Building Envelope Life Cycle Condition Evaluation Using a Distress-Based Methodology

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BACKGROUND

Building assets represent a significant portion of the infrastructure capital held by federal, state, and local agencies, as well as private organizations. For the U.S. military installations, buildings and other infrastructure provide services that enable a mission or processes to be performed. As the building operates in service and ages, building materials, components, and systems deteriorate, leading to some less than optimal performance to support mission. This is especially the case for a building's exterior envelope system. To address this issue, the U.S. Army Corps of Engineers Construction Engineering Research Laboratory has developed a sustainability-focused approach for the improved management of existing building assets for military facilities. Known as an Engineered Management System (EMS), this methodology provides military installations with a decision support tool for sustainment and restoration / modernization (S&RM) decisions. The EMS process supports integrated facility management including inspection, maintenance & repair, record keeping, and reporting. It allows facility managers to measure condition changes and identify timely corrective actions, lower life cycle cost, and focus attention and resources on mission critical assets that provide the best value for short term tactical and long term strategic operations.

Key to the EMS concept is the structured techniques, policies, and processes necessary for effective maintenance management. Included in this concept is the fundamental need for facility or component condition assessment information that supports the infrastructure investment decision making process. While EMSs are expert systems, they do not provide a definitive "answer". Instead, an EMS is a scientifically-based method that provides timely and accurate information to enable sound decisions in support of facility operations.

As time in service passes for a building and its exterior envelope system, quality or condition decreases due to friction, wear, ultraviolet (UV) radiation exposure, fatigue, freeze-thaw cycles, and many other degradation mechanisms. Many times, these "distress" mechanisms interact and compound, accelerating condition deterioration over time. Eventually, this condition deterioration directly affects the performance of the envelope system and other day-to-day facility operations. If performance drops below some acceptable threshold level, recapitalization, restoration, or repair becomes necessary. The cost of these actions increase substantially as condition further degrades, and if not performed, premature failure may result in unrealized asset service life. Thus, a real penalty cost in terms of dollars exists for deferring work on the building envelope past a certain condition.

If the life cycle deterioration of the exterior envelope or its constitutive components could be accurately predicted, facility managers could easily determine the condition of their assets at any point in time and then make the prudent decisions regarding when to do work. However, it is

inconceivable to think that a single deterioration model exists to adequately express the life cycle condition for each building component, 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 maintenance and repair (M&R) actions over the life cycle of the exterior envelope, in addition to a number of other sometimes unpredictable events, the current and future condition states can be altered unexpectedly at any time. The result is that a deterioration model can rarely be applied to a given asset with sufficient confidence at the start of its life cycle. The EMS process strives to establish the accuracy and confidence of any life cycle deterioration curve through a standardized condition assessment methodology - the Condition Index approach and the resulting Condition Index (CI) metric.

As the foundation to any management processes, metrics must be objective, repeatable, and most importantly, affordable within the business operating environment. The Condition Index process was designed to model the summary experience of the diverse yet knowledgeable engineering community in measuring an asset's condition or physical health.

EXTERIOR ENVELOPE IDENTIFICATION

Each building component works interdependently with other components to support the functions of an efficiently operating building. Each component ages and deteriorates over time, adversely affecting its performance and reliability. If left in service for long