standard	80/100	Same
R-Value*	10 Btu-in/(hr-ft2 deg F)	20 Btu-in/(hr-ft2 deg F)
Solar Reflectance*	5	80
Infrared Emittance*	90	90

Next, the model simulates the typical life cycle costs attributed to the component based on present value dollars. Table 58 presents these costs, which include operational costs (energy), repair costs, replacement costs, and salvage value (if applicable). To estimate costs related to maintenance, repair, and replacement activities, RS Means cost source is used, which is simply a unit cost multiplied by the quantity of roof surface. To estimate operational costs related to energy, a web-based roof energy calculator developed by the Department of Energy (DOE) called the DOE Cool Roof Calculator (Oak Ridge National Laboratory, 2015) is used which estimates cooling and heating load and associated costs based on the site, building, and roof surface characteristics. This allows one to estimate the energy savings for replacing the current roof with one having improved thermal properties, resulting in lower energy usages and annual energy costs.

Table 58. Estimated Resource Requirements

Resource Requirement/Cost	Current	Optimal	Delta
Cooling Load (Btu/ft2 per year)	6,476	1,955	-4,521
Cooling Cost ($/ft2 per year)	$0.19	$0.06	-$0.13
Heating Load (Btu/ft2 per year)	17,533	8,184	-9,349
Heating Cost ($/ft2 per year)	$0.18	$0.08	-$0.10
Total Energy Cost ($/ft2 per year)	$0.37	$0.14	-$0.23
Operations Cost	$36,512	$13,914	-22,599
Maintenance Cost	$5,000	$5,000	Same
Repair Cost	$50,000	$55,000	+$5,000
Replace Cost	$100,000	$110,000	+$10,000
Salvage Value	N/A	N/A	N/A

The transition matrices for this particular component are presented below. Table 59 shows the deterioration matrix that is applied to the current expected condition state if the work action decision in any given year is 0-Do Nothing. Table 60 shows the repair matrix that is applied if work action 1-Repair is selected, and Table 61 shows the replacement matrix that is applied if work action 2 or above (replacement or upgrade) is selected. As a result, depending on the work activity decision in any given year, the model uses these matrices to estimate the condition state for the next year.

Table 59. Pure Deterioration Transition Matrix for B3010 Roof Coverings

Do Nothing	1	2	3	4	5	6	7
1	0.692	0.133	0.114	0.014	0.023	0.01	0.014
2	0	0.813	0.11	0.034	0.019	0.013	0.011
3	0	0	0.858	0.082	0.027	0.014	0.019
4	0	0	0	0.83	0.102	0.043	0.025
5	0	0	0	0	0.862	0.1	0.038
6	0	0	0	0	0	0.91	0.09
7	0	0	0	0	0	0	1

Table 60. Repair Transition Matrix for B3010 Roof Coverings

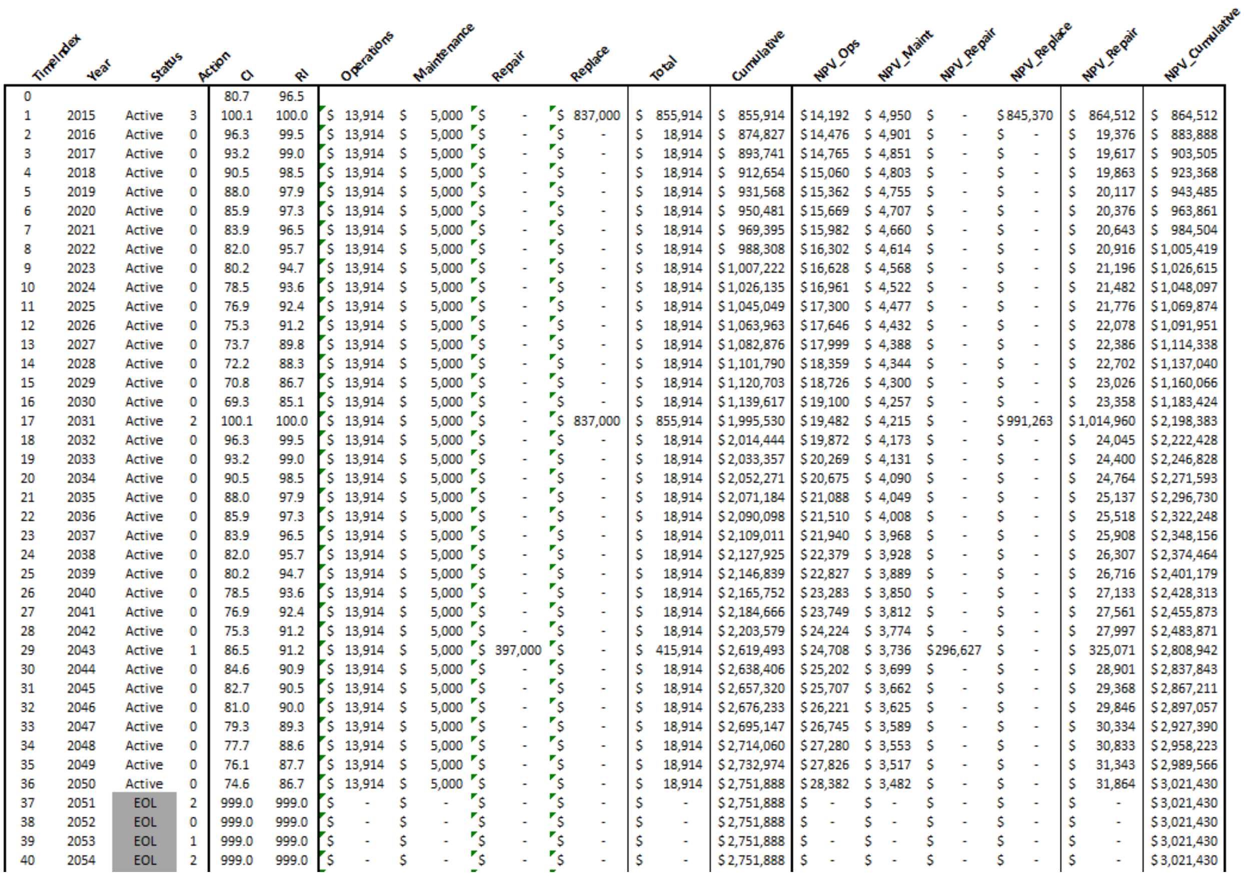
Repair	1	2	3	4	5	6	7
1	0	1.00	0	0	0	0	0
2	0	1.00	0	0	0	0	0
3	0	1.00	0	0	0	0	0
4	0	1.00	0	0	0	0	0
5	0	1.00	0	0	0	0	0
6	0	0	0	0	0	1.00	0
7	0	0	0	0	0	0	1.00

Table 61. Replace Transition Matrix for B3010 Roof Coverings

Replace	1	2	3	4	5	6	7
1	1.00	0	0	0	0	0	0
2	1.00	0	0	0	0	0	0
3	1.00	0	0	0	0	0	0
4	1.00	0	0	0	0	0	0
5	1.00	0	0	0	0	0	0
6	1.00	0	0	0	0	0	0
7	1.00	0	0	0	0	0	0

5.4.3 Analysis Model

This information is then used to model the annual life cycle characteristics of the roof component, including both performance and cost drivers over the course of the analysis period (Figure 21). For each year of the analysis, for which a time index is assigned, the building status is evaluated to determine if it has reached its end of life or divestiture point. Then, depending on the selected work action, the component Condition Index and Reliability Index are projected for each year of the analysis using the models presented in Chapter 3 and the transition matrices above. These values are used to compare against the minimum condition and reliability constraints established by management. For this study, the condition standard was set at a CI of 50 in order to keep condition above the typical failure threshold. To ensure reliability of operations, the reliability standard was set to 80%, meaning management strives for 80% probability of the component not failing in any time period. In addition, the operations, repair, replacement, and upgrade costs are estimated based on the current configuration of the component in the year that the activity occurs. These are then converted to present current value dollars to calculate the total net present value of all component operations and work activities in each year, and the cumulative total over the course of the analysis period.



TimeIndex	Year	Status	Action	CI	RI	Operations	Maintenance	Repair	Replace	Total	Cumulative	NPV_Ops	NPV_Maint	NPV_Repair	NPV_Replace	NPV_Repair	NPV_Cumulative
0				80.7	96.5												
1	2015	Active	3	100.1	100.0	$ 13,914	$ 5,000	$ -	$ 837,000	$ 855,914	$ 855,914	$ 14,192	$ 4,950	$ -	$ 845,370	$ 864,512	$ 864,512
2	2016	Active	0	96.3	99.5	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 874,827	$ 14,476	$ 4,901	$ -	$ -	$ 19,376	$ 883,888
3	2017	Active	0	93.2	99.0	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 893,741	$ 14,765	$ 4,851	$ -	$ -	$ 19,617	$ 903,505
4	2018	Active	0	90.5	98.5	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 912,654	$ 15,060	$ 4,803	$ -	$ -	$ 19,863	$ 923,368
5	2019	Active	0	88.0	97.9	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 931,568	$ 15,362	$ 4,755	$ -	$ -	$ 20,117	$ 943,485
6	2020	Active	0	85.9	97.3	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 950,481	$ 15,669	$ 4,707	$ -	$ -	$ 20,376	$ 963,861
7	2021	Active	0	83.9	96.5	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 969,395	$ 15,982	$ 4,660	$ -	$ -	$ 20,643	$ 984,504
8	2022	Active	0	82.0	95.7	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 988,308	$ 16,302	$ 4,614	$ -	$ -	$ 20,916	$ 1,005,419
9	2023	Active	0	80.2	94.7	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 1,007,222	$ 16,628	$ 4,568	$ -	$ -	$ 21,196	$ 1,026,615
10	2024	Active	0	78.5	93.6	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 1,026,135	$ 16,961	$ 4,522	$ -	$ -	$ 21,482	$ 1,048,097
11	2025	Active	0	76.9	92.4	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 1,045,049	$ 17,300	$ 4,477	$ -	$ -	$ 21,776	$ 1,069,874
12	2026	Active	0	75.3	91.2	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 1,063,963	$ 17,646	$ 4,432	$ -	$ -	$ 22,078	$ 1,091,951
13	2027	Active	0	73.7	89.8	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 1,082,876	$ 17,999	$ 4,388	$ -	$ -	$ 22,386	$ 1,114,338
14	2028	Active	0	72.2	88.3	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 1,101,790	$ 18,359	$ 4,344	$ -	$ -	$ 22,702	$ 1,137,040
15	2029	Active	0	70.8	86.7	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 1,120,703	$ 18,726	$ 4,300	$ -	$ -	$ 23,026	$ 1,160,066
16	2030	Active	0	69.3	85.1	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 1,139,617	$ 19,100	$ 4,257	$ -	$ -	$ 23,358	$ 1,183,424
17	2031	Active	2	100.1	100.0	$ 13,914	$ 5,000	$ -	$ 837,000	$ 855,914	$ 1,995,530	$ 19,482	$ 4,215	$ -	$ 991,263	$ 1,014,960	$ 2,198,383
18	2032	Active	0	96.3	99.5	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 2,014,444	$ 19,872	$ 4,173	$ -	$ -	$ 24,045	$ 2,222,428
19	2033	Active	0	93.2	99.0	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 2,033,357	$ 20,269	$ 4,131	$ -	$ -	$ 24,400	$ 2,246,828
20	2034	Active	0	90.5	98.5	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 2,052,271	$ 20,675	$ 4,090	$ -	$ -	$ 24,764	$ 2,271,593
21	2035	Active	0	88.0	97.9	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 2,071,184	$ 21,088	$ 4,049	$ -	$ -	$ 25,137	$ 2,296,730
22	2036	Active	0	85.9	97.3	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 2,090,098	$ 21,510	$ 4,008	$ -	$ -	$ 25,518	$ 2,322,248
23	2037	Active	0	83.9	96.5	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 2,109,011	$ 21,940	$ 3,968	$ -	$ -	$ 25,908	$ 2,348,156
24	2038	Active	0	82.0	95.7	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 2,127,925	$ 22,379	$ 3,928	$ -	$ -	$ 26,307	$ 2,374,464
25	2039	Active	0	80.2	94.7	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 2,146,839	$ 22,827	$ 3,889	$ -	$ -	$ 26,716	$ 2,401,179
26	2040	Active	0	78.5	93.6	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 2,165,752	$ 23,283	$ 3,850	$ -	$ -	$ 27,133	$ 2,428,313
27	2041	Active	0	76.9	92.4	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 2,184,666	$ 23,749	$ 3,812	$ -	$ -	$ 27,561	$ 2,455,873
28	2042	Active	0	75.3	91.2	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 2,203,579	$ 24,224	$ 3,774	$ -	$ -	$ 27,997	$ 2,483,871
29	2043	Active	1	86.5	91.2	$ 13,914	$ 5,000	$ 397,000	$ -	$ 415,914	$ 2,619,493	$ 24,708	$ 3,736	$ 296,627	$ -	$ 325,071	$ 2,808,942
30	2044	Active	0	84.6	90.9	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 2,638,406	$ 25,202	$ 3,699	$ -	$ -	$ 28,901	$ 2,837,843
31	2045	Active	0	82.7	90.5	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 2,657,320	$ 25,707	$ 3,662	$ -	$ -	$ 29,368	$ 2,867,211
32	2046	Active	0	81.0	90.0	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 2,676,233	$ 26,221	$ 3,625	$ -	$ -	$ 29,846	$ 2,897,057
33	2047	Active	0	79.3	89.3	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 2,695,147	$ 26,745	$ 3,589	$ -	$ -	$ 30,334	$ 2,927,390
34	2048	Active	0	77.7	88.6	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 2,714,060	$ 27,280	$ 3,553	$ -	$ -	$ 30,833	$ 2,958,223
35	2049	Active	0	76.1	87.7	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 2,732,974	$ 27,826	$ 3,517	$ -	$ -	$ 31,343	$ 2,989,566
36	2050	Active	0	74.6	86.7	$ 13,914	$ 5,000	$ -	$ -	$ 18,914	$ 2,751,888	$ 28,382	$ 3,482	$ -	$ -	$ 31,864	$ 3,021,430
37	2051	EOL	2	999.0	999.0	$ -	$ -	$ -	$ -	$ -	$ 2,751,888	$ -	$ -	$ -	$ -	$ -	$ 3,021,430
38	2052	EOL	0	999.0	999.0	$ -	$ -	$ -	$ -	$ -	$ 2,751,888	$ -	$ -	$ -	$ -	$ -	$ 3,021,430
39	2053	EOL	1	999.0	999.0	$ -	$ -	$ -	$ -	$ -	$ 2,751,888	$ -	$ -	$ -	$ -	$ -	$ 3,021,430
40	2054	EOL	2	999.0	999.0	$ -	$ -	$ -	$ -	$ -	$ 2,751,888	$ -	$ -	$ -	$ -	$ -	$ 3,021,430

Figure 21. Simulation Results

The objective of the optimization is to minimize the total cumulative net present value life cycle cost over the analysis period, given constraints on CI and RI, by adjusting the decision variable in the Action column. These decision variables are coded as four discrete integer variables as shown previously in Table 53. This analysis assumes operation (as well as maintenance) activities are required every year, but costs related to repair, replacement, or upgrade activities are only realized if those activities are selected. If a work activity is selected, the condition index and reliability index are modified to reflect that work application. In addition, if an upgrade activity with different configuration is selected that lowers operational or maintenance costs, those cost savings are applied to be realized in all subsequent years of the analysis.

The optimal selection of the work activities to be performed in each year to minimize estimated life cycle cost is performed using the Evolver add-in to Microsoft Excel as discussed above. The optimization is run over the course of the analysis period, but if the building is expected to be divested before this period, the performance constraints on CI and RI are removed for those years. The result of this optimization for the case study presented above is shown in Figure 22, which shows the activity total costs in each year, as well as the cumulative cost over the analysis period.

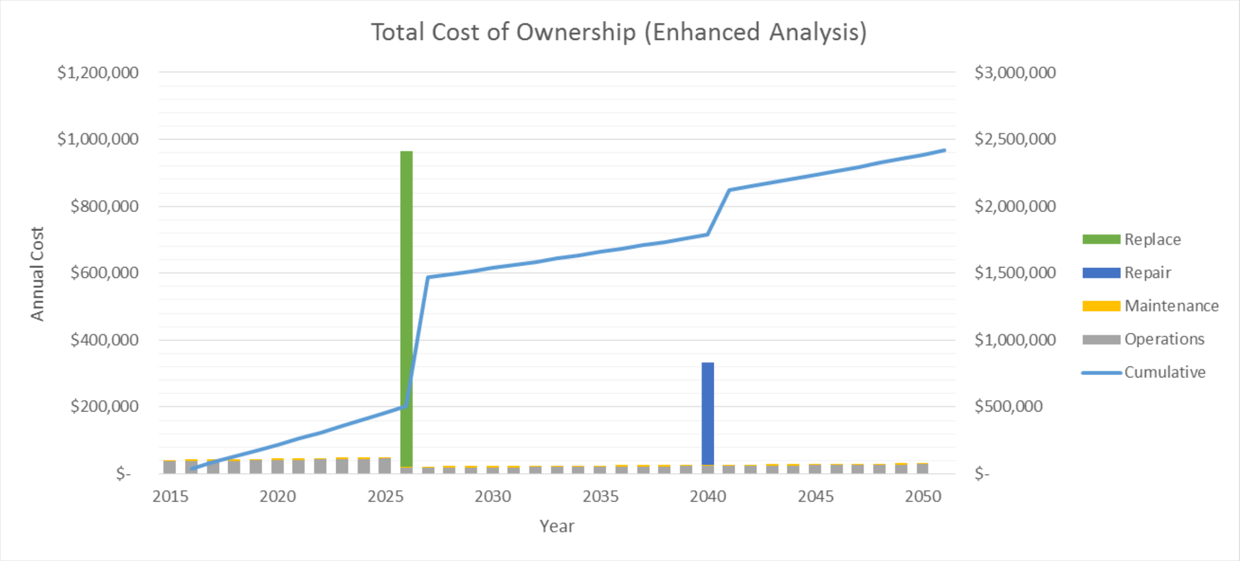


Figure 22. Total Cost of Ownership, Enhanced Analysis Example

The cost profile for this optimized scenario is then compared to the component work plan generated using a rules-based approach as shown below in Figure 23. In this approach, a repair is selected for any year where the projected CI falls below a pre-set standard of 75, and a replacement is selected if the component age is greater than two times its expected design life. Because the rules-based approach evaluates the work alternatives on a year-by-year basis, then moves on to the next year, work to a component above these thresholds is not considered, even if it may have a beneficial impact on long-term life cycle cost. However, the non-linear optimization approach used in the proposed model evaluates alternatives across all years, allowing for the potential for work to occur above a set threshold if it results in lower cost and better fitness function. As a result, the constraints on condition and reliability in the proposed model serve as minimum standards, but not as hard rules for when to consider work.

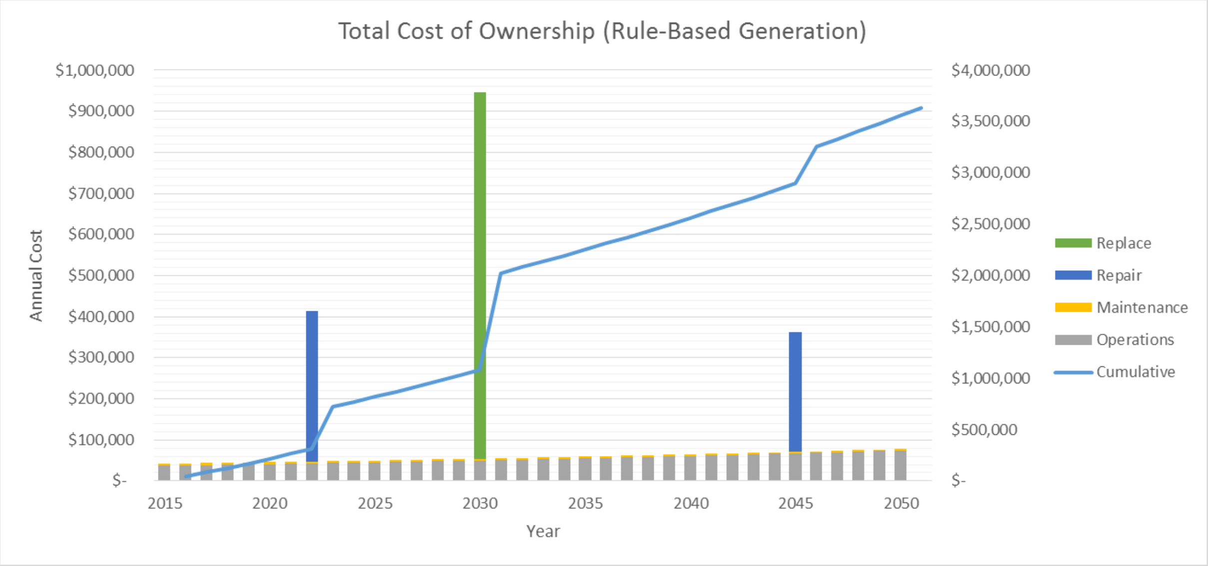


Figure 23. Total Cost of Ownership, Baseline Example

In addition, the rules-based approach does not consider component upgrades to improve energy efficiency, which can result in lower operations costs over the long run. More importantly, it does not consider the reliability standard, as the model proposed in this chapter does. The reliability index as developed in Chapter 3 can help to directly associate risk in the work planning process, versus indirectly via an elevated CI standard.

Table 62 shows a comparison between the rules-based approach and the enhanced analysis approach presented in this chapter. It shows a decrease in both operations cost due to lower energy usage, and total cost of ownership attributed to the roofing component example.

Table 62. Single Component Activity Optimization Example Comparison

Cost Type	Rules-Based	Enhanced	% Change
Operations	$ 1,936,402	$ 1,018,392	-47%
Maintenance	$ 150,275	$ 150,295	
Repair	$ 657,054	$ 305,707	
Replacement	$ 892,332	$ 943,153	
Total	$ 3,636,064	$ 2,417,527	-34%

5.5 Summary of Single Component Work Activity Optimization

Numerous approaches currently exist to support facility management decisions related to component repair and renewal. However, many of these approaches only focus on individual aspects of facility and component performance, such as age or condition. This chapter presented a comprehensive framework to minimize work activity and operational costs, subject to requirements on long-term condition, continuous reliability, and overall risk, by selecting the most efficient alternatives to apply to the components of a building. The framework incorporates the condition and reliability models developed in Chapter 3, building energy savings upgrades, and advanced optimization techniques.

CHAPTER 6 – WHOLE BUILDING WORK ACTIVITY OPTIMIZATION FRAMEWORK

The previous chapters have developed the models for condition prediction and other life cycle metrics and applied those models to the analysis of individual components of a building. While this is an important aspect of facility management, the ultimate goal is to perform this analysis across the entire spectrum of a facility, or even portfolio of facilities. This requires a more advanced and formal object-centric data structure that accounts for all the components, assemblies, and systems to be managed for a facility, as well the appropriate characteristics, activities, and associations among these objects. This data model allows for the consideration of component and system interactions, higher level work activities, and complex work activity effects, all of which are important when performing a whole building analysis. This chapter develops the framework for a whole-building facility management and life cycle optimization, and provides an example case study to implement the framework.

6.1 Overall Framework

Facility asset management requires an understanding of the facility assets that exist, what state those facilities are in, and the events which can occur that affect that state over time. At its core, this is an information-centric process. Generally speaking, there are key pieces of information that describe a facility asset, and knowing these pieces of information can help when faced with important management decisions. These key pieces of information are referred to as characteristics, of which there are numerous characteristics associated with a facility or component asset to describe its type, location, age, condition state, and other pertinent properties.

There are also events that occur which affect the facility or component asset over time. Some events are difficult to predict, and out of the control of the decision maker managing the facility. Other events can be controlled by someone (an agent) responsible for managing the asset. When the events are within the control of an agent, such as a facility manager, they are considered activities. Numerous component work activities where presented in Chapter 5, and include such work actions as operation, maintenance, inspection, repair, and replacement of components and assets.

These events also have characteristics that may include the time, duration, and cost of performing the activity. Many times, the values of these activity characteristics are dependent on the values of the characteristics for the asset against which the activity is applied. When an activity occurs against an asset, the activity changes the values of the attributes that describe the asset. Facility asset management is concerned with making the best decisions about which activities to perform and when, such that performance characteristics meet or exceed standards, while delivering the best value in terms of total cost of ownership. This chapter considers such a problem, and synthesizes the developments of the prior chapters to construct a decision framework that can be applied holistically for an entire building.

To support this process, the following overarching framework is shown in Figure 24, complete with the following data elements and the relationships among them.

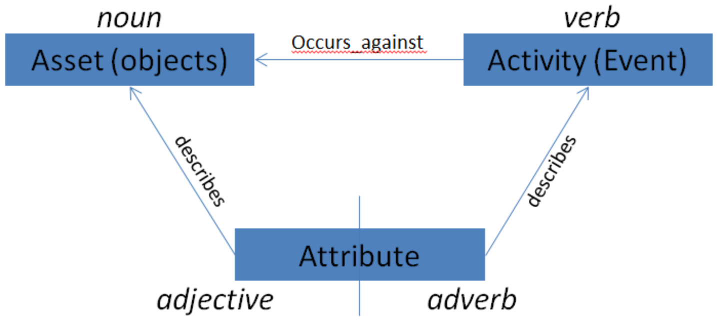


Figure 24. Data Model Object Framework

- Assets: These are the objects or elements to be managed.
- Attributes: This is the information about the objects which aids in asset management.
- Events: These are the occurrences which the object experiences and can affect the object characteristics (attributes).
- Associations: These are the linkages that describe how objects are associated to each other.

6.1.1 Object (Asset) Entities

The proposed data structure uses an entity model to represent physical objects to be managed. The physical objects are generalized as Facility level or Component level objects. Examples of facility object types include buildings, bridges, or segments of a transportation, utility, or communications network, but the focus of this analysis is primarily on buildings. A facility is composed of lower level component objects, which each have individual functions and work independently or in unison to provide the array of higher level functions that are required by the facility to adequately support its purpose or mission. Common dictionary definitions for facilities and components within the context of this research are provided below:

- Facility: Something such as a building or large piece of equipment that is planned, designed, constructed, and maintained to serve a specific purpose of function affording a convenience or service that makes an action, operation, or activity easier.
- Component: Self-contained part of a facility that serves its own purpose which supports the larger purpose or operation of the facility. The component is the lowest level unit at which asset management decisions about specific activities are made.

While management objectives typically align at the facility level, work activities resulting from those management decisions are usually applied to the individual components of a facility. As a result, it is necessary to track the pertinent attributes associated with the components of a facility, and thus information at a component level must be collected, stored, and analyzed.

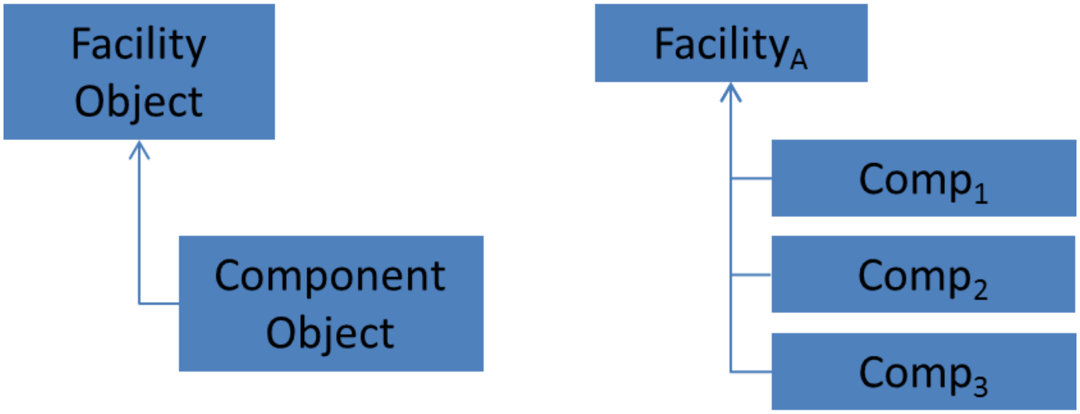


Figure 25. Facility and Component Object Relationship

The model in Figure 25 provides general representation of the relationship between components and the facilities of which they belong, and several levels may exist between a facility and its individual components. These layers include major systems and sub-systems that aggregate component function and behavior to provide increasingly higher level functions. While a component is typically associated with an assembly of a facility, this definition is broadened to allow the component object to represent a low level part of an assembly, the assembly itself, or higher level systems of assemblies. This provides flexibility to allow the facility manager to choose the level at which they prefer to manage. For example, if one chooses to manage his/her facility at a high level, the entire HVAC system may be defined as a component object. If managing at an intermediate level, the major pieces of HVAC equipment such as boilers and chillers along with their auxiliary parts, may be defined as individual components. If managing at a very low level, the individual parts of each piece of equipment may be managed individually (controls, motor, and compressor of a chiller). The decision about what management level is most appropriate is an important practical consideration, but beyond the scope of this research.

6.1.2 Attribute Entities

Once the definition of facility and component objects has been defined, the next step is to describe the instances of each object in a specific facility, such as a building. A broad range of characteristics about the instance of a single component can be described by a finite set of attributes. For the purposes of this model, these attributes are generally classified as basic attributes, extensible attributes, and transient state attributes. Basic attributes represent a core set of attributes that are applicable to all component instances in a domain of interest, regardless of their class or type. Basic component attributes include a global unique ID, the parent facility for which the component belongs, a description, and a component classification. Extensible attributes are properties or characteristics that apply to only a subset of all components, usually based on class or type. For example, U-value and Solar Heat Gain Coefficient (SHGC) are attributes applicable to window components, but not a boiler or chiller component, which would have their own unique set of attributes. In general, the basic and extensible attributes define properties that usually do not continuously change. However, Transient State attributes are needed to represent aspects of the component that do change frequently and sometimes continuously, over time. In many cases, these transient state attributes are measured by indexes, or metrics, such as component age in service, remaining expected design and service life, condition index, performance index, etc. These characteristic types are summarized below:

- Basic Properties: Characteristics about an asset that are static and applicable globally, regardless of an asset's class.
- Attributes: Characteristics that are relatively static (may only change due to the occurrence of an event). Extensible characteristics are applicable to only specific classes of objects
- State Metrics: Characteristics that are time-variant (temporal) in nature. Extensible metrics are applicable to only specific classes of objects.

6.1.3 Event (Activity) Entities

The characteristics discussed above apply to the model at a discrete point in time. They are not all necessarily static, and some may change on a frequent basis, especially as other dependent variables change. As a result, the concept of events can be used, which are occurrences that may change an object's attributes. These events can be continuous events such continuous operations or the normal passage of time and deterioration, periodic discrete events such as schedule routine maintenance activities, or single discrete events such as repair or replacement work activities.

- Activity: Activities are events that can be directly controlled by someone managing the asset.
- Occurrence: The application of an event to an asset.
- Effect: Direct result of the event occurring against an asset, manifested in a change to that assets attributes.

There are many types of event activities that can be applied to a component object. These include but are not limited to the items below, most of which were discussed in depth in section 5.3.3.:

- Operation Activity
- Maintenance Activity
- Repair Activity
- Replacement Activity
- Upgrade Activity
- Inspection Activity

The analysis in this chapter currently focuses on a subset of these activities to include normal operation with no work, repair, replacement, and upgrade. Considerations for the inspection activity were covered in depth previously in Chapter 4, while the Maintenance activity was not part of the research at this time. In general though, each activity type has some effect on the properties and states of each component defined by its attributes. Previously in Chapter 5, it was discussed how an activity matrix operates on the initial attribute state vector to produce a resultant state vector. This is further represented in Figure 26 below which illustrates how the final expected component state at the end of the time period is related to the initial attribute state and asset activities performed.

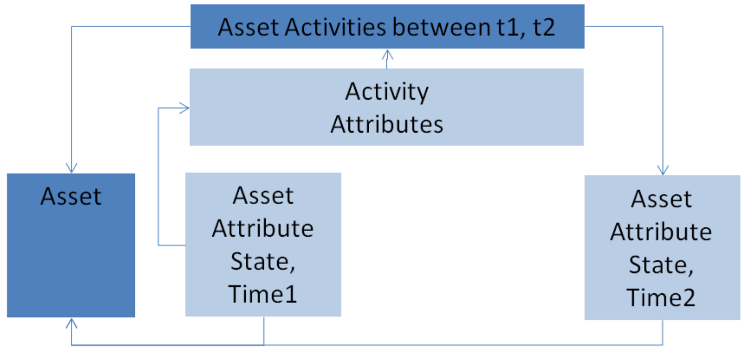


Figure 26. Activity Effects on Asset Attributes

6.1.4 Association Entities

Assets (either facilities or components in the domain specific schema) rarely exist and operate independently, but are usually part of some larger function, network, or system. As a result, it is necessary to define the associations among asset objects to facilitate an understanding of the performance of these larger entities. There are basically two methods of creating this association, either associating an object to another peer object, or to a separately defined collection or group, which may be an object itself.

If the method is a collection association, then the association type is a membership association, of which multiple assets can be members of multiple collections. There are three basic collection types for this domain schema: a network, a system, and a zone.

- Network – Collection of Assets within a site that performs a common function
- System – Collection of Components within a facility that performs a common function
- Zone – Collection of Components within a facility

If the method is a peer-to-peer association, then there is a wide range of association types to be considered. These include but are not limited to:

- is_part_of
- is_located_in
- is_made_up_of
- connects_to

- adjacent_to
- affects_function
- affects_operation
- affects_condition
- affects_reliability
- intersects

6.1.5 Domain Specific Relational Data Model

Based on these assumptions and definitions provided above, a relational data model can be developed, as shown in the Unified Modeling Language (UML) diagram provided in Figure 27 below. At the core of this model is a facility or component object; each has attribute sets that describe it. There are also activities that occur against the objects and these activities affect the attributes of the objects. These activities themselves have attributes, including the resources or costs required to perform them. As these activity events occur over time, the attributes that describe the life cycle performance of the facility objects are affected, and these effects can be modeled. As a result, the selection of certain activities has a direct impact on the performance of the facility. One can use this data model to develop an optimization approach that selects the optimum mixture of work activities to attain facility performance goals with the best use of resources. This requires an explicit definition of performance measurement, which is discussed in the next section.

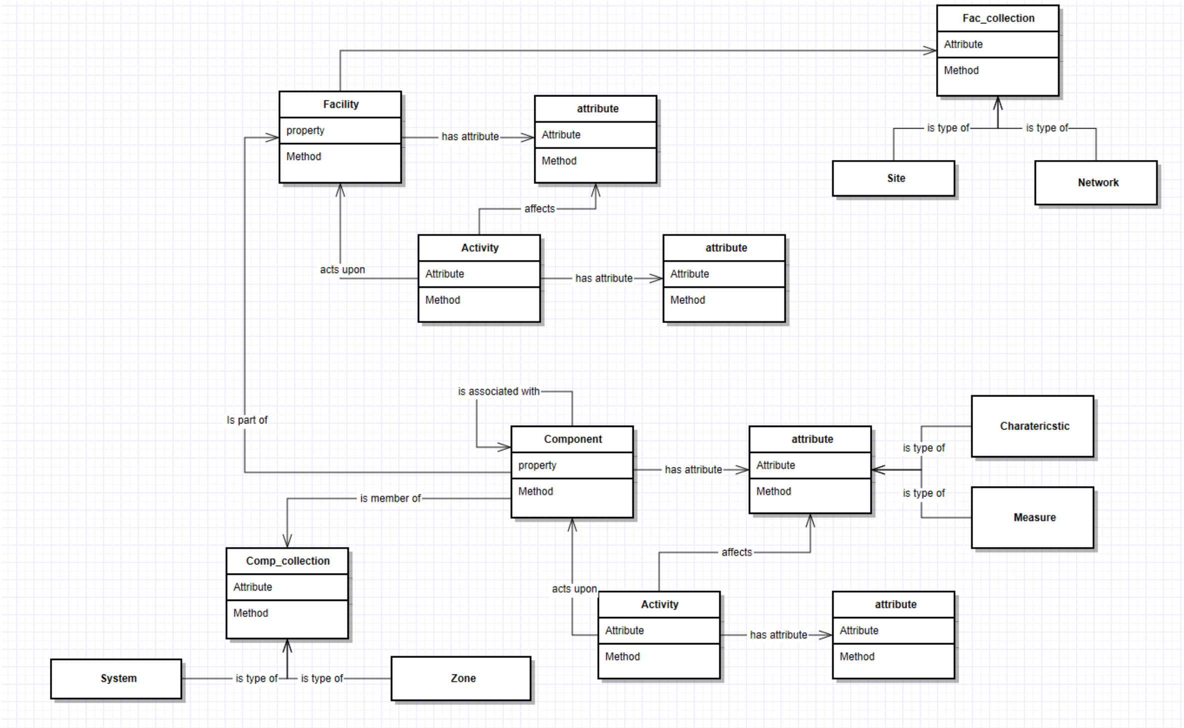


Figure 27. UML Diagram

6.2 Key Performance Indicators for Building Life Cycle Management

Once the building is decomposed into its components, with a hierarchy among components and an association between components established, the next step is to determine the performance state of each. This is accomplished through assessments that collect information to objectively measure or determine the key performance indicators (KPIs) of the building. A number of applicable performance indicators for buildings and building components are provided below.

6.2.1 Age

One measure of the life cycle performance is the age of an asset. Physical facilities and components generally deteriorate over time with use in service, and so age is commonly used as an indicator of condition or performance. Age is easily calculated and easily communicated to decision makers, making it a popular metric to look at for initial decisions.

One of the main limitations of the age metric is the difficulty with determining the true installation date or construction date of an asset. Furthermore, as alluded to in Chapter 3, not all assets deteriorate at a similar rate due to variations in environmental conditions, usage patterns, maintenance levels, etc., meaning age alone is not a reliable predictor of condition or performance.

6.2.2 Remaining Design and Service Life

Most assets have a finite life and eventually require replacement. Given predefined knowledge of this expected life and the actual age of the asset, one can calculate the remaining design life (RDL). This metric relates to the amount of time an asset is expected to perform in service before replacement is required. The remaining design life can provide a more complete picture of an asset's performance since it takes into account the longevity of building components.

However, the length of time that an individual component provides useful service before requiring replacement can vary significantly based on environmental factors, use, and maintenance and repairs performed. To account for this variability, the remaining service life (RSL) can be used, because it takes specific observed deterioration into account. Chapter 3 presented an approach for calculating the remaining service life by accounting for both typical component deterioration and local observed conditions.

6.2.3 Replacement and Depreciated Value

In addition to age and service life, asset value is also an important measure that can be tracked to indicate condition or performance. Each asset, either a facility or component, has an estimated cost to replace, bringing the condition back to a like-new condition at the originally designed or constructed capacity or configuration. At the facility level, this is referred to as the plant replacement value (PRV) and at the component level as the component replacement value (CRV).

While the replacement value accounts for the current cost to replace the asset, it does not reflect the current value of an actual asset due to depreciation and/or deterioration. Chapter 4 presented an approach to address this depreciation and calculate current asset value as a percentage of the replacement value, based on the ratio of the expected remaining service life to the overall design life, both discussed above. The whole building optimization method addressed here utilizes the same methodology to estimate the current value or a component or facility object.

6.2.4 Condition Index

The SMS inspection process discussed in Chapter 2 results in a condition index scale that stretches across the wide array of building systems and component types to measure physical condition loss in a more objective and consistent way. This condition loss stems from a number of different mechanisms (distresses), each of which contributes in some way to component performance loss. The SMS inspection process takes all these observations and translates them into a single condition metric that serves as a communication tool providing a common language through a numerical index to reflect the amount of condition related performance lost due to degradation stemming from natural deterioration, damage, deferred maintenance, etc.

Chapter 3 explored the grouping of these numerical CI values into discrete index states, and subsequently calculated the probability for transitioning among these condition states over time to model expected deterioration. The result of that process is used in the investigation that follows for projecting CI for each analysis year, similar to the single component optimization problem discussed in Chapter 5.

In addition to measuring accumulated deterioration, the CI metric has also been used as an indicator of potential failure. Furthermore, condition index standards have been used as an indirect means of accounting for the consequence of failure. These consequences fall into several categories, including: 1) safety/environmental consequences, 2) operational consequences, 3) aesthetic/quality of life consequences. If any of these consequences of failure are more adverse (unacceptable) than normal, it may lead to a higher standard threshold setting. For example, if the failure of a system or component results in a high safety risk, the condition standard would normally be set higher to compensate for that risk. This is similar to a safety standard being applied to reduce the uncertainty of falling below a safety limit by maintaining the component at a higher condition. Likewise, if the failure of a component affects mission operations, it may be important to maintain a higher condition for the same logic. Finally, if there is a stringent aesthetic or quality of life requirement, that too may lead to maintenance at a higher level, and thus a higher condition standard.

6.2.5 Reliability Index

For many building components, simply defining what constitutes a failure state can be ambiguous because failure could have different meanings for different building uses or building occupants. As was illustrated in Chapter 3, while the CI metric does not directly measure probability of failure, it does provide a way of defining a quantitative failure state objectively and consistently. Using this logic, the reliability index for a component was defined as the probability of remaining in a non-failed condition state over the course of the annual work cycle. This probability stems from the fact that the actual condition index or true condition state is never known with 100% certainty, especially in the absence of a recent inspection.

6.2.5.1 Aggregation considerations using component reliability and importance indexes

While the reliability index for a component is a valuable metric to use for facility management, the aggregation of these component reliabilities to a system or overall building level is also highly desirable. The typical approach of using weighted averages, such as with the condition index (Uzarski & Grussing, Building Condition Assessment Metrics: Best Practices, 2008) is not applicable for reliability because it fails to consider the absolute factors of criticality, as illustrated in the following example.

Given a system made up of two components, C1 and C2, with reliability indexes of 0.2 and 0.8 respectively, a criticality factor that represents the criticality of the component in terms of system operation on a scale from 0 to 1 is assigned for each component. This thesis uses this criticality factor, the Component Importance Index, as a proxy indicator of the component failure consequence on system performance. As a result of this assumption, for example, a component importance index of 0.75 indicates a 75% chance of system interruption if that component fails. Given component C1 has an importance of 0.75, and component C2 has an importance factor of 0.25, the aggregated reliability of the system comprised of those two components, weighted based on the respective importance factors, is (0.75*0.2 + 0.25*0.8) / (0.75 + 0.25) = 0.35. This aggregate result seems reasonable, since the higher criticality component pulls the aggregate system reliability closer to its value.

However, the component importance factors need not sum to one. For example, both component C1 and C2 could have importance factors of 0.1 indicating that neither component, if failed, has a high probability of interrupting system function or performance. In this situation, using the same criticality weighted average above, the system reliability index would fall midway between the two components' RI values, since they have the same relative weighting, resulting in a system RI of 0.5. But if both components' importance factors were alternatively 0.9, indicating a high probability of system interruption if either of the components failed, the criticality weighted average approach would still yield in a system reliability index of 0.5. This seems counterintuitive when considering the reliability of a system, since the second scenario represents a situation with much higher risk than the first. As a result of these issues, an aggregation approach based on Bayesian networks is presented below.

6.2.5.2 System Reliability using Bayesian Networks

A Bayesian network is a probabilistic graphical model that represents a set of random variables and their conditional dependencies and can be used for system failure diagnosis (Fenton & Neil, 2012). In the application to building systems, if one assumes a system is comprised of n building components, where component C_i has a reliability index RI_i and a component importance factor CII_i, the system level reliability can be calculated as follows in Equation 40:

$$RI_s = 1 - \sum P(C_i \text{ caused system failure} \mid C_{i-1} \text{ did not cause system failure}) \tag{40}$$

Figure 28 illustrates the Bayesian approach to modeling this problem. The top tree represents the probability of system failure caused by component C1. The second tree represents the probability of system failure caused by C2, given C1 did not causes system failure. The third tree represents the probability of system failure caused by component Cn, given all previous components did not cause system failure. Each model tree is joined to the subsequent one by the dotted reference lines, which transfers the conditional probability of failure to the nodes above, forming a network of components. The result is a calculation of system failure if any of the components fail. The complement of this system failure probability is the reliability index for the system, which is based on the reliability index and criticality factors for each of the components that are part of it.

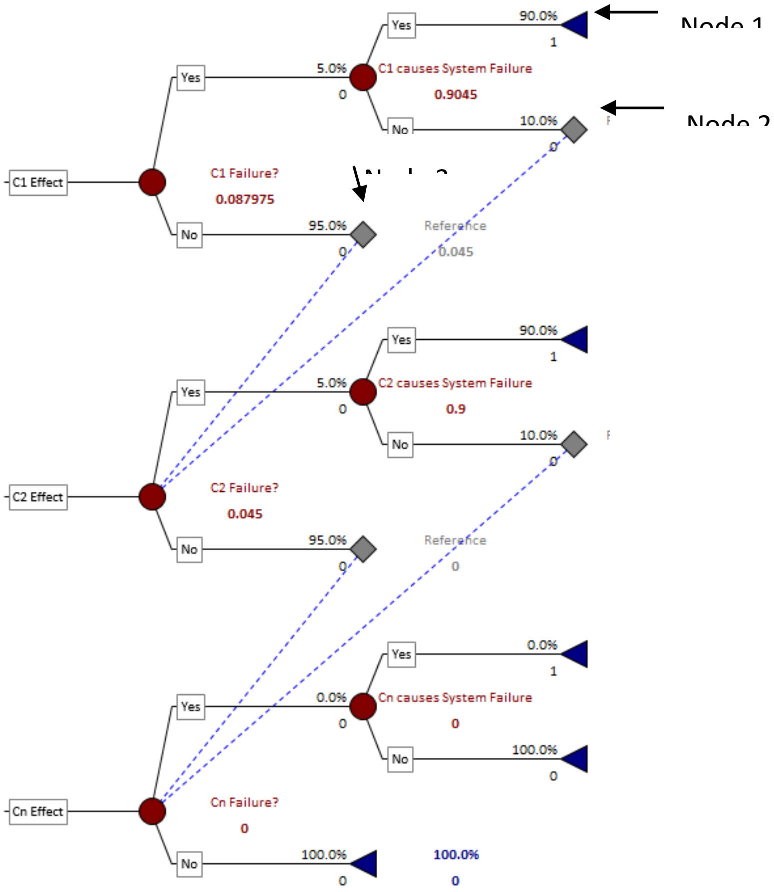


Figure 28. Generalized Bayesian Network for aggregating Component Reliability Index to System Level

The same examples provided above are modeled, but now using a Bayesian network, represented by the logic tree in Figure 29 below. For C1 and C2 reliability indexes of 0.2 and 0.8 respectively, and assuming importance factors of 0.1 for both, the system reliability index using this approach is 0.9016, indicating high system reliability. Assuming component importance factors at a 0.9 criticality level for both, the system reliability index drops to 0.2296. This lower system level reliability is a reflection of the higher impact that a component failure would cause. In these situations, the component reliability should be maintained at a higher level through repair or replacement activities to ensure an adequate system reliability. For example, if a 0.9 system reliability index was established as a minimum threshold, then the reliability index for both components in the second scenario would need to be maintained at an individual reliability index of 0.95 to meet that goal. From this example scenario, it is clear that this approach can be used to allocate work activity resources considering system level risk and reliability.

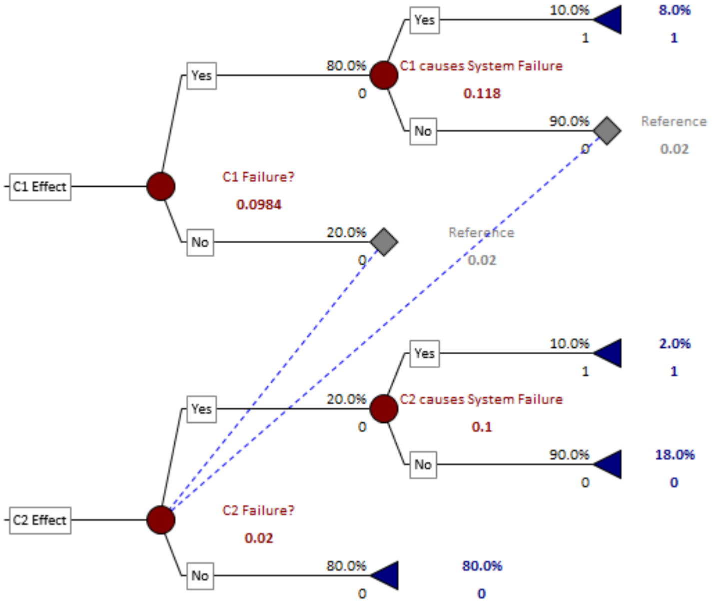


Figure 29. Example Bayesian Network

6.2.5.3 Component Interactions

In addition to a component's importance respective to the building system it is part of, a component may also directly impact the operation, function, or performance of other components. For example, interior lighting fixtures require electrical power, so if the electrical distribution suffers performance loss due to a faulty panel or transformer, that will affect the effective reliability of the lights. One can model these component interactions similar to how the system reliability was modeled above. A decision tree modeling this component interaction for the lighting component example is shown in Figure 30 below.

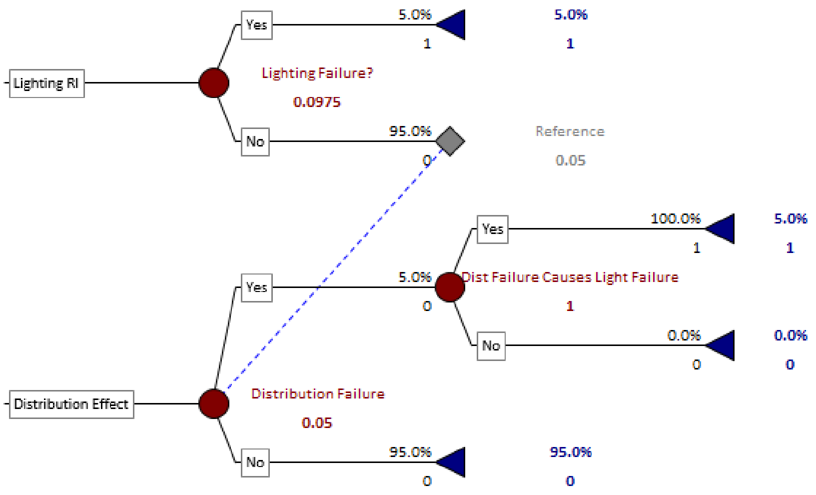


Figure 30. Example Bayesian Network Modeling Component Dependency Interactions

In general, if component Ca is dependent on components C_x, C_y, and C_z to function, the Adjusted reliability index, RIA, of component Ca is given in Equation 41 by:

$$RIA_a = 1- (((((1-RI_a) \times RIA_x) + (1-RIA_x)) \times RIA_y + (1-RIA_y)) \times RIA_z = (1-RIA_z)) \qquad (41)$$

This feature allows one to adjust the observed reliability of a component based on its condition information to account for the associated reliability of other components that it depends on for its operation. This adjusted effective reliability is then used to aggregate the reliability index to a system and building level and results in a more accurate picture of performance, since component dependencies are accounted for.

6.2.5.4 Mathematical Framework

Creating decision trees is beneficial for developing the framework for this approach, but using these trees to implement the above approach for a larger scale model becomes cumbersome. As a result, a mathematical table is created that replicates the calculations in a more compact form for multiple systems, components, and interactions. Table 63 illustrates this example mathematical framework

Table 63. Tabular framework for system and building reliability index calculation

ID	Level	Critical	RI	RI Adj (RIA)	P Node 1 (PN1)	P Node 2 (PN2)	P Node 3 (PN3)	P Total (P)
B1	Bldg			$1\text{-}P_1$				
S1	Sys	SII_1		$1\text{-}P_{11}$	$(1\text{-}RIA_1) \times SII_1$	$(1\text{-}RIA_1) \times (1\text{-}SII_1)$	RIA_1	$PN1_1+(PN2_1+PN3_1)xP_{i+1}$
C11	Comp	CII_{11}	RI_{11}	$1\text{-}(1\text{-}RI_{11}) \times DE$	$(1\text{-}RIA_{11}) \times CII_{11}$	$(1\text{-}RIA_{11}) \times (1\text{-}CII_{11})$	RIA_{11}	$PN1_{11}+(PN2_{11}+PN3_{11})xP_{1i+1}$
C12	Comp	CII_{12}	RI_{12}	$1\text{-}(1\text{-}RI_{12}) \times DE$	$(1\text{-}RIA_{12}) \times CII_{12}$	$(1\text{-}RIA_{12}) \times (1\text{-}CII_{12})$	RIA_{12}	$PN1_{12}+(PN2_{12}+PN3_{12})xP_{1i+1}$
…	Comp	$CII_{\dots}$	$RI_{\dots}$	$1\text{-}(1\text{-}RI_{\dots}) \times DE$	$(1\text{-}RIA_{\dots}) \times CII_{\dots}$	$(1\text{-}RIA_{\dots}) \times (1\text{-}CII_{\dots})$	$RIA_{\dots}$	$PN1_{\dots}+(PN2_{\dots}+PN3_{\dots})xP_{1i+1}$
C1n	Comp	CII_{1n}	RI_{1n}	$1\text{-}(1\text{-}RI_{1n}) \times DE$	$(1\text{-}RIA_{1n}) \times CII_{1n}$	$(1\text{-}RIA_{1n}) \times (1\text{-}CII_{1n})$	RIA_{1n}	$PN1_{1n}$
S2	Sys	SII_2		$1\text{-}P_{21}$	$(1\text{-}RIA_2) \times SII_2$	$(1\text{-}RIA_2) \times (1\text{-}SII_2)$	RIA_2	$PN1_2+(PN2_2+PN3_2)xP_{i+1}$
C21	Comp	CII_{21}	RI_{21}	$1\text{-}(1\text{-}RI_{21}) \times DE$	$(1\text{-}RIA_{21}) \times CII_{21}$	$(1\text{-}RIA_{21}) \times (1\text{-}CII_{21})$	RIA_{21}	$PN1_{21}+(PN2_{21}+PN3_{21})xP_{2i+1}$
C22	Comp	CII_{22}	RI_{22}	$1\text{-}(1\text{-}RI_{22}) \times DE$	$(1\text{-}RIA_{22}) \times CII_{22}$	$(1\text{-}RIA_{22}) \times (1\text{-}CII_{22})$	RIA_{22}	$PN1_{22}+(PN2_{22}+PN3_{22})xP_{2i+1}$
…	Comp	$CII_{\dots}$	$RI_{\dots}$	$1\text{-}(1\text{-}RI_{\dots}) \times DE$	$(1\text{-}RIA_{\dots}) \times CII_{\dots}$	$(1\text{-}RIA_{\dots}) \times (1\text{-}CII_{\dots})$	$RIA_{\dots}$	$PN1_{\dots}+(PN2_{\dots}+PN3_{\dots})xP_{2i+1}$
C2n	Comp	CII_{2n}	RI_{2n}	$1\text{-}(1\text{-}RI_{2n}) \times DE$	$(1\text{-}RIA_{2n}) \times CII_{2n}$	$(1\text{-}RIA_{2n}) \times (1\text{-}CII_{2n})$	RIA_{2n}	$PN1_{2n}$
Sn	Sys	SII_n		$1\text{-}P_{n1}$	$(1\text{-}RIA_n) \times SII_n$	$(1\text{-}RIA_n) \times (1\text{-}SII_n)$	RIA_n	$PN1_n$

In this framework, each component is grouped into a system. Each component has a criticality index and a reliability index that is based on most recent inspection data. Based on these values, the probabilities for Nodes 1-3 in the Bayesian Network tree shown previously in Figure 28 can be calculated for each component. The total probability of component i causing a system failure, given component i-1 did not cause failure, is calculated in the last column, which is aggregated up from the last component in each system to the first component in each system, which is then used to calculate the system reliability. Once all the system reliability indexes have been calculated, they can be aggregated to the building level using the same process. If a component's operation is dependent on another component's reliability, equation 33 can be used to adjust the RI of the component based on this information. While the component RI is the input into Table 63, the adjusted RI is used to calculate the total system and building level reliability indexes.

6.3 Example Application

To illustrate the framework discussed in this chapter for whole-building optimization, an example vehicle maintenance facility is modeled. A simple schematic of this facility is shown in Figure 31, and Table 64 shows the objects used for modeling this facility. This model consists of a single building level object, several component level objects, and group objects made up of components that represent the systems of the building. The objective of this analysis is to determine the optimal mix of work activities against the building over a 10-year period by minimizing life costs while ensuring the facility meets or exceeds annual reliability limits and long-term condition targets.

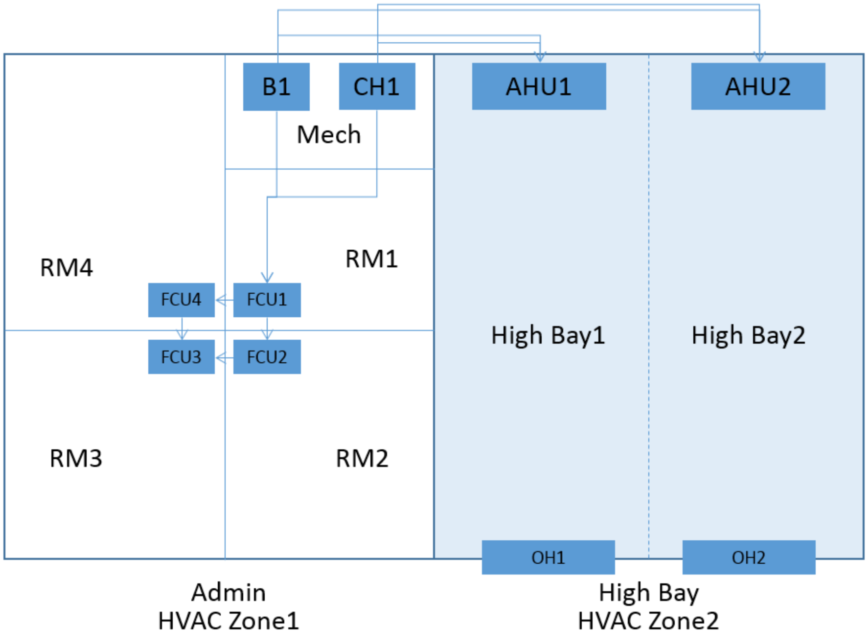


Figure 31. Example building schematic

Table 64. Example Application Building Objects

ObjectID	ObjectType	ObjectClass	ObjectSubClass	Name	Importance	Quantity	UM	Year
B1	Building	214-Tank and Automotive Maintenance Facilities	2141-Vehicle Maintenance Shop	Vehicle Maintenance		10,000	SF	1985
S1	System	B20 Exterior Envelope	N/A	B20 Exterior Envelope	0.26	5,000	SF	1985
S2	System	B30 Roofing	N/A	B30 Roofing	0.26	10,000	SF	1985
S3	System	D20 Plumbing	N/A	D20 Plumbing	0.4	10,000	SF	1985
S4	System	D30 HVAC	N/A	D30 HVAC	0.44	10,000	SF	1985
S5	System	D50 Electrical	N/A	D50 Electrical	0.56	10,000	SF	1985
C1	Component	B2010 EXTERIOR WALLS	B2010109 - Concrete Block	Wall	0.76	5,000	SF	1985
C2	Component	B2030 EXTERIOR DOORS	B2030410 - Overhead Doors	Door	0.61	2	EA	1985
C3	Component	B2020 EXTERIOR WINDOWS	B2020104 - Steel Windows	Window	0.37	4	EA	1985
C4	Component	B3010 ROOF COVERINGS	B3010120 - Single Ply Membrane	Roof Membrane	0.32	10,000	SF	1985
C5	Component	D2020 DOMESTIC WATER DISTRIBUTION	D2020250 - Water Heaters, Commercial, Gas	Water Heater	0.07	1	EA	1985
C6	Component	D2020 DOMESTIC WATER DISTRIBUTION	D2020905 - Piping/Fittings	Water Distribution	0.55	500	LF	1985
C7	Component	D2010 PLUMBING FIXTURES	D2010310 - Lavatory	Plumbing Fixtures	0.52	5	EA	1985
C8	Component	D3020 HEAT GENERATING SYSTEMS	D3020130 - Boiler, Cast Iron, Hot Water, Gas	Boiler	0.54	1	EA	1985
C9	Component	D3030 COOLING GENERATING SYSTEMS	D3030130 - Chiller, Reciprocating, Water Cooled	Chiller	0.58	1	EA	1985
C10	Component	D3040 DISTRIBUTION SYSTEMS	D3040903 - Fan Coil A/C, DX	Fan Coil Unit	0.5	4	EA	1985
C11	Component	D3040 DISTRIBUTION SYSTEMS	D3040110 - Air Handling Unit, Central Station	Air Handling Unit	0.5	1	EA	1985
C12	Component	D5010 ELECTRICAL SERVICE & DISTRIBUTION	D5010240 - Switchgear	Switchgear	0.84	1	EA	1985
C13	Component	D5020 LIGHTING & BRANCH WIRING	D5020252 - Interior Lighting, High Intensity	Lighting Fixtures	0.68	100	EA	1985

The table above lists characteristic attributes associated with basic properties of the facility objects. These include the object name and classification, quantity, unit of measure (UM), year installed or constructed, and Importance Index. In addition, a number of extensible attributes can be defined based on each object class and subclass. As an illustration, Table 65 shows a number of extensible attributes for the boiler and chiller components. These component specific attributes are used in the model to estimate certain performance characteristics such as energy consumption. They are also used to capture the effects of upgrades that may occur.

Table 65. Boiler and Chiller Component Extensible Attributes

Boiler Extensible Attributes	Chiller Extensible Attributes
Boiler Type = Gas	Chiller Type = Centrifugal
Nominal Efficiency = 70%	Chiller COP = 4.0
Capacity = 1000 MBH	Capacity = 100 tons
Upgrade Efficiency = 85%	Upgrade Efficiency = 6.0

The arrangement of the components into systems is illustrated in Figure 32. This figure annotates the reliability index for each component, calculated using probabilities from the Markov model as discussed in Chapter 3, and component importance index for each component and system. Refer to Appendix L for a table of importance Index values. The arrows in this figure indicate the operational dependencies among components. For example, if the electrical distribution suffers a performance loss or failure, it directly affects the operation of the water heater, boiler, chiller, fan coil units, air handling unit, and lighting fixtures, since those all require power.

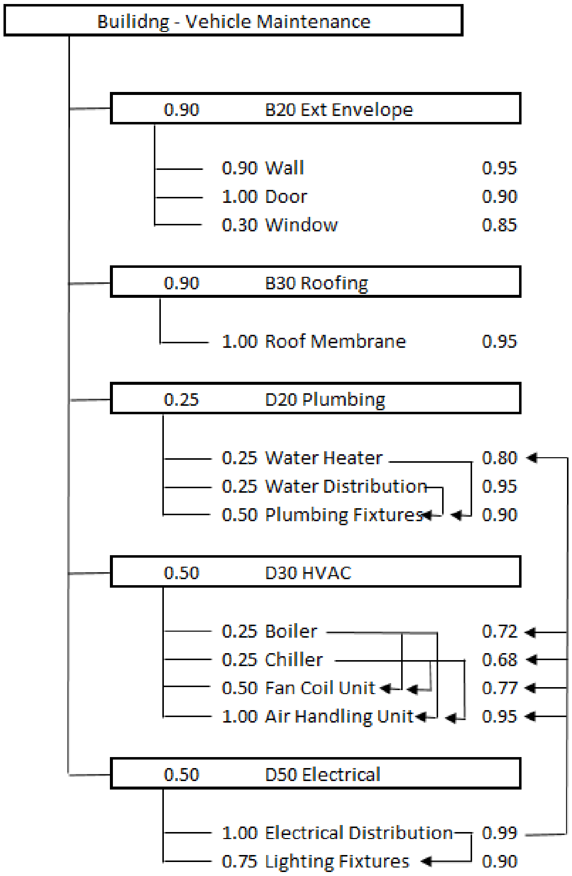


Figure 32. Component Interaction Diagram

The approach presented in section 6.2.5 is used to model the building and system reliability indexes using Bayesian networks (0.263 and 0.909 respectively in Table 66). The resulting initial Reliability Index for the overall building in this example is 0.457, while the reliability indexes of the Exterior Envelope, Roofing, Plumbing, HVAC, and Electrical systems are 0.821, 0.95, 0.785, 0.263, and 0.909 respectively.

Table 66. Example Building and System Reliability Index Aggregation Calculation

ID	Description	CII	RI	RI Adj.	P Node 1	P Node 2	P Node 3	P Total
B1	Vehicle Maintenance			0.457				
S1	B20 Exterior Envelope	0.90		0.821	0.161	0.018	0.821	0.543
C1	Wall	0.90	0.95	0.950	0.045	0.005	0.950	0.179
C2	Door	1.00	0.90	0.900	0.100	0.000	0.900	0.141
C3	Window	0.30	0.85	0.850	0.045	0.105	0.850	0.045
S2	B30 Roofing	0.90		0.950	0.045	0.005	0.950	0.455
C1	Roof Membrane	1.00	0.95	0.950	0.050	0.000	0.950	0.050
S3	D20 Plumbing	0.25		0.785	0.054	0.161	0.785	0.430
C1	Water Heater	0.25	0.80	0.792	0.052	0.156	0.792	0.215
C2	Water Distribution	0.25	0.95	0.950	0.013	0.038	0.950	0.172
C3	Plumbing Fixtures	0.50	0.90	0.677	0.161	0.161	0.677	0.161
S4	D30 HVAC	0.50		0.263	0.369	0.369	0.263	0.397
C1	Boiler	0.25	0.72	0.713	0.072	0.215	0.713	0.737
C2	Chiller	0.25	0.68	0.673	0.082	0.245	0.673	0.717
C3	Fan Coil Unit	0.50	0.77	0.366	0.317	0.317	0.366	0.692
C4	Air Handling Unit	1.00	0.95	0.451	0.549	0.000	0.451	0.549
S5	D50 Electrical	0.50		0.909	0.045	0.045	0.909	0.045
C1	Electrical Distribution	1.00	0.99	0.990	0.010	0.000	0.990	0.091
C2	Lighting Fixtures	0.75	0.90	0.891	0.082	0.027	0.891	0.082

6.3.1 Decision Variables

As discussed above, the goal of the whole building optimization model is to select the appropriate set of work activities against the components, systems, and overall building which meets all performance objectives and minimizes the life cycle costs. As a result, each work activity type is coded using the same integer decision variables previously presented in Chapter 5, but which can now be applied to objects at the component, system, or building level, as shown in Table 67.

Table 67. Integer Decision Variables for Whole Building Optimization

Code	Activity Type	Applies to
0	Do Nothing	Components, System, Building
1	Repair	Components
2	Replace	Components, System, Building
3	Upgrade	Components

All four activity choices listed above are considered viable options at the component object level, while the do nothing and replacement activities are considered applicable at the system and building object level. This allows for system or whole building replacement considerations, versus replacement of all child objects. The repair activity is not considered for the building or system level because repair at this level is handled by repair or replacement of select child objects. The upgrade activity allows for replacement of components with a different set of design attributes than the original component, but this activity is assumed not applicable at the system or building level.

In Chapter 5, the work optimization was considered for a single component; therefore the decision space was a single vector with elements representing each year of the analysis. For the whole building optimization, each set of applicable work activity decision variables is considered for each asset object (component, system, and building) for each year of the analysis period, in this example chosen as 10 years. As a result, the decision space can be represented as a matrix, as shown below in Table 68. This matrix represents a single solution, with the numbers representing the type of activity selected to be performed against each component in each year of the analysis. For example, row C2, column Y1 indicates an upgrade (referring to Table 67) to component C2 in the first year of the work analysis.

Table 68. Example Application Decision Space

Object	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
B1	0	0	0	0	0	0	0	0	0	0
S1	0	0	0	0	0	0	0	0	0	0
S2	0	0	0	0	0	0	0	0	0	0
S3	0	0	0	0	0	0	0	0	0	0
S4	0	0	0	0	0	0	0	0	0	0
S5	2	0	0	0	0	0	0	0	0	0
C1	0	0	0	0	0	0	0	2	0	0
C2	3	0	0	0	0	0	0	0	0	0
C3	2	0	0	0	0	0	0	0	0	0
C4	3	0	0	0	0	0	0	0	0	0
C5	0	0	0	0	0	0	0	3	0	0
C6	0	0	0	0	0	0	0	0	0	0
C7	2	0	0	0	0	0	0	0	0	0
C8	3	0	0	0	0	0	0	0	0	0
C9	2	0	0	0	0	0	0	0	0	0
C10	1	0	0	0	0	0	0	0	2	0
C11	1	0	0	0	0	0	0	0	0	2
C12	2	0	0	0	0	0	0	0	0	1
C13	2	0	0	0	0	0	0	0	0	0

6.3.2 Life Cycle Cost Model and Fitness Function

Similar to the case study in Chapter 5, the objective of the optimization process for this example is the minimization of the total estimated life cycle costs of the facility. Table 69 below is used to calculate this objective function, which results in the sum of all pertinent activity costs (in present value dollars) for the objects of the facility over each year of the analysis. For this example, the same facility cost activities discussed in section 5.3.1 for the single component optimization approach are applicable here. The sum of these costs for each year determines the total estimated life cycle cost. This total over the course of all analysis years is used in the optimization objective to minimize total life cycle cost.

Table 69. Example Application Life cycle Cost Estimates

	Activity				
Year	**Operate**	**Repair**	**Replace**	**Upgrade**	**Total Cost**
Y1	$ 12,596	$ 5,348	$ 420,514	$ 133,517	$ 571,975
Y2	$ 13,817	$ -	$ -	$ -	$ 13,817
Y3	$ 14,932	$ -	$ -	$ -	$ 14,932
Y4	$ 15,968	$ -	$ -	$ -	$ 15,968
Y5	$ 16,951	$ -	$ -	$ -	$ 16,951
Y6	$ 17,905	$ -	$ -	$ -	$ 17,905
Y7	$ 18,847	$ -	$ -	$ -	$ 18,847
Y8	$ 19,790	$ -	$ 65,849	$ 45,711	$ 131,350
Y9	$ 20,745	$ -	$ 40,854	$ -	$ 61,598
Y10	$ 21,718	$ 333	$ 33,418	$ -	$ 55,470
Totals	$ 173,269	$ 5,682	$ 560,635	$ 179,228	$ 918,813

6.3.3 Constraints

Since the objective is not just to minimize cost, but to do so while achieving an acceptable level of performance, constraints are defined to ensure the facility meets key performance indicator targets. While several of the performance indicators discussed above were considered, this analysis utilizes the condition and reliability metrics in defining constraints.

6.3.3.1 Condition Constraints

Condition constraints are defined to ensure each object meets minimum condition standards. For this example, a condition standard is applied at the component level to ensure that no component drops below a minimum condition index of 50, indicating technical component failure. In addition, a building condition index (BCI) standard is defined to establish a minimum aggregated BCI of 90 at the end of the analysis period. The first condition constraint guards against excessive component deterioration in any given year. The second condition constraint, which is applied only in the final year of the analysis, is employed to achieve a desirable overall facility condition target.

6.3.3.2 Reliability Constraints

The reliability constraint is defined by setting the overall building reliability index to a minimum of 0.65 for each year of the analysis period. This reliability level was selected to indicate a building of significant but not critical importance, which is based on the Mission Dependency Index scale shown in Figure 33 below, corresponding to an MDI range of Significant (60-75). While the Mission Dependency Index (discussed in Chapter 2) was not developed specifically as a gauge of required reliability, this research assumes that facility importance as measured by MDI is directly proportional to the building reliability threshold. Thus, MDI can serve as an indicator in establishing reliability index constraints at a facility level.

Figure 33. Mission Dependency Index Scale Definition

6.3.3.3 Compatibility constraints

The compatibility constraints do not relate to building performance, but instead ensure work activities are compatible among each other. For example, if a system level replacement is selected, the compatibility constraint ensures that the child components of this system all have work activities of replacement or higher selected. This is necessary since it its assumed replacement of the system results in replacement of all its components and associated performance improvements.

6.3.4 Optimization Model Setup

Similar to Chapter 5, the Microsoft Excel add-in called Evolver was again used as the optimization engine for the work selection process. The objective function in the model definition was minimization of the total life cycle costs across all components of the plan. This total lifecycle cost is the sum of the yearly net present value costs for operation, maintenance, repair, replacement, and upgrade activities performed. The constraints are applied to the yearly projected component CIs, the yearly projected facility RI, the final year facility BC, and the compatibility constraints. Finally, the decision variable cells are defined and set to accept an integer value of 0, 1, 2, or 3 corresponding to the work activities from Table 67.

6.3.5 Discussion of Results

Once the optimization model is defined, a number of interesting scenarios can be explored for this case study. As a base scenario, the following global variables are input (Table 70), the optimization is then run, and the recommended work activities for the optimized profile (as shown in Table 71) are returned.

Table 70. Whole Building Optimization Global Variable Settings

Global Variable	Value
Start Year	2015
Analysis Years	10
Discount Rate	5%
Inflation Rate	2%
Energy Escalation Rate	2%
Construction Escalation Rate	1%
Electricity Rate ($/kWh)	$0.30
Energy Cost ($/kBTU)	$0.09
HDD	6000
CDD	4000
Solar Load	2000

For this scenario, a number of components are repaired, replaced, or upgraded in year 1 of the analysis to ensure it captures operational savings from energy upgrades early on and meets performance standards over the next several years.

Table 71. Recommended Work Activities for Optimized Profile

Year	Activity	ID	Item	Cost
2016	Repair	C10	Fan Coil Unit	$ 4,257
2016	Repair	C11	Air Handling Unit	$ 1,091
2016	Replace	S5	D50 Electrical	$267,066
2016	Replace	C3	Window	$ 7,432
2016	Replace	C7	Plumbing Fixtures	$ 3,719
2016	Replace	C9	Chiller	$ 142,296
2016	Upgrade	C2	Door	$ 9,422
2016	Upgrade	C4	Roof Membrane	$ 82,026
2016	Upgrade	C8	Boiler	$ 42,069
2023	Replace	C1	Wall	$ 65,849
2023	Upgrade	C5	Water Heater	$ 45,711
2024	Replace	C10	Fan Coil Unit	$ 40,854
2025	Repair	C12	Switchgear	$ 333
2025	Replace	C11	Air Handling Unit	$ 33,418

Referring to this recommended set of work items that is generated by the optimization model, the total activity costs for each year of the analysis is calculated, as shown in Table 72.

Table 72. Life cycle Costs and Building Value for Optimized Profile

Year	Operate	Repair	Replace	Upgrade	Total Cost
Y1	$ 12,596	$ 5,348	$ 420,514	$133,517	$571,975
Y2	$ 13,817	$-	$ -	$-	$ 13,817
Y3	$ 14,932	$-	$-	$-	$ 14,932
Y4	$ 15,968	$-	$-	$-	$ 15,968
Y5	$ 16,951	$-	$-	$-	$ 16,951
Y6	$ 17,905	$-	$-	$-	$ 17,905
Y7	$ 18,847	$-	$-	$-	$ 18,847
Y8	$ 19,790	$-	$ 65,849	$ 45,711	$131,350
Y9	$ 20,745	$-	$ 40,854	$-	$ 61,598
Y10	$ 21,718	$ 333	$ 33,418	$-	$ 55,470
Totals	$173,269	$ 5,682	$560,635	$179,228	$918,813

If a lower energy rate is assumed ($0.15/kWh versus $0.30/kWh) and the optimization performed under the new set of parameters, a different recommended work plan results. Table 73 shows that under this scenario, many of the component upgrades recommended in the first scenario are now simply replacements as the lower energy savings does not warrant a higher initial replacement cost premium.

Table 73. Recommended Work Activities for Lower Energy Rate

Year	Activity	ID	Item	Cost
2016	Repair	C10	Fan Coil Unit	$ 4,257
2016	Repair	C11	Air Handling Unit	$ 1,091
2016	Replace	S5	D50 Electrical	$ 267,066
2016	Replace	C3	Window	$ 7,432
2016	Replace	C7	Plumbing Fixtures	$ 3,719
2016	Replace	C9	Chiller	$ 142,296
2016	Upgrade	C4	Roof Membrane	$ 82,026
2023	Replace	C1	Wall	$ 65,849
2024	Replace	C10	Fan Coil Unit	$ 40,854
2025	Repair	C12	Switchgear	$ 333
2025	Replace	C11	Air Handling Unit	$ 33,418

Another interesting factor to explore is the adjustment of the component important index value. If for example, high importance index associated with the switchgear component is lowered from 0.84 to 0.5, the subsequent repair activity for this component in year 10 is no longer recommended because its failure risk is lowered, as shown in Table 74. This allows the work cost from that repair activity to be re-allocated to a more critical component or facility

Table 74. Recommended Work Activities for Reduced Switchgear Importance Index

Year	Activity	ID	Item	Cost
2016	Repair	C10	Fan Coil Unit	$ 4,257
2016	Repair	C11	Air Handling Unit	$ 1,091
2016	Replace	S5	D50 Electrical	$ 267,066
2016	Replace	C2	Door	$ 8,565
2016	Replace	C3	Window	$ 7,432
2016	Replace	C7	Plumbing Fixtures	$ 3,719
2016	Replace	C9	Chiller	$ 142,296
2016	Upgrade	C4	Roof Membrane	$ 82,026
2016	Upgrade	C8	Boiler	$ 42,069
2023	Replace	C1	Wall	$ 65,849
2023	Replace	C5	Water Heater	$ 41,556
2024	Replace	C10	Fan Coil Unit	$ 40,854
2025	Replace	C11	Air Handling Unit	$ 33,418

Finally, if the facility wide minimum reliability index level is changed from 0.65 to 0.85, indicating a more critical facility, then the recommended course of action is an entire facility replacement in the first year, in order to increase the condition and reliability of all components of the building in order to meet the very high reliability demands due to its high mission criticality.

As a result, using the reliability index at a component level, defined from the developments of the Markov condition model presented in Chapter 3, along with the aggregated system reliability index developed in this chapter, one can generate work activity recommendations that consider the whole facility when allocating resources based on risk.

6.4 Summary of Whole Building Work Activity Optimization

While the reliability index at a component level is important, facility management requires an understanding of risk and reliability at a system and building level as well. This chapter presents an approach for logically aggregating component reliability to determine the reliability of a system made up of those components. As a result, given component reliability indexes, which can be calculated using a probabilistic model of component condition deterioration, system reliability indexes and building interactive effects can be modeled and computed using a Bayesian network. This approach provides a much more realistic result than traditional weighted average methods by accounting for both relative and absolute component criticality.

It should be noted that the system level reliability index present here is not intended to calculate the probability that a system will actually fail. This is difficult to predict, and system failure in and of itself is sometimes ill defined. For example, an HVAC system may temporarily cease operation due to a power outage, but does not necessarily represent failure of the system or components of the system. This work is primarily focused on identifying system and component level work activities that can more effectively improve system and building level performance. Future research should further explore and attempt to quantify the true impact that component performance degradation has on system and building level performance, as a means of continuously improving on failure consequence estimation.

The case study presented shows a practical application of the whole building optimization approach for a vehicle maintenance facility, and illustrates how component reliability, criticality, and even energy efficiency can help to allocate resources. In these cases, the problem defined a specific single objective, to minimize total life cycle cost, and a set of minimum performance constraints on condition and reliability. This single-objective optimization problem can help in establishing and justifying budget levels for facility portfolios. From a practical standpoint however, facility managers typically find themselves working with constrained budgets, and the task then becomes to maximize performance given these budgetary constraints.

The same framework presented above can address this problem as well, but may require a multi-criteria optimization approach if overall facility performance is defined by several performance indicators, including condition, reliability, efficiency, and even functionality. Creating a weighting process to consider multiple performance criteria was beyond the scope of this work and reserved for future research. Doing so would also support a multi-modal optimization process where multiple solutions residing on the pareto-optimal front are identified in the trade-off between cost and performance. This would allow decision makers to develop more informed and meaningful budgets and facility mangers to then execute a work plan strategy to maximize performance given the selected budget level.

CHAPTER 7 – CONTRIBUTIONS AND FUTURE RESEARCH

7.1 Conclusions

The U.S. building stock is large, diverse, and of critical importance to the economic and social wellbeing of the country. As a result, a proactive approach to facility asset management is required to ensure these buildings support the purposes, functions, and missions for which they were built. For federal facilities, including the US Department of Defense in particular, the goal is to deliver an acceptable level of performance at the lowest life cycle cost. Processes currently exist to manage these buildings based on a condition-driven rules-based approach. These processes consider the notional importance of risk and reliability, but do not have the means to explicitly measure risk and uncertainty for use in sustainment, restoration, and modernization decision making because the current state-of-the-art analysis tools are based on traditional deterministic methods for prediction of condition and performance. The goal above underlies the importance of a probabilistic approach that provides a true risk-based and data-driven process for facility asset management. This research presents a framework that explicitly measures risk and uncertainty, and uses it support better decisions for facility investment and resource allocation. Specifically, the proposed framework provides a model for optimizing the selection and application of building work activities ranging from inspection to repair to replacement and recapitalization.

Realizing the importance of physical condition in the determination of a building's performance, a major objective of this research was to improve the overall accuracy of building component condition prediction models by using a probabilistic approach. To do this, a discrete Markov chain model was proposed and developed. Markov chains have been used to develop condition prediction models for many types of civil infrastructure systems with much success. However, the complexity of buildings brings some challenges in the traditional application of Markov chain models to the facility domain. This research has addressed those challenges to ensure the fundamental assumptions in using this methodology are valid. The result of this work is a robust process for developing Markov transition probabilities to model the condition degradation process using existing condition assessment data that has been acquired and continues to be collected for a large portfolio of facilities. It solves the problems with data quality issues, effects from major repair interventions, and variable inspection observation times.

This process has resulted in transition matrices developed for a wide range of building component classifications, broken down by component and material subtypes, and even regional climate zones. These models have been observed to predict aggregate results using an independent test dataset with a high degree of confidence, and localized individual point predictions with remarkably good accuracy considering the stochastic nature of component condition deterioration. This verifies the applicability of the discrete Markov Chain approach, and validates its improvement as a predictor over the current deterministic approaches.

Beyond its improved capability as a predictor of condition, the model also provides a direct means of measuring uncertainty, reliability, and risk of component failure. This is because the discrete Markov chain model is a probabilistic model and results in a probability distribution across all condition states, not just a single estimate of condition like the deterministic approach. This distribution allows one to measure the inherent uncertainty associated with a condition state point estimate from the Markov model. It also supports the measure of a component reliability index which is the probability of being in a set of pre-defined acceptable condition states, as well as its complement, a failure index which is the probability of being in a failed condition state. Finally, it supports an unbiased process of determining expected service life for components by using the Markov chain model to compute the average number of time cycles to reach the failure state, assuming no intervening repairs occur. More importantly, the result of this model formally links the concepts of condition, reliability, and service life and provides a way of estimating measures of each at a point in time.

The probabilistic Markov chain prediction model provides a foundation towards a risk-based framework for facility management decision making. In the past, condition measurements have been used as a proxy for reliability and failure probability, but the research provided makes clear condition and reliability are linked but separate phenomena. Having a more direct measure of failure probability through the condition state distribution allows for the use of fault trees and decision trees. For example, the concept of Value of Information was used in Chapter 4 to explicitly quantify the benefit of a component inspection for the purposes of optimized building inspection scheduling. This Value of Inspection Information model combines the probability distribution from the Markov prediction model with the decision tree logic from a value of information approach to determine the optimum interval from the last to the next inspection, using the last inspection results and the cost of component repair, replacement, and potential failure. This approach provides a means of allocating and balancing inspection resources based on risk, as well as the opportunity that more accurate information can provide in the decision making process.

In addition to component inspection scheduling, the use of the Markov prediction model was also applied to the work activity selection process. Thus, the objective is to select the best activity to perform against a building component at a point in time that minimizes life cycle cost yet meets performance constraints. Traditionally these constraints have been condition based, but the proposed model also allows for risk-based reliability performance measures as well. Including risk more explicitly in the decision framework has the potential to change the selection optimization process. This has been demonstrated with case study examples for the single component optimization framework.

Aggregating condition data from a component up to a system and building level can provide a challenge when attempting to consider the interactions that take place. Traditionally, this aggregation has used a weighted average approach, which does not account for interactions. But the reliability index, and its direct association to failure provides a more direct way of determining system and building level performance from component level information. Using component and system criticality factors previously derived, the research shows how to aggregate reliability through a decision tree approach with conditional probabilities. This approach was applied to an example case study to illustrate the use of the reliability index in a whole building optimization framework.

In conclusion, the overall framework provides a logical approach that utilizes historic data to develop a more realistic model for building component condition and reliability. The approach analyzes component re-inspection information for a large building assessment dataset (multiple inspections over time for a single component) to determine how past observed conditions correlate to future observed conditions to predict future reliability and service life. This model provides a stronger correlation to future condition and reliability estimates compared to an age-based deterministic model and helps to counteract the situations where the recorded age of a component is not representative or design life is unknown. This allows a facility manager to proactively manage facility requirements using real-time risk-based metrics aligned with a data-driven probabilistic process.

7.2 Research Contributions

This research provides several contributions to the body of knowledge for facility asset management and construction management. First, it builds on the past work done in condition assessment, prediction and discrete Markov models to develop a probabilistic approach to building component condition state prediction, and subsequently proposes a novel process for developing discrete Markov Chain transition matrices for these building components using existing building assessment information. Most importantly, the methodology allows for variable observation intervals to estimate the transition probabilities and test the discrete Markov chain model. This allows for utilizing a wider range of inspection observations and aligns better with reality where inspections are not always performed on a fixed calendar basis.

Second, it uses the development of the Markov chain process and transition matrices to better predict condition state and condition index over time. It also uses a formal mathematical definition of failure to develop a reliability index for a building component using the same process. This building component reliability index is a new measure that supports a more risk based approach to facility management. The model thus formally links condition and reliability and supports the calculation of component service life that is purely deterioration based and independent of obsolescence and other drivers of performance.

Third, the research develops a risk-based framework that applies the Markov model for multi-year building component work activity selection and optimization of total cost of ownership. This framework uses both the condition index and reliability index as performance constraints in the optimization model. The framework is developed and illustrated for both a single component decision process, and whole building optimization. For the whole building optimization, the reliability index is aggregated using a non-linear conditional probability framework to determine the reliability at a system and building level, where performance constraints can also be applied.

Finally, a process for risk-based component inspection scheduling is developed, using the Markov prediction model integrated with a value of information decision tree logic model. The result is an ability to calculate the value of an inspection at a certain point in time, given the cost of different work activity events and the results of past inspections. This provides a more effective way to allocate inspection resources and attention to the most critical components as a way of maximizing the return on inspection costs.

The results of this work are already beginning to be implemented in Sustainment Management Systems facility asset management software used to support facility investment decisions for the Department of Defense and other federal agencies. While there are still many aspects of this overall methodology that would benefit from further study, as presented below, the improvement of this framework over other existing methods will greatly help to support facility management practitioners.

7.3 Future Research Work

7.3.1 Further Transition Matrix Partitioning and Development

This analysis provides a logical approach for the mining of historic data to develop a component age versus reliability relationship. As more data become available, the components can be partitioned into additional groups by component subtypes, material types, building ages, and other potential factors uniquely affecting degradation. Doing so will begin to isolate the specific characteristics that uniquely affect deterioration, allowing for even better prediction of condition over time for an individual component.

In addition, further integration with databases and systems that track actual work execution, such as in a computerized maintenance management system (CMMS), is needed to begin to build similar Markov transition matrices for component repair and even maintenance activities. This is accomplished by cross-referencing the current condition dataset with information about past executed work activities to determine and measure the effect of different maintenance, repair, and renovation applications. Several federal agencies currently maintain such CMMS databases, and steps are being taken to integrate with the vast condition assessment information utilized in this research. Having this additional capability would allow decision makers to more accurately predict the future condition state of a facility component as specific maintenance and repair activities are performed. It also provides a way of measuring and quantifying the direct effect of those activities, to determine which ones provide the most value in a budget constrained environment.

7.3.2 Further Development of Object Interactions on Performance

Both the inspection scheduling model and the single component replace in-kind model consider the criticality of discrete components in a building system, but it considers the performance of those discrete components independently. This simplification ignores the potential interaction effects between components. The whole building MR&R investment optimization approach presents a risk-based model for component dependencies, but there are many additional associations to be mapped and determined. Future research should explore these interactive effects formally to determine the total system performance, efficiency, reliability, and degradation profile as these effects accumulate.

7.3.3 Link Whole Building Optimization with Energy Modeling

The MR&R investment optimization model proposed in this research does consider life cycle cost savings from potential energy cost savings, but those savings have to be known, or calculable, prior to running the simulation. In the future, integration in whole building energy modeling software, such as EQuest or EnergyPlus, would allow these energy savings to be estimated for each set of decision variables for an optimization trial. This would eventually allow the facility manager to better incorporate energy upgrades into the decision framework and accurately calculate the savings of interactive effects.

7.3.4 Specific Consequences and Costs of Component Failure for Inspection Schedule Optimization

This research develops a risk-based framework for facility management which is primarily focused on the probability of component condition loss or failure. Risk, however, also includes the consequence of failure, which requires further research to better quantify. This consequence can be difficult to measure since it varies by a number of factors. One method used in the whole-building optimization approach presented in this research was to link criticality scores for different components to the cost of component replacement as a means of estimating cost of failure consequences. Other approaches may look at the value of services a facility supports and the likelihood of service interruption if failure occurs. While outside the scope of this research, condition loss and failure consequence is a critical aspect of a risk-based facility management process.

7.3.5 Measuring and Quantifying Inspection Accuracy

The Markov Chain model is a cumulative damage model that is based on the condition determined from the last inspection. However, an inspection will not always be 100% accurate, and there is some probability that the inspection result will not identify the actual condition of the asset. This is especially true for certain types of components where damage or deterioration may be difficult to observe if it happens internally and the inspector is forced to rely on other clues. As a result, inspection accuracy may vary depending on the component being inspected, the true condition of that component, the type or detail of the inspection being performed, and even the experience of the inspector. All these factors could be explored to develop a matrix that describes the probability of each true condition state, given the resulting condition state from an inspection. This analysis could then be used in the inspection scheduling framework presented in this research to determine the best type of inspection, as well as optimal frequency, for different component classes.

7.3.6 Additional Optimization Techniques

This research explored a number ways in which the Markov condition deterioration model could be used in conjunction with a non-linear evolutionary search process to optimize the selection of facility work activities in order to achieve lowest life cycle cost subject to minimum performance constraints. This optimization approach was shown to be applicable for both single component and whole-building work decisions. The proposed methodology and subsequent examples provide a framework that improves on existing rule-based work planning methods, yet there are a number of additional practical considerations that could be explored as part of a long-range work plan.

First, while this research focused on the use of a Microsoft Excel add-in called Evolver to implement a genetic algorithm optimization with discrete integer decision variables, future research should explore other optimization methods, such as hill climbing algorithms, particle swarm optimization, artificial bee colony optimization, and others. The goal is to determine which approaches work best as the problem size is scaled up, especially for complex problems having hundreds of buildings and thousands of interconnected components that require a robust optimization procedure.

Also, while this research explored a single-objective optimization (to minimize total life cycle cost), multi-objective optimization problems should also be explored. For example, future studies can expand beyond the condition and reliability performance metrics used in this work, to include other functionality and obsolescence related issues. The optimization could further consider the problem of optimizing performance, subject to annual or multi-year budgetary constraints, provided individual performance metrics can be aggregated to a representative fitness function. These budgetary constraints may have complex rules for multiple funding sources that are likely to exist in a real work planning environment, as well as guidelines for the types of activities each source can fund. Finally, future research should explore the simultaneous optimization of cost and performance using multiple objective genetic algorithms to search for pareto-optimality in multi-modal optimization problems.

7.3.7 Integration with Facility Management Tools and Practices

While this research has many important findings to expand the knowledge base of facility asset management, more work is needed to bring these concepts fully from theory into practice. These methods and processes need to be incorporated into the software and analysis tools already in use in managing building assets. Doing so requires further development and integration to make the computational processes fast and efficient, the data inputs compatible with existing facility information, and the outputs easy to visualize, interpret, and understand. The end result of this effort is an expanded toolset that facility practitioners can use to manage their critical assets in a more risk-informed environment, and ultimately improve facility investment decisions.

REFERENCES

Abu Dabous, S., & Alkass, S. (2008). Decision support method for multi-criteria selection of bridge rehabilitiation strategy. *Construction Management and Economics, 26*(8), 883-893.

Agrawal, A. K., Kawaguchi, A., & Chen, Z. (2010). Deterioration Rates of Typical Bridge Elements in New York. *Journal of Bridge Engineering, 15*(4), 419-429.

Aktan, A., & Farhey, D. N. (1997). Structural identification for condition assessment: Experimental arts. *Journal of Structural Engineering, 123*(12), 1674.

Al-Mashta, S., & Alkass, S. (2010). Integrated Cost Budgeting and Estimating Model for Building Projects. *AACE International Transactions*, BIM.02.1-BIM.02.16.

American Concrete Institute. (2008). *Guide for Conducting a Visual Inspection of Concrete in Service.* Farmington, MI: American Concrete Institute.

American Society of Civil Engineers. (1999). *Guideline for Structural Condition Assessment of Existing Buildings.* Reston, VA: American Society of Civil Engineers.

American Society of Civil Engineers. (2013, Sept 9). *2013 Report Card for America's Infrastructure*. Retrieved from infrastructurereportcard.org: http://www.infrastructurereportcard.org/

Antelman, A., Dempsey, J., & Brodt, B. (2008). Mission Dependency Index - A Metric for Determining Infrastructure Criticality. *ASCE Special Report Infrastructure Reporting and Asset Management* (pp. 141-146). Reston, VA: American Society of Civil Engineers.

Aschauer, D. A. (1990). Why is infrastructure important? *Is there a shortfall in Public Capital Investment? Proceedings of a Conference.*

Baik, H. S., Jeong, H. S., & Abraham, D. M. (2006). Estimating Transition Probabilities in Markov chain-based deterioration models for Management of Wastewater Systems. *Journal of Water Resources Planning and Management, 132*(1), 15-24.

Bailey, D. M., Brotherson, D. E., Tobiasson, W., & Knehans, A. (1989). *Roofer: an engineered management system for bituminous built-up roofs.* Champaign, IL: U.S. Army Construction Engineering Research Laboratory.

Bailey, D. M., Brotherson, D. E., Tobiasson, W., Foltz, S. D., & Knehans, A. (1993). *ROOFER: Membrane and Flashing Condition Indexes for Single-Ply Membrane Roofs - Inspectino and Distress Manual.* Champaign, IL: U.S. Army Construction Engineering Research Laboratory.

Bandurowski, T. (2010). Silver Lining in Campus Building Renovations. *Engineered Systems, 27*(6), 44-48.

Bogdanoff, J. L. (1978). A New Cumulative Damage Model: Part 1. *Journal of Applied Mechanics, 45*(2), 246-250.

Brand, S. (1995). *How Buildings Learn: What happens when they're built.* Harmonsworth, Middlesex, England: Penguin Books Ltd.

Charette, R. P., & Marshall, H. E. (1999). *UNIFORMAT II elemental classification for building specifications, cost estimating, and cost analysis.* U.S. Department of Commerce, Technology Administration, National Institute of Standards and Technology.

Coberley, M. (2009). Repair and Renovation Projects. *School Planning and Management, 48*(12), 26-27.

Cohen, A. (2004, September). Making the Upgrade with Funds for New Facilties Increasingly Hard to come by, Renovations and Phased Retrofits are allowing Large Spectator Venues to change with the Times. *Athletic Business, 28*(9), 50-58.

Construction Engineering Research Laboratory. (2012, Semptember 9). *RAILER*. Retrieved from Sustainment Management System: http://sms.cecer.army.mil/SitePages/RAILER.aspx

Construction Specifications Institute. (2012, January 1). *MasterFormat*. Retrieved from csinet.org: http://www.csinet.org/masterformat

Construction Specifications Institute. (2012, January 1). *UniFormat*. Retrieved from csinet.org: http://www.csinet.org/uniformat

Construction Specifications Institute. (2013, February 26). *OmniClass Table 11 - Construction Entities by Function.* Retrieved from omniclass.org: http://www.omniclass.org/pdf.asp?id=2&table=Table 11

Construction Specifications Institute. (2015, January 1). *OmniClass*. Retrieved from omniclass.org: http://www.omniclass.org/

Craig, B. A., & Sendi, P. P. (2002). Estimation of the transition matrix of a discrete-time Markov chain. *Health Economics, 11*(1), 33-42.

Cyrenne, P., Fenton, R., & Warbanski, J. (2006). Comparative Analysis of Life-Cycle Costing for Rehabilitating Infrastructure Systems. *Journal of Real Estate Research, 28*(4), 349-379.

Dell'Isola, A. J., & Kirk, S. J. (2003). *Life Cycle Costing for Facilities: Economic analysis for owners and professionals in planning, programming, and real estate development: Designing, specifying, and construction, maintenance, operations, and procurement.* Kingston, MA: Reed Construction Data.

East, W. E., & Brodt, W. (2007). BIM for Construction handover. *Journal of Building Information Modeling*, 28-35.

Edirisinghe, R., Setunge, S., & Zhang, G. (2015). Markov-Model-Based Building Deterioration Prediction and ISO Factor Analysis for Building Management. *Journal of Management in Engineering*.

El-Rayes, K., Liu, L., & Abdallah, M. (2013). *"Green-Friendly" best management practices (BMPs) for interstate rest Areas-Phase II.* Urbana, IL: University of Illinois.

Ewada, A., Zayed, T., & Alkass, S. (2010). An integrated condition assessment model for buildings. *Construction Research Congress 2010: Innovation for Reshaping Construction Practice* (pp. 1386-1395). Reston, VA: American Society of Civil Engineers.

Farran, M., & Zayed, T. (2009). Comparative Analysis of Life-Cycle Costing for Rehabilitating Infrastructure Systems. *Journal of Performance of Constructed Facilities, 23*(5), 320-326.

Federal Register. (2004, February 6). *Executive Order 13327.* Retrieved from gpo.gov: http://www.gpo.gov/fdsys/pkg/FR-2004-02-06/pdf/04-2773.pdf

Fenton, N., & Neil, M. (2012). *Risk Assessment and Decision Analysis with Bayesian Networks.* Boca Raton, FL: CRC Press.

Funk, M. (2010, October 24). Software Solutions for Remodels and Retrofits. *Green Building Pro*.

Goldberg, D. E., & Holland, J. H. (1988). Genetic algorithms and machine Learning. *Machine learning, 3*(2), 95-99.

Government Accountability Office. (2001). *Mission Dependency Index - A Metric for Determining Infrastructure Criticality.* Washington, DC: Government Accountability Office.

Government Accountability Office. (2003). *Defense Infrastructure: Changes in Funding and Priorities and Strategic Planning Needed to Improve the Condition of Military Facilities.* Washington, DC: Government Accountability Office.

Government Accountability Office. (2006). *Risk Management: Further Refinements Needed to Assess Risks and Prioritize Protective Measures at Ports and Other Critical Infrastructure.* Washington, DC: Government Accountability Office.

Government Accountability Office. (2007). *DEFENSE INFRASTRUCTURE: Management Actions Needed to Ensure Effectiveness of DOD's Risk Management Approach for the Defense Industrial Base.* Washington, DC: Government Accountability Office.

Government Accountability Office. (2008). *Defense Infrastructure: Continued Management Attention is Needed to Support Installation Facilities and Operations.* Washington, DC: Government Accountability Office.

Government Accountability Office. (2008). *Federal Real Property: Government's Fiscal Exposure for Repair and Maintenance Backlogs Is Unclear.* Washington, DC: Government Accountability Office.

Governmental Accounting Standards Board. (1999, June 30). *Summary of Statement No. 34*. Retrieved from gasb.org: http://www.gasb.org/st/summary/gstsm34.html

Gramlich, E. M. (1994). Infrastructure Investment: A Review Essay. *Journal of Economic Literature, XXXII*, 1176-1196.

Grigg, N. S. (2010). *Economics and Finance for Engineers and Planners.* Reston, VA: American Society of Civil Engineers.

Grussing, M. N. (2013). Life Cycle Asset Management Methodologies for Buildings. *ASCE Journal of Infrastructure Systems, 20*(1).

Grussing, M. N., Uzarski, D. R., & Marrano, L. R. (2006). Condition and Reliability Prediction models using the weibull probability distribution. *ASCE Conference on Advanced Applications in Transportation Technology* (pp. 81-86). Reston, VA: American Society of Civil Engineers.

Grussing, M. N., Uzarski, D. R., & Marrano, L. R. (2006). Optimizing facility component maintenance, repair, and restoration investment strategies using financial ROI metrics and consequence analysis. *Advanced Applications in Transportation Technology ASCE Conference* (pp. 81-86). Reston, VA: American Society of Civil Engineers.

Grussing, M. N., Uzarski, D. R., & Marrano, L. R. (2009). Building infrastructure functional capacity measurement framework. *ASCE Journal of Infrastructure Systems, 15*(4), 371-377.

Halfawy, M. R. (2008). Integration of Municipal Infrastructure Asset Management Processes: Challenges and Solutions. *Journal of Computing in Civil Engineering, 22*(3), 216-229.

Hassanain, M. A., Froese, T. M., & Vanier, D. J. (2003). Framework model for asset maintenance management. *ASCE Journal of Performance of Constructed Facilities, 17*(1), 51-64.

Health Facilities Management. (2010). Laser Scanning helps bring Older Facilities up to Date. *Health Facilities Management, 23*(7), 6.

Hegazy, T., Elhakeem, A., Singh Ahluwalia, S., & Attalla, M. (2012). MOST-FIT: Support techniques for inspection and life cycle optimization in building asset management. *Journal of Computer-Aided Civil and Infrastructure Engineering, 27*(2), 130-142.

Hicks, T. (2005, July). LEED-EB: Effective Building Management, 'Environmental Design and Construction'. *Business News Publishing*.

Housing Association Proerty Mutual. (1995). *Lifespans of building components.* London, UK: Housing Association Property Mutual, Ltd.

Illen, E., & Iano, J. (2009). *Fundamentals of Building Construction Materials and Methods 5th Edition.* Hoboken, NJ: John Wiley and Sons, Inc.

International Building Performance Simulation Association. (2014, December 10). *Building Energy Software Tools*. Retrieved from Best Directory: http://www.buildingenergysoftwaretools.com/

International Facility Management Association. (2014, January 1). *11 Core Competencies of Facility Management*. Retrieved from ifma.org: http://www.ifma.org/know-base/fm-knowledge-base/knowledge-base-details/11-core-competencies-of-facility-management

Jido, M., Otazawa, T., & Kobayashi, K. (2008). Optimal Repair and Inspection Rules under Uncertainty. *ASCE Journal of Infrastructure Systems, 14*(2), 150-158.

Jrade, A., & Alkass, S. (2007). Computer-Integrated System for Estimating the Costs of Building Projects. *Journal of Architectural Engineering, 13*(4), 205-223.

Kemeny, J. G., & Snell, J. L. (1960). *Finite Markov Chains* (Vol. 356). Princeton, NJ: Van Nostrand.

Kleiner, Y., & Rajani, B. (2001). Comprehensive review of structural deterioration of water mains: statistical models. *Urban Water, 3*(3), 131-150.

Kollie, E. (2009, May). Performance Contract Saves Energy and Money. *School Planning and Management, 48*(5), pp. 26-31.

Laefer, D. F., & Manke, J. P. (2008). Building reuse assessment for sustainable urban reconstruction. *Journal of Construction Engineering and Management, 134*(3), 217-227.

Lemer, A. (1996). Infrastructure Obsolescence and Design Service Life. *Journal of Infrastructure Systems*, 153-161.

Lemer, A. (1999). Building Public Works Infrastructure Management Systems for Achieving High Return on Public Assets. *Public Works Management and Policy, 3*(3), 255.

Levitt, J. (2003). *Complete Guide to Preventive and Predictive Maintenance.* New York, NY: Industrial Press Inc.

Lindey, D. V. (1985). *Making Decisions.* New York, NY: Wiley.

Lou, Z., Gunaratne, M., Lu, J. J., & Dietrich, B. (2001). Application of neural network model to forecast short-term pavement crack condition: Flirida case study. *ASCE Journal of Infrastructure Systems, 7*(4), 166-171.

Lounis, Z. (2000). Reliability-based life prediction of aging concrete bridge decks. *Life Prediction and Aging Management of Concrete Structures*, 229-238.

Lounis, Z., & Vanier, D. J. (2000). A Multiobjective and Stochastic System for Building Maintenance Management. *Journal of Computer-Aided Civil Infrastructure Engineering, 15*(5), 320-329.

Loy, H., & Coleman, P. (2006). A 21st century approach to the condition surveying of building services systems. *Journal of Building Appraisal*, 161-170.

Lufkin, P. S. (2005). Estimating the Restoration and Modernization Costs of Infrastructure and Facilities. *Public Works Management and Policy, 10*(1), 40-52.

Madanat, S., Mishalani, R., & Wan Ibrahim, W. H. (1995). Estimation of Infrastructure Transition Probabilities from Condition Rating Data. *ASCE Journal of Infrastructure Systems, 1*(2), 120-125.

Marseguerra, M., Zio, E., & Podofillini, L. (2002). Condition-based maintenance optimization by means of genetic algorithms and monte carlo simulation. *Reliability Engineering and System Safety, 77*(2), 151-165.

McCuen, T. L. (2009). The Quantification Process and Standards for BIM. *AACC International Transactions*, BIM.01.01-BIM01.11.

Micevski, T., Kuczera, G., & Coombes, P. (2002). Markov Model for Storm Water Pipe Deterioration. *ASCE Journal of Infrastructure Systems, 8*(2), 49-56.

Morcous, G. (2006). Performance Prediction of Bridge Deck Systems Using Markov Chains. *ASCE Journal of Performance of Constructed Facilities, 20*(2), 146-155.

Morcous, G., Rivard, H., & Hanna, A. M. (2002). Case-based reasoning system for modeling infrastructure deterioration. *Journal of Computing in Civil Engineering, 16*(2), 104-114.

Moubray, J. (1997). *Reliability-Centered Maintenance* (Second ed.). New York, NY: Industrial Press Inc.

National Aeronautics and Space Administration. (2003). *The NASA Deferred Maintenance Parametric Estimating Guide.* Washington, DC: NASA Facilities Engineering Division.

National Research Council. (2012). *Predicting Outcomes of Investments in Maintenance and Repair of Federal Facilities.* Washington, DC: National Academy of Sciences.

Oak Ridge National Laboratory. (2015, January 1). *DOE Cool Roof Calculator*. Retrieved from Oak Ridge National Laboratory: http://web.ornl.gov/sci/roofs+walls/facts/CoolCalcEnergy.htm

Ortiz-Garcia, J. J., Costello, S. B., & Snaith, M. S. (2006). Derivation of Transition Probability Matrices for Pavement Deterioration Modeling. *Journal of Transportation Engineering, 132*(2), 141-161.

Palisade Corporation. (2015, January 1). *Evolver Sophisticated Optimization for Spreadsheets*. Retrieved from palisade.com: http://www.palisade.com/evolver/

Palisade Corporation. (2015, January 1). *Precision Tree Decision Tree in Microsoft Excel*. Retrieved from palisade.com: http://www.palisade.com/precisiontree/

Pfaehler, G. K. (2009). Get your project off on the right foot: Building codes and historic rehabilitation and renovation projects. *Real Estate Review, 38*(4), 39.

Piper, J. E. (2004). *Handbook of Facility Assessment.* Lilburn, GA: The Fairmont Press Inc.

R.S. Means. (1996). *Cost Planning and Estimating for Facilities Maintenance.* Kingston, MA: R.S. Means Company, Inc.

R.S. Means. (2014, January 1). RSMeans Cost Works 2014. Kingston, MA, USA.

Salem, O., AbouRizk, S., & Ariaratnam, S. (2003). Risk-Based Life-cycle Costing of Infrastructure Rehabilitation and Construction Alternatives. *ASCE Journal of Infrastructure Systems*, 6-15.

Sarja, A. (2006). *Predictive and Optimised Life Cycle Management.* New York, NY: Taylor and Francis.

Shahin, M. Y., & Kohn, S. D. (1979). *Development of a Pavement Condition Rating Procedure for Roads, Streets, and Parking Lots. Volume II Distress Identification Manual.* Champaign, IL: U.S. Army Construction Engineering Research Laboratory.

Shahin, M. Y., Cation, K. A., & Broten, M. R. (1987). *Micro PAVER Concept and Development Airport Pavement Management System.* Champaign, IL: U.S. Army Construction Engineering Research Laboratory.

Shami, M. (2008). Solid waste sustainability related to building deconstruction. *International Journal of Environmental Technology and Management, 8*(2), 117-191.

Sheppard, L. M. (2004). Virtual building for construction projects. *Computer Graphics and Applications, IEEE, 24*(1), 6-12.

Shipley, R., Utz, S., & Parsons, M. (2006). Does adaptive reuse pay? A study of the business of building renovation in Ontario, Canada. *International Journal of Heritage Studies, 12*(6), 505-520.

Shohet, I. M., & Perelstein, E. (2004). Decision Support Model for the Allocation of Resources in Rehabilitation Projects. *ASCE Journal of Construction Engineering and Management*, 249-257.

Simonoff, J. S., Restrepo, C. E., & Zimmerman, R. (2010). Risk management of cost consequences in natural gas transmissio and distribution infrastructures. *Journal of Loss Prevention in the Process Industries, 23*(2), 269-279.

Sinha, S. K., & Knight, M. A. (2004). Intelligent System for Condition Monitoring of Underground Pipelines. *Computer-Aided Civil and Infrastructure Engineering, 19*(1), 42-53.

Smerkers, S. (2008). *Renovation versus New Construction.* Fort Lauderdale, FL: ACIA Associates.

Staneff, S. T., Ibbs, W. C., & Bea, R. G. (1995). Risk Management Systems for Infrastructure Condition Assessment. *ASCE Journal of Infrastructure Systems*, 221-229.

Tesfamariam, S., & Vanier, D. J. (2005). The Analytical hierarchy process for eliciting decision preferences in asset management. *Urban Infrastructure: Managing the Assets, Mastering the Technology.* Montreal, Quebec: National Research Council Canada.

U.S. Army Construction Engineering Research Laboratory. (2015, January 1). *BUILDER Sustainment Managment System*. Retrieved from Systainment Management System: http://sms.cecer.army.mil/SitePages/BUILDER.aspx

U.S. Army Corps of Engineers. (2014, October 1). *Tri-Service Automated Cost Engineering System (TRACES)*. Retrieved from U.S. Army Corps of Engineers: http://www.hnc.usace.army.mil/Media/FactSheets/FactSheetArticleView/tabid/10784/Article/482084/tri-services-automated-cost-engineering-system.aspx

U.S. Department of Defense. (2010, June 9). *Real Property Inventory Requirements Initiative*. Retrieved from Office of the Deputy Under Secretary of Defense Installations and Environment: http://www.acq.osd.mil/ie/bei/rpi.shtml

U.S. Department of Defense. (2014). *Base Structure Report - Fiscal Year 2014 Baseline.* Retrieved from Office of the Deputy Under Secretary of Defense Installations and Environment: http://www.acq.osd.mil/ie/download/bsr/Base%20Structure%20Report%20FY14.pdf

U.S. Department of Defense. (2014, May 2). *Facility Program Requirements Suite*. Retrieved from Office of the Deputy Under Secretary of Defense Installations and Environment: http://www.acq.osd.mil/ie/fprs.shtml

U.S. Department of Defense. (2015, July 8). *DoD Facilities Pricing Guide.* Retrieved from Whole Building Design Guide: https://www.wbdg.org/ccb/DOD/UFC/ufc_3_701_01.pdf

U.S. Department of Energy. (2014, January 1). *Building America Climate Zones*. Retrieved from energy.gov: http://energy.gov/eere/buildings/climate-zones

U.S. Department of Energy. (2015, Sept 9). *Buildings Energy Data Book*. Retrieved from Energy Efficiency and Renewable Energy: http://buildingsdatabook.eere.energy.gov/ChapterIntro1.aspx

U.S. Department of Transportation. (1999). *Asset Management Primer.*

U.S. Department of Transportation. (2015, September 9). *Asset Managment*. Retrieved from Federal Highway Administration: https://www.fhwa.dot.gov/asset/

U.S. General Services Administration. (2015, September 9). *Federal Real Property Profile*. Retrieved from gsa.gov: http://www.gsa.gov/portal/content/104199

U.S. Green Building Council. (2012, January 1). *LEED Rating Systems*. Retrieved from usgbc.org: http://www.usgbc.org/leed/rating-systems/

U.S. Navy. (1993). *Inspection of Shoreline Facilities, Volume 2.* Washington, DC: Naval Failities Engineering Command.

United States Census Bureau. (2015, September 9). *Construction Spending*. Retrieved from Census.gov: http://www.census.gov/construction/c30/historical_data.html

Uzarski, D. R. (1993). *Development of condition indexes for low volume railroad track.* Champaign, IL: U.S. Army Construction Engineering Research Laboratory.

Uzarski, D. R., & Burley Jr, L. A. (1997). Assessing Building Condition by the use of Condition Indexes. *Proceedings of the Specialty Conference on Infrastructure Condition Assessment: Art, Science, Practice* (pp. 365-374). Reston, VA: American Society of Civil Engineers.

Uzarski, D. R., & Grussing, M. N. (2004). *Knowledge-based condition assessment manual for building component-sections.* Champaign, IL: U.S. Army Construction Engineering Research Laboratory.

Uzarski, D. R., & Grussing, M. N. (2008). Building Condition Assessment Metrics: Best Practices. *ASCE Special Report: Infrastructure Reporting and Asset Management* (pp. 147-152). Reston, VA: American Society of Civil Engineers.

Uzarski, D. R., Grussing, M. N., & Clayton, J. B. (2007). Knowledge-based condition survey inspection concepts. *Journal of Infrastructure Systems, 13*(1), 72-79.

Vanier, D. J. (2000). Whole Life Building Management: Occupancy to dismantling. *Construction Information Technology*, 983-995.

Wirahadikusumah, R., Abraham, D., & Iseley, T. (2001). Challenging Issues in modeling deterioration of combined sewers. *ASCE Journal of Infrastructure Systems, 7*(2), 77-84.

Zhang, Z., & Damnjanovic, I. (2006). Applying method of moments to model reliability of pavements infrastructure. *Journal of Transportation Engineering, 132*(5), 416-424.

APPENDIX A – BUILDER SMS Direct Rating Definitions

From: (U.S. Army Construction Engineering Research Laboratory, 2015)

Rating	SRM Needs	Rating Definition
Green (+) CI = 100	Sustainment consisting of possible preventive maintenance (where applicable).	Entire component-section or component-section sample free of observable or known distress.
Green CI = 99-93	Sustainment consisting of possible preventive maintenance (where applicable) and minor repairs (corrective maintenance) to possibly few or some subcomponents.	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.
Green (-) CI = 92-86		Slight or no serviceability or reliability reduction overall to the component-section or sample. 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.
Amber (+) CI = 85-75	Sustainment or restoration to any of the following: Minor repairs to several subcomponents; or Significant repair, rehabilitation, or replacement of one or more subcomponents, but not enough to encompass the component-section as a whole; or Combinations thereof.	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.
Amber CI = 74-65		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.
Amber (-) CI = 64-56		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.
Red (+) CI = 55-37	Sustainment or restoration required consisting of major repair, rehabilitation, or replacement to the component-section as a whole.	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.
Red CI = 36-11		Severe serviceability or reliability reduction to the component-section or sample such that it is barely able to perform. Most subcomponents are severely degraded.
Red (-) CI = 10-0		Overall component-section degradation is total. Few, if any, subcomponents salvageable. Complete loss of component-section or sample serviceability.

APPENDIX B – PAIRED CONDITION DATASET FOR B301005 BUILT-UP ROOFING

						Inspection 1			Inspection 2				
Region	**Component**	**Design Life**	**Year Installed**	**Quantity**	**UM**	**Date**	**Rating**	**State**	**Date**	**Rating**	**State**	**Obs. Interval**	**Random Number**
Hot-Humid	B3010105 - Built-Up	28	2000	8100	SF	7/28/2010	67	5	2/22/2013	61	6	3	0.06231
Hot-Humid	B3010105 - Built-Up	28	1998	2052	SF	5/16/2012	88	3	3/31/2014	88	3	2	0.116101
Hot-Humid	B3010105 - Built-Up	28	1990	975	SF	7/28/2010	61	6	11/15/2011	61	6	1	0.368817
Hot-Humid	B3010105 - Built-Up	28	1996	3677	SF	7/28/2010	23	7	11/15/2011	10	7	1	0.402422
Hot-Humid	B3010105 - Built-Up	28	1957	529	SF	9/30/2010	61	6	7/16/2013	88	3	3	0.129804
Hot-Humid	B3010105 - Built-Up	28	1990	169	SF	9/30/2010	61	6	11/15/2011	61	6	1	0.559609
Hot-Humid	B3010105 - Built-Up	28	1995	7750	SF	4/27/2012	80	4	1/17/2014	80	4	2	0.837859
Hot-Humid	B3010105 - Built-Up	28	1989	180	SF	7/28/2010	80	4	11/15/2011	80	4	1	0.689568
Hot-Humid	B3010105 - Built-Up	28	2005	25648	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.870092
Hot-Humid	B3010105 - Built-Up	28	2006	20700	SF	7/28/2010	72	5	7/12/2014	71	5	4	0.279587
Hot-Humid	B3010105 - Built-Up	28	2006	2240	SF	7/28/2010	67	5	7/12/2014	71	5	4	0.836934
Hot-Humid	B3010105 - Built-Up	28	1995	3786	SF	7/7/2010	71	5	1/26/2014	95	2	4	0.638061
Hot-Humid	B3010105 - Built-Up	28	1964	1488	SF	9/30/2010	58	6	11/15/2011	61	6	1	0.331666
Hot-Humid	B3010105 - Built-Up	28	2000	3000	SF	9/30/2010	50	7	11/15/2011	50	7	1	0.935633
Hot-Humid	B3010105 - Built-Up	28	1995	62909	SF	9/30/2010	53	7	4/16/2014	30	7	4	0.061126
Hot-Humid	B3010105 - Built-Up	28	2005	29500	SF	9/30/2010	40	7	4/24/2014	71	5	4	0.989134
Hot-Humid	B3010105 - Built-Up	28	1976	3450	SF	7/7/2010	41	7	4/1/2014	88	3	4	0.174195
Hot-Humid	B3010105 - Built-Up	28	1993	7260	SF	9/30/2010	38	7	4/14/2013	30	7	3	0.517345
Hot-Humid	B3010105 - Built-Up	28	1986	10160	SF	9/30/2010	40	7	5/28/2014	10	7	4	0.956937
Hot-Humid	B3010105 - Built-Up	28	1999	24244	SF	9/30/2010	53	7	7/2/2014	88	3	4	0.944351
Hot-Humid	B3010105 - Built-Up	28	2002	1272	SF	7/28/2010	61	6	9/26/2014	80	4	4	0.818934
Hot-Humid	B3010105 - Built-Up	28	1997	5618	SF	7/28/2010	48	7	9/26/2014	71	5	4	0.675773
Hot-Humid	B3010105 - Built-Up	28	1992	7056	SF	7/28/2010	43	7	9/26/2014	71	5	4	0.991712
Hot-Humid	B3010105 - Built-Up	28	2007	28968	SF	9/30/2010	55	7	6/26/2014	80	4	4	0.235103

						Inspection 1			Inspection 2				
Region	**Component**	**Design Life**	**Year Installed**	**Quantity**	**UM**	**Date**	**Rating**	**State**	**Date**	**Rating**	**State**	**Obs. Interval**	**Random Number**
Hot-Humid	B3010105 - Built-Up	28	1994	13426	SF	7/7/2010	43	7	8/20/2014	88	3	4	0.623179
Hot-Humid	B3010105 - Built-Up	28	1990	1043	SF	7/28/2010	80	4	11/15/2011	80	4	1	0.164802
Hot-Humid	B3010105 - Built-Up	28	1995	1628	SF	7/28/2010	80	4	11/15/2011	80	4	1	0.312012
Hot-Humid	B3010105 - Built-Up	28	1990	1869	SF	7/28/2010	61	6	8/21/2014	61	6	4	0.921754
Hot-Humid	B3010105 - Built-Up	28	1990	600	SF	7/28/2010	61	6	8/21/2014	61	6	4	0.114927
Hot-Humid	B3010105 - Built-Up	28	1959	484	SF	7/28/2010	61	6	11/15/2011	61	6	1	0.888852
Hot-Humid	B3010105 - Built-Up	28	2002	20	SF	7/28/2010	52	7	9/30/2014	61	6	4	0.877611
Hot-Humid	B3010105 - Built-Up	28	1995	140	SF	7/28/2010	71	5	8/21/2014	30	7	4	0.038092
Hot-Humid	B3010105 - Built-Up	28	1985	231	SF	7/28/2010	61	6	8/23/2014	30	7	4	0.233868
Hot-Humid	B3010105 - Built-Up	28	1995	77341	SF	9/30/2010	88	3	1/27/2014	71	5	3	0.603508
Hot-Humid	B3010105 - Built-Up	28	1988	150	SF	7/28/2010	92	3	11/15/2011	95	2	1	0.451748
Hot-Humid	B3010105 - Built-Up	28	1989	1664	SF	7/28/2010	66	5	4/4/2013	61	6	3	0.118121
Hot-Humid	B3010105 - Built-Up	28	1988	35070	SF	9/30/2010	94	2	1/11/2014	88	3	3	0.00365
Hot-Humid	B3010105 - Built-Up	28	1995	11410	SF	7/7/2010	57	6	9/7/2014	88	3	4	0.917915
Hot-Humid	B3010105 - Built-Up	28	2003	3000	SF	7/28/2010	71	5	1/16/2014	80	4	3	0.819862
Hot-Humid	B3010105 - Built-Up	28	2005	5377	SF	2/1/2013	88	3	2/1/2013	88	3	0	0.78587
Hot-Humid	B3010105 - Built-Up	28	1999	480	SF	9/30/2010	53	7	11/15/2011	50	7	1	0.202597
Hot-Humid	B3010105 - Built-Up	28	1980	2016	SF	7/28/2010	79	4	11/15/2011	80	4	1	0.005113
Hot-Humid	B3010105 - Built-Up	28	2005	28452	SF	9/30/2010	67	5	2/26/2014	71	5	3	0.737896
Hot-Humid	B3010105 - Built-Up	28	1980	11041	SF	7/28/2010	51	7	11/15/2011	50	7	1	0.282512
Hot-Humid	B3010105 - Built-Up	28	1980	2000	SF	7/28/2010	61	6	7/9/2014	50	7	4	0.962479
Hot-Humid	B3010105 - Built-Up	28	1995	3186	SF	7/28/2010	50	7	6/29/2014	50	7	4	0.474024
Hot-Humid	B3010105 - Built-Up	28	1995	758	SF	7/28/2010	45	7	6/29/2014	50	7	4	0.42603
Hot-Humid	B3010105 - Built-Up	28	1965	14292	SF	9/30/2010	48	7	5/20/2013	88	3	3	0.44924
Hot-Humid	B3010105 - Built-Up	28	1970	588	SF	7/28/2010	22	7	2/20/2013	10	7	3	0.75562
Hot-Humid	B3010105 - Built-Up	28	2013	73681	SF	9/30/2010	67	5	9/22/2014	88	3	4	0.221853
Hot-Humid	B3010105 - Built-Up	28	1993	38622	SF	9/30/2010	38	7	11/15/2011	30	7	1	0.395097
Hot-Humid	B3010105 - Built-Up	28	2005	25578	SF	9/30/2010	67	5	7/24/2014	88	3	4	0.815555

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	2007	2200	SF	9/30/2010	73	5	7/24/2014	88	3	4	0.924383
Hot-Humid	B3010105 - Built-Up	28	1986	5852	SF	9/30/2010	58	6	11/15/2011	61	6	1	0.009346
Hot-Humid	B3010105 - Built-Up	28	2005	11651	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.886812
Hot-Humid	B3010105 - Built-Up	28	1957	1100	SF	3/17/2013	30	7	3/17/2013	30	7	0	0.588062
Hot-Humid	B3010105 - Built-Up	28	2005	4100	SF	7/28/2010	59	6	2/8/2013	100	1	3	0.596696
Hot-Humid	B3010105 - Built-Up	28	1975	72076	SF	7/28/2010	39	7	11/15/2011	30	7	1	0.288897
Hot-Humid	B3010105 - Built-Up	28	1990	9950	SF	9/30/2010	68	5	1/11/2014	61	6	3	0.11488
Hot-Humid	B3010105 - Built-Up	28	1980	50894	SF	9/30/2010	50	7	5/30/2014	88	3	4	0.973248
Hot-Humid	B3010105 - Built-Up	28	1995	21068	SF	7/28/2010	63	6	11/15/2011	61	6	1	0.36176
Hot-Humid	B3010105 - Built-Up	28	1987	2000	SF	9/30/2010	71	5	11/15/2011	71	5	1	0.119258
Hot-Humid	B3010105 - Built-Up	28	1957	192	SF	2/20/2013	71	5	9/22/2014	71	5	2	0.473369
Hot-Humid	B3010105 - Built-Up	28	1990	8300	SF	9/30/2010	43	7	3/29/2013	30	7	2	0.724325
Hot-Humid	B3010105 - Built-Up	28	1996	18780	SF	9/30/2010	51	7	4/29/2014	71	5	4	0.308425
Hot-Humid	B3010105 - Built-Up	28	2004	3000	SF	9/30/2010	100	1	5/29/2013	80	4	3	0.29327
Hot-Humid	B3010105 - Built-Up	28	1998	7134	SF	9/30/2010	67	5	3/9/2014	88	3	3	0.655757
Hot-Humid	B3010105 - Built-Up	28	1959	14472	SF	7/7/2010	100	1	5/29/2013	95	2	3	0.707826
Hot-Humid	B3010105 - Built-Up	28	1997	2067	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.686867
Hot-Humid	B3010105 - Built-Up	28	1998	26510	SF	9/30/2010	41	7	8/8/2014	80	4	4	0.91888
Hot-Humid	B3010105 - Built-Up	28	2004	143	SF	9/30/2010	64	6	3/27/2013	71	5	2	0.174016
Hot-Humid	B3010105 - Built-Up	28	1980	990	SF	7/28/2010	91	3	11/15/2011	95	2	1	0.485089
Hot-Humid	B3010105 - Built-Up	28	2004	1000	SF	9/30/2010	64	6	11/15/2011	61	6	1	0.004616
Hot-Humid	B3010105 - Built-Up	28	1971	15248	SF	7/7/2010	100	1	12/23/2013	88	3	3	0.75685
Hot-Humid	B3010105 - Built-Up	28	1990	5950	SF	7/28/2010	95	2	11/15/2011	95	2	1	0.976149
Hot-Humid	B3010105 - Built-Up	28	2007	27000	SF	9/30/2010	95	2	11/15/2011	95	2	1	0.74279
Hot-Humid	B3010105 - Built-Up	28	1975	2151	SF	9/30/2010	43	7	5/28/2014	88	3	4	0.419477
Hot-Humid	B3010105 - Built-Up	28	2004	70461	SF	9/30/2010	47	7	11/15/2011	50	7	1	0.144101
Hot-Humid	B3010105 - Built-Up	28	1983	32760	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.129086
Hot-Humid	B3010105 - Built-Up	28	1988	8988	SF	9/30/2010	51	7	2/11/2014	88	3	3	0.178625

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1999	6870	SF	1/16/2013	80	4	1/16/2013	80	4	0	0.842595
Hot-Humid	B3010105 - Built-Up	28	2000	11088	SF	2/5/2013	80	4	2/5/2013	80	4	0	0.620889
Hot-Humid	B3010105 - Built-Up	28	1992	342	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.655933
Hot-Humid	B3010105 - Built-Up	28	1980	2100	SF	9/30/2010	66	5	11/15/2011	61	6	1	0.230184
Hot-Humid	B3010105 - Built-Up	28	1995	31815	SF	9/30/2010	100	1	5/21/2013	80	4	3	0.380081
Hot-Humid	B3010105 - Built-Up	28	1942	108	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.401842
Hot-Humid	B3010105 - Built-Up	28	2005	4800	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.736234
Hot-Humid	B3010105 - Built-Up	28	1986	4569	SF	9/30/2010	58	6	3/21/2013	61	6	2	0.557886
Hot-Humid	B3010105 - Built-Up	28	1986	2462	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.010841
Hot-Humid	B3010105 - Built-Up	28	1948	304	SF	9/30/2010	43	7	11/15/2011	50	7	1	0.447357
Hot-Humid	B3010105 - Built-Up	28	2006	211221	SF	9/30/2010	70	5	5/21/2013	95	2	3	0.422549
Hot-Humid	B3010105 - Built-Up	28	2006	1237	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.297426
Hot-Humid	B3010105 - Built-Up	28	1955	221	SF	9/30/2010	37	7	3/7/2014	80	4	3	0.072229
Hot-Humid	B3010105 - Built-Up	28	1986	34700	SF	9/30/2010	86	3	1/11/2014	88	3	3	0.023923
Hot-Humid	B3010105 - Built-Up	28	1990	6000	SF	9/30/2010	37	7	4/23/2014	88	3	4	0.633112
Hot-Humid	B3010105 - Built-Up	28	2005	19800	SF	9/30/2010	67	5	4/23/2014	88	3	4	0.998737
Hot-Humid	B3010105 - Built-Up	28	1987	6000	SF	9/30/2010	95	2	1/11/2014	95	2	3	0.318861
Hot-Humid	B3010105 - Built-Up	28	1988	29700	SF	9/30/2010	41	7	9/17/2013	88	3	3	0.20595
Hot-Humid	B3010105 - Built-Up	28	2000	412143	SF	9/30/2010	53	7	7/7/2014	80	4	4	0.643265
Hot-Humid	B3010105 - Built-Up	28	1993	1225	SF	7/28/2010	66	5	11/15/2011	61	6	1	0.241109
Hot-Humid	B3010105 - Built-Up	28	1990	8400	SF	9/30/2010	80	4	11/15/2011	80	4	1	0.747679
Hot-Humid	B3010105 - Built-Up	28	1987	9672	SF	10/3/2011	30	7	3/8/2014	88	3	2	0.87108
Hot-Humid	B3010105 - Built-Up	28	1979	120	SF	9/30/2010	95	2	11/15/2011	95	2	1	0.011254
Hot-Humid	B3010105 - Built-Up	28	1990	88	SF	7/28/2010	71	5	11/15/2011	71	5	1	0.959289
Hot-Humid	B3010105 - Built-Up	28	1995	915	SF	7/28/2010	80	4	11/15/2011	80	4	1	0.130385
Hot-Humid	B3010105 - Built-Up	28	2006	5500	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.805305
Hot-Humid	B3010105 - Built-Up	28	2000	6760	SF	9/30/2010	100	1	6/12/2013	88	3	3	0.580987
Hot-Humid	B3010105 - Built-Up	28	1995	4073	SF	7/28/2010	80	4	11/15/2011	80	4	1	0.322099

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	2003	26510	SF	9/30/2010	41	7	8/18/2014	50	7	4	0.027244
Hot-Humid	B3010105 - Built-Up	28	2005	22100	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.694149
Hot-Humid	B3010105 - Built-Up	28	1998	10112	SF	7/28/2010	21	7	7/30/2014	88	3	4	0.460649
Hot-Humid	B3010105 - Built-Up	28	1944	576	SF	7/28/2010	71	5	9/12/2014	71	5	4	0.932964
Hot-Humid	B3010105 - Built-Up	28	1996	14859	SF	9/30/2010	88	3	1/27/2014	71	5	3	0.125709
Hot-Humid	B3010105 - Built-Up	28	2000	17524	SF	9/30/2010	59	6	5/19/2014	61	6	4	0.418588
Hot-Humid	B3010105 - Built-Up	28	1990	480	SF	7/28/2010	61	6	8/21/2014	61	6	4	0.860822
Hot-Humid	B3010105 - Built-Up	28	1941	2852	SF	9/30/2010	45	7	5/19/2014	88	3	4	0.950129
Hot-Humid	B3010105 - Built-Up	28	1981	44337	SF	9/30/2010	96	2	11/15/2011	95	2	1	0.740689
Hot-Humid	B3010105 - Built-Up	28	1980	30450	SF	7/7/2010	100	1	7/28/2014	88	3	4	0.411202
Hot-Humid	B3010105 - Built-Up	28	1998	5120	SF	9/30/2010	80	4	11/15/2011	80	4	1	0.860019
Hot-Humid	B3010105 - Built-Up	28	1990	3597	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.473563
Hot-Humid	B3010105 - Built-Up	28	1972	10000	SF	9/30/2010	100	1	6/13/2014	88	3	4	0.303129
Hot-Humid	B3010105 - Built-Up	28	2005	7260	SF	9/30/2010	67	5	5/4/2013	30	7	3	0.569654
Hot-Humid	B3010105 - Built-Up	28	1995	1660	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.512742
Hot-Humid	B3010105 - Built-Up	28	1939	63	SF	1/18/2013	50	7	1/18/2013	50	7	0	0.828918
Hot-Humid	B3010105 - Built-Up	28	1998	400805	SF	3/21/2012	30	7	6/6/2014	71	5	2	0.894494
Hot-Humid	B3010105 - Built-Up	28	1989	1764	SF	7/28/2010	71	5	9/15/2014	71	5	4	0.566083
Hot-Humid	B3010105 - Built-Up	28	2005	2625	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.109811
Hot-Humid	B3010105 - Built-Up	28	1966	4000	SF	9/30/2010	88	3	3/3/2014	88	3	3	0.887662
Hot-Humid	B3010105 - Built-Up	28	1970	3723	SF	7/28/2010	9	7	11/15/2011	10	7	1	0.252
Hot-Humid	B3010105 - Built-Up	28	1939	121	SF	2/1/2013	71	5	2/1/2013	71	5	0	0.706207
Hot-Humid	B3010105 - Built-Up	28	1990	1800	SF	3/6/2012	80	4	9/11/2014	71	5	3	0.321096
Hot-Humid	B3010105 - Built-Up	28	1997	612	SF	7/28/2010	80	4	9/15/2014	71	5	4	0.487658
Hot-Humid	B3010105 - Built-Up	28	1995	58820	SF	9/30/2010	59	6	11/15/2011	61	6	1	0.332301
Hot-Humid	B3010105 - Built-Up	28	1972	468	SF	7/28/2010	71	5	9/11/2014	61	6	4	0.473443
Hot-Humid	B3010105 - Built-Up	28	1998	1500	SF	7/28/2010	32	7	6/18/2013	50	7	3	0.758135
Hot-Humid	B3010105 - Built-Up	28	2000	900	SF	7/28/2010	63	6	6/18/2013	30	7	3	0.362409

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1995	1350	SF	7/28/2010	51	7	6/18/2013	50	7	3	0.094473
Hot-Humid	B3010105 - Built-Up	28	1975	336	SF	7/28/2010	61	6	8/21/2014	10	7	4	0.839507
Hot-Humid	B3010105 - Built-Up	28	1990	40300	SF	9/30/2010	38	7	8/25/2014	88	3	4	0.626598
Hot-Humid	B3010105 - Built-Up	28	1956	184	SF	9/30/2010	43	7	3/7/2014	88	3	3	0.290982
Hot-Humid	B3010105 - Built-Up	28	2010	43638	SF	7/28/2010	33	7	6/6/2014	100	1	4	0.351972
Hot-Humid	B3010105 - Built-Up	28	1991	840	SF	7/28/2010	80	4	9/4/2014	71	5	4	0.585527
Hot-Humid	B3010105 - Built-Up	28	2000	6530	SF	9/30/2010	55	7	8/18/2014	88	3	4	0.719418
Hot-Humid	B3010105 - Built-Up	28	1992	3750	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.51561
Hot-Humid	B3010105 - Built-Up	28	1996	27000	SF	7/7/2010	100	1	3/4/2014	95	2	4	0.49369
Hot-Humid	B3010105 - Built-Up	28	2007	31120	SF	9/30/2010	45	7	8/28/2014	88	3	4	0.769209
Hot-Humid	B3010105 - Built-Up	28	2000	120	SF	2/6/2013	88	3	2/6/2013	88	3	0	0.049251
Hot-Humid	B3010105 - Built-Up	28	1995	15860	SF	7/28/2010	84	4	9/3/2014	95	2	4	0.77653
Hot-Humid	B3010105 - Built-Up	28	2005	9300	SF	9/30/2010	100	1	3/18/2014	88	3	3	0.302015
Hot-Humid	B3010105 - Built-Up	28	2005	76801	SF	9/30/2010	67	5	5/14/2013	95	2	3	0.894803
Hot-Humid	B3010105 - Built-Up	28	1948	127002	SF	2/26/2013	50	7	1/30/2014	50	7	1	0.725519
Hot-Humid	B3010105 - Built-Up	28	1965	3380	SF	9/30/2010	40	7	5/31/2014	30	7	4	0.74627
Hot-Humid	B3010105 - Built-Up	28	1998	16860	SF	9/30/2010	64	6	7/2/2014	10	7	4	0.167502
Hot-Humid	B3010105 - Built-Up	28	1995	8296	SF	7/28/2010	100	1	11/15/2011	100	1	1	0.287913
Hot-Humid	B3010105 - Built-Up	28	2005	210	SF	7/28/2010	59	6	9/22/2014	61	6	4	0.254328
Hot-Humid	B3010105 - Built-Up	28	1986	25488	SF	9/30/2010	41	7	11/15/2011	50	7	1	0.482958
Hot-Humid	B3010105 - Built-Up	28	1986	1258	SF	7/28/2010	62	6	11/15/2011	61	6	1	0.199263
Hot-Humid	B3010105 - Built-Up	28	2003	15600	SF	9/30/2010	62	6	11/15/2011	61	6	1	0.807427
Hot-Humid	B3010105 - Built-Up	28	2005	8550	SF	9/30/2010	67	5	4/22/2014	88	3	4	0.061039
Hot-Humid	B3010105 - Built-Up	28	1990	6050	SF	9/30/2010	100	1	5/14/2014	71	5	4	0.492439
Hot-Humid	B3010105 - Built-Up	28	1987	21000	SF	9/30/2010	67	5	7/24/2014	95	2	4	0.748031
Hot-Humid	B3010105 - Built-Up	28	1999	20600	SF	9/30/2010	40	7	3/18/2014	61	6	3	0.214793
Hot-Humid	B3010105 - Built-Up	28	1990	3322	SF	9/30/2010	80	4	5/6/2014	88	3	4	0.094299
Hot-Humid	B3010105 - Built-Up	28	2005	206	SF	7/28/2010	63	6	9/22/2014	61	6	4	0.976739

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1980	2448	SF	9/30/2010	43	7	11/15/2011	50	7	1	0.310525
Hot-Humid	B3010105 - Built-Up	28	1993	14400	SF	9/30/2010	84	4	11/15/2011	88	3	1	0.920049
Hot-Humid	B3010105 - Built-Up	28	1999	2520	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.180578
Hot-Humid	B3010105 - Built-Up	28	1998	10384	SF	7/28/2010	100	1	9/10/2014	71	5	4	0.437077
Hot-Humid	B3010105 - Built-Up	28	1971	26880	SF	9/30/2010	43	7	7/22/2014	50	7	4	0.122029
Hot-Humid	B3010105 - Built-Up	28	2005	2700	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.297442
Hot-Humid	B3010105 - Built-Up	28	1998	340	SF	7/28/2010	24	7	11/15/2011	10	7	1	0.106737
Hot-Humid	B3010105 - Built-Up	28	2007	8287	SF	7/28/2010	59	6	11/15/2011	61	6	1	0.729583
Hot-Humid	B3010105 - Built-Up	28	1999	1980	SF	7/28/2010	71	5	9/15/2014	71	5	4	0.984756
Hot-Humid	B3010105 - Built-Up	28	1997	1007	SF	6/25/2012	88	3	7/30/2014	80	4	2	0.260908
Hot-Humid	B3010105 - Built-Up	28	1990	7538	SF	9/30/2010	100	1	1/17/2014	95	2	3	0.102103
Hot-Humid	B3010105 - Built-Up	28	2000	98165	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.48952
Hot-Humid	B3010105 - Built-Up	28	2000	6112	SF	7/28/2010	80	4	11/15/2011	80	4	1	0.135735
Hot-Humid	B3010105 - Built-Up	28	1985	6161	SF	9/30/2010	61	6	7/25/2014	61	6	4	0.288322
Hot-Humid	B3010105 - Built-Up	28	2005	24460	SF	9/30/2010	43	7	11/15/2011	50	7	1	0.315721
Hot-Humid	B3010105 - Built-Up	28	1997	1983	SF	7/28/2010	88	3	11/15/2011	88	3	1	0.869295
Hot-Humid	B3010105 - Built-Up	28	1987	22219	SF	9/30/2010	100	1	2/5/2014	88	3	3	0.287937
Hot-Humid	B3010105 - Built-Up	28	1988	48946	SF	9/30/2010	33	7	1/11/2014	61	6	3	0.416513
Hot-Humid	B3010105 - Built-Up	28	2003	3428	SF	9/30/2010	62	6	5/22/2013	88	3	3	0.434037
Hot-Humid	B3010105 - Built-Up	28	1956	756	SF	9/30/2010	43	7	8/22/2013	50	7	3	0.720459
Hot-Humid	B3010105 - Built-Up	28	2008	1850	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.709173
Hot-Humid	B3010105 - Built-Up	28	1970	588	SF	7/28/2010	22	7	2/15/2013	10	7	3	0.448846
Hot-Humid	B3010105 - Built-Up	28	2005	1015	SF	9/30/2010	67	5	8/17/2014	88	3	4	0.691096
Hot-Humid	B3010105 - Built-Up	28	2009	3300	SF	12/28/2012	80	4	12/28/2012	80	4	0	0.572405
Hot-Humid	B3010105 - Built-Up	28	1985	6985	SF	9/30/2010	100	1	9/6/2013	88	3	3	0.270114
Hot-Humid	B3010105 - Built-Up	28	1986	11966	SF	9/30/2010	43	7	11/15/2011	50	7	1	0.777447
Hot-Humid	B3010105 - Built-Up	28	1995	3172	SF	7/28/2010	88	3	11/15/2011	88	3	1	0.621857
Hot-Humid	B3010105 - Built-Up	28	2006	1438	SF	9/30/2010	73	5	11/15/2011	71	5	1	0.111076

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1987	41833	SF	9/30/2010	52	7	1/11/2014	95	2	3	0.784202
Hot-Humid	B3010105 - Built-Up	28	1998	12201	SF	9/5/2012	88	3	9/16/2014	88	3	2	0.365406
Hot-Humid	B3010105 - Built-Up	28	1964	3676	SF	7/7/2010	100	1	3/19/2014	95	2	4	0.028078
Hot-Humid	B3010105 - Built-Up	28	1990	224	SF	5/15/2012	71	5	9/5/2014	71	5	2	0.470343
Hot-Humid	B3010105 - Built-Up	28	2001	810	SF	9/30/2010	95	2	6/10/2013	71	5	3	0.327312
Hot-Humid	B3010105 - Built-Up	28	2001	3400	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.251648
Hot-Humid	B3010105 - Built-Up	28	1990	2376	SF	9/30/2010	71	5	1/27/2014	71	5	3	0.810069
Hot-Humid	B3010105 - Built-Up	28	2002	10800	SF	9/30/2010	43	7	5/20/2013	95	2	3	0.590142
Hot-Humid	B3010105 - Built-Up	28	2005	17200	SF	9/30/2010	74	5	7/30/2014	71	5	4	0.897284
Hot-Humid	B3010105 - Built-Up	28	1989	13000	SF	9/30/2010	92	3	7/30/2014	95	2	4	0.216953
Hot-Humid	B3010105 - Built-Up	28	1965	117	SF	9/30/2010	61	6	6/27/2013	10	7	3	0.003243
Hot-Humid	B3010105 - Built-Up	28	1990	15163	SF	9/30/2010	100	1	5/1/2014	88	3	4	0.370454
Hot-Humid	B3010105 - Built-Up	28	2005	3156	SF	9/30/2010	43	7	8/1/2014	88	3	4	0.936797
Hot-Humid	B3010105 - Built-Up	28	1963	2470	SF	9/30/2010	43	7	2/21/2014	71	5	3	0.550307
Hot-Humid	B3010105 - Built-Up	28	2006	39530	SF	9/30/2010	98	2	11/15/2011	100	1	1	0.506808
Hot-Humid	B3010105 - Built-Up	28	2005	3500	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.800823
Hot-Humid	B3010105 - Built-Up	28	1988	3750	SF	7/28/2010	62	6	2/27/2013	30	7	3	0.24615
Hot-Humid	B3010105 - Built-Up	28	1985	5481	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.27683
Hot-Humid	B3010105 - Built-Up	28	2005	19435	SF	9/30/2010	67	5	11/15/2011	71	5	1	0.72841
Hot-Humid	B3010105 - Built-Up	28	1993	570	SF	9/30/2010	41	7	11/15/2011	50	7	1	0.08252
Hot-Humid	B3010105 - Built-Up	28	1985	4920	SF	7/28/2010	94	2	7/12/2014	95	2	4	0.519628
Hot-Humid	B3010105 - Built-Up	28	2005	18965	SF	7/28/2010	61	6	11/15/2011	61	6	1	0.484623
Hot-Humid	B3010105 - Built-Up	28	1998	500	SF	7/28/2010	100	1	12/3/2013	100	1	3	0.698438
Hot-Humid	B3010105 - Built-Up	28	1985	578	SF	7/28/2010	76	4	11/15/2011	71	5	1	0.830787
Hot-Humid	B3010105 - Built-Up	28	1986	5852	SF	9/30/2010	58	6	11/15/2011	61	6	1	0.16153
Hot-Humid	B3010105 - Built-Up	28	1985	11500	SF	9/30/2010	43	7	4/26/2014	71	5	4	0.672354
Hot-Humid	B3010105 - Built-Up	28	1954	3910	SF	7/7/2010	100	1	4/30/2013	95	2	3	0.976965
Hot-Humid	B3010105 - Built-Up	28	1968	3901	SF	9/30/2010	97	2	4/30/2014	88	3	4	0.749137

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1995	10500	SF	9/30/2010	38	7	11/15/2011	30	7	1	0.164038
Hot-Humid	B3010105 - Built-Up	28	1996	107706	SF	9/30/2010	40	7	10/16/2014	88	3	4	0.91748
Hot-Humid	B3010105 - Built-Up	28	2000	27418	SF	2/28/2013	80	4	7/3/2014	80	4	1	0.982524
Hot-Humid	B3010105 - Built-Up	28	2000	75730	SF	2/28/2013	80	4	7/3/2014	80	4	1	0.440091
Hot-Humid	B3010105 - Built-Up	28	2005	11340	SF	2/28/2013	80	4	7/3/2014	80	4	1	0.549142
Hot-Humid	B3010105 - Built-Up	28	2009	13160	SF	2/28/2013	88	3	7/3/2014	88	3	1	0.578706
Hot-Humid	B3010105 - Built-Up	28	1937	1452	SF	9/30/2010	95	2	10/10/2014	61	6	4	0.925572
Hot-Humid	B3010105 - Built-Up	28	2005	21832	SF	9/30/2010	67	5	8/25/2014	88	3	4	0.975338
Hot-Humid	B3010105 - Built-Up	28	2004	29016	SF	7/28/2010	62	6	8/28/2013	50	7	3	0.387921
Hot-Humid	B3010105 - Built-Up	28	1974	4825	SF	9/30/2010	63	6	5/17/2013	95	2	3	0.417138
Hot-Humid	B3010105 - Built-Up	28	1982	700	SF	5/2/2012	10	7	12/21/2012	10	7	1	0.297295
Hot-Humid	B3010105 - Built-Up	28	1987	8385	SF	9/30/2010	84	4	2/5/2014	88	3	3	0.468428
Hot-Humid	B3010105 - Built-Up	28	1990	270	SF	9/30/2010	43	7	9/4/2013	80	4	3	0.308294
Hot-Humid	B3010105 - Built-Up	28	1980	1200	SF	7/28/2010	16	7	6/27/2014	80	4	4	0.04417
Hot-Humid	B3010105 - Built-Up	28	1995	1485	SF	7/28/2010	79	4	11/15/2011	80	4	1	0.876223
Hot-Humid	B3010105 - Built-Up	28	1982	1206	SF	7/28/2010	61	6	9/13/2014	50	7	4	0.498369
Hot-Humid	B3010105 - Built-Up	28	2005	12000	SF	9/30/2010	67	5	6/14/2013	95	2	3	0.676162
Hot-Humid	B3010105 - Built-Up	28	1973	460	SF	7/28/2010	79	4	11/15/2011	80	4	1	0.032993
Hot-Humid	B3010105 - Built-Up	28	1991	10150	SF	9/30/2010	55	7	7/16/2013	95	2	3	0.200864
Hot-Humid	B3010105 - Built-Up	28	2006	26058	SF	9/30/2010	70	5	6/14/2013	88	3	3	0.944269
Hot-Humid	B3010105 - Built-Up	28	2006	12825	SF	9/30/2010	70	5	11/15/2011	71	5	1	0.863771
Hot-Humid	B3010105 - Built-Up	28	1999	300	SF	7/28/2010	71	5	8/21/2014	30	7	4	0.255292
Hot-Humid	B3010105 - Built-Up	28	1939	63	SF	2/6/2013	30	7	2/6/2013	30	7	0	0.262636
Hot-Humid	B3010105 - Built-Up	28	2000	2832	SF	7/28/2010	36	7	11/15/2011	30	7	1	0.354823
Hot-Humid	B3010105 - Built-Up	28	1964	26416	SF	7/7/2010	100	1	9/7/2014	88	3	4	0.417699
Hot-Humid	B3010105 - Built-Up	28	2006	52044	SF	9/30/2010	76	4	6/17/2013	61	6	3	0.699993
Hot-Humid	B3010105 - Built-Up	28	1979	4539	SF	7/7/2010	47	7	9/13/2012	88	3	2	0.476884
Hot-Humid	B3010105 - Built-Up	28	1979	1280	SF	9/30/2010	50	7	11/15/2011	50	7	1	0.060786

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1995	432	SF	7/28/2010	88	3	11/15/2011	88	3	1	0.227774
Hot-Humid	B3010105 - Built-Up	28	2005	1728	SF	9/30/2010	67	5	3/15/2014	88	3	3	0.160496
Hot-Humid	B3010105 - Built-Up	28	1988	14069	SF	9/30/2010	62	6	5/28/2014	61	6	4	0.204637
Hot-Humid	B3010105 - Built-Up	28	1990	8080	SF	7/28/2010	100	1	6/16/2014	61	6	4	0.061238
Hot-Humid	B3010105 - Built-Up	28	2004	5750	SF	7/28/2010	59	6	3/4/2013	61	6	3	0.375706
Hot-Humid	B3010105 - Built-Up	28	1985	6468	SF	9/30/2010	67	5	1/17/2014	71	5	3	0.902771
Hot-Humid	B3010105 - Built-Up	28	2000	32544	SF	9/30/2010	65	5	11/15/2011	61	6	1	0.881225
Hot-Humid	B3010105 - Built-Up	28	2006	1152	SF	9/30/2010	100	1	8/23/2013	71	5	3	0.949332
Hot-Humid	B3010105 - Built-Up	28	1987	22500	SF	9/30/2010	63	6	9/18/2014	88	3	4	0.060787
Hot-Humid	B3010105 - Built-Up	28	1982	110	SF	9/30/2010	43	7	8/22/2013	50	7	3	0.531617
Hot-Humid	B3010105 - Built-Up	28	2001	17030	SF	9/30/2010	41	7	4/4/2014	88	3	4	0.738899
Hot-Humid	B3010105 - Built-Up	28	2008	9374	SF	9/30/2010	83	4	6/11/2013	95	2	3	0.900136
Hot-Humid	B3010105 - Built-Up	28	1975	588	SF	7/28/2010	30	7	3/21/2013	61	6	3	0.921595
Hot-Humid	B3010105 - Built-Up	28	1941	200	SF	3/19/2013	61	6	3/19/2013	61	6	0	0.449615
Hot-Humid	B3010105 - Built-Up	28	1997	782	SF	7/28/2010	80	4	11/15/2011	80	4	1	0.46452
Hot-Humid	B3010105 - Built-Up	28	1995	1292	SF	9/30/2010	45	7	4/23/2013	30	7	3	0.062094
Hot-Humid	B3010105 - Built-Up	28	1980	515	SF	7/28/2010	61	6	9/12/2013	50	7	3	0.955011
Hot-Humid	B3010105 - Built-Up	28	2000	4932	SF	7/28/2010	45	7	11/15/2011	50	7	1	0.655391
Hot-Humid	B3010105 - Built-Up	28	1989	1350	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.738569
Hot-Humid	B3010105 - Built-Up	28	1998	40742	SF	9/30/2010	51	7	5/31/2014	50	7	4	0.064622
Hot-Humid	B3010105 - Built-Up	28	2005	3064	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.407878
Hot-Humid	B3010105 - Built-Up	28	1992	1123	SF	9/30/2010	43	7	3/15/2013	88	3	2	0.048331
Hot-Humid	B3010105 - Built-Up	28	1985	2240	SF	9/13/2011	88	3	3/18/2014	88	3	3	0.227815
Hot-Humid	B3010105 - Built-Up	28	1940	13542	SF	9/30/2010	95	2	11/15/2011	95	2	1	0.367056
Hot-Humid	B3010105 - Built-Up	28	2007	21680	SF	9/30/2010	67	5	3/18/2014	71	5	3	0.143592
Hot-Humid	B3010105 - Built-Up	28	1972	14000	SF	9/30/2010	100	1	5/9/2014	30	7	4	0.323194
Hot-Humid	B3010105 - Built-Up	28	2006	10221	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.988153
Hot-Humid	B3010105 - Built-Up	28	1986	320	SF	9/30/2010	47	7	11/15/2011	50	7	1	0.73419

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1980	1720	SF	7/28/2010	79	4	11/15/2011	80	4	1	0.474372
Hot-Humid	B3010105 - Built-Up	28	2006	108001	SF	9/30/2010	70	5	11/15/2011	71	5	1	0.708832
Hot-Humid	B3010105 - Built-Up	28	1987	20010	SF	9/30/2010	45	7	11/15/2011	50	7	1	0.139227
Hot-Humid	B3010105 - Built-Up	28	1951	2030	SF	7/28/2010	56	6	11/15/2011	61	6	1	0.793584
Hot-Humid	B3010105 - Built-Up	28	1999	26049	SF	9/30/2010	67	5	6/10/2014	95	2	4	0.623789
Hot-Humid	B3010105 - Built-Up	28	1984	8910	SF	9/30/2010	59	6	5/14/2014	88	3	4	0.280743
Hot-Humid	B3010105 - Built-Up	28	2000	170	SF	9/30/2010	99	2	11/15/2011	100	1	1	0.2863
Hot-Humid	B3010105 - Built-Up	28	1999	10829	SF	7/28/2010	50	7	5/28/2014	30	7	4	0.701759
Hot-Humid	B3010105 - Built-Up	28	1990	26510	SF	9/30/2010	82	4	8/21/2014	88	3	4	0.160296
Hot-Humid	B3010105 - Built-Up	28	1985	25000	SF	9/30/2010	59	6	5/28/2014	61	6	4	0.221782
Hot-Humid	B3010105 - Built-Up	28	1988	192	SF	9/30/2010	37	7	11/15/2011	30	7	1	0.436738
Hot-Humid	B3010105 - Built-Up	28	1990	345	SF	2/4/2013	61	6	2/4/2013	61	6	0	0.894088
Hot-Humid	B3010105 - Built-Up	28	1995	468	SF	7/28/2010	80	4	9/11/2014	71	5	4	0.23131
Hot-Humid	B3010105 - Built-Up	28	1995	384	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.467887
Hot-Humid	B3010105 - Built-Up	28	1939	126	SF	1/14/2013	30	7	1/14/2013	30	7	0	0.405415
Hot-Humid	B3010105 - Built-Up	28	1994	8780	SF	7/7/2010	100	1	8/10/2014	88	3	4	0.034732
Hot-Humid	B3010105 - Built-Up	28	1977	3864	SF	9/30/2010	57	6	5/31/2013	30	7	3	0.092942
Hot-Humid	B3010105 - Built-Up	28	1956	255	SF	7/28/2010	71	5	8/23/2014	80	4	4	0.083638
Hot-Humid	B3010105 - Built-Up	28	1983	1166	SF	6/28/2012	10	7	12/7/2012	61	6	0	0.674758
Hot-Humid	B3010105 - Built-Up	28	1983	10520	SF	7/7/2010	40	7	10/21/2012	95	2	2	0.67696
Hot-Humid	B3010105 - Built-Up	28	2004	10980	SF	7/28/2010	88	3	11/15/2011	88	3	1	0.035098
Hot-Humid	B3010105 - Built-Up	28	1979	10100	SF	7/7/2010	47	7	9/12/2012	88	3	2	0.62748
Hot-Humid	B3010105 - Built-Up	28	2001	27160	SF	9/30/2010	100	1	3/12/2014	88	3	3	0.541336
Hot-Humid	B3010105 - Built-Up	28	1954	800	SF	9/30/2010	61	6	11/15/2011	61	6	1	0.22513
Hot-Humid	B3010105 - Built-Up	28	1979	3721	SF	7/7/2010	43	7	2/18/2014	80	4	4	0.688297
Hot-Humid	B3010105 - Built-Up	28	2004	161342	SF	7/28/2010	47	7	11/15/2011	50	7	1	0.349966
Hot-Humid	B3010105 - Built-Up	28	1980	6211	SF	9/30/2010	30	7	11/15/2011	30	7	1	0.706993
Hot-Humid	B3010105 - Built-Up	28	1983	1700	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.229049

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	2000	20336	SF	9/30/2010	55	7	5/14/2014	88	3	4	0.721229
Hot-Humid	B3010105 - Built-Up	28	1990	19650	SF	1/31/2012	88	3	5/14/2014	88	3	2	0.846917
Hot-Humid	B3010105 - Built-Up	28	1993	750	SF	1/31/2012	88	3	5/14/2014	88	3	2	0.031358
Hot-Humid	B3010105 - Built-Up	28	1993	1050	SF	1/31/2012	88	3	5/14/2014	88	3	2	0.515633
Hot-Humid	B3010105 - Built-Up	28	1985	4000	SF	7/28/2010	82	4	11/15/2011	80	4	1	0.42255
Hot-Humid	B3010105 - Built-Up	28	1962	972	SF	7/28/2010	63	6	6/17/2013	71	5	3	0.2763
Hot-Humid	B3010105 - Built-Up	28	1989	7920	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.759258
Hot-Humid	B3010105 - Built-Up	28	2005	11500	SF	9/30/2010	73	5	3/19/2014	71	5	3	0.165926
Hot-Humid	B3010105 - Built-Up	28	1990	15112	SF	12/20/2012	61	6	8/1/2014	80	4	2	0.072644
Hot-Humid	B3010105 - Built-Up	28	2003	1950	SF	7/28/2010	72	5	7/8/2014	71	5	4	0.464259
Hot-Humid	B3010105 - Built-Up	28	2000	1575	SF	9/30/2010	100	1	6/12/2013	88	3	3	0.536771
Hot-Humid	B3010105 - Built-Up	28	1964	21188	SF	1/29/2013	95	2	2/2/2014	95	2	1	0.204278
Hot-Humid	B3010105 - Built-Up	28	1988	7320	SF	7/7/2010	100	1	4/9/2014	88	3	4	0.829651
Hot-Humid	B3010105 - Built-Up	28	1985	15384	SF	9/30/2010	65	5	5/11/2014	80	4	4	0.776681
Hot-Humid	B3010105 - Built-Up	28	1995	636	SF	9/30/2010	41	7	11/15/2011	50	7	1	0.329479
Hot-Humid	B3010105 - Built-Up	28	1978	600	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.931791
Hot-Humid	B3010105 - Built-Up	28	1992	16245	SF	9/30/2010	37	7	5/10/2014	61	6	4	0.824109
Hot-Humid	B3010105 - Built-Up	28	2005	23508	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.303198
Hot-Humid	B3010105 - Built-Up	28	2005	1630	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.717045
Hot-Humid	B3010105 - Built-Up	28	1970	1020	SF	7/28/2010	22	7	3/27/2013	30	7	3	0.526085
Hot-Humid	B3010105 - Built-Up	28	2008	14307	SF	2/13/2013	100	1	2/13/2013	100	1	0	0.300334
Hot-Humid	B3010105 - Built-Up	28	1986	5852	SF	9/30/2010	58	6	11/15/2011	61	6	1	0.56412
Hot-Humid	B3010105 - Built-Up	28	1995	196	SF	12/26/2012	71	5	9/18/2014	71	5	2	0.572685
Hot-Humid	B3010105 - Built-Up	28	1984	11824	SF	7/28/2010	55	7	11/15/2011	50	7	1	0.921604
Hot-Humid	B3010105 - Built-Up	28	2010	1000	SF	7/28/2010	50	7	9/20/2013	95	2	3	0.812395
Hot-Humid	B3010105 - Built-Up	28	2003	700	SF	7/28/2010	68	5	11/15/2011	71	5	1	0.218195
Hot-Humid	B3010105 - Built-Up	28	1997	1360	SF	9/30/2010	49	7	5/2/2013	95	2	3	0.767383
Hot-Humid	B3010105 - Built-Up	28	1969	2600	SF	9/30/2010	57	6	6/18/2013	61	6	3	0.204707

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1976	6653	SF	9/30/2010	61	6	1/27/2014	71	5	3	0.148337
Hot-Humid	B3010105 - Built-Up	28	1939	171	SF	2/5/2013	30	7	2/5/2013	30	7	0	0.018863
Hot-Humid	B3010105 - Built-Up	28	1996	2464	SF	7/20/2012	80	4	8/6/2014	80	4	2	0.183535
Hot-Humid	B3010105 - Built-Up	28	1992	3465	SF	9/30/2010	71	5	1/10/2014	88	3	3	0.228317
Hot-Humid	B3010105 - Built-Up	28	1964	1640	SF	7/28/2010	88	3	11/15/2011	88	3	1	0.748594
Hot-Humid	B3010105 - Built-Up	28	2000	6779	SF	7/28/2010	80	4	11/15/2011	80	4	1	0.796848
Hot-Humid	B3010105 - Built-Up	28	1979	55231	SF	7/7/2010	38	7	9/10/2012	88	3	2	0.244071
Hot-Humid	B3010105 - Built-Up	28	1997	6400	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.371079
Hot-Humid	B3010105 - Built-Up	28	1997	32572	SF	9/30/2010	94	2	11/15/2011	95	2	1	0.505174
Hot-Humid	B3010105 - Built-Up	28	1944	504	SF	9/30/2010	61	6	1/27/2014	71	5	3	0.696731
Hot-Humid	B3010105 - Built-Up	28	2005	2000	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.679324
Hot-Humid	B3010105 - Built-Up	28	1988	324	SF	7/28/2010	61	6	6/26/2013	61	6	3	0.508958
Hot-Humid	B3010105 - Built-Up	28	1994	7450	SF	9/30/2010	83	4	11/15/2011	88	3	1	0.113907
Hot-Humid	B3010105 - Built-Up	28	2004	555	SF	4/26/2012	88	3	4/26/2012	88	3	0	0.083183
Hot-Humid	B3010105 - Built-Up	28	1995	469	SF	7/28/2010	80	4	6/11/2014	71	5	4	0.032396
Hot-Humid	B3010105 - Built-Up	28	1990	992	SF	2/7/2013	71	5	2/7/2013	71	5	0	0.116535
Hot-Humid	B3010105 - Built-Up	28	2007	16416	SF	3/6/2012	80	4	1/30/2014	80	4	2	0.702035
Hot-Humid	B3010105 - Built-Up	28	1942	288004	SF	4/5/2012	61	6	4/5/2012	61	6	0	0.19689
Hot-Humid	B3010105 - Built-Up	28	1980	765	SF	7/28/2010	41	7	11/15/2011	50	7	1	0.189935
Hot-Humid	B3010105 - Built-Up	28	1993	1000	SF	7/28/2010	100	1	9/4/2013	95	2	3	0.632352
Hot-Humid	B3010105 - Built-Up	28	1995	600	SF	7/28/2010	15	7	1/27/2014	10	7	3	0.820519
Hot-Humid	B3010105 - Built-Up	28	1998	1500	SF	7/28/2010	55	7	1/27/2014	30	7	3	0.725361
Hot-Humid	B3010105 - Built-Up	28	1995	1220	SF	7/28/2010	22	7	1/27/2014	10	7	3	0.418061
Hot-Humid	B3010105 - Built-Up	28	1993	150	SF	12/19/2012	10	7	9/11/2014	10	7	2	0.935433
Hot-Humid	B3010105 - Built-Up	28	1986	16742	SF	7/7/2010	100	1	8/11/2014	88	3	4	0.405568
Hot-Humid	B3010105 - Built-Up	28	1974	1930	SF	7/28/2010	59	6	11/15/2011	61	6	1	0.410873
Hot-Humid	B3010105 - Built-Up	28	1992	4000	SF	9/30/2010	80	4	11/15/2011	80	4	1	0.808289
Hot-Humid	B3010105 - Built-Up	28	1985	1590	SF	7/28/2010	33	7	3/28/2014	80	4	4	0.232001

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1982	11470	SF	9/30/2010	68	5	11/15/2011	71	5	1	0.108931
Hot-Humid	B3010105 - Built-Up	28	1980	224	SF	6/18/2012	61	6	9/11/2013	61	6	1	0.457704
Hot-Humid	B3010105 - Built-Up	28	2000	2520	SF	7/28/2010	59	6	11/15/2011	61	6	1	0.360916
Hot-Humid	B3010105 - Built-Up	28	1996	827	SF	7/7/2010	43	7	5/8/2014	50	7	4	0.073408
Hot-Humid	B3010105 - Built-Up	28	1995	3866	SF	7/7/2010	100	1	8/11/2014	88	3	4	0.753867
Hot-Humid	B3010105 - Built-Up	28	1991	1692	SF	7/28/2010	88	3	9/25/2014	80	4	4	0.014503
Hot-Humid	B3010105 - Built-Up	28	1979	200	SF	7/7/2010	40	7	9/9/2012	71	5	2	0.355683
Hot-Humid	B3010105 - Built-Up	28	1988	200	SF	7/28/2010	80	4	9/12/2014	80	4	4	0.236906
Hot-Humid	B3010105 - Built-Up	28	1985	4500	SF	9/30/2010	67	5	11/15/2011	71	5	1	0.174243
Hot-Humid	B3010105 - Built-Up	28	1975	8151	SF	9/30/2010	95	2	11/15/2011	95	2	1	0.682272
Hot-Humid	B3010105 - Built-Up	28	1970	588	SF	7/28/2010	23	7	2/20/2013	10	7	3	0.506395
Hot-Humid	B3010105 - Built-Up	28	2005	4500	SF	9/30/2010	100	1	9/25/2014	30	7	4	0.007334
Hot-Humid	B3010105 - Built-Up	28	1976	703	SF	5/9/2012	71	5	7/8/2014	50	7	2	0.106876
Hot-Humid	B3010105 - Built-Up	28	2001	168	SF	7/28/2010	95	2	9/11/2014	88	3	4	0.012296
Hot-Humid	B3010105 - Built-Up	28	1970	6515	SF	7/28/2010	6	7	9/5/2014	61	6	4	0.26882
Hot-Humid	B3010105 - Built-Up	28	2003	13073	SF	9/30/2010	98	2	11/15/2011	100	1	1	0.042827
Hot-Humid	B3010105 - Built-Up	28	2005	71401	SF	9/30/2010	43	7	5/10/2013	30	7	3	0.383622
Hot-Humid	B3010105 - Built-Up	28	1968	3	SF	9/30/2010	43	7	5/10/2013	30	7	3	0.333534
Hot-Humid	B3010105 - Built-Up	28	1969	5790	SF	9/30/2010	43	7	3/15/2013	95	2	2	0.873508
Hot-Humid	B3010105 - Built-Up	28	1980	35681	SF	9/30/2010	43	7	4/26/2014	71	5	4	0.019527
Hot-Humid	B3010105 - Built-Up	28	1970	10818	SF	7/28/2010	23	7	9/22/2014	61	6	4	0.481151
Hot-Humid	B3010105 - Built-Up	28	1941	5900	SF	6/12/2012	61	6	6/10/2014	61	6	2	0.376871
Hot-Humid	B3010105 - Built-Up	28	1997	4811	SF	7/28/2010	59	6	6/23/2014	61	6	4	0.089402
Hot-Humid	B3010105 - Built-Up	28	1971	2344	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.797673
Hot-Humid	B3010105 - Built-Up	28	2006	10740	SF	2/1/2013	80	4	2/1/2013	80	4	0	0.675401
Hot-Humid	B3010105 - Built-Up	28	1985	12845	SF	9/30/2010	67	5	2/5/2014	30	7	3	0.962856
Hot-Humid	B3010105 - Built-Up	28	1971	224	SF	2/12/2013	30	7	2/12/2013	30	7	0	0.744395
Hot-Humid	B3010105 - Built-Up	28	1980	228	SF	9/30/2010	30	7	11/15/2011	30	7	1	0.672294

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1995	540	SF	7/28/2010	71	5	8/23/2014	80	4	4	0.504929
Hot-Humid	B3010105 - Built-Up	28	2010	9151	SF	2/21/2013	88	3	9/11/2014	80	4	2	0.688553
Hot-Humid	B3010105 - Built-Up	28	1990	4000	SF	2/21/2013	61	6	9/11/2014	61	6	2	0.542995
Hot-Humid	B3010105 - Built-Up	28	2000	450	SF	9/30/2010	55	7	11/15/2011	50	7	1	0.871069
Hot-Humid	B3010105 - Built-Up	28	1995	51051	SF	9/30/2010	43	7	11/15/2011	50	7	1	0.792446
Hot-Humid	B3010105 - Built-Up	28	1980	12750	SF	7/28/2010	50	7	11/15/2011	50	7	1	0.223293
Hot-Humid	B3010105 - Built-Up	28	1954	1866	SF	7/7/2010	100	1	12/8/2013	88	3	3	0.1329
Hot-Humid	B3010105 - Built-Up	28	1960	884	SF	9/30/2010	43	7	5/17/2014	88	3	4	0.738813
Hot-Humid	B3010105 - Built-Up	28	2008	2573	SF	7/28/2010	100	1	9/12/2014	71	5	4	0.438639
Hot-Humid	B3010105 - Built-Up	28	1986	5040	SF	7/28/2010	44	7	3/12/2013	50	7	3	0.108964
Hot-Humid	B3010105 - Built-Up	28	2007	504	SF	9/30/2010	95	2	5/9/2014	88	3	4	0.936448
Hot-Humid	B3010105 - Built-Up	28	2003	180	SF	7/28/2010	68	5	4/10/2013	71	5	3	0.851023
Hot-Humid	B3010105 - Built-Up	28	2005	2250	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.241239
Hot-Humid	B3010105 - Built-Up	28	2003	600	SF	7/28/2010	68	5	1/3/2014	71	5	3	0.692131
Hot-Humid	B3010105 - Built-Up	28	1995	5082	SF	7/28/2010	77	4	9/12/2014	71	5	4	0.640562
Hot-Humid	B3010105 - Built-Up	28	1998	840	SF	7/28/2010	87	3	9/12/2014	80	4	4	0.136158
Hot-Humid	B3010105 - Built-Up	28	1995	5324	SF	7/28/2010	77	4	9/15/2014	71	5	4	0.753118
Hot-Humid	B3010105 - Built-Up	28	1998	2619	SF	7/28/2010	87	3	9/15/2014	88	3	4	0.861798
Hot-Humid	B3010105 - Built-Up	28	1995	4719	SF	7/28/2010	87	3	9/5/2014	80	4	4	0.713921
Hot-Humid	B3010105 - Built-Up	28	1998	2832	SF	7/28/2010	78	4	9/5/2014	71	5	4	0.12386
Hot-Humid	B3010105 - Built-Up	28	2005	4100	SF	9/30/2010	45	7	6/5/2014	88	3	4	0.162926
Hot-Humid	B3010105 - Built-Up	28	2000	275	SF	7/28/2010	29	7	11/15/2011	30	7	1	0.274317
Hot-Humid	B3010105 - Built-Up	28	1995	4750	SF	7/28/2010	68	5	6/18/2013	88	3	3	0.394317
Hot-Humid	B3010105 - Built-Up	28	1995	16908	SF	9/30/2010	51	7	11/15/2011	50	7	1	0.08926
Hot-Humid	B3010105 - Built-Up	28	1984	7920	SF	9/30/2010	56	6	11/15/2011	61	6	1	0.750883
Hot-Humid	B3010105 - Built-Up	28	1995	8349	SF	9/30/2010	95	2	4/15/2014	71	5	4	0.468428
Hot-Humid	B3010105 - Built-Up	28	2005	1885	SF	9/30/2010	67	5	4/14/2014	88	3	4	0.70752
Hot-Humid	B3010105 - Built-Up	28	1985	221	SF	9/30/2010	80	4	11/15/2011	80	4	1	0.099415

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1943	336	SF	7/28/2010	61	6	8/21/2014	10	7	4	0.972635
Hot-Humid	B3010105 - Built-Up	28	2003	70501	SF	9/30/2010	43	7	8/14/2014	61	6	4	0.553871
Hot-Humid	B3010105 - Built-Up	28	1990	888	SF	7/28/2010	80	4	11/15/2011	80	4	1	0.513598
Hot-Humid	B3010105 - Built-Up	28	1992	5060	SF	7/28/2010	80	4	11/15/2011	80	4	1	0.671242
Hot-Humid	B3010105 - Built-Up	28	1993	1533	SF	7/28/2010	88	3	9/10/2014	71	5	4	0.069584
Hot-Humid	B3010105 - Built-Up	28	2005	7260	SF	9/30/2010	55	7	4/7/2013	30	7	3	0.54604
Hot-Humid	B3010105 - Built-Up	28	1965	2640	SF	7/28/2010	45	7	11/15/2011	50	7	1	0.571508
Hot-Humid	B3010105 - Built-Up	28	1982	1206	SF	7/28/2010	61	6	9/13/2014	61	6	4	0.208334
Hot-Humid	B3010105 - Built-Up	28	2003	5500	SF	7/28/2010	100	1	11/15/2011	100	1	1	0.022865
Hot-Humid	B3010105 - Built-Up	28	1996	25300	SF	9/30/2010	53	7	4/2/2013	88	3	3	0.748828
Hot-Humid	B3010105 - Built-Up	28	2005	12220	SF	9/30/2010	47	7	11/15/2011	50	7	1	0.330983
Hot-Humid	B3010105 - Built-Up	28	1986	7476	SF	7/28/2010	43	7	9/24/2014	30	7	4	0.705768
Hot-Humid	B3010105 - Built-Up	28	1984	432	SF	9/30/2010	41	7	4/12/2014	88	3	4	0.80818
Hot-Humid	B3010105 - Built-Up	28	1932	20700	SF	7/28/2010	84	4	11/15/2011	88	3	1	0.509023
Hot-Humid	B3010105 - Built-Up	28	1998	600	SF	3/1/2012	71	5	3/1/2012	71	5	0	0.733402
Hot-Humid	B3010105 - Built-Up	28	1980	81	SF	7/28/2010	30	7	11/15/2011	30	7	1	0.035366
Hot-Humid	B3010105 - Built-Up	28	2000	3316	SF	7/28/2010	100	1	1/18/2013	80	4	2	0.402278
Hot-Humid	B3010105 - Built-Up	28	1998	1000	SF	3/15/2013	71	5	3/15/2013	71	5	0	0.803422
Hot-Humid	B3010105 - Built-Up	28	1997	10500	SF	9/30/2010	89	3	11/15/2011	88	3	1	0.420115
Hot-Humid	B3010105 - Built-Up	28	2005	17810	SF	9/30/2010	67	5	5/27/2013	50	7	3	0.009675
Hot-Humid	B3010105 - Built-Up	28	1980	81	SF	7/28/2010	30	7	11/15/2011	30	7	1	0.626489
Hot-Humid	B3010105 - Built-Up	28	2005	27543	SF	9/30/2010	67	5	8/16/2014	88	3	4	0.259267
Hot-Humid	B3010105 - Built-Up	28	2000	1875	SF	12/20/2012	80	4	2/10/2014	80	4	1	0.367042
Hot-Humid	B3010105 - Built-Up	28	1980	162	SF	9/30/2010	80	4	11/15/2011	80	4	1	0.578309
Hot-Humid	B3010105 - Built-Up	28	2005	12000	SF	9/30/2010	67	5	6/14/2013	95	2	3	0.612261
Hot-Humid	B3010105 - Built-Up	28	1993	336	SF	7/28/2010	71	5	8/21/2014	10	7	4	0.528926
Hot-Humid	B3010105 - Built-Up	28	1981	1300	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.517324
Hot-Humid	B3010105 - Built-Up	28	1990	6200	SF	9/30/2010	74	5	11/15/2011	71	5	1	0.397688

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	2010	384	SF	1/29/2013	88	3	1/29/2013	88	3	0	0.223179
Hot-Humid	B3010105 - Built-Up	28	1942	3612	SF	7/28/2010	36	7	1/17/2014	30	7	3	0.171389
Hot-Humid	B3010105 - Built-Up	28	1995	19733	SF	9/30/2010	98	2	11/15/2011	100	1	1	0.58621
Hot-Humid	B3010105 - Built-Up	28	2004	5200	SF	9/30/2010	100	1	9/25/2014	88	3	4	0.729536
Hot-Humid	B3010105 - Built-Up	28	1986	12500	SF	9/30/2010	96	2	6/23/2013	95	2	3	0.933074
Hot-Humid	B3010105 - Built-Up	28	1989	1500	SF	9/30/2010	81	4	11/15/2011	80	4	1	0.48287
Hot-Humid	B3010105 - Built-Up	28	2006	31000	SF	9/30/2010	70	5	6/5/2014	80	4	4	0.932973
Hot-Humid	B3010105 - Built-Up	28	1988	1250	SF	9/30/2010	61	6	11/15/2011	61	6	1	0.49272
Hot-Humid	B3010105 - Built-Up	28	1944	84	SF	2/12/2013	71	5	2/12/2013	71	5	0	0.963159
Hot-Humid	B3010105 - Built-Up	28	2005	316	SF	7/28/2010	59	6	11/15/2011	61	6	1	0.728951
Hot-Humid	B3010105 - Built-Up	28	1932	20700	SF	7/28/2010	84	4	11/15/2011	88	3	1	0.217436
Hot-Humid	B3010105 - Built-Up	28	1985	10244	SF	7/28/2010	87	3	11/15/2011	88	3	1	0.231466
Hot-Humid	B3010105 - Built-Up	28	1988	5600	SF	7/28/2010	40	7	11/15/2011	30	7	1	0.507941
Hot-Humid	B3010105 - Built-Up	28	1988	1530	SF	7/28/2010	65	5	11/15/2011	61	6	1	0.822454
Hot-Humid	B3010105 - Built-Up	28	1988	1575	SF	9/30/2010	65	5	11/15/2011	61	6	1	0.194859
Hot-Humid	B3010105 - Built-Up	28	1979	9600	SF	7/7/2010	43	7	9/12/2012	88	3	2	0.550064
Hot-Humid	B3010105 - Built-Up	28	1999	68489	SF	9/30/2010	37	7	3/30/2013	61	6	3	0.329393
Hot-Humid	B3010105 - Built-Up	28	2008	20150	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.705706
Hot-Humid	B3010105 - Built-Up	28	2004	10400	SF	9/30/2010	64	6	5/5/2014	61	6	4	0.635365
Hot-Humid	B3010105 - Built-Up	28	2000	32400	SF	9/30/2010	55	7	4/15/2014	88	3	4	0.148994
Hot-Humid	B3010105 - Built-Up	28	2002	416	SF	1/31/2013	95	2	1/31/2013	95	2	0	0.805357
Hot-Humid	B3010105 - Built-Up	28	1985	14760	SF	7/28/2010	61	6	2/26/2014	50	7	4	0.500622
Hot-Humid	B3010105 - Built-Up	28	2004	7150	SF	7/28/2010	100	1	9/9/2014	95	2	4	0.503675
Hot-Humid	B3010105 - Built-Up	28	1995	112501	SF	3/21/2012	80	4	3/21/2012	80	4	0	0.522697
Hot-Humid	B3010105 - Built-Up	28	1993	988	SF	7/7/2010	50	7	9/9/2014	88	3	4	0.71722
Hot-Humid	B3010105 - Built-Up	28	2005	832	SF	9/30/2010	76	4	9/29/2014	61	6	4	0.730542
Hot-Humid	B3010105 - Built-Up	28	1984	3360	SF	7/28/2010	88	3	9/25/2014	80	4	4	0.342267
Hot-Humid	B3010105 - Built-Up	28	1996	11200	SF	9/30/2010	82	4	11/15/2011	80	4	1	0.246464

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	2000	10650	SF	9/30/2010	67	5	1/17/2014	80	4	3	0.439667
Hot-Humid	B3010105 - Built-Up	28	2002	7567	SF	7/7/2010	59	6	2/3/2014	95	2	4	0.739991
Hot-Humid	B3010105 - Built-Up	28	1990	6600	SF	9/30/2010	67	5	11/15/2011	71	5	1	0.755151
Hot-Humid	B3010105 - Built-Up	28	1990	101745	SF	9/30/2010	64	6	4/24/2013	71	5	3	0.426896
Hot-Humid	B3010105 - Built-Up	28	1939	63	SF	2/5/2013	30	7	2/5/2013	30	7	0	0.720381
Hot-Humid	B3010105 - Built-Up	28	2000	217	SF	7/28/2010	40	7	11/15/2011	30	7	1	0.007343
Hot-Humid	B3010105 - Built-Up	28	2000	1050	SF	9/30/2010	88	3	1/27/2014	71	5	3	0.266786
Hot-Humid	B3010105 - Built-Up	28	1970	26952	SF	7/28/2010	57	6	11/6/2012	61	6	2	0.033169
Hot-Humid	B3010105 - Built-Up	28	1956	2951	SF	7/7/2010	100	1	11/24/2013	88	3	3	0.775126
Hot-Humid	B3010105 - Built-Up	28	1946	63	SF	2/5/2013	30	7	2/5/2013	30	7	0	0.131044
Hot-Humid	B3010105 - Built-Up	28	1970	588	SF	7/28/2010	17	7	3/11/2013	10	7	3	0.631941
Hot-Humid	B3010105 - Built-Up	28	1989	3600	SF	9/30/2010	80	4	11/15/2011	80	4	1	0.662128
Hot-Humid	B3010105 - Built-Up	28	1960	33000	SF	4/27/2012	10	7	4/27/2012	10	7	0	0.568365
Hot-Humid	B3010105 - Built-Up	28	1995	22450	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.707028
Hot-Humid	B3010105 - Built-Up	28	1943	60501	SF	9/30/2010	43	7	4/21/2013	61	6	3	0.387658
Hot-Humid	B3010105 - Built-Up	28	1979	1950	SF	9/30/2010	54	7	11/15/2011	50	7	1	0.814174
Hot-Humid	B3010105 - Built-Up	28	1996	8371	SF	3/12/2013	80	4	6/9/2014	80	4	1	0.250637
Hot-Humid	B3010105 - Built-Up	28	2011	9275	SF	7/28/2010	71	5	6/9/2014	61	6	4	0.361152
Hot-Humid	B3010105 - Built-Up	28	2005	2640	SF	9/30/2010	74	5	11/15/2011	71	5	1	0.509181
Hot-Humid	B3010105 - Built-Up	28	2000	9558	SF	2/6/2013	95	2	7/2/2014	80	4	1	0.101408
Hot-Humid	B3010105 - Built-Up	28	2003	39237	SF	9/30/2010	67	5	7/19/2013	10	7	3	0.867682
Hot-Humid	B3010105 - Built-Up	28	1965	27300	SF	7/28/2010	74	5	11/15/2011	71	5	1	0.642162
Hot-Humid	B3010105 - Built-Up	28	1990	8090	SF	9/30/2010	76	4	11/15/2011	71	5	1	0.991473
Hot-Humid	B3010105 - Built-Up	28	1983	1796	SF	1/22/2013	61	6	9/11/2014	50	7	2	0.594868
Hot-Humid	B3010105 - Built-Up	28	1996	2010	SF	7/28/2010	69	5	11/15/2011	71	5	1	0.546351
Hot-Humid	B3010105 - Built-Up	28	1978	23430	SF	9/30/2010	64	6	11/15/2011	61	6	1	0.792267
Hot-Humid	B3010105 - Built-Up	28	1990	12284	SF	6/5/2012	50	7	1/18/2013	30	7	1	0.615427
Hot-Humid	B3010105 - Built-Up	28	1985	2214	SF	9/30/2010	30	7	1/27/2014	71	5	3	0.96296

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	2005	70374	SF	9/30/2010	43	7	10/16/2014	88	3	4	0.120086
Hot-Humid	B3010105 - Built-Up	28	2006	21025	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.121493
Hot-Humid	B3010105 - Built-Up	28	1990	408	SF	2/20/2013	61	6	2/20/2013	61	6	0	0.865025
Hot-Humid	B3010105 - Built-Up	28	2011	350	SF	7/28/2010	47	7	6/16/2014	88	3	4	0.866304
Hot-Humid	B3010105 - Built-Up	28	1970	10120	SF	7/28/2010	39	7	11/15/2011	30	7	1	0.008019
Hot-Humid	B3010105 - Built-Up	28	2011	19700	SF	7/28/2010	59	6	6/16/2014	95	2	4	0.498958
Hot-Humid	B3010105 - Built-Up	28	2005	19011	SF	9/30/2010	43	7	8/25/2014	71	5	4	0.190951
Hot-Humid	B3010105 - Built-Up	28	1970	2849	SF	7/28/2010	4	7	6/17/2013	71	5	3	0.032104
Hot-Humid	B3010105 - Built-Up	28	1970	860	SF	7/28/2010	1	7	6/17/2013	61	6	3	0.226138
Hot-Humid	B3010105 - Built-Up	28	2006	1125	SF	7/28/2010	73	5	9/20/2013	71	5	3	0.074611
Hot-Humid	B3010105 - Built-Up	28	1993	21000	SF	7/28/2010	58	6	9/20/2013	61	6	3	0.011103
Hot-Humid	B3010105 - Built-Up	28	2010	759	SF	1/2/2012	82	4	11/15/2011	80	4	0	0.054048
Hot-Humid	B3010105 - Built-Up	28	2008	8758	SF	9/30/2010	67	5	5/20/2013	95	2	3	0.421358
Hot-Humid	B3010105 - Built-Up	28	1998	9600	SF	9/30/2010	51	7	4/17/2013	71	5	3	0.812213
Hot-Humid	B3010105 - Built-Up	28	1987	4346	SF	7/28/2010	30	7	11/15/2011	30	7	1	0.519794
Hot-Humid	B3010105 - Built-Up	28	1990	121	SF	7/28/2010	80	4	9/6/2014	50	7	4	0.40486
Hot-Humid	B3010105 - Built-Up	28	2001	94875	SF	9/30/2010	88	3	4/11/2014	71	5	4	0.453135
Hot-Humid	B3010105 - Built-Up	28	1999	31625	SF	9/30/2010	80	4	4/11/2014	61	6	4	0.197207
Hot-Humid	B3010105 - Built-Up	28	2007	8000	SF	9/30/2010	100	1	6/3/2014	88	3	4	0.466944
Hot-Humid	B3010105 - Built-Up	28	1992	855	SF	5/16/2012	80	4	3/29/2013	80	4	1	0.216557
Hot-Humid	B3010105 - Built-Up	28	1995	270	SF	7/28/2010	100	1	8/12/2014	95	2	4	0.453971
Hot-Humid	B3010105 - Built-Up	28	1941	300	SF	3/21/2013	80	4	9/18/2014	80	4	1	0.616059
Hot-Humid	B3010105 - Built-Up	28	1997	14149	SF	9/30/2010	55	7	5/21/2014	88	3	4	0.93114
Hot-Humid	B3010105 - Built-Up	28	2005	7152	SF	9/30/2010	97	2	11/15/2011	100	1	1	0.570998
Hot-Humid	B3010105 - Built-Up	28	1944	8835	SF	9/30/2010	95	2	11/15/2011	95	2	1	0.378988
Hot-Humid	B3010105 - Built-Up	28	1996	1490	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.072439
Hot-Humid	B3010105 - Built-Up	28	2005	9440	SF	9/30/2010	76	4	11/15/2011	71	5	1	0.519808
Hot-Humid	B3010105 - Built-Up	28	1988	54451	SF	9/30/2010	38	7	11/15/2011	30	7	1	0.365934

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1955	11679	SF	7/7/2010	100	1	12/4/2013	88	3	3	0.163483
Hot-Humid	B3010105 - Built-Up	28	2003	19589	SF	9/30/2010	62	6	6/3/2013	88	3	3	0.355601
Hot-Humid	B3010105 - Built-Up	28	2003	1280	SF	7/28/2010	100	1	11/15/2011	100	1	1	0.963641
Hot-Humid	B3010105 - Built-Up	28	1988	2000	SF	9/30/2010	61	6	11/15/2011	61	6	1	0.601403
Hot-Humid	B3010105 - Built-Up	28	1985	12440	SF	9/30/2010	40	7	4/13/2014	61	6	4	0.651188
Hot-Humid	B3010105 - Built-Up	28	2005	25478	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.541145
Hot-Humid	B3010105 - Built-Up	28	1958	97406	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.217403
Hot-Humid	B3010105 - Built-Up	28	1980	840	SF	7/28/2010	80	4	11/15/2011	80	4	1	0.394254
Hot-Humid	B3010105 - Built-Up	28	1984	13823	SF	7/28/2010	57	6	11/15/2011	61	6	1	0.584774
Hot-Humid	B3010105 - Built-Up	28	1990	43539	SF	2/12/2013	80	4	2/12/2013	80	4	0	0.982221
Hot-Humid	B3010105 - Built-Up	28	2010	1000	SF	2/12/2013	95	2	2/12/2013	95	2	0	0.718512
Hot-Humid	B3010105 - Built-Up	28	2001	2329	SF	7/28/2010	80	4	11/15/2011	80	4	1	0.132134
Hot-Humid	B3010105 - Built-Up	28	2001	2848	SF	9/30/2010	50	7	11/15/2011	50	7	1	0.994235
Hot-Humid	B3010105 - Built-Up	28	1989	2545	SF	9/30/2010	43	7	3/29/2013	50	7	2	0.800954
Hot-Humid	B3010105 - Built-Up	28	1942	3000	SF	9/30/2010	38	7	11/15/2011	30	7	1	0.304223
Hot-Humid	B3010105 - Built-Up	28	1984	435	SF	9/30/2010	43	7	9/4/2013	80	4	3	0.968168
Hot-Humid	B3010105 - Built-Up	28	1980	15811	SF	3/19/2013	50	7	3/19/2013	50	7	0	0.332285
Hot-Humid	B3010105 - Built-Up	28	1990	84	SF	7/28/2010	61	6	11/15/2011	61	6	1	0.213608
Hot-Humid	B3010105 - Built-Up	28	1995	195	SF	7/28/2010	59	6	4/12/2013	61	6	3	0.640837
Hot-Humid	B3010105 - Built-Up	28	1995	756	SF	7/28/2010	59	6	4/12/2013	61	6	3	0.694328
Hot-Humid	B3010105 - Built-Up	28	1995	9027	SF	9/30/2010	62	6	3/6/2014	61	6	3	0.615703
Hot-Humid	B3010105 - Built-Up	28	2006	121	SF	9/30/2010	95	2	11/15/2011	95	2	1	0.398582
Hot-Humid	B3010105 - Built-Up	28	1999	8664	SF	9/30/2010	53	7	3/10/2014	95	2	3	0.754893
Hot-Humid	B3010105 - Built-Up	28	1996	208	SF	5/4/2012	80	4	7/31/2013	80	4	1	0.523435
Hot-Humid	B3010105 - Built-Up	28	1974	4125	SF	9/30/2010	100	1	2/25/2014	71	5	3	0.896518
Hot-Humid	B3010105 - Built-Up	28	1988	18156	SF	7/28/2010	57	6	11/15/2011	61	6	1	0.549217
Hot-Humid	B3010105 - Built-Up	28	1964	23048	SF	7/7/2010	100	1	5/28/2014	88	3	4	0.603489
Hot-Humid	B3010105 - Built-Up	28	1998	484	SF	9/30/2010	51	7	6/18/2013	88	3	3	0.834476

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1990	22000	SF	9/30/2010	91	3	5/20/2013	88	3	3	0.533322
Hot-Humid	B3010105 - Built-Up	28	2002	2025	SF	9/30/2010	100	1	5/1/2014	100	1	4	0.136765
Hot-Humid	B3010105 - Built-Up	28	1994	2500	SF	9/30/2010	27	7	11/15/2011	30	7	1	0.423917
Hot-Humid	B3010105 - Built-Up	28	1992	5700	SF	9/30/2010	62	6	11/15/2011	61	6	1	0.086599
Hot-Humid	B3010105 - Built-Up	28	1980	3379	SF	9/30/2010	50	7	11/15/2011	50	7	1	0.505133
Hot-Humid	B3010105 - Built-Up	28	1932	6525	SF	7/28/2010	53	7	4/10/2013	50	7	3	0.655604
Hot-Humid	B3010105 - Built-Up	28	2003	37572	SF	7/7/2010	100	1	3/9/2014	95	2	4	0.926181
Hot-Humid	B3010105 - Built-Up	28	2003	52089	SF	9/30/2010	73	5	4/13/2014	50	7	4	0.431078
Hot-Humid	B3010105 - Built-Up	28	2003	60	SF	7/28/2010	61	6	11/15/2011	61	6	1	0.353821
Hot-Humid	B3010105 - Built-Up	28	1983	3200	SF	4/27/2012	30	7	2/28/2013	30	7	1	0.341822
Hot-Humid	B3010105 - Built-Up	28	2006	3040	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.08499
Hot-Humid	B3010105 - Built-Up	28	2006	3300	SF	9/30/2010	95	2	11/15/2011	95	2	1	0.24401
Hot-Humid	B3010105 - Built-Up	28	1980	6050	SF	4/27/2012	30	7	2/28/2013	30	7	1	0.17996
Hot-Humid	B3010105 - Built-Up	28	1990	40500	SF	4/27/2012	30	7	2/28/2013	30	7	1	0.508423
Hot-Humid	B3010105 - Built-Up	28	1988	2030	SF	4/27/2012	50	7	2/28/2013	50	7	1	0.804317
Hot-Humid	B3010105 - Built-Up	28	2004	26256	SF	9/30/2010	100	1	1/10/2014	95	2	3	0.838384
Hot-Humid	B3010105 - Built-Up	28	1995	312	SF	7/28/2010	80	4	8/14/2014	61	6	4	0.751386
Hot-Humid	B3010105 - Built-Up	28	1985	8712	SF	9/30/2010	43	7	11/15/2011	50	7	1	0.016611
Hot-Humid	B3010105 - Built-Up	28	2004	130	SF	7/28/2010	90	3	11/15/2011	95	2	1	0.409135
Hot-Humid	B3010105 - Built-Up	28	2004	60	SF	7/28/2010	90	3	11/15/2011	95	2	1	0.273105
Hot-Humid	B3010105 - Built-Up	28	1972	296	SF	7/28/2010	71	5	11/15/2011	71	5	1	0.449653
Hot-Humid	B3010105 - Built-Up	28	1999	17649	SF	9/30/2010	53	7	6/10/2013	88	3	3	0.153195
Hot-Humid	B3010105 - Built-Up	28	1944	47261	SF	9/30/2010	62	6	6/16/2014	10	7	4	0.504686
Hot-Humid	B3010105 - Built-Up	28	1985	1200	SF	7/28/2010	75	4	11/15/2011	71	5	1	0.789289
Hot-Humid	B3010105 - Built-Up	28	1990	4026	SF	7/28/2010	88	3	7/8/2014	71	5	4	0.049868
Hot-Humid	B3010105 - Built-Up	28	2004	27280	SF	7/28/2010	94	2	2/18/2014	71	5	4	0.575872
Hot-Humid	B3010105 - Built-Up	28	1955	21224	SF	7/7/2010	100	1	1/28/2014	88	3	4	0.945704
Hot-Humid	B3010105 - Built-Up	28	2006	640	SF	9/30/2010	70	5	9/22/2014	71	5	4	0.192493

						Inspection 1			Inspection 2				
Region	**Component**	**Design Life**	**Year Installed**	**Quantity**	**UM**	**Date**	**Rating**	**State**	**Date**	**Rating**	**State**	**Obs. Interval**	**Random Number**
Hot-Humid	B3010105 - Built-Up	28	2006	6212	SF	7/7/2010	38	7	7/17/2014	95	2	4	0.037834
Hot-Humid	B3010105 - Built-Up	28	2005	1620	SF	9/30/2010	51	7	11/15/2011	50	7	1	0.971988
Hot-Humid	B3010105 - Built-Up	28	1993	640	SF	9/30/2010	41	7	3/19/2014	61	6	3	0.572704
Hot-Humid	B3010105 - Built-Up	28	1980	10785	SF	9/30/2010	49	7	10/30/2013	95	2	3	0.243404
Hot-Humid	B3010105 - Built-Up	28	2004	1215	SF	9/30/2010	67	5	10/30/2013	95	2	3	0.357769
Hot-Humid	B3010105 - Built-Up	28	1993	3724	SF	9/30/2010	94	2	11/15/2011	95	2	1	0.977595
Hot-Humid	B3010105 - Built-Up	28	1990	112	SF	9/30/2010	41	7	11/15/2011	50	7	1	0.11565
Hot-Humid	B3010105 - Built-Up	28	1992	450	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.808048
Hot-Humid	B3010105 - Built-Up	28	1996	29514	SF	2/7/2013	80	4	2/7/2013	80	4	0	0.782717
Hot-Humid	B3010105 - Built-Up	28	1952	10164	SF	7/7/2010	43	7	7/23/2014	95	2	4	0.438988
Hot-Humid	B3010105 - Built-Up	28	1997	1216	SF	7/28/2010	61	6	11/15/2011	61	6	1	0.750388
Hot-Humid	B3010105 - Built-Up	28	1986	5852	SF	9/30/2010	58	6	11/15/2011	61	6	1	0.63134
Hot-Humid	B3010105 - Built-Up	28	1983	1274	SF	7/28/2010	100	1	5/30/2013	80	4	3	0.923035
Hot-Humid	B3010105 - Built-Up	28	1999	1976	SF	7/28/2010	71	5	9/5/2014	71	5	4	0.482036
Hot-Humid	B3010105 - Built-Up	28	1998	22000	SF	4/18/2012	71	5	8/29/2013	71	5	1	0.94615
Hot-Humid	B3010105 - Built-Up	28	1994	1750	SF	9/30/2010	90	3	11/15/2011	95	2	1	0.087719
Hot-Humid	B3010105 - Built-Up	28	1973	19838	SF	7/28/2010	68	5	8/7/2014	88	3	4	0.482323
Hot-Humid	B3010105 - Built-Up	28	1990	53917	SF	7/28/2010	96	2	11/15/2011	95	2	1	0.912757
Hot-Humid	B3010105 - Built-Up	28	1982	576	SF	9/30/2010	43	7	9/4/2013	80	4	3	0.093512
Hot-Humid	B3010105 - Built-Up	28	1972	42786	SF	9/30/2010	40	7	11/15/2011	30	7	1	0.592342
Hot-Humid	B3010105 - Built-Up	28	1992	2016	SF	9/30/2010	59	6	5/20/2014	61	6	4	0.140614
Hot-Humid	B3010105 - Built-Up	28	1995	2200	SF	7/28/2010	69	5	11/15/2011	71	5	1	0.284347
Hot-Humid	B3010105 - Built-Up	28	1995	2480	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.635809
Hot-Humid	B3010105 - Built-Up	28	2005	33264	SF	9/30/2010	41	7	9/20/2013	80	4	3	0.501865
Hot-Humid	B3010105 - Built-Up	28	2006	7086	SF	9/30/2010	61	6	7/17/2013	88	3	3	0.861079
Hot-Humid	B3010105 - Built-Up	28	1995	125	SF	7/28/2010	80	4	8/11/2014	61	6	4	0.676633
Hot-Humid	B3010105 - Built-Up	28	1980	294	SF	7/28/2010	71	5	8/23/2014	30	7	4	0.047455
Hot-Humid	B3010105 - Built-Up	28	2006	5188	SF	7/28/2010	80	4	7/7/2014	71	5	4	0.298419

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	2011	250	SF	3/28/2012	80	4	2/12/2014	95	2	2	0.706637
Hot-Humid	B3010105 - Built-Up	28	2012	5200	SF	3/28/2012	80	4	2/12/2014	95	2	2	0.214619
Hot-Humid	B3010105 - Built-Up	28	2011	1150	SF	3/28/2012	80	4	2/12/2014	95	2	2	0.293011
Hot-Humid	B3010105 - Built-Up	28	2011	970	SF	3/28/2012	80	4	2/12/2014	95	2	2	0.225903
Hot-Humid	B3010105 - Built-Up	28	2011	2550	SF	3/28/2012	80	4	2/12/2014	95	2	2	0.514174
Hot-Humid	B3010105 - Built-Up	28	1993	26000	SF	9/30/2010	41	7	8/19/2014	88	3	4	0.464284
Hot-Humid	B3010105 - Built-Up	28	2008	2562	SF	9/30/2010	100	1	6/16/2013	10	7	3	0.624533
Hot-Humid	B3010105 - Built-Up	28	1999	4620	SF	7/28/2010	62	6	11/15/2011	61	6	1	0.133113
Hot-Humid	B3010105 - Built-Up	28	1975	8697	SF	9/30/2010	43	7	4/16/2014	80	4	4	0.339409
Hot-Humid	B3010105 - Built-Up	28	2003	2016	SF	9/30/2010	62	6	11/15/2011	61	6	1	0.942971
Hot-Humid	B3010105 - Built-Up	28	1995	4400	SF	5/23/2012	71	5	5/23/2012	71	5	0	0.616116
Hot-Humid	B3010105 - Built-Up	28	1985	10500	SF	9/30/2010	41	7	5/17/2013	95	2	3	0.835745
Hot-Humid	B3010105 - Built-Up	28	1987	3990	SF	9/30/2010	40	7	9/23/2014	88	3	4	0.85337
Hot-Humid	B3010105 - Built-Up	28	1993	3264	SF	7/28/2010	59	6	11/15/2011	61	6	1	0.779842
Hot-Humid	B3010105 - Built-Up	28	1986	5852	SF	9/30/2010	58	6	11/15/2011	61	6	1	0.425364
Hot-Humid	B3010105 - Built-Up	28	1984	6400	SF	9/30/2010	41	7	4/13/2014	80	4	4	0.468953
Hot-Humid	B3010105 - Built-Up	28	2008	12100	SF	9/30/2010	100	1	9/25/2014	88	3	4	0.334116
Hot-Humid	B3010105 - Built-Up	28	2008	9600	SF	9/30/2010	98	2	9/25/2014	88	3	4	0.42006
Hot-Humid	B3010105 - Built-Up	28	1989	5200	SF	9/30/2010	70	5	11/15/2011	71	5	1	0.077038
Hot-Humid	B3010105 - Built-Up	28	1993	1200	SF	9/30/2010	100	1	1/23/2014	71	5	3	0.243477
Hot-Humid	B3010105 - Built-Up	28	1989	5400	SF	9/30/2010	37	7	3/30/2013	80	4	3	0.831713
Hot-Humid	B3010105 - Built-Up	28	1978	9980	SF	9/30/2010	68	5	11/15/2011	71	5	1	0.873527
Hot-Humid	B3010105 - Built-Up	28	1983	6920	SF	7/28/2010	47	7	9/7/2014	50	7	4	0.325779
Hot-Humid	B3010105 - Built-Up	28	1983	800	SF	7/28/2010	23	7	9/7/2014	10	7	4	0.197735
Hot-Humid	B3010105 - Built-Up	28	1999	6682	SF	7/18/2012	95	2	9/3/2014	61	6	2	0.014213
Hot-Humid	B3010105 - Built-Up	28	2012	1050	SF	7/28/2010	68	5	8/28/2013	100	1	3	0.947081
Hot-Humid	B3010105 - Built-Up	28	2012	910	SF	7/28/2010	36	7	8/28/2013	100	1	3	0.170979
Hot-Humid	B3010105 - Built-Up	28	1962	44282	SF	9/30/2010	30	7	11/15/2011	30	7	1	0.222649

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1976	759	SF	7/7/2010	61	6	5/8/2014	80	4	4	0.172177
Hot-Humid	B3010105 - Built-Up	28	1979	9444	SF	7/28/2010	3	7	11/15/2011	10	7	1	0.699766
Hot-Humid	B3010105 - Built-Up	28	1993	8050	SF	9/30/2010	41	7	3/19/2014	71	5	3	0.714253
Hot-Humid	B3010105 - Built-Up	28	1996	17500	SF	9/30/2010	81	4	5/23/2013	88	3	3	0.404442
Hot-Humid	B3010105 - Built-Up	28	1941	4268	SF	1/24/2012	80	4	8/7/2014	71	5	3	0.62437
Hot-Humid	B3010105 - Built-Up	28	1981	20777	SF	9/30/2010	83	4	1/15/2014	88	3	3	0.496056
Hot-Humid	B3010105 - Built-Up	28	1997	11500	SF	9/30/2010	67	5	6/10/2014	71	5	4	0.585283
Hot-Humid	B3010105 - Built-Up	28	1982	14868	SF	9/30/2010	55	7	6/10/2014	71	5	4	0.323712
Hot-Humid	B3010105 - Built-Up	28	1995	6772	SF	9/30/2010	100	1	9/16/2011	100	1	1	0.847084
Hot-Humid	B3010105 - Built-Up	28	1980	81	SF	7/28/2010	30	7	11/15/2011	30	7	1	0.434797
Hot-Humid	B3010105 - Built-Up	28	1985	29525	SF	9/30/2010	59	6	4/22/2014	80	4	4	0.11987
Hot-Humid	B3010105 - Built-Up	28	2003	119501	SF	9/30/2010	62	6	1/16/2014	95	2	3	0.225107
Hot-Humid	B3010105 - Built-Up	28	1989	4780	SF	9/30/2010	47	7	11/15/2011	50	7	1	0.798467
Hot-Humid	B3010105 - Built-Up	28	1953	2976	SF	7/28/2010	1	7	1/30/2014	10	7	4	0.484415
Hot-Humid	B3010105 - Built-Up	28	1978	3960	SF	7/28/2010	100	1	6/26/2013	80	4	3	0.295805
Hot-Humid	B3010105 - Built-Up	28	1990	19532	SF	9/30/2010	43	7	3/8/2014	61	6	3	0.513735
Hot-Humid	B3010105 - Built-Up	28	1971	224	SF	2/6/2013	71	5	2/6/2013	71	5	0	0.146916
Hot-Humid	B3010105 - Built-Up	28	2006	36000	SF	9/30/2010	49	7	4/17/2013	71	5	3	0.797846
Hot-Humid	B3010105 - Built-Up	28	1992	26800	SF	9/30/2010	41	7	8/19/2014	88	3	4	0.402474
Hot-Humid	B3010105 - Built-Up	28	1985	252	SF	2/7/2013	61	6	9/12/2014	61	6	2	0.442716
Hot-Humid	B3010105 - Built-Up	28	2005	33409	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.393719
Hot-Humid	B3010105 - Built-Up	28	1975	8000	SF	7/28/2010	67	5	4/4/2013	71	5	3	0.926224
Hot-Humid	B3010105 - Built-Up	28	2004	150	SF	1/15/2013	88	3	1/15/2013	88	3	0	0.591014
Hot-Humid	B3010105 - Built-Up	28	2000	25776	SF	9/30/2010	55	7	3/29/2013	30	7	2	0.311384
Hot-Humid	B3010105 - Built-Up	28	2000	42901	SF	7/28/2010	87	3	12/13/2013	80	4	3	0.420189
Hot-Humid	B3010105 - Built-Up	28	2000	2680	SF	7/17/2012	30	7	1/14/2014	30	7	1	0.895467
Hot-Humid	B3010105 - Built-Up	28	1985	1050	SF	7/17/2012	88	3	12/17/2013	80	4	1	0.569479
Hot-Humid	B3010105 - Built-Up	28	2008	1850	SF	9/30/2010	100	1	6/17/2013	95	2	3	0.101278

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1960	4600	SF	7/7/2010	0	7	8/13/2012	71	5	2	0.959582
Hot-Humid	B3010105 - Built-Up	28	1995	75726	SF	2/13/2013	80	4	9/11/2014	80	4	2	0.209979
Hot-Humid	B3010105 - Built-Up	28	2000	500	SF	3/6/2012	80	4	3/6/2012	80	4	0	0.523012
Hot-Humid	B3010105 - Built-Up	28	1999	187	SF	2/12/2013	80	4	2/12/2013	80	4	0	0.911775
Hot-Humid	B3010105 - Built-Up	28	1955	14784	SF	7/28/2010	33	7	11/15/2011	30	7	1	0.460236
Hot-Humid	B3010105 - Built-Up	28	1970	6000	SF	6/8/2012	61	6	7/29/2014	61	6	2	0.637608
Hot-Humid	B3010105 - Built-Up	28	2010	28562	SF	1/2/2012	82	4	9/4/2013	30	7	2	0.503293
Hot-Humid	B3010105 - Built-Up	28	1995	3889	SF	9/30/2010	76	4	11/15/2011	71	5	1	0.232112
Hot-Humid	B3010105 - Built-Up	28	1963	1970	SF	7/28/2010	87	3	11/15/2011	88	3	1	0.716494
Hot-Humid	B3010105 - Built-Up	28	1994	15000	SF	9/30/2010	99	2	11/15/2011	100	1	1	0.147428
Hot-Humid	B3010105 - Built-Up	28	1998	44501	SF	9/30/2010	41	7	6/11/2014	71	5	4	0.500698
Hot-Humid	B3010105 - Built-Up	28	1975	2796	SF	9/30/2010	50	7	4/16/2013	71	5	3	0.300428
Hot-Humid	B3010105 - Built-Up	28	1988	1144	SF	9/30/2010	79	4	9/23/2014	95	2	4	0.030373
Hot-Humid	B3010105 - Built-Up	28	2012	11139	SF	3/4/2013	95	2	3/4/2013	95	2	0	0.33226
Hot-Humid	B3010105 - Built-Up	28	2004	8397	SF	9/30/2010	64	6	4/22/2014	88	3	4	0.324526
Hot-Humid	B3010105 - Built-Up	28	1941	63	SF	2/5/2013	50	7	2/5/2013	50	7	0	0.680149
Hot-Humid	B3010105 - Built-Up	28	2004	960	SF	9/30/2010	70	5	11/15/2011	71	5	1	0.351766
Hot-Humid	B3010105 - Built-Up	28	1959	7858	SF	7/7/2010	100	1	7/8/2014	88	3	4	0.794926
Hot-Humid	B3010105 - Built-Up	28	1990	75	SF	1/31/2013	71	5	7/2/2014	71	5	1	0.01522
Hot-Humid	B3010105 - Built-Up	28	1977	112	SF	3/18/2013	71	5	9/24/2014	80	4	2	0.653696
Hot-Humid	B3010105 - Built-Up	28	1990	1255	SF	9/30/2010	43	7	3/17/2013	95	2	2	0.620308
Hot-Humid	B3010105 - Built-Up	28	1980	1003	SF	7/28/2010	61	6	9/13/2014	71	5	4	0.751275
Hot-Humid	B3010105 - Built-Up	28	1939	63	SF	2/13/2013	30	7	2/13/2013	30	7	0	0.094977
Hot-Humid	B3010105 - Built-Up	28	1986	2575	SF	2/20/2013	80	4	9/22/2014	80	4	2	0.937545
Hot-Humid	B3010105 - Built-Up	28	2005	3277	SF	12/26/2012	80	4	12/26/2012	80	4	0	0.704857
Hot-Humid	B3010105 - Built-Up	28	1975	7550	SF	7/28/2010	43	7	11/15/2011	50	7	1	0.65898
Hot-Humid	B3010105 - Built-Up	28	1975	10900	SF	7/28/2010	65	5	11/15/2011	61	6	1	0.595434
Hot-Humid	B3010105 - Built-Up	28	2005	8732	SF	9/30/2010	97	2	9/7/2013	80	4	3	0.766093

						Inspection 1			Inspection 2				
Region	**Component**	**Design Life**	**Year Installed**	**Quantity**	**UM**	**Date**	**Rating**	**State**	**Date**	**Rating**	**State**	**Obs. Interval**	**Random Number**
Hot-Humid	B3010105 - Built-Up	28	1994	7550	SF	9/30/2010	91	3	11/15/2011	95	2	1	0.87229
Hot-Humid	B3010105 - Built-Up	28	2003	306	SF	7/28/2010	100	1	9/19/2014	61	6	4	0.087269
Hot-Humid	B3010105 - Built-Up	28	1986	8020	SF	9/30/2010	61	6	4/13/2014	88	3	4	0.435619
Hot-Humid	B3010105 - Built-Up	28	1955	4062	SF	7/7/2010	41	7	9/23/2014	95	2	4	0.288294
Hot-Humid	B3010105 - Built-Up	28	2002	120	SF	7/28/2010	88	3	8/14/2014	71	5	4	0.514434
Hot-Humid	B3010105 - Built-Up	28	1986	11966	SF	9/30/2010	43	7	11/15/2011	50	7	1	0.308339
Hot-Humid	B3010105 - Built-Up	28	1975	23394	SF	8/8/2011	61	6	3/31/2014	88	3	3	0.968047
Hot-Humid	B3010105 - Built-Up	28	2001	4700	SF	9/30/2010	67	5	5/5/2014	95	2	4	0.427953
Hot-Humid	B3010105 - Built-Up	28	2004	19243	SF	9/30/2010	64	6	4/9/2013	61	6	3	0.737937
Hot-Humid	B3010105 - Built-Up	28	1953	1333	SF	7/18/2012	88	3	8/25/2014	10	7	2	0.788654
Hot-Humid	B3010105 - Built-Up	28	2004	4515	SF	9/30/2010	64	6	2/20/2014	88	3	3	0.85865
Hot-Humid	B3010105 - Built-Up	28	1990	2697	SF	7/28/2010	64	6	11/15/2011	61	6	1	0.5599
Hot-Humid	B3010105 - Built-Up	28	1980	3068	SF	7/28/2010	19	7	11/15/2011	10	7	1	0.487217
Hot-Humid	B3010105 - Built-Up	28	1999	9515	SF	7/28/2010	71	5	11/15/2011	71	5	1	0.209661
Hot-Humid	B3010105 - Built-Up	28	1990	400	SF	2/12/2013	80	4	2/12/2013	80	4	0	0.413721
Hot-Humid	B3010105 - Built-Up	28	1990	2079	SF	9/30/2010	40	7	3/29/2013	80	4	2	0.011503
Hot-Humid	B3010105 - Built-Up	28	2008	26296	SF	2/13/2013	88	3	2/13/2013	88	3	0	0.870868
Hot-Humid	B3010105 - Built-Up	28	1999	63251	SF	9/30/2010	40	7	2/13/2014	80	4	3	0.341279
Hot-Humid	B3010105 - Built-Up	28	1973	4416	SF	5/10/2012	71	5	5/10/2012	71	5	0	0.67521
Hot-Humid	B3010105 - Built-Up	28	1984	8372	SF	9/30/2010	30	7	1/27/2014	71	5	3	0.298806
Hot-Humid	B3010105 - Built-Up	28	2006	3800	SF	1/30/2013	95	2	9/11/2014	80	4	2	0.905507
Hot-Humid	B3010105 - Built-Up	28	1988	200	SF	3/19/2012	80	4	9/23/2014	80	4	3	0.212409
Hot-Humid	B3010105 - Built-Up	28	1988	1000	SF	7/28/2010	49	7	4/8/2013	71	5	3	0.705064
Hot-Humid	B3010105 - Built-Up	28	1988	1200	SF	7/28/2010	63	6	4/8/2013	61	6	3	0.482148
Hot-Humid	B3010105 - Built-Up	28	2005	20800	SF	9/30/2010	100	1	8/17/2014	88	3	4	0.86627
Hot-Humid	B3010105 - Built-Up	28	1956	481	SF	9/30/2010	62	6	3/20/2014	61	6	3	0.486457
Hot-Humid	B3010105 - Built-Up	28	1973	8880	SF	7/28/2010	68	5	8/15/2014	80	4	4	0.648316
Hot-Humid	B3010105 - Built-Up	28	1997	2125	SF	7/28/2010	32	7	7/8/2014	50	7	4	0.304381

						Inspection 1			Inspection 2				
Region	**Component**	**Design Life**	**Year Installed**	**Quantity**	**UM**	**Date**	**Rating**	**State**	**Date**	**Rating**	**State**	**Obs. Interval**	**Random Number**
Hot-Humid	B3010105 - Built-Up	28	1991	176	SF	9/30/2010	71	5	11/15/2011	71	5	1	0.082641
Hot-Humid	B3010105 - Built-Up	28	1943	336	SF	7/28/2010	30	7	8/23/2014	50	7	4	0.510787
Hot-Humid	B3010105 - Built-Up	28	1990	1258	SF	5/4/2012	80	4	6/19/2014	61	6	2	0.747461
Hot-Humid	B3010105 - Built-Up	28	1975	2151	SF	9/30/2010	43	7	5/28/2014	88	3	4	0.220586
Hot-Humid	B3010105 - Built-Up	28	1985	10000	SF	7/28/2010	35	7	7/18/2014	30	7	4	0.721834
Hot-Humid	B3010105 - Built-Up	28	1999	13225	SF	9/30/2010	47	7	3/13/2014	95	2	3	0.102117
Hot-Humid	B3010105 - Built-Up	28	1966	1850	SF	9/30/2010	85	4	3/3/2014	61	6	3	0.837377
Hot-Humid	B3010105 - Built-Up	28	1967	10979	SF	9/30/2010	61	6	11/15/2011	61	6	1	0.320655
Hot-Humid	B3010105 - Built-Up	28	2006	14000	SF	9/30/2010	47	7	11/15/2011	50	7	1	0.356797
Hot-Humid	B3010105 - Built-Up	28	1990	6982	SF	9/30/2010	80	4	5/19/2014	80	4	4	0.37792
Hot-Humid	B3010105 - Built-Up	28	2006	2545	SF	12/19/2012	95	2	9/11/2014	80	4	2	0.778196
Hot-Humid	B3010105 - Built-Up	28	1987	207828	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.238318
Hot-Humid	B3010105 - Built-Up	28	1991	1062	SF	7/28/2010	88	3	8/28/2014	61	6	4	0.677829
Hot-Humid	B3010105 - Built-Up	28	1997	2352	SF	7/28/2010	88	3	7/25/2014	88	3	4	0.067179
Hot-Humid	B3010105 - Built-Up	28	2005	2100	SF	7/28/2010	69	5	11/15/2011	71	5	1	0.776074
Hot-Humid	B3010105 - Built-Up	28	2005	37946	SF	9/30/2010	92	3	5/23/2013	88	3	3	0.731197
Hot-Humid	B3010105 - Built-Up	28	1987	1508	SF	9/30/2010	47	7	11/15/2011	50	7	1	0.667428
Hot-Humid	B3010105 - Built-Up	28	2005	24125	SF	9/30/2010	76	4	7/18/2014	88	3	4	0.712377
Hot-Humid	B3010105 - Built-Up	28	1986	1225	SF	9/30/2010	50	7	1/31/2014	88	3	3	0.899073
Hot-Humid	B3010105 - Built-Up	28	1996	63501	SF	9/30/2010	47	7	11/15/2011	50	7	1	0.734078
Hot-Humid	B3010105 - Built-Up	28	2007	7300	SF	9/30/2010	73	5	9/23/2014	71	5	4	0.939213
Hot-Humid	B3010105 - Built-Up	28	1969	2219	SF	9/30/2010	49	7	11/15/2011	50	7	1	0.837489
Hot-Humid	B3010105 - Built-Up	28	2008	2960	SF	9/30/2010	100	1	6/11/2013	95	2	3	0.46986
Hot-Humid	B3010105 - Built-Up	28	2005	25960	SF	9/30/2010	82	4	11/15/2011	80	4	1	0.616405
Hot-Humid	B3010105 - Built-Up	28	1949	6519	SF	1/28/2013	95	2	1/28/2014	88	3	1	0.275567
Hot-Humid	B3010105 - Built-Up	28	1990	1485	SF	9/30/2010	38	7	11/15/2011	30	7	1	0.183174
Hot-Humid	B3010105 - Built-Up	28	2008	1155	SF	7/28/2010	100	1	2/25/2013	100	1	3	0.784803
Hot-Humid	B3010105 - Built-Up	28	1941	63	SF	2/7/2013	30	7	2/7/2013	30	7	0	0.091428

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	2010	12858	SF	1/2/2012	82	4	11/15/2011	80	4	0	0.807321
Hot-Humid	B3010105 - Built-Up	28	1979	9461	SF	7/7/2010	41	7	9/28/2014	10	7	4	0.398392
Hot-Humid	B3010105 - Built-Up	28	1988	18950	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.866924
Hot-Humid	B3010105 - Built-Up	28	1980	3552	SF	7/28/2010	79	4	10/2/2014	61	6	4	0.682328
Hot-Humid	B3010105 - Built-Up	28	1995	2900	SF	9/30/2010	100	1	2/15/2014	88	3	3	0.76052
Hot-Humid	B3010105 - Built-Up	28	2004	512	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.588095
Hot-Humid	B3010105 - Built-Up	28	1957	96	SF	7/28/2010	61	6	11/15/2011	61	6	1	0.247404
Hot-Humid	B3010105 - Built-Up	28	1942	8453	SF	9/30/2010	30	7	5/28/2013	71	5	3	0.355625
Hot-Humid	B3010105 - Built-Up	28	2006	3200	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.053894
Hot-Humid	B3010105 - Built-Up	28	2003	180	SF	7/28/2010	68	5	4/12/2013	71	5	3	0.150191
Hot-Humid	B3010105 - Built-Up	28	1946	130	SF	9/30/2010	95	2	11/15/2011	95	2	1	0.373984
Hot-Humid	B3010105 - Built-Up	28	2005	510	SF	9/30/2010	67	5	11/15/2011	71	5	1	0.408191
Hot-Humid	B3010105 - Built-Up	28	2003	10800	SF	2/22/2013	71	5	2/22/2013	71	5	0	0.355364
Hot-Humid	B3010105 - Built-Up	28	1980	3625	SF	9/30/2010	75	4	1/17/2014	88	3	3	0.111744
Hot-Humid	B3010105 - Built-Up	28	1985	629	SF	9/30/2010	37	7	3/20/2014	71	5	3	0.835312
Hot-Humid	B3010105 - Built-Up	28	2006	940	SF	9/30/2010	95	2	8/14/2014	88	3	4	0.880223
Hot-Humid	B3010105 - Built-Up	28	1969	133	SF	2/1/2013	50	7	2/1/2013	50	7	0	0.070181
Hot-Humid	B3010105 - Built-Up	28	1978	39200	SF	7/28/2010	83	4	11/15/2011	88	3	1	0.119892
Hot-Humid	B3010105 - Built-Up	28	1978	18070	SF	7/28/2010	26	7	2/7/2013	30	7	3	0.42774
Hot-Humid	B3010105 - Built-Up	28	1990	234	SF	7/28/2010	61	6	8/22/2014	61	6	4	0.385766
Hot-Humid	B3010105 - Built-Up	28	1943	620	SF	7/28/2010	22	7	11/15/2011	10	7	1	0.783931
Hot-Humid	B3010105 - Built-Up	28	2005	15000	SF	9/30/2010	100	1	3/14/2014	95	2	3	0.930707
Hot-Humid	B3010105 - Built-Up	28	1995	17669	SF	7/28/2010	80	4	7/3/2014	80	4	4	0.934656
Hot-Humid	B3010105 - Built-Up	28	1990	1848	SF	7/28/2010	55	7	12/2/2013	50	7	3	0.513875
Hot-Humid	B3010105 - Built-Up	28	1995	240	SF	2/12/2013	80	4	2/12/2013	80	4	0	0.194854
Hot-Humid	B3010105 - Built-Up	28	1990	384	SF	7/28/2010	61	6	8/23/2014	30	7	4	0.727679
Hot-Humid	B3010105 - Built-Up	28	1970	3500	SF	6/13/2012	50	7	6/13/2012	50	7	0	0.331993
Hot-Humid	B3010105 - Built-Up	28	1989	7426	SF	9/30/2010	55	7	11/15/2011	50	7	1	0.829749

						Inspection 1			Inspection 2				
Region	**Component**	**Design Life**	**Year Installed**	**Quantity**	**UM**	**Date**	**Rating**	**State**	**Date**	**Rating**	**State**	**Obs. Interval**	**Random Number**
Hot-Humid	B3010105 - Built-Up	28	1997	19830	SF	9/30/2010	100	1	3/19/2013	10	7	2	0.612041
Hot-Humid	B3010105 - Built-Up	28	1972	4301	SF	3/7/2013	95	2	3/5/2014	95	2	1	0.1426
Hot-Humid	B3010105 - Built-Up	28	1996	10808	SF	9/30/2010	100	1	6/2/2014	71	5	4	0.035618
Hot-Humid	B3010105 - Built-Up	28	2005	3530	SF	9/30/2010	45	7	5/27/2014	50	7	4	0.9191
Hot-Humid	B3010105 - Built-Up	28	1987	1555	SF	9/30/2010	74	5	11/15/2011	71	5	1	0.922185
Hot-Humid	B3010105 - Built-Up	28	1981	60517	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.665255
Hot-Humid	B3010105 - Built-Up	28	2003	4960	SF	2/7/2013	88	3	2/7/2013	88	3	0	0.744519
Hot-Humid	B3010105 - Built-Up	28	1998	16100	SF	9/30/2010	96	2	4/29/2014	80	4	4	0.046698
Hot-Humid	B3010105 - Built-Up	28	1990	917	SF	2/12/2013	61	6	9/10/2014	61	6	2	0.717502
Hot-Humid	B3010105 - Built-Up	28	1995	782	SF	9/30/2010	71	5	11/15/2011	71	5	1	0.878356
Hot-Humid	B3010105 - Built-Up	28	2008	6800	SF	9/30/2010	73	5	4/24/2014	88	3	4	0.840828
Hot-Humid	B3010105 - Built-Up	28	2007	13840	SF	9/30/2010	73	5	5/20/2014	71	5	4	0.567622
Hot-Humid	B3010105 - Built-Up	28	2006	9900	SF	9/30/2010	100	1	4/30/2013	71	5	3	0.778858
Hot-Humid	B3010105 - Built-Up	28	1998	10850	SF	7/28/2010	84	4	11/15/2011	88	3	1	0.304437
Hot-Humid	B3010105 - Built-Up	28	1990	1040	SF	9/30/2010	59	6	11/15/2011	61	6	1	0.39712
Hot-Humid	B3010105 - Built-Up	28	1999	4482	SF	9/30/2010	76	4	6/27/2013	61	6	3	0.278628
Hot-Humid	B3010105 - Built-Up	28	2007	8400	SF	9/30/2010	100	1	5/1/2014	88	3	4	0.828432
Hot-Humid	B3010105 - Built-Up	28	1988	13404	SF	7/28/2010	64	6	2/6/2013	61	6	3	0.607237
Hot-Humid	B3010105 - Built-Up	28	1952	9744	SF	7/7/2010	43	7	8/14/2012	95	2	2	0.919812
Hot-Humid	B3010105 - Built-Up	28	1985	12760	SF	9/30/2010	99	2	11/15/2011	100	1	1	0.927276
Hot-Humid	B3010105 - Built-Up	28	1955	17630	SF	7/7/2010	100	1	7/8/2014	88	3	4	0.060558
Hot-Humid	B3010105 - Built-Up	28	1995	17721	SF	7/28/2010	98	2	11/15/2011	100	1	1	0.789966
Hot-Humid	B3010105 - Built-Up	28	1989	1555	SF	9/30/2010	64	6	1/11/2014	88	3	3	0.356411
Hot-Humid	B3010105 - Built-Up	28	1956	17337	SF	1/29/2013	95	2	1/30/2014	95	2	1	0.498621
Hot-Humid	B3010105 - Built-Up	28	1985	744	SF	9/30/2010	50	7	1/27/2014	71	5	3	0.318325
Hot-Humid	B3010105 - Built-Up	28	1985	430	SF	7/28/2010	71	5	8/23/2014	30	7	4	0.287982
Hot-Humid	B3010105 - Built-Up	28	1974	6764	SF	7/28/2010	1	7	11/15/2011	10	7	1	0.687167
Hot-Humid	B3010105 - Built-Up	28	1986	15995	SF	9/30/2010	43	7	2/12/2014	71	5	3	0.167535

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1964	16656	SF	7/7/2010	100	1	5/20/2014	88	3	4	0.208352
Hot-Humid	B3010105 - Built-Up	28	2000	860	SF	12/27/2011	95	2	2/13/2014	88	3	2	0.237573
Hot-Humid	B3010105 - Built-Up	28	1979	400	SF	6/15/2012	61	6	9/27/2013	61	6	1	0.821722
Hot-Humid	B3010105 - Built-Up	28	1979	24625	SF	6/15/2012	61	6	9/27/2013	61	6	1	0.563694
Hot-Humid	B3010105 - Built-Up	28	1979	400	SF	6/15/2012	61	6	9/27/2013	61	6	1	0.654136
Hot-Humid	B3010105 - Built-Up	28	1979	24625	SF	6/15/2012	61	6	9/27/2013	61	6	1	0.986048
Hot-Humid	B3010105 - Built-Up	28	1970	7200	SF	7/28/2010	40	7	9/19/2014	80	4	4	0.623503
Hot-Humid	B3010105 - Built-Up	28	1985	144	SF	7/28/2010	71	5	8/12/2014	71	5	4	0.202172
Hot-Humid	B3010105 - Built-Up	28	1978	1044	SF	9/30/2010	50	7	4/10/2014	50	7	4	0.869648
Hot-Humid	B3010105 - Built-Up	28	1965	984	SF	7/7/2010	43	7	9/7/2014	50	7	4	0.547749
Hot-Humid	B3010105 - Built-Up	28	1988	20010	SF	9/30/2010	45	7	11/15/2011	50	7	1	0.44246
Hot-Humid	B3010105 - Built-Up	28	1992	25776	SF	9/30/2010	41	7	6/4/2014	50	7	4	0.648079
Hot-Humid	B3010105 - Built-Up	28	1973	1100	SF	9/30/2010	76	4	11/15/2011	71	5	1	0.601507
Hot-Humid	B3010105 - Built-Up	28	1995	31696	SF	7/28/2010	87	3	11/15/2011	88	3	1	0.52842
Hot-Humid	B3010105 - Built-Up	28	1943	20700	SF	7/28/2010	69	5	8/14/2014	30	7	4	0.849805
Hot-Humid	B3010105 - Built-Up	28	1999	8664	SF	9/30/2010	53	7	3/10/2014	95	2	3	0.810308
Hot-Humid	B3010105 - Built-Up	28	1990	1555	SF	9/30/2010	76	4	11/15/2011	71	5	1	0.203334
Hot-Humid	B3010105 - Built-Up	28	1983	1298	SF	7/28/2010	59	6	11/15/2011	61	6	1	0.781628
Hot-Humid	B3010105 - Built-Up	28	1985	22528	SF	7/28/2010	63	6	3/22/2013	71	5	3	0.652091
Hot-Humid	B3010105 - Built-Up	28	2001	3968	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.781017
Hot-Humid	B3010105 - Built-Up	28	2005	15475	SF	9/30/2010	67	5	8/19/2014	71	5	4	0.170354
Hot-Humid	B3010105 - Built-Up	28	2005	20720	SF	7/28/2010	47	7	12/19/2012	50	7	2	0.303245
Hot-Humid	B3010105 - Built-Up	28	1995	1144	SF	7/28/2010	80	4	1/17/2014	80	4	3	0.978795
Hot-Humid	B3010105 - Built-Up	28	2004	527	SF	7/28/2010	80	4	9/15/2014	80	4	4	0.113863
Hot-Humid	B3010105 - Built-Up	28	1993	1400	SF	7/28/2010	33	7	5/5/2014	30	7	4	0.271806
Hot-Humid	B3010105 - Built-Up	28	2006	82001	SF	9/30/2010	40	7	4/20/2013	50	7	3	0.459646
Hot-Humid	B3010105 - Built-Up	28	1992	29076	SF	9/30/2010	43	7	3/17/2013	88	3	2	0.499191
Hot-Humid	B3010105 - Built-Up	28	1980	211003	SF	9/30/2010	41	7	4/20/2013	50	7	3	0.708192

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1969	10251	SF	9/30/2010	43	7	3/18/2014	95	2	3	0.062705
Hot-Humid	B3010105 - Built-Up	28	2000	10981	SF	1/23/2013	80	4	9/11/2014	80	4	2	0.644346
Hot-Humid	B3010105 - Built-Up	28	1996	2750	SF	9/30/2010	47	7	5/23/2013	61	6	3	0.533747
Hot-Humid	B3010105 - Built-Up	28	1964	140462	SF	7/7/2010	100	1	6/13/2013	88	3	3	0.440609
Hot-Humid	B3010105 - Built-Up	28	2002	3000	SF	7/28/2010	100	1	9/19/2012	61	6	2	0.768956
Hot-Humid	B3010105 - Built-Up	28	1984	2000	SF	2/7/2013	71	5	2/7/2013	71	5	0	0.103628
Hot-Humid	B3010105 - Built-Up	28	1989	3825	SF	9/30/2010	43	7	9/4/2013	10	7	3	0.708051
Hot-Humid	B3010105 - Built-Up	28	1959	4524	SF	7/28/2010	88	3	11/15/2011	88	3	1	0.143362
Hot-Humid	B3010105 - Built-Up	28	1980	18392	SF	9/30/2010	89	3	11/15/2011	88	3	1	0.594049
Hot-Humid	B3010105 - Built-Up	28	1995	23600	SF	9/30/2010	59	6	4/15/2014	80	4	4	0.323199
Hot-Humid	B3010105 - Built-Up	28	1995	60274	SF	9/30/2010	88	3	3/27/2013	61	6	2	0.464598
Hot-Humid	B3010105 - Built-Up	28	2005	63491	SF	9/30/2010	40	7	8/26/2014	88	3	4	0.157
Hot-Humid	B3010105 - Built-Up	28	1965	2640	SF	7/28/2010	52	7	11/15/2011	50	7	1	0.83069
Hot-Humid	B3010105 - Built-Up	28	2005	9162	SF	9/30/2010	72	5	4/16/2014	88	3	4	0.666236
Hot-Humid	B3010105 - Built-Up	28	1975	84801	SF	7/28/2010	93	2	11/15/2011	95	2	1	0.589907
Hot-Humid	B3010105 - Built-Up	28	2006	9375	SF	9/30/2010	70	5	11/15/2011	71	5	1	0.339617
Hot-Humid	B3010105 - Built-Up	28	1980	76001	SF	9/30/2010	47	7	6/4/2014	88	3	4	0.014341
Hot-Humid	B3010105 - Built-Up	28	2000	45581	SF	9/30/2010	40	7	6/4/2014	88	3	4	0.013168
Hot-Humid	B3010105 - Built-Up	28	1994	4000	SF	9/30/2010	92	3	11/15/2011	95	2	1	0.939303
Hot-Humid	B3010105 - Built-Up	28	1990	330	SF	9/30/2010	88	3	8/28/2014	88	3	4	0.447618
Hot-Humid	B3010105 - Built-Up	28	1998	44398	SF	7/28/2010	71	5	11/15/2011	71	5	1	0.917876
Hot-Humid	B3010105 - Built-Up	28	2003	48114	SF	9/30/2010	88	3	4/14/2014	88	3	4	0.757513
Hot-Humid	B3010105 - Built-Up	28	1985	187	SF	7/28/2010	61	6	8/21/2014	61	6	4	0.431659
Hot-Humid	B3010105 - Built-Up	28	1995	23183	SF	9/30/2010	40	7	9/18/2014	88	3	4	0.357632
Hot-Humid	B3010105 - Built-Up	28	2006	14260	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.043321
Hot-Humid	B3010105 - Built-Up	28	1975	9931	SF	7/7/2010	43	7	6/18/2014	95	2	4	0.065036
Hot-Humid	B3010105 - Built-Up	28	1992	12140	SF	9/30/2010	43	7	6/3/2014	80	4	4	0.091487
Hot-Humid	B3010105 - Built-Up	28	1972	77001	SF	6/13/2012	50	7	5/27/2014	50	7	2	0.256099

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	2000	19788	SF	7/28/2010	100	1	11/15/2011	100	1	1	0.861483
Hot-Humid	B3010105 - Built-Up	28	2000	19788	SF	7/28/2010	59	6	11/15/2011	61	6	1	0.809513
Hot-Humid	B3010105 - Built-Up	28	2000	11576	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.115939
Hot-Humid	B3010105 - Built-Up	28	1992	1236	SF	9/30/2010	88	3	9/23/2014	95	2	4	0.040956
Hot-Humid	B3010105 - Built-Up	28	2003	24860	SF	9/30/2010	77	4	5/29/2013	30	7	3	0.83183
Hot-Humid	B3010105 - Built-Up	28	2007	26460	SF	9/30/2010	73	5	11/15/2011	71	5	1	0.978258
Hot-Humid	B3010105 - Built-Up	28	1958	14500	SF	7/28/2010	87	3	11/15/2011	88	3	1	0.318441
Hot-Humid	B3010105 - Built-Up	28	1989	5400	SF	9/30/2010	86	3	1/11/2014	95	2	3	0.181603
Hot-Humid	B3010105 - Built-Up	28	1975	1600	SF	7/28/2010	27	7	9/8/2014	50	7	4	0.226913
Hot-Humid	B3010105 - Built-Up	28	1988	7212	SF	9/30/2010	47	7	3/12/2014	88	3	3	0.053062
Hot-Humid	B3010105 - Built-Up	28	1999	187	SF	2/12/2013	71	5	2/12/2013	71	5	0	0.499104
Hot-Humid	B3010105 - Built-Up	28	1991	720	SF	7/28/2010	80	4	9/15/2014	80	4	4	0.603823
Hot-Humid	B3010105 - Built-Up	28	1979	2116	SF	7/28/2010	57	6	9/22/2014	61	6	4	0.812842
Hot-Humid	B3010105 - Built-Up	28	1995	3172	SF	7/28/2010	57	6	11/15/2011	61	6	1	0.749379
Hot-Humid	B3010105 - Built-Up	28	1970	54	SF	7/28/2010	100	1	7/3/2014	50	7	4	0.413653
Hot-Humid	B3010105 - Built-Up	28	1950	490	SF	2/11/2013	50	7	2/11/2013	50	7	0	0.676151
Hot-Humid	B3010105 - Built-Up	28	1975	8560	SF	9/30/2010	37	7	2/14/2014	61	6	3	0.054708
Hot-Humid	B3010105 - Built-Up	28	2003	16275	SF	4/27/2012	80	4	1/15/2014	80	4	2	0.175665
Hot-Humid	B3010105 - Built-Up	28	2002	10701	SF	9/30/2010	100	1	3/12/2014	30	7	3	0.31421
Hot-Humid	B3010105 - Built-Up	28	2003	11835	SF	9/30/2010	73	5	5/21/2014	88	3	4	0.889664
Hot-Humid	B3010105 - Built-Up	28	2013	3475	SF	9/30/2010	44	7	6/17/2014	95	2	4	0.040066
Hot-Humid	B3010105 - Built-Up	28	1977	293	SF	2/6/2013	88	3	6/3/2014	80	4	1	0.900966
Hot-Humid	B3010105 - Built-Up	28	1993	10980	SF	7/28/2010	37	7	11/15/2011	30	7	1	0.445376
Hot-Humid	B3010105 - Built-Up	28	2005	9848	SF	9/30/2010	67	5	11/15/2011	71	5	1	0.988642
Hot-Humid	B3010105 - Built-Up	28	2008	12941	SF	1/17/2013	88	3	1/17/2013	88	3	0	0.412034
Hot-Humid	B3010105 - Built-Up	28	2003	16442	SF	9/30/2010	67	5	4/7/2014	71	5	4	0.627066
Hot-Humid	B3010105 - Built-Up	28	1946	63	SF	2/1/2013	50	7	2/1/2013	50	7	0	0.859058
Hot-Humid	B3010105 - Built-Up	28	2000	5550	SF	9/30/2010	47	7	5/30/2014	88	3	4	0.579304

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1943	3143	SF	5/4/2012	80	4	5/4/2012	80	4	0	0.922822
Hot-Humid	B3010105 - Built-Up	28	1981	1700	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.483439
Hot-Humid	B3010105 - Built-Up	28	1970	10120	SF	7/28/2010	39	7	11/15/2011	30	7	1	0.032714
Hot-Humid	B3010105 - Built-Up	28	1970	1516	SF	7/28/2010	41	7	11/15/2011	50	7	1	0.144816
Hot-Humid	B3010105 - Built-Up	28	1970	1516	SF	7/28/2010	38	7	11/15/2011	30	7	1	0.61529
Hot-Humid	B3010105 - Built-Up	28	1982	435	SF	9/30/2010	47	7	9/4/2013	71	5	3	0.663104
Hot-Humid	B3010105 - Built-Up	28	1970	3440	SF	7/28/2010	56	6	11/15/2011	61	6	1	0.234542
Hot-Humid	B3010105 - Built-Up	28	2005	8621	SF	9/30/2010	67	5	11/15/2011	71	5	1	0.632606
Hot-Humid	B3010105 - Built-Up	28	1980	3440	SF	7/28/2010	33	7	2/25/2013	30	7	3	0.741704
Hot-Humid	B3010105 - Built-Up	28	1989	8446	SF	9/30/2010	62	6	4/25/2013	95	2	3	0.617029
Hot-Humid	B3010105 - Built-Up	28	1984	1664	SF	9/30/2010	43	7	3/13/2013	30	7	2	0.61516
Hot-Humid	B3010105 - Built-Up	28	2000	10500	SF	9/30/2010	40	7	3/5/2014	30	7	3	0.464947
Hot-Humid	B3010105 - Built-Up	28	1999	5286	SF	9/30/2010	59	6	2/19/2014	71	5	3	0.464984
Hot-Humid	B3010105 - Built-Up	28	2005	3630	SF	9/30/2010	67	5	8/25/2014	88	3	4	0.276007
Hot-Humid	B3010105 - Built-Up	28	1954	12031	SF	7/7/2010	40	7	11/8/2012	80	4	2	0.143875
Hot-Humid	B3010105 - Built-Up	28	1969	200	SF	2/6/2013	61	6	2/6/2013	61	6	0	0.883214
Hot-Humid	B3010105 - Built-Up	28	1961	19684	SF	9/30/2010	41	7	5/20/2013	95	2	3	0.623994
Hot-Humid	B3010105 - Built-Up	28	1989	8402	SF	9/30/2010	41	7	11/15/2011	50	7	1	0.260648
Hot-Humid	B3010105 - Built-Up	28	1984	7920	SF	9/30/2010	33	7	11/15/2011	30	7	1	0.389068
Hot-Humid	B3010105 - Built-Up	28	2010	9774	SF	9/12/2011	100	1	3/17/2013	95	2	2	0.899592
Hot-Humid	B3010105 - Built-Up	28	1969	1280	SF	7/28/2010	49	7	5/6/2013	71	5	3	0.340307
Hot-Humid	B3010105 - Built-Up	28	2006	11930	SF	9/30/2010	70	5	9/23/2014	71	5	4	0.187045
Hot-Humid	B3010105 - Built-Up	28	2005	8250	SF	9/30/2010	98	2	11/15/2011	100	1	1	0.927776
Hot-Humid	B3010105 - Built-Up	28	1992	29076	SF	9/30/2010	43	7	3/14/2013	88	3	2	0.468211
Hot-Humid	B3010105 - Built-Up	28	1980	5338	SF	7/28/2010	87	3	8/3/2014	88	3	4	0.870489
Hot-Humid	B3010105 - Built-Up	28	1978	9980	SF	9/30/2010	78	4	11/15/2011	80	4	1	0.842781
Hot-Humid	B3010105 - Built-Up	28	1999	34515	SF	9/30/2010	53	7	7/1/2014	50	7	4	0.425287
Hot-Humid	B3010105 - Built-Up	28	1980	336	SF	7/28/2010	71	5	11/15/2011	71	5	1	0.967607

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1985	651	SF	7/28/2010	80	4	11/15/2011	80	4	1	0.090834
Hot-Humid	B3010105 - Built-Up	28	1969	8472	SF	1/16/2013	50	7	1/16/2013	50	7	0	0.864746
Hot-Humid	B3010105 - Built-Up	28	1995	9704	SF	9/30/2010	100	1	5/21/2014	88	3	4	0.77575
Hot-Humid	B3010105 - Built-Up	28	1995	2200	SF	9/30/2010	87	3	4/30/2013	71	5	3	0.403242
Hot-Humid	B3010105 - Built-Up	28	1998	38575	SF	9/30/2010	45	7	8/18/2014	50	7	4	0.325916
Hot-Humid	B3010105 - Built-Up	28	1970	61866	SF	7/28/2010	100	1	11/15/2011	100	1	1	0.313518
Hot-Humid	B3010105 - Built-Up	28	1970	619	SF	7/28/2010	37	7	11/15/2011	30	7	1	0.120765
Hot-Humid	B3010105 - Built-Up	28	1987	1938	SF	9/30/2010	100	1	5/14/2014	88	3	4	0.241422
Hot-Humid	B3010105 - Built-Up	28	1999	4000	SF	9/30/2010	100	1	3/5/2014	95	2	3	0.67093
Hot-Humid	B3010105 - Built-Up	28	1982	6402	SF	9/30/2010	76	4	11/15/2011	71	5	1	0.762559
Hot-Humid	B3010105 - Built-Up	28	2005	1740	SF	4/19/2012	80	4	3/19/2013	80	4	1	0.224692
Hot-Humid	B3010105 - Built-Up	28	2000	5350	SF	7/28/2010	100	1	11/25/2013	100	1	3	0.130969
Hot-Humid	B3010105 - Built-Up	28	1998	720	SF	7/28/2010	87	3	12/21/2012	88	3	2	0.861905
Hot-Humid	B3010105 - Built-Up	28	1998	31900	SF	7/28/2010	89	3	12/21/2012	88	3	2	0.126783
Hot-Humid	B3010105 - Built-Up	28	2000	8050	SF	9/30/2010	55	7	8/21/2014	88	3	4	0.204398
Hot-Humid	B3010105 - Built-Up	28	2005	7260	SF	9/30/2010	67	5	10/2/2014	88	3	4	0.015712
Hot-Humid	B3010105 - Built-Up	28	1975	7856	SF	9/30/2010	100	1	4/7/2014	88	3	4	0.424719
Hot-Humid	B3010105 - Built-Up	28	1959	9610	SF	7/7/2010	100	1	5/28/2013	95	2	3	0.974636
Hot-Humid	B3010105 - Built-Up	28	1982	1150	SF	9/30/2010	40	7	9/4/2013	80	4	3	0.960334
Hot-Humid	B3010105 - Built-Up	28	1939	88	SF	2/6/2013	80	4	2/6/2013	80	4	0	0.979618
Hot-Humid	B3010105 - Built-Up	28	2005	105001	SF	9/30/2010	67	5	9/4/2013	80	4	3	0.700189
Hot-Humid	B3010105 - Built-Up	28	1995	1360	SF	9/30/2010	45	7	11/15/2011	50	7	1	0.084726
Hot-Humid	B3010105 - Built-Up	28	1986	67010	SF	9/30/2010	81	4	1/30/2014	30	7	3	0.837434
Hot-Humid	B3010105 - Built-Up	28	1993	15800	SF	7/28/2010	72	5	9/19/2013	71	5	3	0.031304
Hot-Humid	B3010105 - Built-Up	28	2000	2016	SF	7/28/2010	7	7	11/15/2011	10	7	1	0.388852
Hot-Humid	B3010105 - Built-Up	28	2005	792	SF	9/30/2010	67	5	11/15/2011	71	5	1	0.655936
Hot-Humid	B3010105 - Built-Up	28	2005	12000	SF	9/30/2010	67	5	5/17/2013	80	4	3	0.75697
Hot-Humid	B3010105 - Built-Up	28	2006	45497	SF	9/30/2010	76	4	5/21/2013	95	2	3	0.269756

						Inspection 1			Inspection 2				
Region	**Component**	**Design Life**	**Year Installed**	**Quantity**	**UM**	**Date**	**Rating**	**State**	**Date**	**Rating**	**State**	**Obs. Interval**	**Random Number**
Hot-Humid	B3010105 - Built-Up	28	2006	7558	SF	9/30/2010	70	5	2/12/2014	50	7	3	0.772928
Hot-Humid	B3010105 - Built-Up	28	1958	10479	SF	9/30/2010	43	7	11/15/2011	50	7	1	0.893343
Hot-Humid	B3010105 - Built-Up	28	1995	384	SF	9/30/2010	45	7	9/4/2013	80	4	3	0.083056
Hot-Humid	B3010105 - Built-Up	28	1941	63	SF	2/6/2013	30	7	2/6/2013	30	7	0	0.378473
Hot-Humid	B3010105 - Built-Up	28	1982	1206	SF	7/28/2010	80	4	11/15/2011	80	4	1	0.099097
Hot-Humid	B3010105 - Built-Up	28	2000	318	SF	1/14/2013	88	3	9/15/2014	80	4	2	0.755194
Hot-Humid	B3010105 - Built-Up	28	2005	650	SF	9/30/2010	67	5	11/15/2011	71	5	1	0.097363
Hot-Humid	B3010105 - Built-Up	28	2005	1400	SF	9/30/2010	45	7	8/18/2014	88	3	4	0.232492
Hot-Humid	B3010105 - Built-Up	28	1943	20700	SF	7/28/2010	69	5	11/15/2011	71	5	1	0.740206
Hot-Humid	B3010105 - Built-Up	28	1980	1900	SF	7/28/2010	37	7	10/25/2012	30	7	2	0.029177
Hot-Humid	B3010105 - Built-Up	28	2011	481	SF	2/12/2013	95	2	9/12/2014	95	2	2	0.067238
Hot-Humid	B3010105 - Built-Up	28	2003	2000	SF	9/30/2010	100	1	4/30/2013	71	5	3	0.141088
Hot-Humid	B3010105 - Built-Up	28	1946	63	SF	2/12/2013	10	7	2/12/2013	10	7	0	0.928175
Hot-Humid	B3010105 - Built-Up	28	1941	10318	SF	9/30/2010	100	1	3/29/2013	80	4	2	0.490694
Hot-Humid	B3010105 - Built-Up	28	1988	28807	SF	9/30/2010	100	1	1/10/2014	30	7	3	0.954149
Hot-Humid	B3010105 - Built-Up	28	1996	80	SF	7/28/2010	80	4	11/15/2011	80	4	1	0.415337
Hot-Humid	B3010105 - Built-Up	28	2007	27153	SF	7/28/2011	88	3	9/19/2013	88	3	2	0.51259
Hot-Humid	B3010105 - Built-Up	28	1986	5852	SF	9/30/2010	58	6	11/15/2011	61	6	1	0.623649
Hot-Humid	B3010105 - Built-Up	28	1991	194986	SF	9/30/2010	61	6	1/27/2014	71	5	3	0.781939
Hot-Humid	B3010105 - Built-Up	28	1989	129991	SF	9/30/2010	61	6	1/27/2014	71	5	3	0.919473
Hot-Humid	B3010105 - Built-Up	28	1939	63	SF	2/6/2013	30	7	2/6/2013	30	7	0	0.555839
Hot-Humid	B3010105 - Built-Up	28	1969	15608	SF	1/13/2013	95	2	2/9/2014	95	2	1	0.496422
Hot-Humid	B3010105 - Built-Up	28	1951	8849	SF	9/30/2010	95	2	11/15/2011	95	2	1	0.43065
Hot-Humid	B3010105 - Built-Up	28	2003	1750	SF	7/28/2010	89	3	1/10/2014	61	6	3	0.055678
Hot-Humid	B3010105 - Built-Up	28	1990	399	SF	7/28/2010	61	6	8/19/2014	61	6	4	0.854895
Hot-Humid	B3010105 - Built-Up	28	1960	87128	SF	7/18/2012	71	5	10/9/2014	10	7	2	0.14309
Hot-Humid	B3010105 - Built-Up	28	2013	2500	SF	7/28/2010	15	7	8/28/2013	100	1	3	0.678762
Hot-Humid	B3010105 - Built-Up	28	1990	1350	SF	9/30/2010	72	5	11/15/2011	71	5	1	0.649965

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	2005	2160	SF	9/30/2010	99	2	11/15/2011	100	1	1	0.065
Hot-Humid	B3010105 - Built-Up	28	2006	26616	SF	9/30/2010	47	7	8/21/2014	88	3	4	0.964495
Hot-Humid	B3010105 - Built-Up	28	1973	731	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.097253
Hot-Humid	B3010105 - Built-Up	28	1946	196	SF	12/19/2012	71	5	9/11/2014	71	5	2	0.578806
Hot-Humid	B3010105 - Built-Up	28	2000	6793	SF	2/13/2013	88	3	9/10/2014	88	3	2	0.312153
Hot-Humid	B3010105 - Built-Up	28	2002	10701	SF	9/30/2010	59	6	5/6/2013	95	2	3	0.095338
Hot-Humid	B3010105 - Built-Up	28	1990	900	SF	2/5/2013	71	5	2/5/2013	71	5	0	0.537433
Hot-Humid	B3010105 - Built-Up	28	2007	5100	SF	4/27/2012	30	7	7/6/2014	30	7	2	0.125819
Hot-Humid	B3010105 - Built-Up	28	1942	2200	SF	4/27/2012	10	7	7/6/2014	10	7	2	0.45925
Hot-Humid	B3010105 - Built-Up	28	1958	308	SF	9/30/2010	43	7	4/1/2013	10	7	3	0.072642
Hot-Humid	B3010105 - Built-Up	28	1965	2640	SF	7/28/2010	50	7	11/15/2011	50	7	1	0.371037
Hot-Humid	B3010105 - Built-Up	28	2006	3600	SF	9/30/2010	70	5	5/18/2013	71	5	3	0.493934
Hot-Humid	B3010105 - Built-Up	28	1995	989	SF	2/12/2013	80	4	2/12/2013	80	4	0	0.579419
Hot-Humid	B3010105 - Built-Up	28	1995	208	SF	9/30/2010	88	3	5/4/2013	71	5	3	0.599406
Hot-Humid	B3010105 - Built-Up	28	1990	7920	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.072941
Hot-Humid	B3010105 - Built-Up	28	1989	3804	SF	7/28/2010	71	5	11/15/2011	71	5	1	0.217545
Hot-Humid	B3010105 - Built-Up	28	2000	150	SF	7/28/2010	17	7	9/18/2013	50	7	3	0.643305
Hot-Humid	B3010105 - Built-Up	28	2000	700	SF	2/5/2013	80	4	2/5/2013	80	4	0	0.141073
Hot-Humid	B3010105 - Built-Up	28	2011	49301	SF	9/30/2010	55	7	6/20/2014	95	2	4	0.349025
Hot-Humid	B3010105 - Built-Up	28	2005	73510	SF	7/28/2010	55	7	11/15/2011	50	7	1	0.802259
Hot-Humid	B3010105 - Built-Up	28	1995	211	SF	12/26/2012	71	5	9/15/2014	71	5	2	0.210186
Hot-Humid	B3010105 - Built-Up	28	1994	13939	SF	9/30/2010	92	3	11/15/2011	95	2	1	0.925216
Hot-Humid	B3010105 - Built-Up	28	1990	100001	SF	9/30/2010	43	7	5/29/2014	71	5	4	0.163978
Hot-Humid	B3010105 - Built-Up	28	2003	2000	SF	9/30/2010	100	1	5/20/2014	88	3	4	0.620913
Hot-Humid	B3010105 - Built-Up	28	1985	900	SF	9/30/2010	43	7	4/29/2013	50	7	3	0.034971
Hot-Humid	B3010105 - Built-Up	28	1999	900	SF	9/30/2010	53	7	4/30/2013	50	7	3	0.575386
Hot-Humid	B3010105 - Built-Up	28	2000	6530	SF	9/30/2010	55	7	4/11/2013	50	7	3	0.289409
Hot-Humid	B3010105 - Built-Up	28	1952	15128	SF	7/7/2010	40	7	9/7/2014	88	3	4	0.666922

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1975	1344	SF	9/30/2010	87	3	2/27/2014	88	3	3	0.271919
Hot-Humid	B3010105 - Built-Up	28	2006	2994	SF	9/30/2010	70	5	11/15/2011	71	5	1	0.570648
Hot-Humid	B3010105 - Built-Up	28	2001	232	SF	7/25/2012	71	5	7/25/2012	71	5	0	0.808954
Hot-Humid	B3010105 - Built-Up	28	1996	500	SF	9/30/2010	47	7	3/20/2013	95	2	2	0.861925
Hot-Humid	B3010105 - Built-Up	28	1952	5204	SF	9/30/2010	37	7	11/15/2011	30	7	1	0.221207
Hot-Humid	B3010105 - Built-Up	28	2005	507	SF	7/28/2010	80	4	11/15/2011	80	4	1	0.175163
Hot-Humid	B3010105 - Built-Up	28	1943	468	SF	7/28/2010	50	7	11/15/2011	50	7	1	0.271308
Hot-Humid	B3010105 - Built-Up	28	2005	12240	SF	9/30/2010	76	4	9/24/2014	95	2	4	0.292889
Hot-Humid	B3010105 - Built-Up	28	1954	120	SF	9/30/2010	95	2	10/10/2014	61	6	4	0.127973
Hot-Humid	B3010105 - Built-Up	28	1970	600	SF	7/28/2010	87	3	11/15/2011	88	3	1	0.973452
Hot-Humid	B3010105 - Built-Up	28	1985	1100	SF	9/30/2010	88	3	2/1/2014	71	5	3	0.776838
Hot-Humid	B3010105 - Built-Up	28	2006	504	SF	9/30/2010	95	2	10/15/2014	88	3	4	0.673612
Hot-Humid	B3010105 - Built-Up	28	1997	8050	SF	9/30/2010	49	7	3/29/2013	95	2	2	0.76571
Hot-Humid	B3010105 - Built-Up	28	1992	450	SF	9/30/2010	95	2	11/15/2011	95	2	1	0.413272
Hot-Humid	B3010105 - Built-Up	28	2000	3280	SF	7/28/2010	1	7	11/15/2011	10	7	1	0.665236
Hot-Humid	B3010105 - Built-Up	28	2002	26823	SF	9/30/2010	73	5	4/26/2014	71	5	4	0.026696
Hot-Humid	B3010105 - Built-Up	28	1998	2628	SF	7/28/2010	100	1	11/15/2011	100	1	1	0.267658
Hot-Humid	B3010105 - Built-Up	28	2012	1450	SF	1/14/2013	95	2	7/22/2014	88	3	2	0.27804
Hot-Humid	B3010105 - Built-Up	28	1966	16527	SF	7/7/2010	100	1	10/14/2014	80	4	4	0.298275
Hot-Humid	B3010105 - Built-Up	28	1995	1314	SF	9/30/2010	43	7	11/15/2011	50	7	1	0.566581
Hot-Humid	B3010105 - Built-Up	28	1988	13125	SF	9/30/2010	77	4	1/30/2014	80	4	3	0.493908
Hot-Humid	B3010105 - Built-Up	28	1975	384	SF	9/30/2010	45	7	11/15/2011	50	7	1	0.318587
Hot-Humid	B3010105 - Built-Up	28	1980	10767	SF	9/30/2010	100	1	4/20/2013	88	3	3	0.957234
Hot-Humid	B3010105 - Built-Up	28	2000	1050	SF	9/30/2010	88	3	1/27/2014	71	5	3	0.336498
Hot-Humid	B3010105 - Built-Up	28	1960	4695	SF	9/30/2010	45	7	3/13/2014	88	3	3	0.007819
Hot-Humid	B3010105 - Built-Up	28	1993	384	SF	7/28/2010	61	6	11/15/2011	61	6	1	0.300807
Hot-Humid	B3010105 - Built-Up	28	2000	26357	SF	9/30/2010	55	7	4/26/2014	50	7	4	0.534679
Hot-Humid	B3010105 - Built-Up	28	1990	12273	SF	7/28/2010	68	5	11/15/2011	71	5	1	0.673688

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1987	28960	SF	9/30/2010	72	5	7/21/2014	30	7	4	0.47537
Hot-Humid	B3010105 - Built-Up	28	2004	756	SF	7/28/2010	88	3	9/15/2014	61	6	4	0.477193
Hot-Humid	B3010105 - Built-Up	28	1965	204	SF	3/14/2013	71	5	9/11/2014	71	5	1	0.81755
Hot-Humid	B3010105 - Built-Up	28	1983	1209	SF	9/30/2010	71	5	11/15/2011	71	5	1	0.318985
Hot-Humid	B3010105 - Built-Up	28	1984	1705	SF	9/30/2010	100	1	4/7/2014	71	5	4	0.288169
Hot-Humid	B3010105 - Built-Up	28	1970	2560	SF	7/28/2010	58	6	7/29/2014	61	6	4	0.583057
Hot-Humid	B3010105 - Built-Up	28	1991	2640	SF	7/28/2010	40	7	5/16/2014	30	7	4	0.084594
Hot-Humid	B3010105 - Built-Up	28	1992	266	SF	9/30/2010	41	7	9/4/2013	80	4	3	0.744465
Hot-Humid	B3010105 - Built-Up	28	1988	1350	SF	7/28/2010	26	7	11/21/2013	30	7	3	0.971898
Hot-Humid	B3010105 - Built-Up	28	2000	690	SF	7/28/2010	80	4	11/15/2011	80	4	1	0.367818
Hot-Humid	B3010105 - Built-Up	28	1986	5852	SF	9/30/2010	58	6	11/15/2011	61	6	1	0.41735
Hot-Humid	B3010105 - Built-Up	28	1992	4800	SF	9/30/2010	43	7	9/19/2014	50	7	4	0.72597
Hot-Humid	B3010105 - Built-Up	28	1939	63	SF	2/12/2013	30	7	2/12/2013	30	7	0	0.433545
Hot-Humid	B3010105 - Built-Up	28	1990	17355	SF	9/30/2010	41	7	4/22/2014	10	7	4	0.000125
Hot-Humid	B3010105 - Built-Up	28	1994	2000	SF	9/30/2010	71	5	11/15/2011	71	5	1	0.04312
Hot-Humid	B3010105 - Built-Up	28	1984	1896	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.511991
Hot-Humid	B3010105 - Built-Up	28	1994	39520	SF	9/30/2010	40	7	3/4/2014	88	3	3	0.334944
Hot-Humid	B3010105 - Built-Up	28	2006	179752	SF	9/30/2010	70	5	11/15/2011	71	5	1	0.633787
Hot-Humid	B3010105 - Built-Up	28	1989	10059	SF	9/30/2010	91	3	11/15/2011	95	2	1	0.021181
Hot-Humid	B3010105 - Built-Up	28	1996	6814	SF	3/29/2012	80	4	5/6/2014	80	4	2	0.423177
Hot-Humid	B3010105 - Built-Up	28	1978	38400	SF	9/30/2010	43	7	6/3/2013	61	6	3	0.828941
Hot-Humid	B3010105 - Built-Up	28	1990	234	SF	7/28/2010	71	5	8/23/2014	80	4	4	0.210782
Hot-Humid	B3010105 - Built-Up	28	1995	10494	SF	7/28/2010	100	1	11/15/2011	100	1	1	0.997512
Hot-Humid	B3010105 - Built-Up	28	2000	6530	SF	9/30/2010	55	7	8/15/2014	88	3	4	0.779599
Hot-Humid	B3010105 - Built-Up	28	2006	12100	SF	9/30/2010	100	1	1/15/2014	95	2	3	0.973085
Hot-Humid	B3010105 - Built-Up	28	1956	1800	SF	1/28/2013	95	2	2/4/2014	95	2	1	0.133081
Hot-Humid	B3010105 - Built-Up	28	1998	1083	SF	9/30/2010	93	2	3/13/2014	88	3	3	0.72832
Hot-Humid	B3010105 - Built-Up	28	1990	2108	SF	7/28/2010	47	7	9/6/2014	61	6	4	0.967982

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1999	3735	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.083155
Hot-Humid	B3010105 - Built-Up	28	1990	9000	SF	9/30/2010	76	4	2/20/2014	88	3	3	0.351616
Hot-Humid	B3010105 - Built-Up	28	1990	6500	SF	12/17/2012	80	4	6/27/2014	80	4	2	0.383419
Hot-Humid	B3010105 - Built-Up	28	1998	17080	SF	9/30/2010	98	2	9/25/2014	88	3	4	0.050087
Hot-Humid	B3010105 - Built-Up	28	1985	7933	SF	7/7/2010	100	1	9/3/2014	88	3	4	0.906181
Hot-Humid	B3010105 - Built-Up	28	1985	884	SF	9/30/2010	37	7	11/15/2011	30	7	1	0.864761
Hot-Humid	B3010105 - Built-Up	28	1946	63	SF	1/18/2013	61	6	1/18/2013	61	6	0	0.058666
Hot-Humid	B3010105 - Built-Up	28	1980	19926	SF	7/28/2010	87	3	3/19/2013	88	3	3	0.298798
Hot-Humid	B3010105 - Built-Up	28	1997	225	SF	7/28/2010	95	2	11/15/2011	95	2	1	0.679399
Hot-Humid	B3010105 - Built-Up	28	1983	2675	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.533302
Hot-Humid	B3010105 - Built-Up	28	1990	324	SF	9/30/2010	43	7	8/28/2014	71	5	4	0.544639
Hot-Humid	B3010105 - Built-Up	28	1995	4400	SF	9/30/2010	49	7	10/3/2014	88	3	4	0.22961
Hot-Humid	B3010105 - Built-Up	28	1995	62017	SF	9/30/2010	88	3	1/27/2014	71	5	3	0.83676
Hot-Humid	B3010105 - Built-Up	28	1972	2538	SF	7/28/2010	52	7	11/15/2011	50	7	1	0.592519
Hot-Humid	B3010105 - Built-Up	28	1964	1500	SF	7/28/2010	31	7	3/8/2013	30	7	3	0.269991
Hot-Humid	B3010105 - Built-Up	28	1996	1260	SF	9/30/2010	82	4	11/15/2011	80	4	1	0.723559
Hot-Humid	B3010105 - Built-Up	28	1987	46117	SF	9/30/2010	94	2	1/10/2014	50	7	3	0.010412
Hot-Humid	B3010105 - Built-Up	28	2005	8850	SF	9/30/2010	67	5	11/15/2011	71	5	1	0.19064
Hot-Humid	B3010105 - Built-Up	28	1965	36622	SF	7/7/2010	41	7	3/1/2014	95	2	4	0.05656
Hot-Humid	B3010105 - Built-Up	28	1996	5040	SF	2/13/2013	80	4	2/13/2013	80	4	0	0.775731
Hot-Humid	B3010105 - Built-Up	28	2001	13000	SF	9/30/2010	79	4	5/14/2014	88	3	4	0.06064
Hot-Humid	B3010105 - Built-Up	28	1967	85853	SF	9/30/2010	56	6	5/13/2014	88	3	4	0.69836
Hot-Humid	B3010105 - Built-Up	28	1991	2000	SF	9/30/2010	61	6	11/15/2011	61	6	1	0.927896
Hot-Humid	B3010105 - Built-Up	28	1995	37797	SF	8/8/2011	61	6	2/9/2014	71	5	3	0.711398
Hot-Humid	B3010105 - Built-Up	28	1994	1650	SF	7/28/2010	80	4	7/7/2014	71	5	4	0.150156
Hot-Humid	B3010105 - Built-Up	28	1973	22300	SF	7/28/2010	1	7	8/18/2014	50	7	4	0.440777
Hot-Humid	B3010105 - Built-Up	28	1975	39600	SF	9/30/2010	55	7	8/16/2014	50	7	4	0.598865
Hot-Humid	B3010105 - Built-Up	28	1996	370081	SF	9/30/2010	47	7	8/16/2014	50	7	4	0.427552

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	2004	2868	SF	7/28/2010	59	6	11/15/2011	61	6	1	0.998659
Hot-Humid	B3010105 - Built-Up	28	1993	660	SF	7/28/2010	31	7	11/15/2011	30	7	1	0.982859
Hot-Humid	B3010105 - Built-Up	28	1942	3243	SF	7/28/2010	94	2	11/15/2011	95	2	1	0.04054
Hot-Humid	B3010105 - Built-Up	28	1989	91984	SF	9/30/2010	43	7	10/9/2014	61	6	4	0.764043
Hot-Humid	B3010105 - Built-Up	28	1995	1581	SF	7/28/2010	80	4	8/14/2014	61	6	4	0.894781
Hot-Humid	B3010105 - Built-Up	28	1995	55888	SF	9/30/2010	55	7	5/11/2014	71	5	4	0.572216
Hot-Humid	B3010105 - Built-Up	28	1965	2640	SF	7/28/2010	43	7	11/15/2011	50	7	1	0.34354
Hot-Humid	B3010105 - Built-Up	28	1957	96	SF	7/28/2010	61	6	11/15/2011	61	6	1	0.13401
Hot-Humid	B3010105 - Built-Up	28	2005	3500	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.63702
Hot-Humid	B3010105 - Built-Up	28	1976	7950	SF	9/30/2010	43	7	3/4/2014	100	1	3	0.67496
Hot-Humid	B3010105 - Built-Up	28	1999	5280	SF	9/30/2010	100	1	6/18/2013	88	3	3	0.785125
Hot-Humid	B3010105 - Built-Up	28	1995	2184	SF	11/3/2012	100	1	4/10/2013	80	4	0	0.546015
Hot-Humid	B3010105 - Built-Up	28	1982	8765	SF	9/30/2010	50	7	11/15/2011	50	7	1	0.114451
Hot-Humid	B3010105 - Built-Up	28	1946	859	SF	9/30/2010	100	1	3/19/2014	88	3	3	0.57596
Hot-Humid	B3010105 - Built-Up	28	1990	21742	SF	9/30/2010	43	7	8/26/2013	30	7	3	0.611308
Hot-Humid	B3010105 - Built-Up	28	2003	30141	SF	9/30/2010	62	6	3/13/2013	95	2	2	0.592401
Hot-Humid	B3010105 - Built-Up	28	1990	24700	SF	9/30/2010	50	7	11/15/2011	50	7	1	0.39745
Hot-Humid	B3010105 - Built-Up	28	2003	3896	SF	9/30/2010	36	7	5/23/2013	30	7	3	0.214607
Hot-Humid	B3010105 - Built-Up	28	1944	1140	SF	7/28/2010	100	1	11/15/2011	100	1	1	0.107696
Hot-Humid	B3010105 - Built-Up	28	1970	4503	SF	7/28/2010	1	7	12/28/2012	30	7	2	0.48832
Hot-Humid	B3010105 - Built-Up	28	1990	7260	SF	4/12/2012	71	5	4/12/2012	71	5	0	0.426427
Hot-Humid	B3010105 - Built-Up	28	2005	7260	SF	9/30/2010	37	7	10/3/2014	88	3	4	0.032742
Hot-Humid	B3010105 - Built-Up	28	1993	231	SF	9/30/2010	50	7	11/15/2011	50	7	1	0.942072
Hot-Humid	B3010105 - Built-Up	28	2005	7260	SF	9/30/2010	55	7	5/11/2013	30	7	3	0.022488
Hot-Humid	B3010105 - Built-Up	28	2001	13450	SF	7/28/2010	80	4	11/15/2011	80	4	1	0.41009
Hot-Humid	B3010105 - Built-Up	28	1983	121	SF	9/30/2010	30	7	11/15/2011	30	7	1	0.816296
Hot-Humid	B3010105 - Built-Up	28	1999	4945	SF	9/30/2010	73	5	3/19/2014	88	3	3	0.700087
Hot-Humid	B3010105 - Built-Up	28	1994	45196	SF	9/30/2010	38	7	5/1/2014	80	4	4	0.054206

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	2000	567	SF	6/19/2012	10	7	9/7/2014	10	7	2	0.207397
Hot-Humid	B3010105 - Built-Up	28	1987	5143	SF	7/28/2010	61	6	11/15/2011	61	6	1	0.272534
Hot-Humid	B3010105 - Built-Up	28	1988	560	SF	7/28/2010	88	3	9/25/2014	88	3	4	0.752227
Hot-Humid	B3010105 - Built-Up	28	1985	50	SF	6/27/2012	61	6	3/15/2013	61	6	1	0.970518
Hot-Humid	B3010105 - Built-Up	28	1991	27858	SF	9/30/2010	38	7	3/29/2013	10	7	2	0.799835
Hot-Humid	B3010105 - Built-Up	28	1986	5852	SF	9/30/2010	58	6	11/15/2011	61	6	1	0.793819
Hot-Humid	B3010105 - Built-Up	28	1959	320	SF	2/1/2013	61	6	2/1/2013	61	6	0	0.134814
Hot-Humid	B3010105 - Built-Up	28	1989	8150	SF	9/30/2010	56	6	10/14/2014	88	3	4	0.225221
Hot-Humid	B3010105 - Built-Up	28	1989	10772	SF	9/30/2010	79	4	6/5/2013	80	4	3	0.56693
Hot-Humid	B3010105 - Built-Up	28	2005	2550	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.126121
Hot-Humid	B3010105 - Built-Up	28	1985	89	SF	7/28/2010	80	4	11/15/2011	80	4	1	0.048398
Hot-Humid	B3010105 - Built-Up	28	2000	60501	SF	9/30/2010	55	7	1/17/2014	71	5	3	0.67381
Hot-Humid	B3010105 - Built-Up	28	1984	120	SF	9/30/2010	50	7	11/15/2011	50	7	1	0.357843
Hot-Humid	B3010105 - Built-Up	28	1995	1188	SF	7/28/2010	80	4	11/15/2011	80	4	1	0.937685
Hot-Humid	B3010105 - Built-Up	28	1995	19055	SF	9/30/2010	45	7	9/19/2014	88	3	4	0.355986
Hot-Humid	B3010105 - Built-Up	28	2001	5808	SF	9/30/2010	57	6	9/19/2014	88	3	4	0.107939
Hot-Humid	B3010105 - Built-Up	28	1987	130	SF	9/30/2010	88	3	9/4/2013	61	6	3	0.318692
Hot-Humid	B3010105 - Built-Up	28	1986	4920	SF	9/30/2010	58	6	11/15/2011	61	6	1	0.245126
Hot-Humid	B3010105 - Built-Up	28	1990	7337	SF	7/28/2010	18	7	6/17/2013	61	6	3	0.953885
Hot-Humid	B3010105 - Built-Up	28	1991	2250	SF	7/28/2010	11	7	2/12/2014	30	7	4	0.530347
Hot-Humid	B3010105 - Built-Up	28	1995	1882	SF	9/30/2010	88	3	6/13/2013	88	3	3	0.59748
Hot-Humid	B3010105 - Built-Up	28	1990	5500	SF	9/30/2010	94	2	11/15/2011	95	2	1	0.101453
Hot-Humid	B3010105 - Built-Up	28	1943	2480	SF	7/28/2010	79	4	11/15/2011	80	4	1	0.141464
Hot-Humid	B3010105 - Built-Up	28	1970	513	SF	7/28/2010	57	6	11/15/2011	61	6	1	0.23502
Hot-Humid	B3010105 - Built-Up	28	1990	1169	SF	7/28/2010	80	4	9/15/2014	71	5	4	0.20325
Hot-Humid	B3010105 - Built-Up	28	1975	4129	SF	7/28/2010	37	7	9/19/2014	61	6	4	0.851097
Hot-Humid	B3010105 - Built-Up	28	2002	16000	SF	9/30/2010	67	5	11/15/2011	71	5	1	0.363463
Hot-Humid	B3010105 - Built-Up	28	1995	93729	SF	9/30/2010	62	6	5/7/2014	80	4	4	0.151403

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1972	2205	SF	7/28/2010	52	7	11/15/2011	50	7	1	0.886156
Hot-Humid	B3010105 - Built-Up	28	1997	128002	SF	9/30/2010	71	5	11/15/2011	71	5	1	0.286322
Hot-Humid	B3010105 - Built-Up	28	2001	705	SF	9/30/2010	95	2	11/15/2011	95	2	1	0.817186
Hot-Humid	B3010105 - Built-Up	28	2003	798	SF	9/30/2010	43	7	3/15/2014	80	4	3	0.68815
Hot-Humid	B3010105 - Built-Up	28	1980	2520	SF	9/30/2010	55	7	5/13/2014	61	6	4	0.036244
Hot-Humid	B3010105 - Built-Up	28	2005	38535	SF	9/30/2010	73	5	4/21/2014	88	3	4	0.897702
Hot-Humid	B3010105 - Built-Up	28	1999	38885	SF	7/28/2010	71	5	11/15/2011	71	5	1	0.014612
Hot-Humid	B3010105 - Built-Up	28	1985	320	SF	7/28/2010	61	6	9/12/2014	61	6	4	0.296388
Hot-Humid	B3010105 - Built-Up	28	1949	2300	SF	9/30/2010	100	1	5/1/2014	100	1	4	0.792463
Hot-Humid	B3010105 - Built-Up	28	1989	3040	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.891647
Hot-Humid	B3010105 - Built-Up	28	1990	14100	SF	9/30/2010	59	6	5/22/2013	88	3	3	0.97783
Hot-Humid	B3010105 - Built-Up	28	1956	1530	SF	9/30/2010	43	7	9/16/2014	50	7	4	0.744441
Hot-Humid	B3010105 - Built-Up	28	2007	73601	SF	9/30/2010	100	1	5/6/2014	88	3	4	0.88693
Hot-Humid	B3010105 - Built-Up	28	1990	1312	SF	7/28/2010	43	7	11/15/2011	50	7	1	0.419217
Hot-Humid	B3010105 - Built-Up	28	1990	7473	SF	7/28/2010	69	5	11/15/2011	71	5	1	0.211812
Hot-Humid	B3010105 - Built-Up	28	2006	36148	SF	9/30/2010	67	5	5/3/2013	95	2	3	0.640942
Hot-Humid	B3010105 - Built-Up	28	2007	7700	SF	9/30/2010	99	2	11/15/2011	100	1	1	0.293843
Hot-Humid	B3010105 - Built-Up	28	1976	1652	SF	9/30/2010	81	4	5/19/2014	88	3	4	0.597978
Hot-Humid	B3010105 - Built-Up	28	2006	3968	SF	9/30/2010	87	3	11/15/2011	88	3	1	0.438764
Hot-Humid	B3010105 - Built-Up	28	2011	5000	SF	7/28/2010	12	7	4/1/2013	95	2	3	0.06749
Hot-Humid	B3010105 - Built-Up	28	2003	2800	SF	7/28/2010	89	3	4/1/2013	88	3	3	0.132655
Hot-Humid	B3010105 - Built-Up	28	1943	840	SF	7/28/2010	88	3	11/15/2011	88	3	1	0.549442
Hot-Humid	B3010105 - Built-Up	28	1983	76326	SF	7/28/2010	52	7	6/27/2014	88	3	4	0.395534
Hot-Humid	B3010105 - Built-Up	28	1983	1000	SF	7/28/2010	1	7	6/27/2014	30	7	4	0.193195
Hot-Humid	B3010105 - Built-Up	28	1979	16800	SF	7/7/2010	41	7	9/12/2012	88	3	2	0.616789
Hot-Humid	B3010105 - Built-Up	28	1990	14518	SF	12/19/2012	61	6	12/19/2012	61	6	0	0.523275
Hot-Humid	B3010105 - Built-Up	28	1998	5867	SF	3/19/2012	71	5	2/26/2014	71	5	2	0.84859
Hot-Humid	B3010105 - Built-Up	28	1984	17393	SF	9/30/2010	40	7	5/31/2014	71	5	4	0.327981

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	2007	13584	SF	9/30/2010	73	5	11/15/2011	71	5	1	0.686374
Hot-Humid	B3010105 - Built-Up	28	2011	10146	SF	12/28/2011	100	1	2/13/2014	88	3	2	0.39147
Hot-Humid	B3010105 - Built-Up	28	1995	225	SF	2/21/2013	71	5	6/23/2014	71	5	1	0.246725
Hot-Humid	B3010105 - Built-Up	28	1980	400	SF	7/28/2010	38	7	11/15/2011	30	7	1	0.379037
Hot-Humid	B3010105 - Built-Up	28	1995	9660	SF	7/28/2010	100	1	8/21/2014	88	3	4	0.48361
Hot-Humid	B3010105 - Built-Up	28	2007	8571	SF	9/30/2010	71	5	8/8/2013	95	2	3	0.943442
Hot-Humid	B3010105 - Built-Up	28	2002	3456	SF	7/28/2010	95	2	11/15/2011	95	2	1	0.717243
Hot-Humid	B3010105 - Built-Up	28	1990	82351	SF	9/30/2010	41	7	6/26/2014	88	3	4	0.658199
Hot-Humid	B3010105 - Built-Up	28	2000	110	SF	7/28/2010	31	7	11/15/2011	30	7	1	0.217684
Hot-Humid	B3010105 - Built-Up	28	2000	60001	SF	7/28/2010	63	6	6/6/2014	61	6	4	0.187402
Hot-Humid	B3010105 - Built-Up	28	1990	3613	SF	3/14/2013	80	4	3/14/2013	80	4	0	0.721511
Hot-Humid	B3010105 - Built-Up	28	1990	111001	SF	9/30/2010	43	7	11/15/2011	50	7	1	0.659749
Hot-Humid	B3010105 - Built-Up	28	1985	231	SF	7/28/2010	61	6	8/23/2014	30	7	4	0.141534
Hot-Humid	B3010105 - Built-Up	28	1995	1	SF	7/28/2010	78	4	11/15/2011	80	4	1	0.441875
Hot-Humid	B3010105 - Built-Up	28	2002	37946	SF	9/30/2010	84	4	5/24/2013	88	3	3	0.340305
Hot-Humid	B3010105 - Built-Up	28	1988	72421	SF	9/30/2010	78	4	1/11/2014	88	3	3	0.702469
Hot-Humid	B3010105 - Built-Up	28	1990	325	SF	7/28/2010	61	6	8/6/2014	61	6	4	0.438362
Hot-Humid	B3010105 - Built-Up	28	1994	7260	SF	9/30/2010	77	4	4/21/2013	80	4	3	0.520166
Hot-Humid	B3010105 - Built-Up	28	1988	260	SF	7/28/2010	42	7	7/31/2013	50	7	3	0.375253
Hot-Humid	B3010105 - Built-Up	28	2000	2975	SF	7/28/2010	45	7	7/31/2013	50	7	3	0.635695
Hot-Humid	B3010105 - Built-Up	28	1991	1194	SF	7/28/2010	23	7	7/31/2013	10	7	3	0.670747
Hot-Humid	B3010105 - Built-Up	28	1985	4649	SF	12/19/2012	61	6	12/19/2012	61	6	0	0.940862
Hot-Humid	B3010105 - Built-Up	28	2009	1756	SF	7/7/2010	100	1	8/18/2013	95	2	3	0.615452
Hot-Humid	B3010105 - Built-Up	28	1988	58	SF	7/28/2010	87	3	6/4/2014	80	4	4	0.936126
Hot-Humid	B3010105 - Built-Up	28	2000	504	SF	7/28/2010	66	5	2/25/2014	50	7	4	0.150912
Hot-Humid	B3010105 - Built-Up	28	2004	67201	SF	3/28/2012	80	4	1/23/2014	71	5	2	0.465127
Hot-Humid	B3010105 - Built-Up	28	1990	300	SF	7/28/2010	31	7	11/15/2011	30	7	1	0.138831
Hot-Humid	B3010105 - Built-Up	28	1978	5935	SF	7/28/2010	8	7	9/24/2014	30	7	4	0.207593

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	2006	10100	SF	9/30/2010	70	5	3/14/2014	30	7	3	0.806206
Hot-Humid	B3010105 - Built-Up	28	1999	13225	SF	9/30/2010	47	7	3/13/2014	95	2	3	0.720901
Hot-Humid	B3010105 - Built-Up	28	1996	795	SF	9/30/2010	71	5	5/20/2013	61	6	3	0.222643
Hot-Humid	B3010105 - Built-Up	28	1960	3000	SF	9/30/2010	92	3	9/4/2013	71	5	3	0.571405
Hot-Humid	B3010105 - Built-Up	28	2000	23180	SF	7/28/2010	64	6	11/26/2013	61	6	3	0.25774
Hot-Humid	B3010105 - Built-Up	28	1994	1014	SF	7/28/2010	100	1	11/15/2011	100	1	1	0.758774
Hot-Humid	B3010105 - Built-Up	28	1990	1176	SF	4/26/2012	80	4	2/21/2013	80	4	1	0.46548
Hot-Humid	B3010105 - Built-Up	28	1985	16254	SF	9/30/2010	43	7	11/15/2011	50	7	1	0.371983
Hot-Humid	B3010105 - Built-Up	28	1988	156162	SF	9/30/2010	100	1	1/10/2014	88	3	3	0.445272
Hot-Humid	B3010105 - Built-Up	28	1960	15245	SF	7/28/2010	1	7	11/15/2011	10	7	1	0.429832
Hot-Humid	B3010105 - Built-Up	28	2005	48961	SF	9/30/2010	43	7	8/18/2014	50	7	4	0.962078
Hot-Humid	B3010105 - Built-Up	28	2005	1500	SF	9/30/2010	41	7	8/18/2014	50	7	4	0.66313
Hot-Humid	B3010105 - Built-Up	28	1981	6350	SF	7/7/2010	100	1	12/4/2013	88	3	3	0.453472
Hot-Humid	B3010105 - Built-Up	28	1974	5176	SF	9/30/2010	43	7	11/15/2011	50	7	1	0.170722
Hot-Humid	B3010105 - Built-Up	28	1992	22081	SF	9/30/2010	43	7	4/30/2014	95	2	4	0.734785
Hot-Humid	B3010105 - Built-Up	28	2007	9615	SF	9/30/2010	33	7	11/15/2011	30	7	1	0.759387
Hot-Humid	B3010105 - Built-Up	28	1986	11808	SF	7/28/2010	98	2	10/2/2014	10	7	4	0.109388
Hot-Humid	B3010105 - Built-Up	28	1970	882	SF	7/28/2010	47	7	11/15/2011	50	7	1	0.660824
Hot-Humid	B3010105 - Built-Up	28	1970	10260	SF	7/28/2010	48	7	11/15/2011	50	7	1	0.748961
Hot-Humid	B3010105 - Built-Up	28	1989	4300	SF	9/30/2010	80	4	11/15/2011	80	4	1	0.17454
Hot-Humid	B3010105 - Built-Up	28	2005	11133	SF	9/30/2010	42	7	8/6/2013	71	5	3	0.692867
Hot-Humid	B3010105 - Built-Up	28	2004	9576	SF	7/7/2010	43	7	9/7/2014	88	3	4	0.180542
Hot-Humid	B3010105 - Built-Up	28	1970	3420	SF	7/28/2010	17	7	9/23/2014	71	5	4	0.994838
Hot-Humid	B3010105 - Built-Up	28	2000	2016	SF	7/28/2010	35	7	11/15/2011	30	7	1	0.265836
Hot-Humid	B3010105 - Built-Up	28	1990	406	SF	7/28/2010	87	3	9/3/2014	88	3	4	0.043694
Hot-Humid	B3010105 - Built-Up	28	1986	32400	SF	9/30/2010	68	5	1/27/2014	50	7	3	0.717897
Hot-Humid	B3010105 - Built-Up	28	1989	2285	SF	7/7/2010	100	1	8/5/2013	95	2	3	0.473068
Hot-Humid	B3010105 - Built-Up	28	1981	3234	SF	9/30/2010	93	2	2/12/2014	95	2	3	0.784393

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1983	7000	SF	9/30/2010	43	7	3/18/2013	30	7	2	0.858109
Hot-Humid	B3010105 - Built-Up	28	1971	2079	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.180668
Hot-Humid	B3010105 - Built-Up	28	1999	11880	SF	9/30/2010	73	5	8/4/2014	71	5	4	0.611082
Hot-Humid	B3010105 - Built-Up	28	1989	288	SF	6/8/2012	80	4	3/6/2014	80	4	2	0.854308
Hot-Humid	B3010105 - Built-Up	28	2002	720	SF	6/8/2012	80	4	3/6/2014	80	4	2	0.177812
Hot-Humid	B3010105 - Built-Up	28	1989	3938	SF	6/8/2012	80	4	3/6/2014	80	4	2	0.559291
Hot-Humid	B3010105 - Built-Up	28	1987	266	SF	6/8/2012	80	4	3/6/2014	80	4	2	0.808303
Hot-Humid	B3010105 - Built-Up	28	1987	666	SF	6/8/2012	61	6	3/6/2014	80	4	2	0.104649
Hot-Humid	B3010105 - Built-Up	28	1999	72	SF	6/8/2012	61	6	3/6/2014	80	4	2	0.507766
Hot-Humid	B3010105 - Built-Up	28	1989	1194	SF	6/8/2012	80	4	3/6/2014	80	4	2	0.025543
Hot-Humid	B3010105 - Built-Up	28	1989	361	SF	6/8/2012	80	4	3/6/2014	80	4	2	0.271569
Hot-Humid	B3010105 - Built-Up	28	1998	81	SF	6/8/2012	80	4	3/6/2014	80	4	2	0.315387
Hot-Humid	B3010105 - Built-Up	28	1997	795	SF	6/8/2012	80	4	3/6/2014	80	4	2	0.034628
Hot-Humid	B3010105 - Built-Up	28	1989	189	SF	6/8/2012	71	5	3/6/2014	71	5	2	0.654307
Hot-Humid	B3010105 - Built-Up	28	1987	1400	SF	7/28/2010	88	3	11/15/2011	88	3	1	0.862442
Hot-Humid	B3010105 - Built-Up	28	1997	1537	SF	7/28/2010	95	2	11/15/2011	95	2	1	0.970485
Hot-Humid	B3010105 - Built-Up	28	2006	141350	SF	4/27/2012	61	6	7/12/2014	61	6	2	0.148369
Hot-Humid	B3010105 - Built-Up	28	2006	18117	SF	4/27/2012	71	5	7/12/2014	71	5	2	0.991981
Hot-Humid	B3010105 - Built-Up	28	1963	1825	SF	9/30/2010	47	7	2/25/2014	30	7	3	0.377705
Hot-Humid	B3010105 - Built-Up	28	1969	5790	SF	9/30/2010	43	7	3/16/2013	88	3	2	0.235489
Hot-Humid	B3010105 - Built-Up	28	2000	18409	SF	9/30/2010	88	3	5/23/2013	30	7	3	0.944523
Hot-Humid	B3010105 - Built-Up	28	2005	2576	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.14629
Hot-Humid	B3010105 - Built-Up	28	2004	450	SF	7/28/2010	80	4	9/16/2014	61	6	4	0.660052
Hot-Humid	B3010105 - Built-Up	28	1980	16264	SF	7/28/2010	39	7	11/15/2011	30	7	1	0.859675
Hot-Humid	B3010105 - Built-Up	28	1954	1115	SF	9/30/2010	80	4	7/17/2013	95	2	3	0.078401
Hot-Humid	B3010105 - Built-Up	28	1995	5160	SF	7/28/2010	42	7	1/21/2014	50	7	3	0.288246
Hot-Humid	B3010105 - Built-Up	28	2005	19035	SF	7/28/2010	70	5	1/21/2014	71	5	3	0.066408
Hot-Humid	B3010105 - Built-Up	28	2005	30555	SF	7/28/2010	70	5	1/21/2014	71	5	3	0.912858

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1953	6505	SF	9/30/2010	100	1	5/10/2014	30	7	4	0.533971
Hot-Humid	B3010105 - Built-Up	28	1969	4680	SF	1/3/2013	88	3	1/14/2014	88	3	1	0.453215
Hot-Humid	B3010105 - Built-Up	28	1985	1256	SF	9/30/2010	50	7	11/15/2011	50	7	1	0.097054
Hot-Humid	B3010105 - Built-Up	28	2000	3500	SF	9/30/2010	45	7	4/30/2014	50	7	4	0.449651
Hot-Humid	B3010105 - Built-Up	28	1986	1900	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.871591
Hot-Humid	B3010105 - Built-Up	28	1975	6300	SF	7/28/2010	47	7	11/15/2011	50	7	1	0.227304
Hot-Humid	B3010105 - Built-Up	28	2003	864	SF	7/28/2010	80	4	9/12/2014	71	5	4	0.308541
Hot-Humid	B3010105 - Built-Up	28	2006	19374	SF	9/30/2010	88	3	4/14/2014	71	5	4	0.183849
Hot-Humid	B3010105 - Built-Up	28	1998	106027	SF	9/30/2010	67	5	5/7/2014	71	5	4	0.278226
Hot-Humid	B3010105 - Built-Up	28	1970	3278	SF	7/7/2010	100	1	8/11/2014	88	3	4	0.851198
Hot-Humid	B3010105 - Built-Up	28	1978	800	SF	9/30/2010	55	7	5/15/2014	50	7	4	0.373416
Hot-Humid	B3010105 - Built-Up	28	1987	24747	SF	9/30/2010	88	3	2/5/2014	88	3	3	0.386683
Hot-Humid	B3010105 - Built-Up	28	1982	1400	SF	4/12/2012	10	7	1/25/2013	10	7	1	0.425954
Hot-Humid	B3010105 - Built-Up	28	1998	46023	SF	9/30/2010	40	7	6/23/2014	95	2	4	0.867851
Hot-Humid	B3010105 - Built-Up	28	1941	1428	SF	9/30/2010	42	7	11/15/2011	50	7	1	0.372963
Hot-Humid	B3010105 - Built-Up	28	1988	5177	SF	9/30/2010	61	6	4/28/2014	88	3	4	0.96233
Hot-Humid	B3010105 - Built-Up	28	2004	19680	SF	9/30/2010	64	6	11/15/2011	61	6	1	0.786217
Hot-Humid	B3010105 - Built-Up	28	1983	560	SF	7/28/2010	57	6	11/15/2011	61	6	1	0.491955
Hot-Humid	B3010105 - Built-Up	28	1995	2500	SF	9/30/2010	37	7	11/15/2011	30	7	1	0.42957
Hot-Humid	B3010105 - Built-Up	28	1999	3000	SF	9/30/2010	45	7	3/17/2014	88	3	3	0.804485
Hot-Humid	B3010105 - Built-Up	28	1996	5624	SF	9/30/2010	47	7	7/3/2014	71	5	4	0.217771
Hot-Humid	B3010105 - Built-Up	28	2004	29997	SF	9/30/2010	64	6	8/19/2014	88	3	4	0.827093
Hot-Humid	B3010105 - Built-Up	28	2003	13076	SF	9/30/2010	62	6	5/6/2013	95	2	3	0.995663
Hot-Humid	B3010105 - Built-Up	28	1998	2000	SF	4/3/2012	50	7	1/23/2014	50	7	2	0.079817
Hot-Humid	B3010105 - Built-Up	28	1998	16000	SF	4/3/2012	50	7	1/23/2014	50	7	2	0.329134
Hot-Humid	B3010105 - Built-Up	28	2000	16000	SF	4/3/2012	50	7	1/23/2014	50	7	2	0.617918
Hot-Humid	B3010105 - Built-Up	28	2000	34000	SF	4/3/2012	50	7	1/23/2014	50	7	2	0.440508
Hot-Humid	B3010105 - Built-Up	28	1999	3551	SF	9/30/2010	80	4	1/10/2014	80	4	3	0.628173

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	2007	25318	SF	9/30/2010	100	1	5/7/2014	88	3	4	0.004252
Hot-Humid	B3010105 - Built-Up	28	1998	15750	SF	7/28/2010	70	5	6/6/2014	61	6	4	0.977433
Hot-Humid	B3010105 - Built-Up	28	1998	1150	SF	7/28/2010	67	5	6/6/2014	61	6	4	0.210808
Hot-Humid	B3010105 - Built-Up	28	1998	600	SF	7/28/2010	65	5	6/6/2014	61	6	4	0.283409
Hot-Humid	B3010105 - Built-Up	28	2009	6065	SF	12/18/2012	95	2	6/19/2014	61	6	2	0.014932
Hot-Humid	B3010105 - Built-Up	28	1975	15807	SF	9/30/2010	100	1	5/15/2014	30	7	4	0.982851
Hot-Humid	B3010105 - Built-Up	28	1975	3640	SF	7/28/2010	47	7	11/15/2011	50	7	1	0.721808
Hot-Humid	B3010105 - Built-Up	28	1987	78573	SF	7/28/2010	42	7	2/6/2013	50	7	3	0.353809
Hot-Humid	B3010105 - Built-Up	28	1983	7920	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.089654
Hot-Humid	B3010105 - Built-Up	28	1990	1182	SF	7/28/2010	88	3	9/15/2014	88	3	4	0.671351
Hot-Humid	B3010105 - Built-Up	28	2004	38011	SF	4/12/2012	30	7	9/2/2014	30	7	2	0.106306
Hot-Humid	B3010105 - Built-Up	28	2000	7436	SF	9/30/2010	83	4	9/25/2014	88	3	4	0.152183
Hot-Humid	B3010105 - Built-Up	28	1983	4951	SF	9/30/2010	57	6	5/17/2013	88	3	3	0.039287
Hot-Humid	B3010105 - Built-Up	28	1980	2000	SF	9/30/2010	100	1	7/12/2013	88	3	3	0.700046
Hot-Humid	B3010105 - Built-Up	28	2008	154473	SF	9/30/2010	76	4	4/30/2014	88	3	4	0.892223
Hot-Humid	B3010105 - Built-Up	28	1980	736	SF	7/28/2010	74	5	11/15/2011	71	5	1	0.275783
Hot-Humid	B3010105 - Built-Up	28	1994	120	SF	2/5/2013	88	3	2/5/2013	88	3	0	0.902882
Hot-Humid	B3010105 - Built-Up	28	2005	10900	SF	9/30/2010	67	5	6/11/2014	88	3	4	0.680623
Hot-Humid	B3010105 - Built-Up	28	2000	399	SF	7/28/2010	80	4	8/19/2014	80	4	4	0.817259
Hot-Humid	B3010105 - Built-Up	28	2000	2468	SF	7/28/2010	71	5	11/15/2011	71	5	1	0.198147
Hot-Humid	B3010105 - Built-Up	28	2003	1800	SF	7/28/2010	68	5	1/9/2014	61	6	3	0.403833
Hot-Humid	B3010105 - Built-Up	28	1994	7450	SF	9/30/2010	90	3	11/15/2011	95	2	1	0.693429
Hot-Humid	B3010105 - Built-Up	28	1946	143	SF	12/19/2012	71	5	7/2/2014	71	5	2	0.176852
Hot-Humid	B3010105 - Built-Up	28	1989	6000	SF	9/30/2010	91	3	11/15/2011	95	2	1	0.214655
Hot-Humid	B3010105 - Built-Up	28	1995	5309	SF	9/30/2010	59	6	4/21/2013	88	3	3	0.950509
Hot-Humid	B3010105 - Built-Up	28	2000	5440	SF	9/30/2010	64	6	6/18/2013	88	3	3	0.700335
Hot-Humid	B3010105 - Built-Up	28	1990	512	SF	9/30/2010	50	7	7/16/2013	88	3	3	0.563555
Hot-Humid	B3010105 - Built-Up	28	1997	11656	SF	9/30/2010	49	7	6/10/2013	71	5	3	0.712482

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1988	1500	SF	9/30/2010	38	7	6/14/2013	71	5	3	0.953229
Hot-Humid	B3010105 - Built-Up	28	2000	9200	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.501775
Hot-Humid	B3010105 - Built-Up	28	2005	23457	SF	9/30/2010	67	5	4/13/2014	88	3	4	0.457523
Hot-Humid	B3010105 - Built-Up	28	1990	33750	SF	7/28/2010	41	7	2/13/2013	61	6	3	0.878222
Hot-Humid	B3010105 - Built-Up	28	1985	1012	SF	7/28/2010	79	4	9/13/2014	10	7	4	0.356713
Hot-Humid	B3010105 - Built-Up	28	1960	190	SF	9/30/2010	40	7	9/4/2013	71	5	3	0.093033
Hot-Humid	B3010105 - Built-Up	28	1990	5334	SF	9/30/2010	47	7	11/15/2011	50	7	1	0.034214
Hot-Humid	B3010105 - Built-Up	28	2003	4758	SF	9/30/2010	95	2	11/15/2011	95	2	1	0.458497
Hot-Humid	B3010105 - Built-Up	28	2002	53670	SF	9/30/2010	61	6	5/16/2014	30	7	4	0.187892
Hot-Humid	B3010105 - Built-Up	28	1965	12000	SF	9/30/2010	67	5	10/22/2013	95	2	3	0.614491
Hot-Humid	B3010105 - Built-Up	28	1998	8025	SF	9/30/2010	40	7	11/15/2011	30	7	1	0.685198
Hot-Humid	B3010105 - Built-Up	28	1995	800	SF	2/7/2013	71	5	2/7/2013	71	5	0	0.342942
Hot-Humid	B3010105 - Built-Up	28	2004	20508	SF	7/28/2010	40	7	9/28/2014	30	7	4	0.582236
Hot-Humid	B3010105 - Built-Up	28	1985	13515	SF	7/28/2010	40	7	9/28/2014	30	7	4	0.248404
Hot-Humid	B3010105 - Built-Up	28	1960	900	SF	7/28/2010	39	7	9/28/2014	30	7	4	0.49529
Hot-Humid	B3010105 - Built-Up	28	1985	725	SF	9/30/2010	37	7	11/15/2011	30	7	1	0.13512
Hot-Humid	B3010105 - Built-Up	28	1970	17276	SF	9/30/2010	37	7	11/15/2011	30	7	1	0.408894
Hot-Humid	B3010105 - Built-Up	28	1993	3480	SF	9/30/2010	41	7	11/15/2011	50	7	1	0.049108
Hot-Humid	B3010105 - Built-Up	28	1995	425	SF	9/30/2010	88	3	11/15/2011	88	3	1	1.95E-05
Hot-Humid	B3010105 - Built-Up	28	1995	17319	SF	9/30/2010	45	7	5/17/2013	95	2	3	0.594327
Hot-Humid	B3010105 - Built-Up	28	1939	63	SF	2/5/2013	30	7	2/5/2013	30	7	0	0.101397
Hot-Humid	B3010105 - Built-Up	28	1985	63	SF	2/11/2013	10	7	2/11/2013	10	7	0	0.951884
Hot-Humid	B3010105 - Built-Up	28	2003	9761	SF	9/30/2010	67	5	6/14/2013	95	2	3	0.604424
Hot-Humid	B3010105 - Built-Up	28	1980	96	SF	7/28/2010	13	7	7/19/2014	10	7	4	0.388279
Hot-Humid	B3010105 - Built-Up	28	1993	1543	SF	9/30/2010	41	7	9/4/2013	71	5	3	0.837008
Hot-Humid	B3010105 - Built-Up	28	1988	49474	SF	9/30/2010	92	3	1/24/2014	30	7	3	0.937775
Hot-Humid	B3010105 - Built-Up	28	1987	160	SF	9/30/2010	41	7	2/26/2014	50	7	3	0.734017
Hot-Humid	B3010105 - Built-Up	28	1986	24747	SF	9/30/2010	53	7	1/30/2014	50	7	3	0.154289

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1952	9400	SF	7/7/2010	45	7	9/15/2014	95	2	4	0.546771
Hot-Humid	B3010105 - Built-Up	28	1993	612	SF	7/7/2010	59	6	2/19/2014	71	5	4	0.112938
Hot-Humid	B3010105 - Built-Up	28	2011	40000	SF	3/9/2013	61	6	3/9/2013	61	6	0	0.788247
Hot-Humid	B3010105 - Built-Up	28	2006	640	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.830314
Hot-Humid	B3010105 - Built-Up	28	2005	15210	SF	9/30/2010	67	5	11/15/2011	71	5	1	0.631364
Hot-Humid	B3010105 - Built-Up	28	1946	143	SF	2/6/2013	71	5	2/6/2013	71	5	0	0.436711
Hot-Humid	B3010105 - Built-Up	28	2004	115910	SF	7/28/2010	65	5	4/1/2014	61	6	4	0.295227
Hot-Humid	B3010105 - Built-Up	28	1983	3360	SF	9/30/2010	61	6	5/9/2014	88	3	4	0.604136
Hot-Humid	B3010105 - Built-Up	28	1983	24424	SF	9/30/2010	65	5	5/9/2014	88	3	4	0.1026
Hot-Humid	B3010105 - Built-Up	28	1985	680	SF	7/28/2010	84	4	11/15/2011	88	3	1	0.908867
Hot-Humid	B3010105 - Built-Up	28	1988	3564	SF	9/30/2010	41	7	5/17/2013	30	7	3	0.011941
Hot-Humid	B3010105 - Built-Up	28	1989	6400	SF	9/30/2010	79	4	11/15/2011	80	4	1	0.679881
Hot-Humid	B3010105 - Built-Up	28	1990	2520	SF	7/28/2010	100	1	11/15/2011	100	1	1	0.467889
Hot-Humid	B3010105 - Built-Up	28	1986	5852	SF	9/30/2010	58	6	11/15/2011	61	6	1	0.349318
Hot-Humid	B3010105 - Built-Up	28	1995	4050	SF	9/30/2010	45	7	1/30/2014	88	3	3	0.504203
Hot-Humid	B3010105 - Built-Up	28	2004	3120	SF	9/30/2010	100	1	8/22/2014	88	3	4	0.136553
Hot-Humid	B3010105 - Built-Up	28	1990	8240	SF	9/30/2010	43	7	11/15/2011	50	7	1	0.846199
Hot-Humid	B3010105 - Built-Up	28	1946	196	SF	12/19/2012	80	4	9/11/2014	80	4	2	0.845572
Hot-Humid	B3010105 - Built-Up	28	1954	75	SF	3/13/2013	80	4	7/30/2014	80	4	1	0.208365
Hot-Humid	B3010105 - Built-Up	28	1990	11286	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.105897
Hot-Humid	B3010105 - Built-Up	28	1998	6520	SF	9/30/2010	40	7	2/7/2014	61	6	3	0.888576
Hot-Humid	B3010105 - Built-Up	28	1969	3700	SF	9/30/2010	41	7	1/23/2014	10	7	3	0.745457
Hot-Humid	B3010105 - Built-Up	28	2006	2336	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.090531
Hot-Humid	B3010105 - Built-Up	28	2005	40100	SF	9/30/2010	76	4	6/13/2014	88	3	4	0.009199
Hot-Humid	B3010105 - Built-Up	28	2006	7100	SF	9/30/2010	100	1	1/17/2014	95	2	3	0.058826
Hot-Humid	B3010105 - Built-Up	28	1985	441	SF	9/30/2010	43	7	5/27/2014	50	7	4	0.308101
Hot-Humid	B3010105 - Built-Up	28	1997	1218	SF	7/28/2010	63	6	11/22/2013	61	6	3	0.645345
Hot-Humid	B3010105 - Built-Up	28	1980	323	SF	5/31/2012	71	5	1/23/2013	71	5	1	0.101674

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1975	2652	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.462909
Hot-Humid	B3010105 - Built-Up	28	2006	40503	SF	9/30/2010	70	5	6/27/2014	88	3	4	0.480195
Hot-Humid	B3010105 - Built-Up	28	1990	25200	SF	9/30/2010	43	7	6/27/2014	88	3	4	0.540893
Hot-Humid	B3010105 - Built-Up	28	1994	423	SF	3/13/2013	71	5	10/24/2013	71	5	1	0.275488
Hot-Humid	B3010105 - Built-Up	28	1984	88	SF	9/30/2010	50	7	11/15/2011	50	7	1	0.40724
Hot-Humid	B3010105 - Built-Up	28	1989	7700	SF	9/30/2010	72	5	11/15/2011	71	5	1	0.803736
Hot-Humid	B3010105 - Built-Up	28	1995	198	SF	11/14/2012	80	4	9/22/2014	30	7	2	0.038794
Hot-Humid	B3010105 - Built-Up	28	1995	2115	SF	7/7/2010	76	4	10/23/2012	88	3	2	0.424365
Hot-Humid	B3010105 - Built-Up	28	2000	8081	SF	7/28/2010	43	7	11/15/2011	50	7	1	0.780724
Hot-Humid	B3010105 - Built-Up	28	1972	2538	SF	7/28/2010	52	7	11/15/2011	50	7	1	0.270194
Hot-Humid	B3010105 - Built-Up	28	1979	19160	SF	7/7/2010	43	7	9/6/2012	88	3	2	0.182096
Hot-Humid	B3010105 - Built-Up	28	1999	963	SF	9/30/2010	88	3	11/15/2011	88	3	1	0.066449
Hot-Humid	B3010105 - Built-Up	28	1999	722	SF	9/30/2010	88	3	1/31/2014	80	4	3	0.884743
Hot-Humid	B3010105 - Built-Up	28	1985	48119	SF	9/30/2010	83	4	2/6/2014	80	4	3	0.659509
Hot-Humid	B3010105 - Built-Up	28	1986	17888	SF	9/30/2010	38	7	6/5/2013	10	7	3	0.539745
Hot-Humid	B3010105 - Built-Up	28	2005	133754	SF	9/30/2010	100	1	1/11/2014	50	7	3	0.922328
Hot-Humid	B3010105 - Built-Up	28	2004	11709	SF	9/30/2010	100	1	3/15/2014	95	2	3	0.515627
Hot-Humid	B3010105 - Built-Up	28	1980	720	SF	7/28/2010	75	4	11/15/2011	71	5	1	0.811739
Hot-Humid	B3010105 - Built-Up	28	1980	4264	SF	7/28/2010	61	6	7/11/2014	61	6	4	0.610935
Hot-Humid	B3010105 - Built-Up	28	2000	1600	SF	4/26/2012	88	3	3/11/2013	88	3	1	0.535373
Hot-Humid	B3010105 - Built-Up	28	2004	1600	SF	9/30/2010	64	6	10/9/2013	80	4	3	0.029235
Hot-Humid	B3010105 - Built-Up	28	1985	6500	SF	9/30/2010	76	4	5/10/2013	61	6	3	0.482986
Hot-Humid	B3010105 - Built-Up	28	1989	2000	SF	9/30/2010	41	7	9/4/2013	30	7	3	0.412297
Hot-Humid	B3010105 - Built-Up	28	1985	1088	SF	9/30/2010	55	7	11/15/2011	50	7	1	0.921037
Hot-Humid	B3010105 - Built-Up	28	1990	15130	SF	9/30/2010	73	5	5/12/2014	88	3	4	0.54091
Hot-Humid	B3010105 - Built-Up	28	1990	40600	SF	9/30/2010	64	6	5/12/2014	88	3	4	0.577183
Hot-Humid	B3010105 - Built-Up	28	1999	19840	SF	9/30/2010	96	2	7/30/2013	10	7	3	0.031685
Hot-Humid	B3010105 - Built-Up	28	1980	6576	SF	9/30/2010	43	7	4/18/2013	71	5	3	0.715087

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1988	1300	SF	7/28/2010	53	7	11/15/2011	50	7	1	0.508065
Hot-Humid	B3010105 - Built-Up	28	1984	650	SF	9/30/2010	100	1	4/30/2013	71	5	3	0.298639
Hot-Humid	B3010105 - Built-Up	28	2005	56283	SF	9/30/2010	98	2	5/23/2013	95	2	3	0.605228
Hot-Humid	B3010105 - Built-Up	28	1996	37248	SF	9/30/2010	37	7	3/20/2013	61	6	2	0.300741
Hot-Humid	B3010105 - Built-Up	28	1926	20240	SF	7/28/2010	43	7	1/14/2013	50	7	2	0.33216
Hot-Humid	B3010105 - Built-Up	28	2002	11206	SF	9/30/2010	100	1	11/15/2011	100	1	1	0.897661
Hot-Humid	B3010105 - Built-Up	28	2002	2025	SF	9/30/2010	76	4	4/7/2014	71	5	4	0.615148
Hot-Humid	B3010105 - Built-Up	28	1990	3574	SF	7/18/2011	30	7	7/18/2011	30	7	0	0.567679
Hot-Humid	B3010105 - Built-Up	28	1995	81	SF	7/28/2010	80	4	8/14/2014	30	7	4	0.293818
Hot-Humid	B3010105 - Built-Up	28	1954	67312	SF	9/30/2010	38	7	8/18/2014	50	7	4	0.413578
Hot-Humid	B3010105 - Built-Up	28	2004	388	SF	12/28/2012	88	3	12/28/2012	88	3	0	0.009699
Hot-Humid	B3010105 - Built-Up	28	2012	22392	SF	1/22/2013	100	1	1/22/2013	100	1	0	0.566676
Hot-Humid	B3010105 - Built-Up	28	1976	1386	SF	9/30/2010	50	7	3/4/2014	95	2	3	0.144811
Hot-Humid	B3010105 - Built-Up	28	2007	4705	SF	9/30/2010	73	5	5/17/2013	50	7	3	0.564623
Hot-Humid	B3010105 - Built-Up	28	1986	5852	SF	9/30/2010	58	6	11/15/2011	61	6	1	0.075802
Hot-Humid	B3010105 - Built-Up	28	1978	1	SF	7/28/2010	1	7	11/15/2011	10	7	1	0.581805
Hot-Humid	B3010105 - Built-Up	28	1978	450	SF	7/28/2010	57	6	11/15/2011	61	6	1	0.708857
Hot-Humid	B3010105 - Built-Up	28	1976	2080	SF	7/7/2010	41	7	7/22/2014	88	3	4	0.67675
Hot-Humid	B3010105 - Built-Up	28	2005	22880	SF	9/30/2010	76	4	11/15/2011	71	5	1	0.113224
Hot-Humid	B3010105 - Built-Up	28	1970	3840	SF	7/28/2010	73	5	11/15/2011	71	5	1	0.583222
Hot-Humid	B3010105 - Built-Up	28	1992	2600	SF	7/28/2010	71	5	8/6/2014	71	5	4	0.17749
Hot-Humid	B3010105 - Built-Up	28	1973	9520	SF	9/30/2010	38	7	5/30/2013	10	7	3	0.693307
Hot-Humid	B3010105 - Built-Up	28	1946	63	SF	1/14/2013	50	7	1/14/2013	50	7	0	0.318685
Hot-Humid	B3010105 - Built-Up	28	2003	3842	SF	7/28/2010	88	3	11/15/2011	88	3	1	0.35853
Hot-Humid	B3010105 - Built-Up	28	1992	7323	SF	7/28/2010	4	7	11/15/2011	10	7	1	0.973832
Hot-Humid	B3010105 - Built-Up	28	1985	42913	SF	7/28/2010	50	7	11/15/2011	50	7	1	0.134375
Hot-Humid	B3010105 - Built-Up	28	1963	6045	SF	9/30/2010	40	7	11/15/2011	30	7	1	0.468077
Hot-Humid	B3010105 - Built-Up	28	2002	10700	SF	9/30/2010	59	6	4/25/2014	95	2	4	0.78538

						Inspection 1			Inspection 2				
Region	Component	Design Life	Year Installed	Quantity	UM	Date	Rating	State	Date	Rating	State	Obs. Interval	Random Number
Hot-Humid	B3010105 - Built-Up	28	1995	56	SF	7/28/2010	80	4	8/11/2014	30	7	4	0.049118
Hot-Humid	B3010105 - Built-Up	28	1980	120	SF	7/28/2010	13	7	9/23/2014	30	7	4	0.340789
Hot-Humid	B3010105 - Built-Up	28	1979	7200	SF	7/7/2010	43	7	9/12/2012	88	3	2	0.59735
Hot-Humid	B3010105 - Built-Up	28	1984	11824	SF	7/28/2010	55	7	11/15/2011	50	7	1	0.181023
Hot-Humid	B3010105 - Built-Up	28	2012	15660	SF	1/18/2013	95	2	1/18/2013	95	2	0	0.049727
Hot-Humid	B3010105 - Built-Up	28	1969	1830	SF	9/30/2010	43	7	3/18/2014	95	2	3	0.007616
Hot-Humid	B3010105 - Built-Up	28	1993	1344	SF	2/1/2013	88	3	2/1/2013	88	3	0	0.582165
Hot-Humid	B3010105 - Built-Up	28	1972	214003	SF	9/30/2010	76	4	6/13/2014	88	3	4	0.983298
Hot-Humid	B3010105 - Built-Up	28	1991	3136	SF	7/28/2010	63	6	11/15/2011	61	6	1	0.218311
Hot-Humid	B3010105 - Built-Up	28	2006	380	SF	4/27/2012	88	3	4/27/2012	88	3	0	0.348682
Hot-Humid	B3010105 - Built-Up	28	1980	7677	SF	9/30/2010	61	6	1/27/2014	71	5	3	0.629988
Hot-Humid	B3010105 - Built-Up	28	1998	26574	SF	9/30/2010	40	7	7/19/2013	10	7	3	0.339019
Hot-Humid	B3010105 - Built-Up	28	1998	46837	SF	9/30/2010	98	2	7/1/2014	50	7	4	0.328646
Hot-Humid	B3010105 - Built-Up	28	1944	352	SF	7/28/2010	71	5	11/15/2011	71	5	1	0.279576
Hot-Humid	B3010105 - Built-Up	28	2001	14880	SF	9/30/2010	57	6	5/5/2014	30	7	4	0.277975
Hot-Humid	B3010105 - Built-Up	28	1941	979	SF	9/30/2010	43	7	9/4/2013	80	4	3	0.577309
Hot-Humid	B3010105 - Built-Up	28	1989	629	SF	9/30/2010	43	7	9/4/2013	80	4	3	0.638679
Hot-Humid	B3010105 - Built-Up	28	2004	1024	SF	9/30/2010	88	3	9/10/2013	88	3	3	0.620806
Hot-Humid	B3010105 - Built-Up	28	2006	3384	SF	7/28/2010	67	5	2/14/2013	71	5	3	0.398174
Hot-Humid	B3010105 - Built-Up	28	2012	5176	SF	11/3/2012	100	1	4/10/2013	95	2	0	0.999335
Hot-Humid	B3010105 - Built-Up	28	2000	900	SF	7/28/2010	55	7	9/11/2013	61	6	3	0.240867
Hot-Humid	B3010105 - Built-Up	28	2000	26700	SF	9/30/2010	88	3	4/18/2013	61	6	3	0.764375
Hot-Humid	B3010105 - Built-Up	28	1980	4056	SF	9/30/2010	59	6	5/10/2014	61	6	4	0.688809
Hot-Humid	B3010105 - Built-Up	28	1986	3700	SF	9/30/2010	68	5	11/15/2011	71	5	1	0.198879
Hot-Humid	B3010105 - Built-Up	28	1996	14014	SF	7/28/2010	35	7	11/15/2011	30	7	1	0.331608
Hot-Humid	B3010105 - Built-Up	28	1944	468	SF	7/28/2010	50	7	11/15/2011	50	7	1	0.309793
Hot-Humid	B3010105 - Built-Up	28	1995	3172	SF	7/28/2010	88	3	11/15/2011	88	3	1	0.598178
Hot-Humid	B3010105 - Built-Up	28	1996	432	SF	7/28/2010	95	2	9/15/2014	71	5	4	0.948665

						Inspection 1			Inspection 2				
Region	**Component**	**Design Life**	**Year Installed**	**Quantity**	**UM**	**Date**	**Rating**	**State**	**Date**	**Rating**	**State**	**Obs. Interval**	**Random Number**
Hot-Humid	B3010105 - Built-Up	28	2009	3260	SF	7/28/2010	95	2	11/15/2011	95	2	1	0.440817
Hot-Humid	B3010105 - Built-Up	28	1989	12480	SF	9/30/2010	59	6	7/9/2013	88	3	3	0.45253
Hot-Humid	B3010105 - Built-Up	28	1990	16625	SF	9/30/2010	49	7	9/16/2014	30	7	4	0.118741
Hot-Humid	B3010105 - Built-Up	28	1999	630	SF	2/5/2013	80	4	6/3/2014	30	7	1	0.504337
Hot-Humid	B3010105 - Built-Up	28	2001	19958	SF	7/28/2010	71	5	11/15/2011	71	5	1	0.63616
Hot-Humid	B3010105 - Built-Up	28	1998	41101	SF	9/30/2010	100	1	6/10/2013	88	3	3	0.723891
Hot-Humid	B3010105 - Built-Up	28	1990	26400	SF	9/30/2010	41	7	11/15/2011	50	7	1	0.701212
Hot-Humid	B3010105 - Built-Up	28	1990	10489	SF	9/30/2010	43	7	9/4/2013	61	6	3	0.314305
Hot-Humid	B3010105 - Built-Up	28	1995	20000	SF	9/30/2010	65	5	9/4/2013	71	5	3	0.342243
Hot-Humid	B3010105 - Built-Up	28	1998	6000	SF	4/30/2012	50	7	7/13/2014	50	7	2	0.558193
Hot-Humid	B3010105 - Built-Up	28	1998	23000	SF	4/30/2012	61	6	7/13/2014	61	6	2	0.575219
Hot-Humid	B3010105 - Built-Up	28	1998	23000	SF	4/30/2012	71	5	7/13/2014	71	5	2	0.334742
Hot-Humid	B3010105 - Built-Up	28	1998	25200	SF	4/30/2012	80	4	7/13/2014	80	4	2	0.290694
Hot-Humid	B3010105 - Built-Up	28	1998	55401	SF	4/30/2012	10	7	7/13/2014	10	7	2	0.131563

APPENDIX C – CHARACTERISTIC DETERIORATION TRANSITION MATRIX FOR ASTM UNIFORMAT L3 COMPONENT CLASSIFICATIONS

Component Classification	Condition Prior	Condition Posterior							Data Points
		C1	C2	C3	C4	C5	C6	C7	
A1010 STANDARD FOUNDATIONS	C1	0.6727	0.2122	0.0563	0.018	0.0161	0.0167	0.0082	9429
	C2	0	0.8733	0.0949	0.0136	0.0136	0.0038	0.0008	
	C3	0	0	0.9026	0.0616	0.0193	0.0056	0.0109	
	C4	0	0	0	0.9174	0.0453	0.0238	0.0136	
	C5	0	0	0	0	0.8875	0.0856	0.0269	
	C6	0	0	0	0	0	0.9233	0.0767	
	C7	0	0	0	0	0	0	1	
A1020 SPECIAL FOUNDATIONS	C1	0.6133	0.2675	0.062	0.0297	0.0177	0.0078	0.002	1384
	C2	0	0.8444	0.1182	0.0156	0.0209	0	0.0009	
	C3	0	0	0.9151	0.0601	0.0207	0	0.0041	
	C4	0	0	0	0.9164	0.0466	0.0316	0.0053	
	C5	0	0	0	0	0.7884	0.1855	0.0261	
	C6	0	0	0	0	0	0.9659	0.0341	
	C7	0	0	0	0	0	0	1	
A1030 SLAB ON GRADE	C1	0.6651	0.1943	0.1042	0.0132	0.0155	0.0032	0.0044	11807
	C2	0	0.879	0.0827	0.0184	0.0131	0.0045	0.0024	
	C3	0	0	0.9195	0.0536	0.0173	0.0044	0.0052	
	C4	0	0	0	0.8985	0.0686	0.0261	0.0068	
	C5	0	0	0	0	0.9115	0.0615	0.0271	
	C6	0	0	0	0	0	0.9467	0.0533	
	C7	0	0	0	0	0	0	1	
A2020 BASEMENT WALLS	C1	0.6366	0.3309	0.016	0.0153	0	0.0012	0	771
	C2	0	0.8255	0.1092	0.0239	0.0334	0.0081	0	
	C3	0	0	0.9128	0.0616	0.0166	0.0073	0.0017	
	C4	0	0	0	0.8611	0.1081	0.029	0.0018	
	C5	0	0	0	0	0.8733	0.1166	0.0101	
	C6	0	0	0	0	0	0.882	0.118	
	C7	0	0	0	0	0	0	1	

Component Classification	Condition Prior	Condition Posterior							Data Points
		C1	C2	C3	C4	C5	C6	C7	
B1010 FLOOR CONSTRUCTION	C1	0.665	0.185	0.087	0.024	0.022	0.008	0.008	6258
	C2	0	0.850	0.106	0.022	0.017	0.004	0.001	
	C3	0	0	0.896	0.069	0.020	0.010	0.005	
	C4	0	0	0	0.898	0.068	0.019	0.015	
	C5	0	0	0	0	0.833	0.150	0.017	
	C6	0	0	0	0	0	0.904	0.096	
	C7	0	0	0	0	0	0	1.000	
B1020 ROOF CONSTRUCTION	C1	0.6634	0.2039	0.0886	0.0146	0.0106	0.0086	0.0102	15139
	C2	0	0.8725	0.0871	0.0209	0.0127	0.0035	0.0033	
	C3	0	0	0.9067	0.067	0.0165	0.0057	0.0042	
	C4	0	0	0	0.8719	0.094	0.0231	0.011	
	C5	0	0	0	0	0.9026	0.0743	0.023	
	C6	0	0	0	0	0	0.9535	0.0465	
	C7	0	0	0	0	0	0	1	
B2010 EXTERIOR WALLS	C1	0.6523	0.1887	0.0998	0.0236	0.0157	0.0105	0.0094	20875
	C2	0	0.8451	0.0938	0.0225	0.0249	0.0075	0.0061	
	C3	0	0	0.8864	0.0735	0.0204	0.0124	0.0073	
	C4	0	0	0	0.881	0.0746	0.0278	0.0166	
	C5	0	0	0	0	0.8964	0.0837	0.02	
	C6	0	0	0	0	0	0.9371	0.0629	
	C7	0	0	0	0	0	0	1	
B2020 EXTERIOR WINDOWS	C1	0.6734	0.1631	0.0787	0.0484	0.018	0.013	0.0054	10191
	C2	0	0.813	0.1138	0.033	0.0177	0.0098	0.0127	
	C3	0	0	0.8568	0.0964	0.0223	0.0117	0.0129	
	C4	0	0	0	0.8405	0.1118	0.0302	0.0175	
	C5	0	0	0	0	0.8476	0.1138	0.0386	
	C6	0	0	0	0	0	0.8987	0.1013	
	C7	0	0	0	0	0	0	1	
B2030 EXTERIOR DOORS	C1	0.6759	0.1616	0.1055	0.025	0.0201	0.0064	0.0055	14496
	C2	0	0.8409	0.1012	0.0329	0.0125	0.0095	0.0031	
	C3	0	0	0.8711	0.0925	0.0169	0.0112	0.0082	
	C4	0	0	0	0.8371	0.1257	0.0272	0.0099	
	C5	0	0	0	0	0.8922	0.0776	0.0302	
	C6	0	0	0	0	0	0.922	0.078	
	C7	0	0	0	0	0	0	1	

Component Classification	Condition Prior	Condition Posterior							Data Points
		C1	C2	C3	C4	C5	C6	C7	
B3010 ROOF COVERINGS	C1	0.692	0.1334	0.114	0.0135	0.0232	0.0104	0.0135	14171
	C2	0	0.8132	0.1104	0.0343	0.019	0.0126	0.0106	
	C3	0	0	0.8576	0.0823	0.027	0.0138	0.0193	
	C4	0	0	0	0.8304	0.1018	0.0429	0.0249	
	C5	0	0	0	0	0.8619	0.1002	0.0379	
	C6	0	0	0	0	0	0.9101	0.0899	
	C7	0	0	0	0	0	0	1	
B3020 ROOF OPENINGS	C1	0.7031	0.1441	0.0874	0.0254	0.018	0.0138	0.0082	1239
	C2	0	0.8149	0.0968	0.0393	0.0229	0.013	0.0132	
	C3	0	0	0.903	0.055	0.0272	0.0118	0.0031	
	C4	0	0	0	0.8825	0.1057	0.0001	0.0116	
	C5	0	0	0	0	0.8788	0.0861	0.035	
	C6	0	0	0	0	0	0.964	0.036	
	C7	0	0	0	0	0	0	1	
C1010 PARTITIONS	C1	0.7003	0.1505	0.0948	0.0286	0.0172	0.0035	0.0051	9435
	C2	0	0.8336	0.1119	0.0276	0.0206	0.0049	0.0013	
	C3	0	0	0.9011	0.066	0.0207	0.0083	0.004	
	C4	0	0	0	0.8798	0.0833	0.0281	0.0088	
	C5	0	0	0	0	0.91	0.0771	0.0129	
	C6	0	0	0	0	0	0.935	0.065	
	C7	0	0	0	0	0	0	1	
C1020 INTERIOR DOORS	C1	0.6614	0.1846	0.107	0.0174	0.0184	0.0073	0.0039	9171
	C2	0	0.8631	0.0897	0.0232	0.0167	0.0048	0.0026	
	C3	0	0	0.93	0.0486	0.0113	0.0064	0.0037	
	C4	0	0	0	0.9071	0.07	0.0152	0.0078	
	C5	0	0	0	0	0.9145	0.0768	0.0087	
	C6	0	0	0	0	0	0.9525	0.0475	
	C7	0	0	0	0	0	0	1	
C1030 SPECIALTIES	C1	0.6508	0.2015	0.1052	0.0415	2E-05	0	0.001	1981
	C2	0	0.8262	0.1324	0.0162	0.0149	0.0089	0.0014	
	C3	0	0	0.8907	0.0796	0.0157	0.0108	0.0032	
	C4	0	0	0	0.8509	0.1061	0.0332	0.0098	
	C5	0	0	0	0	0.8387	0.1235	0.0378	
	C6	0	0	0	0	0	0.9495	0.0505	
	C7	0	0	0	0	0	0	1	

Component	Condition	Condition Posterior							Data
Classification	Prior	C1	C2	C3	C4	C5	C6	C7	Points
C2010 STAIR CONSTRUCTION	C1	0.6822	0.1483	0.1495	0.0132	2E-05	0.0066	0.0003	2015
	C2	0	0.8669	0.0739	0.0273	0.027	0.0045	0.0004	
	C3	0	0	0.9154	0.0596	0.0178	0.0048	0.0024	
	C4	0	0	0	0.9206	0.0481	0.0219	0.0094	
	C5	0	0	0	0	0.9244	0.0571	0.0185	
	C6	0	0	0	0	0	0.9358	0.0642	
	C7	0	0	0	0	0	0	1	
C3010 WALL FINISHES	C1	0.6831	0.2047	0.0553	0.0354	0.0098	0.0095	0.0023	7051
	C2	0	0.7931	0.1496	0.0342	0.0139	0.0042	0.0051	
	C3	0	0	0.8734	0.0785	0.0215	0.0193	0.0072	
	C4	0	0	0	0.8744	0.099	0.022	0.0046	
	C5	0	0	0	0	0.8698	0.1141	0.0161	
	C6	0	0	0	0	0	0.9481	0.0519	
	C7	0	0	0	0	0	0	1	
C3020 FLOOR FINISHES	C1	0.6861	0.147	0.1171	0.0148	0.0137	0.0104	0.0109	13215
	C2	0	0.7969	0.1283	0.039	0.0195	0.0085	0.0078	
	C3	0	0	0.8674	0.0832	0.029	0.0148	0.0056	
	C4	0	0	0	0.8671	0.084	0.0346	0.0143	
	C5	0	0	0	0	0.8856	0.0875	0.0268	
	C6	0	0	0	0	0	0.9305	0.0695	
	C7	0	0	0	0	0	0	1	
C3030 CEILING FINISHES	C1	0.6351	0.1815	0.1212	0.0477	4E-05	0.0082	0.0061	7897
	C2	0	0.8362	0.1116	0.0273	0.0108	0.011	0.0031	
	C3	0	0	0.8836	0.0776	0.0236	0.0092	0.006	
	C4	0	0	0	0.879	0.0843	0.0265	0.0103	
	C5	0	0	0	0	0.9157	0.067	0.0174	
	C6	0	0	0	0	0	0.9412	0.0588	
	C7	0	0	0	0	0	0	1	
D1010 ELEVATORS AND LIFTS	C1	0.7618	0.1078	0.0707	0.0326	5E-05	0.0092	0.0179	433
	C2	0	0.8004	0.0674	0.0749	0.0526	0.0016	0.0031	
	C3	0	0	0.8778	0.0566	0.0126	0.0293	0.0237	
	C4	0	0	0	0.6955	0.226	0.072	0.0065	
	C5	0	0	0	0	0.9237	0.0584	0.0179	
	C6	0	0	0	0	0	0.9787	0.0213	
	C7	0	0	0	0	0	0	1	

Component Classification	Condition Prior	Condition Posterior							Data Points
		C1	C2	C3	C4	C5	C6	C7	
D2010 PLUMBING FIXTURES	C1	0.6894	0.1747	0.1011	0.0108	0.013	0.0048	0.006	17051
	C2	0	0.8289	0.1098	0.035	0.0165	0.0064	0.0034	
	C3	0	0	0.8902	0.0774	0.0142	0.0102	0.0079	
	C4	0	0	0	0.8502	0.1087	0.0283	0.0128	
	C5	0	0	0	0	0.8591	0.1074	0.0335	
	C6	0	0	0	0	0	0.9387	0.0613	
	C7	0	0	0	0	0	0	1	
D2020 DOMESTIC WATER DISTRIBUTION	C1	0.6892	0.1747	0.0688	0.0195	0.0408	0.0008	0.0061	14646
	C2	0	0.7994	0.1173	0.0531	0.0213	0.0066	0.0024	
	C3	0	0	0.8825	0.0886	0.0155	0.0066	0.0068	
	C4	0	0	0	0.839	0.1246	0.0286	0.0079	
	C5	0	0	0	0	0.878	0.1001	0.022	
	C6	0	0	0	0	0	0.9372	0.0628	
	C7	0	0	0	0	0	0	1	
D2030 SANITARY WASTE	C1	0.6954	0.1702	0.0803	0.0197	0.028	0	0.0064	6766
	C2	0	0.8242	0.1074	0.0384	0.0217	0.0067	0.0015	
	C3	0	0	0.8998	0.0712	0.0156	0.008	0.0055	
	C4	0	0	0	0.8184	0.1547	0.0121	0.0149	
	C5	0	0	0	0	0.8881	0.1008	0.0111	
	C6	0	0	0	0	0	0.9524	0.0476	
	C7	0	0	0	0	0	0	1	
D2090 OTHER PLUMBING SYSTEMS	C1	0.6968	0.2079	0.0082	0.0738	0.0106	0	0.0027	324
	C2	0	0.8519	0.1169	0.0193	0.012	0	0	
	C3	0	0	0.9363	0.0448	0.0108	0	0.0081	
	C4	0	0	0	0.9451	0.0461	0.0087	0	
	C5	0	0	0	0	0.9443	0.0557	0	
	C6	0	0	0	0	0	0.9671	0.0329	
	C7	0	0	0	0	0	0	1	
D3020 HEAT GENERATING SYSTEMS	C1	0.6425	0.1615	0.0632	0.048	0.0637	0.0103	0.0108	987
	C2	0	0.8519	0.0853	0.0214	0.0275	0.0097	0.0041	
	C3	0	0	0.9089	0.0478	0.0166	0.0153	0.0114	
	C4	0	0	0	0.9078	0.0832	0.0061	0.0029	
	C5	0	0	0	0	0.9301	0.0489	0.021	
	C6	0	0	0	0	0	0.9537	0.0463	
	C7	0	0	0	0	0	0	1	

Component Classification	Condition Prior	Condition Posterior							Data Points
		C1	C2	C3	C4	C5	C6	C7	
D3030 COOLING GENERATING SYSTEMS	C1	0.6561	0.1094	0.1027	0.0283	0.0844	0.0089	0.0103	2813
	C2	0	0.8139	0.0793	0.0615	0.035	0.005	0.0053	
	C3	0	0	0.856	0.0869	0.0481	0.0033	0.0057	
	C4	0	0	0	0.7901	0.1801	0.0178	0.0119	
	C5	0	0	0	0	0.875	0.1108	0.0142	
	C6	0	0	0	0	0	0.9469	0.0531	
	C7	0	0	0	0	0	0	1	
D3040 DISTRIBUTION SYSTEMS	C1	0.6988	0.1286	0.0617	0.0298	0.0475	4E-06	0.0336	14430
	C2	0	0.8008	0.1072	0.0571	0.025	0.004	0.006	
	C3	0	0	0.867	0.0969	0.0266	0.0032	0.0064	
	C4	0	0	0	0.7636	0.2331	0	0.0033	
	C5	0	0	0	0	0.7815	0.1911	0.0274	
	C6	0	0	0	0	0	0.9177	0.0823	
	C7	0	0	0	0	0	0	1	
D3050 TERMINAL & PACKAGE UNITS	C1	0.7345	0.1453	0.0551	0.0236	0.0261	0.0094	0.0059	7494
	C2	0	0.8019	0.1085	0.0495	0.0291	0.0083	0.0028	
	C3	0	0	0.8834	0.0843	0.014	0.0094	0.0089	
	C4	0	0	0	0.8133	0.1473	0.0263	0.0132	
	C5	0	0	0	0	0.8757	0.1091	0.0152	
	C6	0	0	0	0	0	0.959	0.041	
	C7	0	0	0	0	0	0	1	
D3060 CONTROLS & INSTRUMENTATION	C1	0.6522	0.1103	0.0724	0.044	0.1122	0	0.0088	1192
	C2	0	0.8224	0.0678	0.0396	0.052	0.0059	0.0123	
	C3	0	0	0.914	0.0621	0.0098	0.005	0.0092	
	C4	0	0	0	0.8279	0.1355	0.018	0.0186	
	C5	0	0	0	0	0.8565	0.1226	0.021	
	C6	0	0	0	0	0	0.9604	0.0396	
	C7	0	0	0	0	0	0	1	
D3090 OTHER HVAC SYSTEMS AND EQUIPMENT	C1	0.6216	0.1923	0.114	0.0291	0.0414	0	0.0017	506
	C2	0	0.8584	0.0981	0.0264	0.017	0	0	
	C3	0	0	0.8375	0.1014	0.0545	0.0027	0.0038	
	C4	0	0	0	0.8463	0.1107	0.0293	0.0136	
	C5	0	0	0	0	0.8572	0.1428	0	
	C6	0	0	0	0	0	0.9682	0.0318	
	C7	0	0	0	0	0	0	1	

Component Classification	Condition Prior	Condition Posterior							Data Points
		C1	C2	C3	C4	C5	C6	C7	
D4030 STANDPIPE SYSTEMS	C1	0.6598	0.168	0.0607	0.0022	0.0455	0.0302	0.0335	1901
	C2	0	0.8602	0.0784	0.0307	0.026	0.0023	0.0023	
	C3	0	0	0.8867	0.0683	0.0368	0.0041	0.0041	
	C4	0	0	0	0.8837	0.0843	0.0244	0.0076	
	C5	0	0	0	0	0.9289	0.0605	0.0106	
	C6	0	0	0	0	0	0.962	0.038	
	C7	0	0	0	0	0	0	1	
D4040 SPRINKLERS	C1	0.7264	0.1752	0.0784	0.0135	0.0037	0.0005	0.0023	2915
	C2	0	0.8316	0.0994	0.0319	0.03	0.0029	0.0042	
	C3	0	0	0.8762	0.0627	0.0498	0.0064	0.0049	
	C4	0	0	0	0.8631	0.0906	0.0248	0.0215	
	C5	0	0	0	0	0.8935	0.0777	0.0288	
	C6	0	0	0	0	0	0.9343	0.0657	
	C7	0	0	0	0	0	0	1	
D4050 FIRE PROTECTION SPECIALTIES	C1	0.6428	0.3114	0	0.0408	0.0024	0.0005	0.002	191
	C2	0	0.8251	0.146	0.0004	0.0174	0.0047	0.0063	
	C3	0	0	0.8923	0.0873	0.0204	0	0	
	C4	0	0	0	1	0	0	0	
	C5	0	0	0	0	0.9103	0.0894	0.0003	
	C6	0	0	0	0	0	1	0	
	C7	0	0	0	0	0	0	1	
D4090 OTHER FIRE PROTECTION SYSTEMS	C1	0.7313	0.1338	0.0554	0.0124	0.0458	0.0126	0.0088	1119
	C2	0	0.8277	0.0887	0.0422	0.0336	0.0035	0.0043	
	C3	0	0	0.8721	0.0905	0.0206	0.0021	0.0147	
	C4	0	0	0	0.8523	0.1291	0.0186	0	
	C5	0	0	0	0	0.8665	0.1098	0.0237	
	C6	0	0	0	0	0	0.9612	0.0388	
	C7	0	0	0	0	0	0	1	
D5010 ELECTRICAL SERVICE & DISTRIBUTION	C1	0.7235	0.1349	0.0843	0.0266	0.0229	0.0014	0.0065	26240
	C2	0	0.8209	0.1075	0.0435	0.0149	0.0072	0.0059	
	C3	0	0	0.8942	0.0705	0.0204	0.0098	0.0052	
	C4	0	0	0	0.8861	0.0822	0.0215	0.0103	
	C5	0	0	0	0	0.8707	0.1178	0.0115	
	C6	0	0	0	0	0	0.9542	0.0458	
	C7	0	0	0	0	0	0	1	

Component Classification	Condition Prior	Condition Posterior							Data Points
		C1	C2	C3	C4	C5	C6	C7	
D5020 LIGHTING & BRANCH WIRING	C1	0.6944	0.1381	0.1166	0.0263	0.012	0.0033	0.0092	17960
	C2	0	0.8209	0.1128	0.0361	0.0239	0.0038	0.0026	
	C3	0	0	0.8841	0.0773	0.026	0.0096	0.003	
	C4	0	0	0	0.9084	0.0657	0.0195	0.0064	
	C5	0	0	0	0	0.8936	0.0891	0.0173	
	C6	0	0	0	0	0	0.9449	0.0551	
	C7	0	0	0	0	0	0	1	
D5030 COMMUNICATIONS & SECURITY	C1	0.6808	0.2188	0.04	0.0257	0.0173	0.0078	0.0096	1997
	C2	0	0.8342	0.0833	0.0505	0.0192	0.0097	0.0031	
	C3	0	0	0.8963	0.0687	0.0154	0.0165	0.003	
	C4	0	0	0	0.9107	0.0544	0.0216	0.0133	
	C5	0	0	0	0	0.9243	0.0662	0.0096	
	C6	0	0	0	0	0	0.9782	0.0218	
	C7	0	0	0	0	0	0	1	
D5090 OTHER ELECTRICAL SERVICES	C1	0.7416	0.138	0.0792	0.0264	0.0084	0.0022	0.0043	4053
	C2	0	0.7905	0.1333	0.0408	0.0283	0.0028	0.0043	
	C3	0	0	0.909	0.048	0.0362	0.0059	0.0009	
	C4	0	0	0	0.8897	0.0906	0.0119	0.0078	
	C5	0	0	0	0	0.8511	0.1151	0.0337	
	C6	0	0	0	0	0	0.952	0.048	
	C7	0	0	0	0	0	0	1	

APPENDIX D – CHARACTERISTIC DETERIORATION TRANSITION MATRIX FOR SELECT COMPONENT TYPES (UNIFORMAT L4)

Component Classification	Condition Prior	Condition Posterior							Data Points
		C1	C2	C3	C4	C5	C6	C7	
B3010105 - Built-Up	C1	0.644	0.111	0.173	0.004	0.037	0.010	0.020	3464
	C2	0.000	0.823	0.102	0.034	0.017	0.012	0.012	
	C3	0.000	0.000	0.838	0.090	0.036	0.013	0.022	
	C4	0.000	0.000	0.000	0.771	0.138	0.060	0.032	
	C5	0.000	0.000	0.000	0.000	0.836	0.119	0.044	
	C6	0.000	0.000	0.000	0.000	0.000	0.898	0.102	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B3010120 - Single Ply Membrane	C1	0.679	0.115	0.141	0.035	0.018	0.012	0.000	1154
	C2	0.000	0.829	0.089	0.027	0.035	0.011	0.010	
	C3	0.000	0.000	0.896	0.053	0.030	0.006	0.015	
	C4	0.000	0.000	0.000	0.846	0.091	0.034	0.029	
	C5	0.000	0.000	0.000	0.000	0.910	0.063	0.027	
	C6	0.000	0.000	0.000	0.000	0.000	0.931	0.069	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B3010130 - Preformed Metal	C1	0.705	0.151	0.097	0.001	0.026	0.003	0.016	4368
	C2	0.000	0.810	0.126	0.035	0.016	0.008	0.005	
	C3	0.000	0.000	0.864	0.087	0.022	0.015	0.012	
	C4	0.000	0.000	0.000	0.857	0.082	0.037	0.024	
	C5	0.000	0.000	0.000	0.000	0.863	0.134	0.003	
	C6	0.000	0.000	0.000	0.000	0.000	0.914	0.086	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B3010135 - Formed Metal	C1	0.752	0.123	0.071	0.002	0.033	0.002	0.016	741
	C2	0.000	0.856	0.064	0.033	0.019	0.011	0.017	
	C3	0.000	0.000	0.899	0.066	0.020	0.015	0.000	
	C4	0.000	0.000	0.000	0.901	0.042	0.032	0.025	
	C5	0.000	0.000	0.000	0.000	0.952	0.017	0.032	
	C6	0.000	0.000	0.000	0.000	0.000	0.951	0.049	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	

Component Classification	Condition Prior	Condition Posterior							Data Points
		C1	C2	C3	C4	C5	C6	C7	
B3010140 - Shingle & Tile	C1	0.722	0.108	0.109	0.012	0.009	0.008	0.032	1665
	C2	0.000	0.793	0.112	0.042	0.015	0.018	0.020	
	C3	0.000	0.000	0.878	0.063	0.032	0.027	0.000	
	C4	0.000	0.000	0.000	0.847	0.094	0.038	0.020	
	C5	0.000	0.000	0.000	0.000	0.862	0.076	0.062	
	C6	0.000	0.000	0.000	0.000	0.000	0.865	0.135	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B2010101 - CIP Concrete	C1	0.607	0.277	0.103	0.003	0.000	0.001	0.009	3123
	C2	0.000	0.825	0.081	0.030	0.055	0.006	0.003	
	C3	0.000	0.000	0.903	0.073	0.016	0.008	0.000	
	C4	0.000	0.000	0.000	0.891	0.052	0.040	0.017	
	C5	0.000	0.000	0.000	0.000	0.961	0.028	0.012	
	C6	0.000	0.000	0.000	0.000	0.000	0.965	0.035	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B2010109 - Concrete Block	C1	0.653	0.195	0.087	0.023	0.024	0.010	0.009	4861
	C2	0.000	0.860	0.103	0.009	0.016	0.007	0.005	
	C3	0.000	0.000	0.905	0.063	0.018	0.007	0.007	
	C4	0.000	0.000	0.000	0.909	0.057	0.021	0.013	
	C5	0.000	0.000	0.000	0.000	0.878	0.108	0.014	
	C6	0.000	0.000	0.000	0.000	0.000	0.924	0.076	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B2010125 - Solid Brick - Single Wythe	C1	0.651	0.188	0.105	0.034	0.010	0.005	0.007	1987
	C2	0.000	0.809	0.118	0.022	0.035	0.017	0.000	
	C3	0.000	0.000	0.874	0.052	0.039	0.036	0.000	
	C4	0.000	0.000	0.000	0.862	0.080	0.036	0.022	
	C5	0.000	0.000	0.000	0.000	0.841	0.141	0.018	
	C6	0.000	0.000	0.000	0.000	0.000	0.836	0.164	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B2010146 - Metal Siding Panel	C1	0.669	0.149	0.102	0.031	0.016	0.014	0.019	4920
	C2	0.000	0.839	0.091	0.034	0.023	0.006	0.007	
	C3	0.000	0.000	0.860	0.097	0.020	0.014	0.008	
	C4	0.000	0.000	0.000	0.846	0.107	0.027	0.019	
	C5	0.000	0.000	0.000	0.000	0.889	0.084	0.027	
	C6	0.000	0.000	0.000	0.000	0.000	0.951	0.049	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	

Component Classification	Condition Prior	Condition Posterior							Data Points
		C1	C2	C3	C4	C5	C6	C7	
B2010148 - Wood Cladding w/Stud Backup	C1	0.725	0.106	0.072	0.044	0.004	0.033	0.017	1084
	C2	0.000	0.851	0.083	0.036	0.016	0.000	0.015	
	C3	0.000	0.000	0.852	0.078	0.018	0.030	0.021	
	C4	0.000	0.000	0.000	0.841	0.095	0.033	0.031	
	C5	0.000	0.000	0.000	0.000	0.868	0.089	0.043	
	C6	0.000	0.000	0.000	0.000	0.000	0.907	0.093	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B2010151 - Stucco Wall	C1	0.647	0.189	0.083	0.055	0.007	0.019	0.000	962
	C2	0.000	0.777	0.132	0.025	0.013	0.028	0.025	
	C3	0.000	0.000	0.872	0.083	0.027	0.012	0.006	
	C4	0.000	0.000	0.000	0.859	0.109	0.026	0.006	
	C5	0.000	0.000	0.000	0.000	0.915	0.080	0.005	
	C6	0.000	0.000	0.000	0.000	0.000	0.912	0.088	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B2020102 - Wood Windows	C1	0.707	0.160	0.064	0.041	0.015	0.011	0.003	4248
	C2	0.000	0.710	0.169	0.038	0.024	0.025	0.034	
	C3	0.000	0.000	0.753	0.167	0.027	0.024	0.029	
	C4	0.000	0.000	0.000	0.766	0.168	0.037	0.029	
	C5	0.000	0.000	0.000	0.000	0.812	0.137	0.051	
	C6	0.000	0.000	0.000	0.000	0.000	0.881	0.119	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B2020104 - Steel Windows	C1	0.676	0.083	0.166	0.046	0.016	0.010	0.003	1147
	C2	0.000	0.920	0.040	0.017	0.011	0.007	0.005	
	C3	0.000	0.000	0.882	0.074	0.032	0.003	0.010	
	C4	0.000	0.000	0.000	0.905	0.061	0.028	0.006	
	C5	0.000	0.000	0.000	0.000	0.916	0.069	0.016	
	C6	0.000	0.000	0.000	0.000	0.000	0.913	0.087	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B2020106 - Aluminum Windows	C1	0.601	0.201	0.117	0.055	0.006	0.018	0.003	2847
	C2	0.000	0.841	0.100	0.035	0.019	0.000	0.006	
	C3	0.000	0.000	0.891	0.074	0.021	0.007	0.007	
	C4	0.000	0.000	0.000	0.909	0.061	0.019	0.012	
	C5	0.000	0.000	0.000	0.000	0.870	0.091	0.038	
	C6	0.000	0.000	0.000	0.000	0.000	0.937	0.063	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	

Component Classification	Condition Prior	Condition Posterior							Data Points
		C1	C2	C3	C4	C5	C6	C7	
B2030110 - Glazed Doors	C1	0.670	0.221	0.089	0.000	0.014	0.004	0.002	1347
	C2	0.000	0.841	0.101	0.038	0.011	0.008	0.002	
	C3	0.000	0.000	0.871	0.093	0.029	0.000	0.007	
	C4	0.000	0.000	0.000	0.925	0.037	0.033	0.005	
	C5	0.000	0.000	0.000	0.000	0.885	0.081	0.035	
	C6	0.000	0.000	0.000	0.000	0.000	0.880	0.120	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B2030210 - Wood Doors	C1	0.604	0.092	0.247	0.000	0.002	0.006	0.049	1124
	C2	0.000	0.862	0.083	0.037	0.007	0.011	0.000	
	C3	0.000	0.000	0.814	0.116	0.018	0.035	0.018	
	C4	0.000	0.000	0.000	0.868	0.064	0.046	0.022	
	C5	0.000	0.000	0.000	0.000	0.872	0.086	0.042	
	C6	0.000	0.000	0.000	0.000	0.000	0.912	0.088	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B2030220 - Steel Doors	C1	0.677	0.145	0.120	0.032	0.018	0.006	0.001	7238
	C2	0.000	0.833	0.100	0.038	0.014	0.012	0.003	
	C3	0.000	0.000	0.879	0.089	0.014	0.009	0.009	
	C4	0.000	0.000	0.000	0.817	0.151	0.025	0.008	
	C5	0.000	0.000	0.000	0.000	0.898	0.079	0.024	
	C6	0.000	0.000	0.000	0.000	0.000	0.930	0.070	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B2030230 - Aluminum Doors	C1	0.508	0.445	0.023	0.017	0.000	0.005	0.001	687
	C2	0.000	0.869	0.097	0.018	0.008	0.005	0.003	
	C3	0.000	0.000	0.898	0.069	0.008	0.019	0.006	
	C4	0.000	0.000	0.000	0.915	0.051	0.025	0.009	
	C5	0.000	0.000	0.000	0.000	0.913	0.061	0.025	
	C6	0.000	0.000	0.000	0.000	0.000	0.910	0.090	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B2030410 - Overhead Doors	C1	0.720	0.110	0.105	0.032	0.017	0.006	0.010	3043
	C2	0.000	0.836	0.119	0.019	0.015	0.005	0.006	
	C3	0.000	0.000	0.850	0.109	0.023	0.013	0.004	
	C4	0.000	0.000	0.000	0.824	0.146	0.022	0.008	
	C5	0.000	0.000	0.000	0.000	0.881	0.084	0.036	
	C6	0.000	0.000	0.000	0.000	0.000	0.905	0.095	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	

Component Classification	Condition Prior	Condition Posterior							Data Points
		C1	C2	C3	C4	C5	C6	C7	
B3010130 - Preformed Metal	C1	0.704	0.149	0.095	0.012	0.024	0.002	0.015	4368
	C2	0.000	0.811	0.126	0.033	0.016	0.009	0.005	
	C3	0.000	0.000	0.864	0.087	0.021	0.016	0.012	
	C4	0.000	0.000	0.000	0.857	0.085	0.037	0.021	
	C5	0.000	0.000	0.000	0.000	0.849	0.119	0.032	
	C6	0.000	0.000	0.000	0.000	0.000	0.921	0.079	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B3010140 - Shingle & Tile	C1	0.722	0.108	0.109	0.013	0.010	0.009	0.028	1665
	C2	0.000	0.793	0.113	0.042	0.016	0.020	0.017	
	C3	0.000	0.000	0.872	0.057	0.025	0.016	0.030	
	C4	0.000	0.000	0.000	0.849	0.096	0.040	0.016	
	C5	0.000	0.000	0.000	0.000	0.863	0.077	0.060	
	C6	0.000	0.000	0.000	0.000	0.000	0.868	0.133	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
D2010110 - Toilet	C1	0.691	0.188	0.098	0.004	0.008	0.007	0.005	4579
	C2	0.000	0.832	0.114	0.030	0.015	0.007	0.001	
	C3	0.000	0.000	0.884	0.084	0.014	0.012	0.007	
	C4	0.000	0.000	0.000	0.826	0.119	0.031	0.023	
	C5	0.000	0.000	0.000	0.000	0.865	0.100	0.034	
	C6	0.000	0.000	0.000	0.000	0.000	0.927	0.073	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
D2010210 - Urinal	C1	0.686	0.185	0.085	0.021	0.010	0.002	0.011	2436
	C2	0.000	0.829	0.108	0.031	0.017	0.010	0.005	
	C3	0.000	0.000	0.891	0.080	0.007	0.014	0.008	
	C4	0.000	0.000	0.000	0.859	0.098	0.029	0.014	
	C5	0.000	0.000	0.000	0.000	0.817	0.145	0.039	
	C6	0.000	0.000	0.000	0.000	0.000	0.945	0.055	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
D2010310 - Lavatory	C1	0.701	0.184	0.094	0.001	0.012	0.007	0.001	2139
	C2	0.000	0.843	0.102	0.035	0.010	0.006	0.003	
	C3	0.000	0.000	0.876	0.090	0.013	0.009	0.011	
	C4	0.000	0.000	0.000	0.891	0.089	0.019	0.001	
	C5	0.000	0.000	0.000	0.000	0.873	0.095	0.031	
	C6	0.000	0.000	0.000	0.000	0.000	0.928	0.072	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	

Component Classification	Condition Prior	Condition Posterior							Data Points
		C1	C2	C3	C4	C5	C6	C7	
D2010410 - Sink	C1	0.719	0.119	0.141	0.003	0.009	0.000	0.010	2393
	C2	0.000	0.837	0.106	0.025	0.020	0.007	0.005	
	C3	0.000	0.000	0.895	0.076	0.012	0.009	0.008	
	C4	0.000	0.000	0.000	0.890	0.080	0.019	0.010	
	C5	0.000	0.000	0.000	0.000	0.895	0.079	0.026	
	C6	0.000	0.000	0.000	0.000	0.000	0.950	0.050	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
D2020240 - Water Heaters, Commercial, Electric	C1	0.731	0.118	0.074	0.024	0.054	0.000	0.000	1185
	C2	0.000	0.708	0.177	0.081	0.002	0.022	0.011	
	C3	0.000	0.000	0.844	0.140	0.007	0.005	0.004	
	C4	0.000	0.000	0.000	0.791	0.199	0.010	0.000	
	C5	0.000	0.000	0.000	0.000	0.807	0.150	0.044	
	C6	0.000	0.000	0.000	0.000	0.000	0.970	0.030	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
D2020903 - Backflow Preventer	C1	0.700	0.177	0.080	0.014	0.023	0.001	0.005	1289
	C2	0.000	0.808	0.078	0.094	0.020	0.000	0.000	
	C3	0.000	0.000	0.866	0.102	0.032	0.000	0.001	
	C4	0.000	0.000	0.000	0.884	0.078	0.027	0.011	
	C5	0.000	0.000	0.000	0.000	0.868	0.124	0.008	
	C6	0.000	0.000	0.000	0.000	0.000	0.969	0.032	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
D2020905 - Piping/Fittings	C1	0.678	0.190	0.064	0.018	0.041	0.001	0.007	10219
	C2	0.000	0.804	0.122	0.040	0.026	0.007	0.001	
	C3	0.000	0.000	0.885	0.087	0.012	0.009	0.008	
	C4	0.000	0.000	0.000	0.829	0.136	0.026	0.009	
	C5	0.000	0.000	0.000	0.000	0.884	0.092	0.024	
	C6	0.000	0.000	0.000	0.000	0.000	0.921	0.079	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
D2030902 - Waste/Vent Piping	C1	0.695	0.173	0.080	0.019	0.027	0.000	0.005	6616
	C2	0.000	0.826	0.107	0.039	0.020	0.006	0.002	
	C3	0.000	0.000	0.902	0.070	0.015	0.008	0.006	
	C4	0.000	0.000	0.000	0.816	0.157	0.011	0.015	
	C5	0.000	0.000	0.000	0.000	0.888	0.101	0.011	
	C6	0.000	0.000	0.000	0.000	0.000	0.953	0.047	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	

Component Classification	Condition Prior	Condition Posterior							Data Points
		C1	C2	C3	C4	C5	C6	C7	
D3040110 - Air Handling Unit, Central Station	C1	0.679	0.143	0.067	0.040	0.040	0.004	0.027	3106
	C2	0.000	0.752	0.117	0.066	0.058	0.004	0.002	
	C3	0.000	0.000	0.885	0.084	0.023	0.000	0.008	
	C4	0.000	0.000	0.000	0.550	0.450	0.000	0.000	
	C5	0.000	0.000	0.000	0.000	0.770	0.166	0.064	
	C6	0.000	0.000	0.000	0.000	0.000	0.940	0.060	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
D3040330 - Circulating Pump, End Suction	C1	0.713	0.132	0.076	0.037	0.028	0.000	0.014	2440
	C2	0.000	0.756	0.109	0.096	0.023	0.012	0.004	
	C3	0.000	0.000	0.888	0.096	0.000	0.007	0.009	
	C4	0.000	0.000	0.000	0.832	0.130	0.034	0.004	
	C5	0.000	0.000	0.000	0.000	0.808	0.169	0.023	
	C6	0.000	0.000	0.000	0.000	0.000	0.954	0.046	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	

APPENDIX E – CHARACTERISTIC DETERIORATION TRANSITION MATRIX FOR SELECT COMPONENTS BY CLIMATE REGION

Component Classification	Condition Prior	Condition Posterior							Data Points
		C1	C2	C3	C4	C5	C6	C7	
B3010105 - Built-Up: MARINE	C1	0.688	0.048	0.074	0.000	0.085	0.067	0.038	325
	C2	0.000	0.752	0.182	0.005	0.022	0.021	0.018	
	C3	0.000	0.000	0.823	0.102	0.000	0.003	0.071	
	C4	0.000	0.000	0.000	0.687	0.198	0.053	0.063	
	C5	0.000	0.000	0.000	0.000	0.817	0.131	0.052	
	C6	0.000	0.000	0.000	0.000	0.000	0.847	0.153	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B3010105 - Built-Up: MIXED HUMID	C1	0.771	0.118	0.073	0.003	0.016	0.015	0.003	993
	C2	0.000	0.904	0.049	0.021	0.011	0.004	0.012	
	C3	0.000	0.000	0.931	0.045	0.005	0.002	0.017	
	C4	0.000	0.000	0.000	0.871	0.055	0.060	0.014	
	C5	0.000	0.000	0.000	0.000	0.896	0.068	0.036	
	C6	0.000	0.000	0.000	0.000	0.000	0.908	0.092	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B3010105 - Built-Up: HOT HUMID	C1	0.642	0.237	0.077	0.003	0.010	0.029	0.002	803
	C2	0.000	0.717	0.186	0.067	0.015	0.005	0.010	
	C3	0.000	0.000	0.823	0.123	0.029	0.002	0.022	
	C4	0.000	0.000	0.000	0.688	0.225	0.045	0.042	
	C5	0.000	0.000	0.000	0.000	0.817	0.157	0.026	
	C6	0.000	0.000	0.000	0.000	0.000	0.895	0.105	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B3010105 - Built-Up: HOT DRY	C1	0.651	0.108	0.195	0.003	0.019	0.000	0.025	776
	C2	0.000	0.696	0.156	0.054	0.030	0.033	0.032	
	C3	0.000	0.000	0.803	0.084	0.084	0.024	0.005	
	C4	0.000	0.000	0.000	0.777	0.147	0.051	0.026	
	C5	0.000	0.000	0.000	0.000	0.806	0.103	0.091	
	C6	0.000	0.000	0.000	0.000	0.000	0.893	0.107	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	

Component Classification	Condition Prior	Condition Posterior							Data Points
		C1	C2	C3	C4	C5	C6	C7	
B3010105 - Built-Up: COLD	C1	0.202	0.476	0.254	0.002	0.029	0.038	0.000	201
	C2	0.000	0.747	0.101	0.046	0.077	0.029	0.000	
	C3	0.000	0.000	0.624	0.211	0.032	0.011	0.122	
	C4	0.000	0.000	0.000	0.724	0.113	0.132	0.032	
	C5	0.000	0.000	0.000	0.000	0.798	0.194	0.008	
	C6	0.000	0.000	0.000	0.000	0.000	0.896	0.104	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B3010105 - Built-Up: MARINE	C1	0.609	0.150	0.070	0.048	0.025	0.000	0.097	150
	C2	0.000	0.619	0.153	0.070	0.025	0.044	0.089	
	C3	0.000	0.000	0.791	0.139	0.063	0.007	0.000	
	C4	0.000	0.000	0.000	0.782	0.032	0.186	0.000	
	C5	0.000	0.000	0.000	0.000	0.738	0.081	0.181	
	C6	0.000	0.000	0.000	0.000	0.000	0.880	0.120	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B3010105 - Built-Up: MIXED HUMID	C1	0.799	0.111	0.070	0.003	0.000	0.001	0.016	606
	C2	0.000	0.894	0.060	0.012	0.008	0.013	0.013	
	C3	0.000	0.000	0.907	0.048	0.026	0.019	0.000	
	C4	0.000	0.000	0.000	0.847	0.081	0.034	0.038	
	C5	0.000	0.000	0.000	0.000	0.891	0.066	0.043	
	C6	0.000	0.000	0.000	0.000	0.000	0.849	0.151	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B3010105 - Built-Up: HOT HUMID	C1	0.759	0.164	0.074	0.002	0.000	0.000	0.000	229
	C2	0.000	0.781	0.160	0.039	0.004	0.008	0.008	
	C3	0.000	0.000	0.924	0.048	0.021	0.008	0.000	
	C4	0.000	0.000	0.000	0.872	0.090	0.011	0.027	
	C5	0.000	0.000	0.000	0.000	0.824	0.090	0.085	
	C6	0.000	0.000	0.000	0.000	0.000	0.974	0.026	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B3010105 - Built-Up: HOT DRY	C1	0.698	0.040	0.195	0.000	0.019	0.007	0.041	324
	C2	0.000	0.672	0.224	0.052	0.039	0.000	0.012	
	C3	0.000	0.000	0.800	0.076	0.108	0.017	0.000	
	C4	0.000	0.000	0.000	0.766	0.203	0.013	0.018	
	C5	0.000	0.000	0.000	0.000	0.653	0.262	0.085	
	C6	0.000	0.000	0.000	0.000	0.000	0.904	0.096	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	

Component Classification	Condition Prior	Condition Posterior							Data Points
		C1	C2	C3	C4	C5	C6	C7	
B3010105 - Built-Up: COLD	C1	0.741	0.164	0.058	0.003	0.000	0.000	0.034	144
	C2	0.000	0.744	0.155	0.046	0.010	0.023	0.023	
	C3	0.000	0.000	0.810	0.059	0.078	0.053	0.000	
	C4	0.000	0.000	0.000	0.719	0.281	0.000	0.000	
	C5	0.000	0.000	0.000	0.000	0.622	0.176	0.202	
	C6	0.000	0.000	0.000	0.000	0.000	0.825	0.175	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B3010105 - Built-Up: MARINE	C1	0.646	0.258	0.051	0.044	0.000	0.000	0.000	412
	C2	0.000	0.812	0.096	0.043	0.037	0.005	0.007	
	C3	0.000	0.000	0.853	0.095	0.007	0.031	0.014	
	C4	0.000	0.000	0.000	0.830	0.154	0.001	0.015	
	C5	0.000	0.000	0.000	0.000	0.891	0.105	0.004	
	C6	0.000	0.000	0.000	0.000	0.000	0.967	0.033	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B3010105 - Built-Up: MIXED HUMID	C1	0.711	0.167	0.071	0.024	0.014	0.010	0.003	1357
	C2	0.000	0.900	0.066	0.022	0.006	0.003	0.003	
	C3	0.000	0.000	0.930	0.038	0.014	0.009	0.009	
	C4	0.000	0.000	0.000	0.877	0.101	0.020	0.002	
	C5	0.000	0.000	0.000	0.000	0.912	0.079	0.009	
	C6	0.000	0.000	0.000	0.000	0.000	0.933	0.067	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B3010105 - Built-Up: HOT HUMID	C1	0.704	0.146	0.070	0.060	0.010	0.004	0.006	1017
	C2	0.000	0.872	0.074	0.052	0.000	0.000	0.002	
	C3	0.000	0.000	0.815	0.149	0.011	0.017	0.008	
	C4	0.000	0.000	0.000	0.876	0.093	0.022	0.009	
	C5	0.000	0.000	0.000	0.000	0.880	0.088	0.033	
	C6	0.000	0.000	0.000	0.000	0.000	0.974	0.026	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B3010105 - Built-Up: HOT DRY	C1	0.670	0.134	0.134	0.023	0.004	0.012	0.023	771
	C2	0.000	0.729	0.153	0.035	0.077	0.000	0.005	
	C3	0.000	0.000	0.771	0.104	0.090	0.022	0.012	
	C4	0.000	0.000	0.000	0.699	0.209	0.011	0.081	
	C5	0.000	0.000	0.000	0.000	0.903	0.082	0.015	
	C6	0.000	0.000	0.000	0.000	0.000	0.893	0.107	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	

Component Classification	Condition Prior	Condition Posterior							Data Points
		C1	C2	C3	C4	C5	C6	C7	
B3010105 - Built-Up: COLD	C1	0.689	0.161	0.132	0.003	0.000	0.015	0.000	506
	C2	0.000	0.720	0.142	0.043	0.063	0.001	0.032	
	C3	0.000	0.000	0.819	0.127	0.028	0.019	0.007	
	C4	0.000	0.000	0.000	0.838	0.103	0.038	0.021	
	C5	0.000	0.000	0.000	0.000	0.807	0.130	0.063	
	C6	0.000	0.000	0.000	0.000	0.000	0.949	0.051	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B3010105 - Built-Up: MARINE	C1	0.641	0.285	0.045	0.023	0.006	0.000	0.000	440
	C2	0.000	0.749	0.116	0.124	0.000	0.001	0.010	
	C3	0.000	0.000	0.826	0.110	0.028	0.023	0.014	
	C4	0.000	0.000	0.000	0.710	0.187	0.076	0.027	
	C5	0.000	0.000	0.000	0.000	0.851	0.073	0.076	
	C6	0.000	0.000	0.000	0.000	0.000	0.891	0.109	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B3010105 - Built-Up: MIXED HUMID	C1	0.752	0.140	0.080	0.015	0.009	0.004	0.000	2128
	C2	0.000	0.889	0.056	0.028	0.014	0.012	0.001	
	C3	0.000	0.000	0.903	0.067	0.010	0.007	0.014	
	C4	0.000	0.000	0.000	0.904	0.075	0.020	0.001	
	C5	0.000	0.000	0.000	0.000	0.934	0.040	0.026	
	C6	0.000	0.000	0.000	0.000	0.000	0.918	0.082	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B3010105 - Built-Up: HOT HUMID	C1	0.727	0.150	0.077	0.020	0.020	0.004	0.002	1293
	C2	0.000	0.842	0.108	0.027	0.012	0.009	0.001	
	C3	0.000	0.000	0.891	0.106	0.000	0.000	0.002	
	C4	0.000	0.000	0.000	0.759	0.228	0.010	0.002	
	C5	0.000	0.000	0.000	0.000	0.874	0.115	0.011	
	C6	0.000	0.000	0.000	0.000	0.000	0.948	0.052	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	
B3010105 - Built-Up: HOT DRY	C1	0.606	0.166	0.158	0.036	0.017	0.016	0.003	1354
	C2	0.000	0.706	0.213	0.049	0.017	0.014	0.000	
	C3	0.000	0.000	0.832	0.119	0.036	0.005	0.009	
	C4	0.000	0.000	0.000	0.722	0.245	0.015	0.018	
	C5	0.000	0.000	0.000	0.000	0.894	0.090	0.016	
	C6	0.000	0.000	0.000	0.000	0.000	0.891	0.109	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	

Component Classification	Condition Prior	Condition Posterior C1	C2	C3	C4	C5	C6	C7	Data Points
B3010105 - Built-Up: COLD	C1	0.748	0.219	0.021	0.006	0.002	0.000	0.004	627
	C2	0.000	0.775	0.072	0.052	0.051	0.021	0.029	
	C3	0.000	0.000	0.853	0.063	0.045	0.033	0.006	
	C4	0.000	0.000	0.000	0.779	0.208	0.013	0.000	
	C5	0.000	0.000	0.000	0.000	0.824	0.145	0.031	
	C6	0.000	0.000	0.000	0.000	0.000	0.963	0.037	
	C7	0.000	0.000	0.000	0.000	0.000	0.000	1.000	

APPENDIX F – CHARACTERISTIC REPAIR TRANSITION MATRIX FOR ASTM UNIFORMAT LEVEL 3 COMPONENT CLASSIFICATIONS

Component Classification	Condition	Condition Posterior							Data
	Prior	C1	C2	C3	C4	C5	C6	C7	Points
A1010 STANDARD FOUNDATIONS	C1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	2117
	C2	0.260	0.740	0.000	0.000	0.000	0.000	0.000	
	C3	0.001	0.393	0.606	0.000	0.000	0.000	0.000	
	C4	0.000	0.000	0.828	0.172	0.000	0.000	0.000	
	C5	0.002	0.057	0.134	0.323	0.483	0.000	0.000	
	C6	0.003	0.014	0.000	0.024	0.044	0.915	0.000	
	C7	0.003	0.024	0.064	0.085	0.087	0.096	0.641	
A1020 SPECIAL FOUNDATIONS	C1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	295
	C2	0.264	0.736	0.000	0.000	0.000	0.000	0.000	
	C3	0.001	0.496	0.503	0.000	0.000	0.000	0.000	
	C4	0.000	0.000	0.317	0.683	0.000	0.000	0.000	
	C5	0.002	0.042	0.021	0.220	0.715	0.000	0.000	
	C6	0.003	0.005	0.000	0.067	0.000	0.925	0.000	
	C7	0.003	0.007	0.017	0.156	0.102	0.000	0.714	
A1030 SLAB ON GRADE	C1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	3370
	C2	0.265	0.735	0.000	0.000	0.000	0.000	0.000	
	C3	0.001	0.398	0.601	0.000	0.000	0.000	0.000	
	C4	0.000	0.000	0.466	0.534	0.000	0.000	0.000	
	C5	0.002	0.073	0.135	0.254	0.536	0.000	0.000	
	C6	0.003	0.007	0.000	0.114	0.102	0.773	0.000	
	C7	0.005	0.020	0.166	0.028	0.118	0.115	0.548	
A2020 BASEMENT WALLS	C1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	146
	C2	0.266	0.734	0.000	0.000	0.000	0.000	0.000	
	C3	0.001	0.287	0.712	0.000	0.000	0.000	0.000	
	C4	0.000	0.193	0.100	0.706	0.000	0.000	0.000	
	C5	0.002	0.069	0.058	0.096	0.774	0.000	0.000	
	C6	0.003	0.004	0.000	0.000	0.104	0.889	0.000	
	C7	0.008	0.090	0.019	0.022	0.037	0.068	0.755	

Component Classification	Condition	Condition Posterior							Data
	Prior	C1	C2	C3	C4	C5	C6	C7	Points
B1010 FLOOR CONSTRUCTION	C1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	2265
	C2	0.266	0.734	0.000	0.000	0.000	0.000	0.000	
	C3	0.001	0.335	0.665	0.000	0.000	0.000	0.000	
	C4	0.001	0.000	0.530	0.469	0.000	0.000	0.000	
	C5	0.002	0.006	0.088	0.164	0.740	0.000	0.000	
	C6	0.003	0.005	0.000	0.000	0.153	0.839	0.000	
	C7	0.008	0.062	0.029	0.075	0.063	0.055	0.709	
B1020 ROOF CONSTRUCTION	C1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	6458
	C2	0.267	0.733	0.000	0.000	0.000	0.000	0.000	
	C3	0.001	0.423	0.576	0.000	0.000	0.000	0.000	
	C4	0.000	0.000	0.399	0.601	0.000	0.000	0.000	
	C5	0.000	0.000	0.219	0.198	0.583	0.000	0.000	
	C6	0.009	0.020	0.000	0.000	0.267	0.703	0.000	
	C7	0.008	0.021	0.065	0.070	0.080	0.099	0.657	
B2010 EXTERIOR WALLS	C1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	4595
	C2	0.267	0.733	0.000	0.000	0.000	0.000	0.000	
	C3	0.001	0.267	0.732	0.000	0.000	0.000	0.000	
	C4	0.000	0.000	0.750	0.250	0.000	0.000	0.000	
	C5	0.000	0.060	0.000	0.278	0.662	0.000	0.000	
	C6	0.021	0.077	0.000	0.000	0.198	0.704	0.000	
	C7	0.007	0.016	0.003	0.080	0.069	0.116	0.708	
B2020 EXTERIOR WINDOWS	C1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	3521
	C2	0.523	0.477	0.000	0.000	0.000	0.000	0.000	
	C3	0.001	0.246	0.753	0.000	0.000	0.000	0.000	
	C4	0.000	0.000	0.580	0.420	0.000	0.000	0.000	
	C5	0.000	0.077	0.034	0.204	0.683	0.000	0.000	
	C6	0.021	0.064	0.000	0.023	0.165	0.727	0.000	
	C7	0.012	0.039	0.013	0.096	0.048	0.095	0.698	
B2030 EXTERIOR DOORS	C1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	4703
	C2	0.523	0.477	0.000	0.000	0.000	0.000	0.000	
	C3	0.001	0.245	0.754	0.000	0.000	0.000	0.000	
	C4	0.000	0.000	0.694	0.306	0.000	0.000	0.000	
	C5	0.000	0.085	0.000	0.260	0.654	0.000	0.000	
	C6	0.021	0.066	0.000	0.139	0.103	0.670	0.000	
	C7	0.011	0.034	0.029	0.074	0.075	0.085	0.691	

Component Classification	Condition	Condition Posterior							Data
	Prior	C1	C2	C3	C4	C5	C6	C7	Points
B3010 ROOF COVERINGS	C1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	5048
	C2	0.523	0.477	0.000	0.000	0.000	0.000	0.000	
	C3	0.001	0.431	0.568	0.000	0.000	0.000	0.000	
	C4	0.000	0.000	0.409	0.591	0.000	0.000	0.000	
	C5	0.000	0.030	0.140	0.137	0.693	0.000	0.000	
	C6	0.018	0.053	0.000	0.099	0.156	0.674	0.000	
	C7	0.007	0.013	0.058	0.077	0.070	0.109	0.665	
B3020 ROOF OPENINGS	C1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	249
	C2	0.523	0.477	0.000	0.000	0.000	0.000	0.000	
	C3	0.001	0.233	0.766	0.000	0.000	0.000	0.000	
	C4	0.000	0.000	0.926	0.074	0.000	0.000	0.000	
	C5	0.000	0.086	0.000	0.268	0.646	0.000	0.000	
	C6	0.014	0.017	0.000	0.084	0.315	0.570	0.000	
	C7	0.020	0.055	0.042	0.054	0.093	0.082	0.655	
C1010 PARTITIONS	C1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	3576
	C2	0.523	0.477	0.000	0.000	0.000	0.000	0.000	
	C3	0.001	0.351	0.648	0.000	0.000	0.000	0.000	
	C4	0.000	0.000	0.564	0.436	0.000	0.000	0.000	
	C5	0.000	0.047	0.101	0.223	0.629	0.000	0.000	
	C6	0.018	0.026	0.000	0.172	0.094	0.690	0.000	
	C7	0.021	0.039	0.056	0.100	0.079	0.101	0.603	
C1020 INTERIOR DOORS	C1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	3687
	C2	0.523	0.477	0.000	0.000	0.000	0.000	0.000	
	C3	0.001	0.269	0.731	0.000	0.000	0.000	0.000	
	C4	0.016	0.000	0.807	0.177	0.000	0.000	0.000	
	C5	0.000	0.077	0.000	0.267	0.656	0.000	0.000	
	C6	0.035	0.058	0.000	0.132	0.129	0.645	0.000	
	C7	0.023	0.046	0.004	0.128	0.068	0.071	0.661	
C1030 SPECIALTIES	C1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	963
	C2	0.523	0.477	0.000	0.000	0.000	0.000	0.000	
	C3	0.001	0.221	0.778	0.000	0.000	0.000	0.000	
	C4	0.000	0.000	0.575	0.425	0.000	0.000	0.000	
	C5	0.000	0.065	0.023	0.126	0.786	0.000	0.000	
	C6	0.006	0.000	0.000	0.149	0.121	0.724	0.000	
	C7	0.036	0.084	0.004	0.078	0.101	0.105	0.593	

Component Classification	Condition Prior	Condition Posterior							Data Points
		C1	C2	C3	C4	C5	C6	C7	
C2010 STAIR CONSTRUCTION	C1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	203
	C2	0.523	0.477	0.000	0.000	0.000	0.000	0.000	
	C3	0.001	0.333	0.666	0.000	0.000	0.000	0.000	
	C4	0.000	0.000	0.493	0.507	0.000	0.000	0.000	
	C5	0.000	0.120	0.000	0.401	0.478	0.000	0.000	
	C6	0.006	0.057	0.000	0.038	0.146	0.753	0.000	
	C7	0.027	0.042	0.005	0.098	0.087	0.029	0.713	
C3010 WALL FINISHES	C1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	2547
	C2	0.523	0.477	0.000	0.000	0.000	0.000	0.000	
	C3	0.001	0.703	0.296	0.000	0.000	0.000	0.000	
	C4	0.000	0.000	0.361	0.639	0.000	0.000	0.000	
	C5	0.000	0.005	0.113	0.149	0.731	0.000	0.000	
	C6	0.004	0.046	0.001	0.151	0.086	0.712	0.000	
	C7	0.007	0.030	0.008	0.085	0.079	0.100	0.691	
C3020 FLOOR FINISHES	C1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	6790
	C2	0.523	0.477	0.000	0.000	0.000	0.000	0.000	
	C3	0.001	0.411	0.588	0.000	0.000	0.000	0.000	
	C4	0.000	0.000	0.480	0.520	0.000	0.000	0.000	
	C5	0.000	0.000	0.228	0.177	0.595	0.000	0.000	
	C6	0.004	0.068	0.003	0.114	0.126	0.686	0.000	
	C7	0.006	0.015	0.055	0.096	0.115	0.102	0.611	
C3030 CEILING FINISHES	C1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	3848
	C2	0.523	0.477	0.000	0.000	0.000	0.000	0.000	
	C3	0.001	0.366	0.633	0.000	0.000	0.000	0.000	
	C4	0.000	0.000	0.323	0.677	0.000	0.000	0.000	
	C5	0.000	0.000	0.240	0.172	0.588	0.000	0.000	
	C6	0.004	0.047	0.105	0.060	0.128	0.655	0.000	
	C7	0.006	0.018	0.059	0.074	0.110	0.118	0.615	
D1010 ELEVATORS AND LIFTS	C1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	106
	C2	0.523	0.477	0.000	0.000	0.000	0.000	0.000	
	C3	0.001	0.662	0.337	0.000	0.000	0.000	0.000	
	C4	0.000	0.000	0.191	0.809	0.000	0.000	0.000	
	C5	0.058	0.036	0.115	0.053	0.738	0.000	0.000	
	C6	0.003	0.000	0.000	0.091	0.159	0.748	0.000	
	C7	0.000	0.000	0.000	0.069	0.283	0.037	0.611	

Component Classification	Condition	Condition Posterior							Data
	Prior	C1	C2	C3	C4	C5	C6	C7	Points
D2010 PLUMBING FIXTURES	C1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	5228
	C2	0.523	0.477	0.000	0.000	0.000	0.000	0.000	
	C3	0.001	0.306	0.693	0.000	0.000	0.000	0.000	
	C4	0.000	0.000	0.444	0.556	0.000	0.000	0.000	
	C5	0.049	0.033	0.052	0.166	0.701	0.000	0.000	
	C6	0.003	0.077	0.075	0.057	0.149	0.638	0.000	
	C7	0.069	0.000	0.070	0.074	0.052	0.080	0.655	
D2020 DOMESTIC WATER DISTRIBUTION		1.000	0.000	0.000	0.000	0.000	0.000	0.000	5952
		0.523	0.477	0.000	0.000	0.000	0.000	0.000	
		0.001	0.371	0.628	0.000	0.000	0.000	0.000	
		0.000	0.000	0.461	0.539	0.000	0.000	0.000	
		0.015	0.017	0.074	0.149	0.745	0.000	0.000	
		0.003	0.058	0.048	0.086	0.115	0.690	0.000	
		0.035	0.000	0.035	0.077	0.116	0.068	0.670	
D2030 SANITARY WASTE		1.000	0.000	0.000	0.000	0.000	0.000	0.000	4094
		0.523	0.477	0.000	0.000	0.000	0.000	0.000	
		0.001	0.279	0.720	0.000	0.000	0.000	0.000	
		0.000	0.000	0.343	0.657	0.000	0.000	0.000	
		0.000	0.000	0.213	0.151	0.636	0.000	0.000	
		0.003	0.018	0.042	0.048	0.268	0.621	0.000	
		0.050	0.000	0.027	0.043	0.130	0.070	0.679	
D2090 OTHER PLUMBING SYSTEMS		1.000	0.000	0.000	0.000	0.000	0.000	0.000	40
		0.523	0.477	0.000	0.000	0.000	0.000	0.000	
		0.001	0.230	0.769	0.000	0.000	0.000	0.000	
		0.000	0.000	0.453	0.547	0.000	0.000	0.000	
		0.183	0.216	0.000	0.270	0.331	0.000	0.000	
		0.003	0.029	0.058	0.055	0.855	0.000	0.000	
		0.021	0.000	0.000	0.022	0.005	0.007	0.946	
D3020 HEAT GENERATING SYSTEMS		1.000	0.000	0.000	0.000	0.000	0.000	0.000	178
		0.523	0.477	0.000	0.000	0.000	0.000	0.000	
		0.001	0.403	0.596	0.000	0.000	0.000	0.000	
		0.000	0.000	0.407	0.593	0.000	0.000	0.000	
		0.037	0.014	0.006	0.202	0.741	0.000	0.000	
		0.000	0.000	0.162	0.068	0.111	0.658	0.000	
		0.000	0.000	0.127	0.043	0.084	0.069	0.677	

Component Classification	Condition	Condition Posterior							Data
	Prior	C1	C2	C3	C4	C5	C6	C7	Points
D3030 COOLING GENERATING SYSTEMS		1.000	0.000	0.000	0.000	0.000	0.000	0.000	1062
		0.523	0.477	0.000	0.000	0.000	0.000	0.000	
		0.001	0.599	0.400	0.000	0.000	0.000	0.000	
		0.000	0.000	0.291	0.709	0.000	0.000	0.000	
		0.021	0.012	0.059	0.063	0.846	0.000	0.000	
		0.000	0.088	0.030	0.075	0.131	0.676	0.000	
		0.000	0.000	0.077	0.039	0.177	0.044	0.664	
D3040 DISTRIBUTION SYSTEMS		1.000	0.000	0.000	0.000	0.000	0.000	0.000	5486
		0.523	0.477	0.000	0.000	0.000	0.000	0.000	
		0.001	0.552	0.447	0.000	0.000	0.000	0.000	
		0.000	0.000	0.269	0.731	0.000	0.000	0.000	
		0.000	0.000	0.105	0.086	0.809	0.000	0.000	
		0.000	0.031	0.057	0.040	0.210	0.662	0.000	
		0.000	0.000	0.080	0.042	0.132	0.065	0.681	
D3050 TERMINAL & PACKAGE UNITS		1.000	0.000	0.000	0.000	0.000	0.000	0.000	2272
		0.523	0.477	0.000	0.000	0.000	0.000	0.000	
		0.001	0.733	0.266	0.000	0.000	0.000	0.000	
		0.000	0.000	0.290	0.710	0.000	0.000	0.000	
		0.000	0.000	0.071	0.127	0.802	0.000	0.000	
		0.000	0.046	0.042	0.088	0.163	0.660	0.000	
		0.000	0.000	0.114	0.043	0.111	0.072	0.661	
D3060 CONTROLS & INSTRUMENTATI ON		1.000	0.000	0.000	0.000	0.000	0.000	0.000	332
		0.523	0.477	0.000	0.000	0.000	0.000	0.000	
		0.001	0.334	0.665	0.000	0.000	0.000	0.000	
		0.065	0.000	0.217	0.718	0.000	0.000	0.000	
		0.000	0.000	0.076	0.047	0.877	0.000	0.000	
		0.000	0.284	0.000	0.000	0.367	0.349	0.000	
		0.000	0.000	0.124	0.043	0.192	0.067	0.574	
D3090 OTHER HVAC SYSTEMS AND EQUIPMENT		1.000	0.000	0.000	0.000	0.000	0.000	0.000	125
		0.523	0.477	0.000	0.000	0.000	0.000	0.000	
		0.001	0.807	0.192	0.000	0.000	0.000	0.000	
		0.000	0.000	0.360	0.640	0.000	0.000	0.000	
		0.000	0.000	0.346	0.087	0.567	0.000	0.000	
		0.000	0.000	0.164	0.219	0.485	0.132	0.000	
		0.000	0.000	0.000	0.001	0.043	0.398	0.557	

Component Classification	Condition	Condition Posterior							Data
	Prior	C1	C2	C3	C4	C5	C6	C7	Points
D4030 STANDPIPE SYSTEMS		1.000	0.000	0.000	0.000	0.000	0.000	0.000	370
		0.522	0.478	0.000	0.000	0.000	0.000	0.000	
		0.001	0.577	0.422	0.000	0.000	0.000	0.000	
		0.000	0.000	0.332	0.668	0.000	0.000	0.000	
		0.000	0.000	0.149	0.198	0.653	0.000	0.000	
		0.000	0.240	0.100	0.082	0.577	0.000	0.000	
		0.000	0.001	0.123	0.076	0.096	0.096	0.609	
D4040 SPRINKLERS		1.000	0.000	0.000	0.000	0.000	0.000	0.000	1322
		0.522	0.478	0.000	0.000	0.000	0.000	0.000	
		0.001	0.373	0.626	0.000	0.000	0.000	0.000	
		0.000	0.000	0.691	0.309	0.000	0.000	0.000	
		0.000	0.000	0.120	0.226	0.654	0.000	0.000	
		0.000	0.095	0.037	0.121	0.133	0.614	0.000	
		0.000	0.001	0.100	0.085	0.098	0.046	0.669	
D4090 OTHER FIRE PROTECTION SYSTEMS		1.000	0.000	0.000	0.000	0.000	0.000	0.000	529
		0.522	0.478	0.000	0.000	0.000	0.000	0.000	
		0.001	0.456	0.543	0.000	0.000	0.000	0.000	
		0.000	0.000	0.439	0.561	0.000	0.000	0.000	
		0.000	0.000	0.030	0.248	0.721	0.000	0.000	
		0.000	0.000	0.064	0.079	0.083	0.774	0.000	
		0.000	0.000	0.182	0.014	0.107	0.045	0.651	
D5010 ELECTRICAL SERVICE & DISTRIBUTION		1.000	0.000	0.000	0.000	0.000	0.000	0.000	8183
		0.522	0.478	0.000	0.000	0.000	0.000	0.000	
		0.001	0.584	0.415	0.000	0.000	0.000	0.000	
		0.000	0.000	0.384	0.616	0.000	0.000	0.000	
		0.000	0.000	0.069	0.206	0.725	0.000	0.000	
		0.000	0.000	0.097	0.082	0.101	0.720	0.000	
		0.000	0.000	0.058	0.037	0.077	0.074	0.753	
D5020 LIGHTING & BRANCH WIRING		1.000	0.000	0.000	0.000	0.000	0.000	0.000	8511
		0.522	0.478	0.000	0.000	0.000	0.000	0.000	
		0.001	0.138	0.861	0.000	0.000	0.000	0.000	
		0.000	0.302	0.497	0.201	0.000	0.000	0.000	
		0.000	0.000	0.000	0.371	0.629	0.000	0.000	
		0.000	0.459	0.017	0.004	0.393	0.127	0.000	
		0.000	0.001	0.000	0.152	0.004	0.242	0.601	

Component Classification	Condition Prior	Condition Posterior							Data Points
		C1	C2	C3	C4	C5	C6	C7	
D5030 COMMUNICATIONS & SECURITY		1.000	0.000	0.000	0.000	0.000	0.000	0.000	136
		0.522	0.478	0.000	0.000	0.000	0.000	0.000	
		0.001	0.477	0.522	0.000	0.000	0.000	0.000	
		0.000	0.000	0.559	0.441	0.000	0.000	0.000	
		0.000	0.000	0.053	0.392	0.555	0.000	0.000	
		0.000	0.278	0.000	0.004	0.387	0.331	0.000	
		0.000	0.001	0.105	0.026	0.005	0.462	0.402	
D5090 OTHER ELECTRICAL SERVICES		1.000	0.000	0.000	0.000	0.000	0.000	0.000	1156
		0.522	0.478	0.000	0.000	0.000	0.000	0.000	
		0.001	0.034	0.965	0.000	0.000	0.000	0.000	
		0.197	0.095	0.230	0.478	0.000	0.000	0.000	
		0.000	0.000	0.045	0.362	0.593	0.000	0.000	
		0.000	0.507	0.205	0.000	0.287	0.001	0.000	
		0.000	0.007	0.029	0.095	0.090	0.207	0.572	

APPENDIX G – RELIABILITY AND CONDITION INDEX PARAMETERS

Component	Decay, d	Alpha, a	Beta, b
A1010 STANDARD FOUNDATIONS	0.028	1.623	38.649
A1020 SPECIAL FOUNDATIONS	0.022	1.616	54.285
A1030 SLAB ON GRADE	0.024	1.701	47.069
A2020 BASEMENT WALLS	0.030	2.013	36.189
B1010 FLOOR CONSTRUCTION	0.031	1.794	34.294
B1020 ROOF CONSTRUCTION	0.025	1.623	46.111
B2010 EXTERIOR WALLS	0.030	1.591	36.679
B2010101 - CIP Concrete	0.021	1.498	57.161
B2010109 - Concrete Block	0.028	1.684	38.609
B2010125 - Solid Brick - Single Wythe	0.042	1.837	24.411
B2010146 - Metal Siding Panel	0.032	1.415	35.477
B2010148 - Wood Cladding w/Stud Backup	0.043	1.431	23.921
B2010151 - Stucco Wall	0.033	1.617	34.313
B2020 EXTERIOR WINDOWS	0.040	1.660	26.212
B2020102 - Wood Windows	0.052	1.657	19.804
B2020104 - Steel Windows	0.029	1.682	38.153
B2020106 - Aluminum Windows	0.030	1.619	36.875
B2030 EXTERIOR DOORS	0.033	1.725	33.384
B2030110 - Glazed Doors	0.030	1.831	35.956
B2030210 - Wood Doors	0.040	1.607	26.648
B2030220 - Steel Doors	0.031	1.738	35.483
B2030230 - Aluminum Doors	0.026	1.784	40.822
B2030410 - Overhead Doors	0.036	1.752	30.049
B3010 ROOF COVERINGS	0.041	1.544	25.724
B3010105 - Built-Up	0.047	1.510	21.738
B3010120 - Single Ply Membrane	0.033	1.533	32.531
B3010130 - Preformed Metal	0.036	1.605	29.475
B3010135 - Formed Metal	0.028	1.353	38.879
B3010140 - Shingle & Tile	0.046	1.415	21.316
B3020 ROOF OPENINGS	0.027	1.392	42.929
C1010 PARTITIONS	0.021	1.697	53.682
C1020 INTERIOR DOORS	0.027	1.760	42.312
C1030 SPECIALTIES	0.028	1.730	40.159
C2010 STAIR CONSTRUCTION	0.023	1.811	47.778
C3010 WALL FINISHES	0.028	1.728	41.098
C3020 FLOOR FINISHES	0.033	1.624	33.073
C3030 CEILING FINISHES	0.028	1.667	40.866
D1010 ELEVATORS AND LIFTS	0.025	1.108	52.262

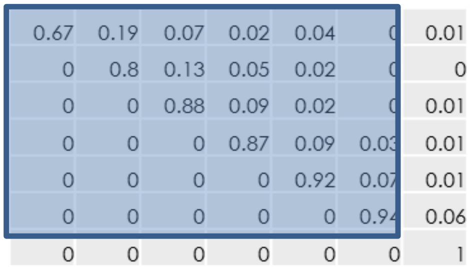
Component	Decay, d	Alpha, a	Beta, b
D2010 PLUMBING FIXTURES	0.031	1.683	36.242
D2010110 - Toilet	0.032	1.762	33.716
D2010210 - Urinal	0.031	1.576	36.287
D2010310 - Lavatory	0.029	1.804	38.343
D2010410 - Sink	0.027	1.598	42.655
D2020 DOMESTIC WATER DISTRIBUTION	0.031	1.704	36.158
D2020240 - Water Heaters, Commercial, Electric	0.036	1.702	31.355
D2020903 - Backflow Preventer	0.023	1.621	53.150
D2020905 - Piping/Fittings	0.033	1.742	33.376
D2030 SANITARY WASTE	0.027	1.666	43.571
D2030902 - Waste/Vent Piping	0.026	1.670	44.135
D2090 OTHER PLUMBING SYSTEMS	0.015	1.850	79.492
D3020 HEAT GENERATING SYSTEMS	0.027	1.438	43.638
D3030 COOLING GENERATING SYSTEMS	0.034	1.541	34.580
D3040 DISTRIBUTION SYSTEMS	0.041	1.504	26.087
D3040110 - Air Handling Unit, Central Station	0.042	1.344	25.611
D3040330 - Circulating Pump, End Suction	0.031	1.506	37.883
D3050 TERMINAL & PACKAGE UNITS	0.028	1.533	42.353
D3060 CONTROLS & INSTRUMENTATION	0.031	1.331	37.691
D3090 OTHER HVAC SYSTEMS AND EQUIPMENT	0.024	1.622	52.176
D4030 STANDPIPE SYSTEMS	0.026	1.323	46.714
D4040 SPRINKLERS	0.030	1.765	36.693
D4090 OTHER FIRE PROTECTION SYSTEMS	0.025	1.650	48.277
D5010 ELECTRICAL SERVICE & DISTRIBUTION	0.027	1.626	44.058
D5020 LIGHTING & BRANCH WIRING	0.027	1.704	43.063
D5030 COMMUNICATIONS & SECURITY	0.020	1.367	65.271
D5090 OTHER ELECTRICAL SERVICES	0.027	1.675	42.872

APPENDIX H – EXPECTED REMAINING SERVICE LIFE CALCULATION USING MARKOV MATRIX HITTING TIME

From: (Craig & Sendi, 2002)

Given characteristic Markov matrix, M, which is an n x n matrix:

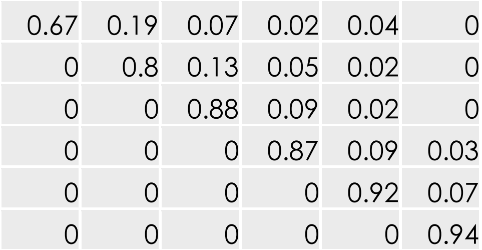
M =



0.67	0.19	0.07	0.02	0.04	0	0.01
0	0.8	0.13	0.05	0.02	0	0
0	0	0.88	0.09	0.02	0	0.01
0	0	0	0.87	0.09	0.03	0.01
0	0	0	0	0.92	0.07	0.01
0	0	0	0	0	0.94	0.06
0	0	0	0	0	0	1

Step 1: Form matrix S, by taking upper left n-1 rows and columns of M

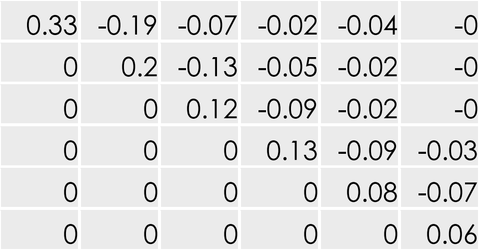
S =



0.67	0.19	0.07	0.02	0.04	0
0	0.8	0.13	0.05	0.02	0
0	0	0.88	0.09	0.02	0
0	0	0	0.87	0.09	0.03
0	0	0	0	0.92	0.07
0	0	0	0	0	0.94

Step 2: Calculated inverse Q matrix, Q-1, by subtracting S from identity matrix I

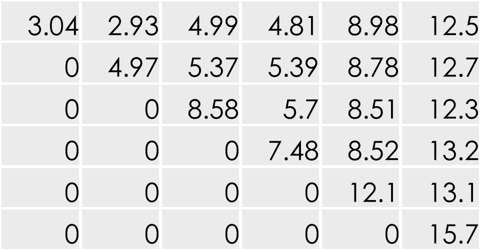
Q-1 = I - S =



0.33	-0.19	-0.07	-0.02	-0.04	-0
0	0.2	-0.13	-0.05	-0.02	-0
0	0	0.12	-0.09	-0.02	-0
0	0	0	0.13	-0.09	-0.03
0	0	0	0	0.08	-0.07
0	0	0	0	0	0.06

Step 3: Take inverse of resulting matrix in step 2, to determine the Q matrix

Q = Inv(Q-1) =



3.04	2.93	4.99	4.81	8.98	12.5
0	4.97	5.37	5.39	8.78	12.7
0	0	8.58	5.7	8.51	12.3
0	0	0	7.48	8.52	13.2
0	0	0	0	12.1	13.1
0	0	0	0	0	15.7

Step 4: Sum of row i in Q matrix is hitting time, or average time to go from state Si to absorption or failure state

C1	37.3
C2	37.2
C3	35.1
C4	29.2
C5	25.2
C6	15.7

APPENDIX I – EXPECTED SERVICE LIFE PARAMETERS

Component	Service Life Direct (years)	Service Life Average (years)	Service Life Median (years)	Service Life Standard Deviation
B2010 EXTERIOR WALLS	34.0	33.5	30	21.0
B2010101 - CIP Concrete	50.3	53.1	46	29.0
B2010109 - Concrete Block	35.8	35.0	33	21.0
B2010146 - Metal Siding Panel	33.2	32.9	29	22.5
Marine	45.7	44.8	40	26.9
Mixed Humid	42.4	43.0	39	24.1
Hot Dry	49.4	46.1	40	28.8
Hot Humid	21.9	22.8	20	14.8
Cold	28.2	29.2	24	19.7
B2010148 - Wood Cladding w/Stud Backup	23.2	22.2	20	15.5
B2010151 - Stucco Wall	32.0	31.2	29	19.5
B2020 EXTERIOR WINDOWS	25.2	24.0	22	14.9
B2020102 - Wood Windows	19.6	18.3	18	11.3
B2020104 - Steel Windows	35.6	34.8	32	20.7
B2020106 - Aluminum Windows	34.6	33.8	31	21.0
B2030 EXTERIOR DOORS	31.6	30.5	29	18.0
B2030110 - Glazed Doors	33.6	32.8	31	18.4
B2030210 - Wood Doors	25.5	24.6	22	15.7
B2030220 - Steel Doors	33.7	32.5	30	19.7
Marine	20.5	21.6	19	11.8
Mixed Humid	39.7	40.2	36	22.7
Hot Dry	40.7	41.1	37	22.0
Hot Humid	25.3	26.0	24	14.6
Cold	35.8	35.8	30	24.8
B2030230 - Aluminum Doors	38.2	37.1	34	21.2
B2030410 - Overhead Doors	28.5	27.4	26	16.0
B3010 ROOF COVERINGS	24.6	23.7	22	15.4
B3010105 - Built-Up	21.2	20.1	19	13.3
Marine	12.4	13.4	11	9.3
Mixed Humid	32.2	33.1	29	21.0
Hot Dry	21.0	21.9	20	12.6
Hot Humid	17.5	18.6	17	11.7
Cold	16.0	17.1	15	11.2
B3010120 - Single Ply Membrane	31.2	30.1	27	19.5
Marine	12.1	13.1	11	10.3
Mixed Humid	27.9	28.9	26	17.7
Hot Dry	46.0	44.1	37	27.3
Hot Humid	17.6	18.8	17	12.6
Cold	15.1	16.1	15	9.3
B3010130 - Preformed Metal	56.4	54.5	51	34.6

Component	Service Life Direct (years)	Service Life Average (years)	Service Life Median (years)	Service Life Standard Deviation
B3010135 - Formed Metal	36.2	36.2	31	25.1
B3010140 - Shingle & Tile	42.6	40.7	38	27.9
B3020 ROOF OPENINGS	40.0	40.3	35	26.0
C1010 PARTITIONS	48.5	48.8	45	26.3
C1020 INTERIOR DOORS	39.2	38.5	36	21.7
C1030 SPECIALTIES	37.8	37.1	33	21.5
C2010 STAIR CONSTRUCTION	44.1	43.5	40	23.7
C3010 WALL FINISHES	38.0	37.7	34	21.6
C3020 FLOOR FINISHES	31.5	30.2	28	19.2
C3030 CEILING FINISHES	38.0	37.3	34	22.5
D1010 ELEVATORS AND LIFTS	46.2	51.4	39	31.9
D2010 PLUMBING FIXTURES	33.9	33.2	31	19.8
D2010110 - Toilet	31.5	30.8	28	17.9
D2010210 - Urinal	33.9	33.3	30	21.2
D2010310 - Lavatory	35.7	34.9	33	19.7
D2010410 - Sink	39.2	39.0	35	23.5
D2020 DOMESTIC WATER DISTRIBUTION	34.0	33.1	30	20.0
D2020240 - Water Heaters, Commercial, Electric	29.6	28.9	26	17.7
D2020903 - Backflow Preventer	47.9	49.6	43	27.1
D2020905 - Piping/Fittings	31.2	30.4	28	17.9
D2030 SANITARY WASTE	40.1	39.9	36	23.3
D2030902 - Waste/Vent Piping	40.5	40.5	36	23.6
D3020 HEAT GENERATING SYSTEMS	39.8	40.2	35	25.5
D3030 COOLING GENERATING SYSTEMS	33.0	32.0	29	20.8
D3040 DISTRIBUTION SYSTEMS	24.9	23.8	22	16.1
D3040110 - Air Handling Unit, Central Station	25.1	24.2	21	17.9
D3040330 - Circulating Pump, End Suction	36.0	35.1	31	23.0
D3050 TERMINAL & PACKAGE UNITS	39.6	39.3	34	24.6
D3060 CONTROLS & INSTRUMENTATION	35.6	35.6	30	24.5
D3090 OTHER HVAC SYSTEMS AND EQUIPMENT	47.6	48.9	42	26.4
D4030 STANDPIPE SYSTEMS	41.8	42.9	38	28.1
D4040 SPRINKLERS	34.5	33.6	31	19.5
D4090 OTHER FIRE PROTECTION SYSTEMS	44.4	44.3	40	25.6
D5010 ELECTRICAL SERVICE & DISTRIBUTION	40.6	40.4	36	24.0
D5020 LIGHTING & BRANCH WIRING	39.9	39.2	36	22.8
D5090 OTHER ELECTRICAL SERVICES	40.2	39.4	36	23.3

APPENDIX J – MARKOV MODEL DATA VALIDATION STATISTICS

			Markov Prediction								Deterministic Comparison		
			Categorical Analysis % Error		Pairwise Condition State			Pairwise Condition Index			Pairwise Condition State		
Component	Climate Region	#Points	p-value	p-value	Perfect	+-1 Range	R2	Perfect	1 Range	R2	Perfect	1 Range	R2
A1010 STANDARD FOUNDATIONS		9,429	0.983	0.734	69%	89%	0.359	68%	93%	0.39	63%	84%	0.058
A1020 SPECIAL FOUNDATIONS		1,384	0.998	0.937	66%	89%	0.425	70%	94%	0.514	59%	83%	0.095
A1030 SLAB ON GRADE		11,807	0.994	0.603	74%	92%	0.672	74%	91%	0.656	68%	88%	0.536
A2020 BASEMENT WALLS		771	0.999	0.836	70%	91%	0.66	73%	93%	0.674	58%	87%	0.462
B1010 FLOOR CONSTRUCTION		6,258	0.998	0.798	68%	90%	0.659	58%	90%	0.704	61%	86%	0.505
B1020 ROOF CONSTRUCTION		13,487	0.992	0.426	77%	93%	0.776	67%	87%	0.757	61%	90%	0.688
B2010 EXTERIOR WALLS		10,395	0.99	0.996	69%	88%	0.58	58%	89%	0.634	60%	83%	0.389
B2010101 - CIP Concrete		1,583	0.955	0.989	67%	87%	0.499	60%	93%	0.588	55%	79%	0.152
B2010109 - Concrete Block		2,381	0.957	0.868	68%	89%	0.468	62%	92%	0.469	58%	82%	0.15
B2010125 - Solid Brick		962	0.982	0.972	61%	85%	0.533	44%	89%	0.557	51%	73%	0.105
B2010146 - Metal Siding Panel		2,493	0.869	0.992	70%	89%	0.632	61%	88%	0.628	59%	86%	0.457
B2010146 - Metal Siding Panel	Marine	208	0.999	0.729	69%	88%	0.646	63%	90%	0.708	58%	85%	0.484
B2010146 - Metal Siding Panel	Mixed-Humid	666	0.925	0.852	80%	94%	0.826	68%	86%	0.782	66%	91%	0.728
B2010146 - Metal Siding Panel	Hot-Dry	504	0.993	0.974	70%	89%	0.68	60%	93%	0.691	59%	90%	0.583
B2010146 - Metal Siding Panel	Hot-Humid	375	0.965	0.987	70%	88%	0.706	51%	87%	0.623	61%	80%	0.334
B2010146 - Metal Siding Panel	Cold	283	0.917	0.953	67%	90%	0.671	53%	91%	0.64	56%	85%	0.513
B2010148 - Wood Cladding		534	0.854	0.79	75%	90%	0.68	55%	83%	0.725	64%	90%	0.616
B2010151 - Stucco Wall		476	0.914	0.317	66%	89%	0.64	53%	90%	0.696	63%	83%	0.386
B2020 EXTERIOR WINDOWS		10,191	0.991	0.325	68%	88%	0.675	51%	87%	0.699	61%	86%	0.543
B2020102 - Wood Windows		2,134	0.997	0.004	62%	87%	0.701	41%	79%	0.682	61%	82%	0.523
B2020104 - Steel Windows		587	0.934	0.356	80%	93%	0.766	65%	87%	0.701	70%	91%	0.701
B2020106 - Aluminum Windows		1,424	0.996	0.863	74%	90%	0.543	72%	93%	0.547	59%	89%	0.41
B2030 EXTERIOR DOORS		14,496	0.986	0.203	72%	92%	0.744	64%	88%	0.728	65%	90%	0.671
B2030110 - Glazed Doors		697	0.993	0.902	74%	91%	0.698	71%	92%	0.751	61%	89%	0.576
B2030210 - Wood Doors		546	0.978	0	77%	90%	0.67	51%	82%	0.646	69%	92%	0.655
B2030220 - Steel Doors		3,639	0.969	0.996	71%	92%	0.732	64%	89%	0.725	66%	90%	0.667
B2030220 - Steel Doors	Marine	241	0.936	0.993	68%	92%	0.742	69%	91%	0.649	72%	90%	0.692

			Markov Prediction								Deterministic Comparison		
			Categorical Analysis % Error		Pairwise Condition State			Pairwise Condition Index			Pairwise Condition State		
Component	Climate Region	#Points	p-value	p-value	Perfect	+-1 Range	R2	Perfect	1 Range	R2	Perfect	1 Range	R2
B2030220 - Steel Doors	Mixed-Humid	1,084	0.932	0.982	78%	92%	0.764	74%	87%	0.754	71%	92%	0.766
B2030220 - Steel Doors	Hot-Dry	637	0.985	0.993	69%	94%	0.78	65%	92%	0.796	65%	93%	0.737
B2030220 - Steel Doors	Hot-Humid	660	0.975	0.988	62%	90%	0.686	57%	89%	0.669	65%	85%	0.462
B2030220 - Steel Doors	Cold	301	0.977	0.998	69%	91%	0.72	48%	78%	0.628	68%	90%	0.68
B2030230 - Aluminum Doors		326	0.994	0.984	79%	92%	0.546	77%	94%	0.631	53%	92%	0.436
B2030410 - Overhead Doors		1,490	0.847	0.906	72%	91%	0.769	65%	87%	0.759	69%	91%	0.701
B3010 ROOF COVERINGS		10,603	0.972	0.909	71%	89%	0.693	47%	84%	0.663	58%	88%	0.602
B3010105 - Built-Up		2,615	0.932	0.422	71%	91%	0.711	45%	80%	0.664	61%	90%	0.631
B3010105 - Built-Up	Marine	255	0.844	0.985	74%	89%	0.642	30%	73%	0.591	71%	90%	0.519
B3010105 - Built-Up	Mixed-Humid	749	0.985	0.91	86%	94%	0.842	61%	77%	0.741	68%	95%	0.844
B3010105 - Built-Up	Hot-Dry	591	0.763	0.212	62%	91%	0.615	45%	79%	0.574	57%	92%	0.639
B3010105 - Built-Up	Hot-Humid	603	0.995	0.484	73%	91%	0.773	44%	80%	0.706	63%	87%	0.584
B3010105 - Built-Up	Cold	150	0.945	0.801	67%	87%	0.696	45%	72%	0.685	62%	87%	0.526
B3010120 - Single Ply Membrane		872	0.947	0.835	77%	90%	0.73	55%	83%	0.733	45%	86%	0.666
B3010120 - Single Ply Membrane	Marine	65	0.592	0.918	75%	91%	0.865	38%	78%	0.595	54%	91%	0.762
B3010120 - Single Ply Membrane	Mixed-Humid	378	0.533	0.997	85%	94%	0.846	62%	84%	0.816	52%	91%	0.77
B3010120 - Single Ply Membrane	Hot-Dry	87	0.259	0.397	64%	91%	0.738	64%	89%	0.734	40%	87%	0.635
B3010120 - Single Ply Membrane	Hot-Humid	109	0.443	0.899	64%	85%	0.689	37%	80%	0.576	57%	85%	0.614
B3010120 - Single Ply Membrane	Cold	307	0.763	0.99	61%	89%	0.769	34%	69%	0.676	45%	84%	0.706
B3010130 - Preformed Metal		3,255	0.959	0.974	71%	89%	0.683	58%	87%	0.664	59%	88%	0.587
B3010135 - Formed Metal		542	0.882	0.917	79%	89%	0.583	66%	89%	0.551	62%	93%	0.648
B3010140 - Shingle & Tile		1,241	0.898	0.797	70%	87%	0.624	46%	84%	0.569	61%	85%	0.48
B3020 ROOF OPENINGS		1,239	0.981	0.999	73%	91%	0.648	63%	93%	0.63	62%	88%	0.473
C1010 PARTITIONS		9,435	0.979	0.008	79%	93%	0.782	76%	91%	0.825	72%	91%	0.697
C1020 INTERIOR DOORS		9,171	0.921	0.000	75%	91%	0.761	65%	90%	0.779	62%	90%	0.673
C1030 SPECIALTIES		1,981	0.998	0.584	75%	93%	0.8	63%	86%	0.791	52%	91%	0.747
C2010 STAIR CONSTRUCTION		2,015	0.999	0.954	78%	92%	0.666	76%	93%	0.681	66%	92%	0.622
C3010 WALL FINISHES		7,051	0.996	0.627	71%	91%	0.737	61%	88%	0.76	61%	91%	0.67
C3020 FLOOR FINISHES		12,700	0.987	0.998	76%	91%	0.753	58%	85%	0.774	51%	85%	0.603

			Markov Prediction								Deterministic Comparison		
			Categorical Analysis % Error		Pairwise Condition State			Pairwise Condition Index			Pairwise Condition State		
Component	Climate Region	#Points	p-value	p-value	Perfect	+-1 Range	R2	Perfect	1 Range	R2	Perfect	1 Range	R2
C3030 CEILING FINISHES		7,897	0.999	0.001	79%	93%	0.802	65%	86%	0.788	56%	91%	#N/A
D1010 ELEVATORS AND LIFTS		357	0.999	0.59	69%	87%	0.669	56%	87%	0.681	56%	82%	0.544
D2010 PLUMBING FIXTURES		14,317	0.917	0.001	69%	91%	0.71	66%	90%	0.755	56%	88%	0.619
D2010110 - Toilet		2,266	0.997	0.997	67%	91%	0.698	62%	90%	0.754	55%	87%	0.59
D2010210 - Urinal		1,259	0.866	0.831	67%	91%	0.69	64%	88%	0.743	56%	88%	0.604
D2010310 - Lavatory		1,095	0.998	0.987	74%	91%	0.672	66%	93%	0.726	59%	93%	0.655
D2010410 - Sink		1,174	0.981	0.875	75%	92%	0.69	73%	93%	0.686	61%	91%	0.627
D2020 DOMESTIC WATER DIST		13,691	0.999	0.98	69%	90%	0.725	63%	88%	0.786	59%	85%	0.588
D2020240 - Water Heaters, Elect		597	0.57	0.582	67%	90%	0.778	53%	85%	0.814	50%	84%	0.618
D2020903 - Backflow Preventer		643	0.991	0.95	73%	90%	0.791	63%	84%	0.8	40%	81%	0.585
D2020905 - Piping/Fittings		5,053	0.999	0.996	68%	90%	0.703	64%	88%	0.781	65%	86%	0.575
D2030 SANITARY WASTE		6,766	0.999	0.709	78%	94%	0.838	70%	87%	0.859	78%	93%	0.809
D2090 OTHER PLUMBING SYS		324	0.999	0.982	79%	94%	0.716	83%	97%	0.783	53%	96%	0.621
D3020 HEAT GENERATING SYS		987	0.999	0.998	72%	87%	0.638	57%	85%	0.716	52%	84%	0.418
D3030 COOLING GEN SYS		2,813	0.999	0.989	69%	87%	0.75	44%	87%	0.74	44%	80%	#N/A
D3040 DISTRIBUTION SYSTEMS		7,078	0.99	0.707	69%	89%	0.737	44%	83%	0.716	53%	85%	0.549
D3040110 - Air Handling Unit		1,551	0.982	0.768	66%	88%	0.727	41%	84%	0.706	51%	83%	0.534
D3040330 - Circulating Pump		1,220	0.997	0.99	73%	91%	0.795	60%	84%	0.82	55%	86%	0.675
D3050 TERMINAL & PACKAGE UN		7,118	0.999	0.83	72%	90%	0.754	63%	87%	0.784	47%	85%	0.63
D3060 CONTROLS & INSTR		1,126	0.994	0.741	64%	83%	0.645	40%	90%	0.653	51%	80%	0.285
D3090 OTHER HVAC EQIP		480	0.999	0.474	68%	90%	0.723	65%	90%	0.813	44%	84%	0.531
D4030 STANDPIPE SYSTEMS		1,821	0.999	0.976	69%	85%	0.549	53%	89%	0.571	63%	84%	0.24
D4040 SPRINKLERS		2,779	0.999	0.981	72%	89%	0.656	62%	90%	0.688	68%	88%	0.612
D4090 OTHER FIRE PROTECTION		1,062	0.957	0	71%	89%	0.667	58%	89%	0.715	65%	88%	0.629
D5010 ELECTRICAL SERVICE		14,672	0.758	0.676	73%	91%	0.782	68%	89%	0.803	63%	87%	0.667
D5020 LIGHTING & BRANCH WIR		12,969	0.951	0.976	76%	92%	0.777	69%	89%	0.805	52%	90%	0.68
D5030 COMM & SECURITY		1,997	0.999	0.976	75%	90%	0.627	72%	91%	0.614	63%	87%	0.671
D5090 OTHER ELECTRICAL SVCS		4,053	0.98	0.472	70%	90%	0.726	70%	92%	0.717	52%	84%	0.542

APPENDIX K – BUILDING AMERICA CLIMATE ZONE MAP

From: (U.S. Department of Energy, 2014)

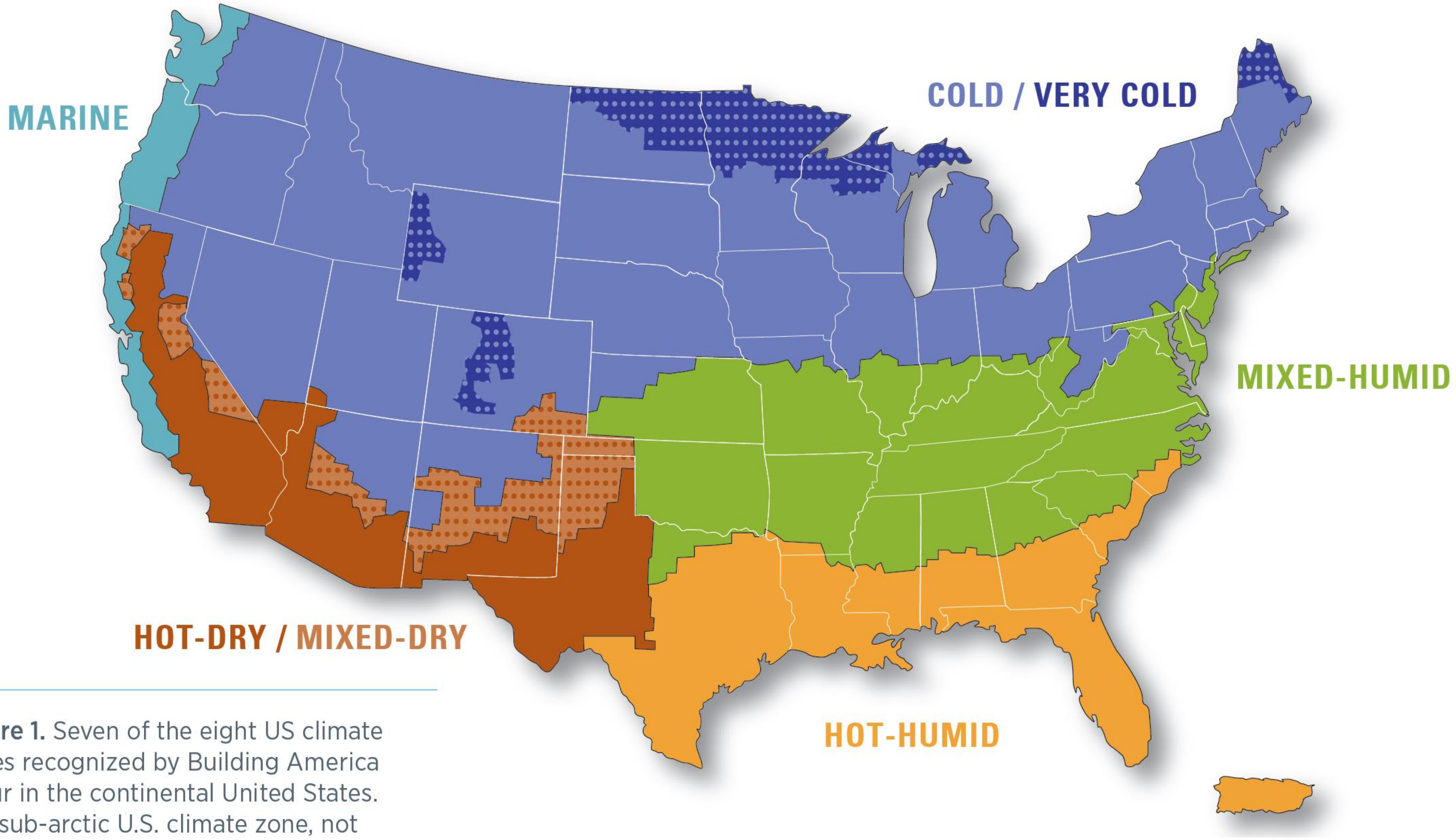


Figure 1. Seven of the eight US climate zones recognized by Building America occur in the continental United States. The sub-arctic U.S. climate zone, not shown on the map, appears only in Alaska.

APPENDIX L – BUILDER COMPONENT CRITICALITY INDEX FACTORS

From: (U.S. Army Construction Engineering Research Laboratory, 2015)

	Criticality Values									
Component	**Admin.**	**Comm**	**Housing**	**Medical**	**Production**	**Training**	**R&D**	**Storage**	**Lodging**	**Average**
B10 Superstructure	0.84	0.83	0.76	0.87	0.73	0.83	0.80	0.77	0.76	0.80
A10 Foundation	0.68	0.71	0.64	0.67	0.64	0.72	0.70	0.80	0.64	0.69
B1010 Floor System	0.89	0.89	0.76	0.90	0.72	0.82	0.82	0.78	0.76	0.82
B1020 Roof System	0.79	0.77	0.76	0.84	0.74	0.84	0.78	0.76	0.76	0.78
B20 Exterior Envelope	0.30	0.28	0.30	0.42	0.26	0.32	0.32	0.21	0.31	0.30
Awning/Canopy	0.21	0.24	0.12	0.78	0.12	0.11	0.22	0.14	0.20	0.24
Chimney	0.22	0.33	0.43	0.31	0.50	0.47	0.39	0.32	0.39	0.37
Exterior Ceiling	0.38	0.35	0.29	0.38	0.18	0.18	0.38	0.11	0.20	0.27
Exterior Cornice	0.01	0.07	0.01	0.04	0.07	0.07	0.05	0.01	0.01	0.04
Exterior Door	0.66	0.58	0.70	0.73	0.61	0.70	0.65	0.71	0.70	0.67
Exterior Wall	0.82	0.74	0.91	0.99	0.76	0.92	0.95	0.64	0.93	0.85
Exterior Wall Finish/Covering	0.19	0.16	0.13	0.32	0.11	0.10	0.19	0.11	0.12	0.16
Exterior Wall Insulation	0.38	0.26	0.29	0.70	0.29	0.29	0.33	0.23	0.51	0.36
Exterior Window	0.51	0.33	0.57	0.64	0.37	0.75	0.45	0.20	0.57	0.49
Exterior Window Covering	0.17	0.17	0.12	0.26	0.07	0.14	0.17	0.07	0.12	0.14
Soffit/Fascia	0.09	0.13	0.05	0.10	0.05	0.08	0.05	0.02	0.05	0.07
Spire	0.07	0.10	0.10	0.08	0.12	0.08	0.08	0.12	0.10	0.09
Window Well	0.19	0.13	0.16	0.19	0.17	0.24	0.19	0.09	0.16	0.17
B30 Roofing	0.32	0.25	0.32	0.52	0.26	0.32	0.36	0.24	0.33	0.33
Flashing	0.27	0.19	0.25	0.36	0.38	0.42	0.36	0.38	0.25	0.32
Roof Drainage	0.33	0.22	0.28	0.60	0.29	0.31	0.34	0.27	0.28	0.32
Roof Insulation	0.29	0.24	0.35	0.56	0.14	0.21	0.31	0.06	0.35	0.28
Roof Specialty	0.30	0.21	0.27	0.53	0.16	0.27	0.35	0.25	0.27	0.29
Roof Surface	0.42	0.40	0.48	0.53	0.32	0.41	0.47	0.25	0.48	0.42
C Interior Construction	0.29	0.27	0.21	0.47	0.19	0.21	0.31	0.23	0.21	0.27
Cabinet/Countertop/Shelf/Etc	0.20	0.13	0.10	0.43	0.16	0.10	0.27	0.28	0.12	0.20
Fireplace	0.08	0.08	0.11	0.08	0.08	0.08	0.07	0.04	0.09	0.08
Interior Ceiling	0.37	0.36	0.36	0.55	0.15	0.24	0.43	0.10	0.36	0.32
Interior Ceiling Finish/Cover	0.23	0.18	0.09	0.44	0.11	0.11	0.33	0.11	0.09	0.19

	Criticality Values									
Component	**Admin.**	**Comm**	**Housing**	**Medical**	**Production**	**Training**	**R&D**	**Storage**	**Lodging**	**Average**
Interior Cornice	0.09	0.02	0.01	0.04	0.07	0.04	0.02	0.01	0.01	0.04
Interior Door	0.47	0.38	0.30	0.82	0.34	0.38	0.36	0.32	0.33	0.41
Interior Floor Finish/Covering	0.54	0.48	0.41	0.80	0.17	0.42	0.58	0.48	0.41	0.48
Interior Insulation	0.24	0.20	0.16	0.55	0.23	0.17	0.32	0.15	0.16	0.24
Interior Ladder	0.05	0.05	0.08	0.19	0.30	0.20	0.14	0.26	0.08	0.15
Interior Stair/Ramp	0.63	0.75	0.64	0.88	0.31	0.32	0.66	0.50	0.64	0.59
Interior Wall	0.43	0.52	0.50	0.76	0.35	0.47	0.50	0.43	0.55	0.50
Interior Wall Finish/Covering	0.24	0.19	0.11	0.43	0.12	0.09	0.10	0.10	0.11	0.16
Interior Window	0.26	0.34	0.09	0.38	0.24	0.20	0.28	0.27	0.09	0.24
Interior Window Covering	0.22	0.20	0.07	0.25	0.11	0.07	0.23	0.14	0.07	0.15
Partition/Screen	0.34	0.18	0.06	0.46	0.12	0.27	0.36	0.17	0.06	0.22
D10 Conveying	0.22	0.25	0.10	0.44	0.27	0.26	0.26	0.25	0.10	0.24
Accessibility Lifts	0.38	0.44	0.55	0.81	0.29	0.28	0.32	0.21	0.55	0.43
Chute/Conveyor/Tube System	0.13	0.11	0.00	0.24	0.26	0.31	0.31	0.12	0.00	0.16
Dumbwaiter	0.11	0.15	0.09	0.31	0.16	0.08	0.14	0.10	0.09	0.14
Elevator	0.33	0.45	0.09	0.87	0.39	0.34	0.56	0.41	0.06	0.39
Escalator	0.30	0.26	0.00	0.31	0.24	0.22	0.13	0.25	0.00	0.19
Lifting Devices	0.12	0.19	0.00	0.16	0.40	0.29	0.25	0.40	0.00	0.20
Moving Walkway	0.15	0.17	0.00	0.39	0.17	0.33	0.12	0.24	0.00	0.18
D20 Plumbing	0.45	0.44	0.52	0.62	0.40	0.53	0.55	0.33	0.52	0.48
Other Plumbing Equipment	0.27	0.22	0.29	0.30	0.25	0.46	0.31	0.32	0.29	0.30
Piping	0.64	0.72	0.74	0.88	0.55	0.79	0.84	0.31	0.74	0.69
Plumbing Fixtures	0.50	0.48	0.54	0.80	0.52	0.56	0.65	0.27	0.55	0.54
Septic Tank	0.52	0.48	0.59	0.65	0.55	0.58	0.63	0.50	0.59	0.57
Sump	0.29	0.22	0.44	0.26	0.42	0.37	0.27	0.46	0.44	0.35
Water Softener/Water Heater/ Heat Exchanger/Etc	0.37	0.46	0.41	0.77	0.07	0.42	0.52	0.11	0.42	0.39
Well	0.53	0.46	0.64	0.70	0.45	0.50	0.63	0.34	0.64	0.54
D30 HVAC	0.44	0.45	0.39	0.67	0.44	0.50	0.50	0.31	0.39	0.46
Air Handling/Ductwork	0.41	0.52	0.37	0.85	0.50	0.46	0.58	0.32	0.37	0.49
Control System	0.47	0.54	0.48	0.89	0.44	0.53	0.57	0.29	0.45	0.52
Cooling and Heating Unit	0.58	0.47	0.53	0.82	0.58	0.66	0.68	0.40	0.53	0.58

	Criticality Values									
Component	**Admin.**	**Comm**	**Housing**	**Medical**	**Production**	**Training**	**R&D**	**Storage**	**Lodging**	**Average**
Cooling Unit/Plant	0.59	0.59	0.45	0.87	0.44	0.70	0.68	0.38	0.48	0.58
Dehumidifier/Desiccator	0.45	0.43	0.35	0.43	0.19	0.33	0.48	0.21	0.35	0.36
Fuel Storage	0.41	0.39	0.60	0.59	0.64	0.67	0.50	0.53	0.60	0.55
Heating Unit/Plant	0.68	0.59	0.66	0.87	0.54	0.67	0.74	0.35	0.63	0.64
Humidity Equipment	0.42	0.42	0.42	0.75	0.42	0.42	0.42	0.42	0.42	0.46
Other HVAC Equipment	0.22	0.45	0.00	0.45	0.58	0.50	0.33	0.39	0.00	0.32
Pump/Compressor/Piping	0.52	0.54	0.56	0.78	0.49	0.59	0.58	0.20	0.51	0.53
Solar Water Heating Unit	0.07	0.19	0.25	0.20	0.22	0.21	0.28	0.17	0.25	0.20
Thermal Storage Unit	0.39	0.17	0.00	0.38	0.27	0.17	0.21	0.19	0.00	0.20
Ventilation/Exhaust Equipment	0.55	0.56	0.44	0.82	0.44	0.57	0.51	0.20	0.46	0.51
D40 Fire Suppression	0.31	0.25	0.31	0.31	0.38	0.49	0.27	0.20	0.30	0.31
Backflow Preventor	0.22	0.13	0.26	0.26	0.39	0.51	0.12	0.16	0.26	0.26
Fire Extinguishing	0.31	0.32	0.31	0.31	0.30	0.52	0.25	0.16	0.31	0.31
Fire Suppression	0.44	0.47	0.49	0.47	0.55	0.66	0.47	0.48	0.43	0.50
Fire/Smoke Alarm	0.30	0.20	0.31	0.31	0.43	0.49	0.25	0.16	0.31	0.31
Jockey Pump	0.30	0.10	0.23	0.23	0.34	0.34	0.27	0.16	0.23	0.24
Piping (Fire Suppression)	0.31	0.23	0.31	0.31	0.37	0.56	0.27	0.11	0.31	0.31
Pump (Fire Suppression)	0.31	0.23	0.32	0.32	0.44	0.56	0.27	0.11	0.32	0.32
Water Treatment (Fire Supp)	0.27	0.27	0.27	0.27	0.26	0.28	0.25	0.27	0.27	0.27
D50 Electrical	0.48	0.48	0.34	0.71	0.56	0.57	0.53	0.48	0.34	0.50
Distribution	0.72	0.68	0.71	0.89	0.84	0.80	0.74	0.74	0.71	0.76
Electrical Service Distribution	0.72	0.68	0.71	0.89	0.84	0.80	0.74	0.74	0.71	0.76
Generator Set	0.29	0.40	0.43	0.76	0.53	0.46	0.49	0.12	0.43	0.43
Grounding	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
Intercom	0.22	0.16	0.08	0.74	0.23	0.16	0.23	0.16	0.12	0.23
Intruder Detection/Security	0.43	0.39	0.38	0.48	0.46	0.52	0.46	0.40	0.44	0.44
Lightning Protection	0.30	0.22	0.15	0.31	0.36	0.27	0.26	0.28	0.15	0.26
Lightning System	0.42	0.69	0.48	0.88	0.68	0.60	0.57	0.48	0.44	0.58
Panels	0.72	0.67	0.71	0.75	0.75	0.87	0.75	0.85	0.71	0.75
Transfer Switch	0.36	0.39	0.00	0.73	0.50	0.73	0.42	0.63	0.00	0.42
Transformers	0.67	0.68	0.00	0.65	0.64	0.64	0.64	0.64	0.00	0.51
Uninterruptible Power Supply	0.53	0.34	0.00	1.00	0.46	0.58	0.62	0.38	0.00	0.43

	Criticality Values									
Component	**Admin.**	**Comm**	**Housing**	**Medical**	**Production**	**Training**	**R&D**	**Storage**	**Lodging**	**Average**
Site	0.23	0.27	0.10	0.40	0.27	0.24	0.26	0.32	0.10	0.24
Balcony	0.09	0.06	0.08	0.07	0.09	0.09	0.03	0.06	0.08	0.07
Chute	0.08	0.03	0.00	0.11	0.21	0.11	0.04	0.20	0.00	0.09
Exterior Decking/Paved Area	0.30	0.39	0.06	0.69	0.22	0.22	0.33	0.42	0.06	0.30
Exterior Ladder	0.15	0.12	0.00	0.18	0.20	0.16	0.15	0.17	0.00	0.13
Exterior Stair/Ramp	0.54	0.75	0.54	0.99	0.60	0.60	0.60	0.61	0.55	0.64
Loading Area	0.23	0.31	0.00	0.51	0.39	0.29	0.43	0.56	0.00	0.30
Walkway	0.22	0.22	0.00	0.22	0.22	0.22	0.22	0.22	0.00	0.17
G Site	0.27	0.40	0.24	0.31	0.25	0.27	0.29	0.24	0.23	0.28
Fencing/Privacy Wall	0.17	0.17	0.17	0.24	0.17	0.22	0.26	0.17	0.17	0.19
Gate	0.36	0.38	0.35	0.53	0.60	0.48	0.60	0.61	0.35	0.47
Grounds	0.17	0.56	0.10	0.25	0.17	0.37	0.18	0.13	0.10	0.23
Play Area	0.17	0.57	0.10	0.00	0.12	0.13	0.09	0.06	0.10	0.15
Playground Equipment	0.09	0.43	0.08	0.00	0.07	0.12	0.00	0.00	0.08	0.10
Retaining Wall	0.36	0.33	0.36	0.33	0.25	0.25	0.28	0.26	0.36	0.31
Seating	0.11	0.25	0.00	0.00	0.13	0.10	0.15	0.12	0.00	0.10
Sidewalk/Pavement/Equip pad	0.25	0.28	0.25	0.28	0.16	0.22	0.24	0.24	0.25	0.24
Site Lighting	0.64	0.77	0.77	0.80	0.71	0.71	0.64	0.48	0.65	0.69
Site Signage	0.42	0.26	0.26	0.73	0.13	0.13	0.43	0.34	0.26	0.33
System Average	0.22	0.30	0.09	0.39	0.30	0.29	0.30	0.28	0.10	0.25
Bowling Lane	0.02	0.08	0.08	0.00	0.05	0.00	0.00	0.00	0.00	0.03
Bumper/Bollard	0.26	0.21	0.00	0.35	0.21	0.37	0.25	0.50	0.19	0.26
Coiling Grille	0.25	0.30	0.00	0.33	0.45	0.15	0.33	0.48	0.00	0.25
Cold Storage Room	0.14	0.57	0.00	0.76	0.42	0.53	0.55	0.56	0.00	0.39
Compressed Air System	0.35	0.21	0.00	0.35	0.43	0.48	0.33	0.22	0.00	0.26
Compressed Gas	0.20	0.22	0.00	0.26	0.42	0.38	0.18	0.18	0.00	0.20
Counter Door/Grille	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.03
Counter Doors (Coiling)	0.25	0.27	0.00	0.25	0.28	0.12	0.28	0.28	0.00	0.19
Dome	0.51	0.37	0.00	0.57	0.55	0.73	0.57	0.72	0.00	0.45
Ductwork (Specialty)	0.32	0.32	0.00	0.53	0.49	0.51	0.47	0.53	0.00	0.35
Exhaust (Specialty)	0.21	0.30	0.00	0.51	0.51	0.51	0.43	0.49	0.00	0.33
Gas Cabinet	0.17	0.17	0.00	0.65	0.30	0.29	0.29	0.34	0.00	0.25

	Criticality Values									
Component	**Admin.**	**Comm**	**Housing**	**Medical**	**Production**	**Training**	**R&D**	**Storage**	**Lodging**	**Average**
Gas Distribution	0.20	0.39	0.00	0.82	0.50	0.40	0.49	0.32	0.00	0.35
Gas System	0.20	0.39	0.00	0.82	0.50	0.48	0.49	0.32	0.00	0.36
Grounding Points	0.37	0.37	0.00	0.51	0.51	0.51	0.37	0.45	0.00	0.34
Indoor Tennis Court	0.04	0.10	0.00	0.04	0.04	0.00	0.00	0.00	0.00	0.02
Indoor Track	0.02	0.04	0.00	0.04	0.04	0.00	0.00	0.00	0.00	0.02
Jacuzzi/Hot Tub	0.02	0.23	0.07	0.26	0.05	0.00	0.00	0.00	0.07	0.08
Lockers/Mail Boxes	0.23	0.29	0.13	0.33	0.21	0.13	0.28	0.21	0.18	0.22
Piping (Specialty)	0.34	0.34	0.34	0.49	0.49	0.49	0.36	0.24	0.34	0.38
Pools	0.16	0.35	0.23	0.35	0.04	0.35	0.38	0.00	0.23	0.23
Prison Cell	0.09	0.62	0.00	0.35	0.21	0.00	0.00	0.46	0.00	0.19
Recreational Components	0.23	0.39	0.07	0.30	0.23	0.23	0.23	0.23	0.24	0.24
Refrigerated Food Case	0.36	0.36	0.00	0.44	0.25	0.41	0.46	0.29	0.00	0.29
Safe (Built-In)	0.35	0.35	0.08	0.39	0.27	0.21	0.43	0.27	0.08	0.27
Sauna	0.00	0.07	0.00	0.07	0.07	0.00	0.00	0.00	0.00	0.02
Seating	0.26	0.56	0.00	0.54	0.30	0.23	0.39	0.16	0.00	0.27
Skating Rinks	0.00	0.03	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.01
Space Frame	0.50	0.44	0.55	0.55	0.49	0.55	0.55	0.55	0.55	0.53
Special Doors	0.37	0.55	0.44	0.50	0.34	0.30	0.49	0.49	0.44	0.43
Spire	0.22	0.30	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.23
Vacuum System	0.15	0.25	0.29	0.32	0.47	0.34	0.35	0.34	0.29	0.31
Vehicle Inspection Pit	0.02	0.32	0.00	0.32	0.33	0.30	0.42	0.49	0.00	0.25
Visual Display Board	0.21	0.15	0.00	0.21	0.22	0.27	0.21	0.21	0.00	0.16
Water Treatment	0.55	0.61	0.74	0.78	0.50	0.56	0.71	0.38	0.73	0.62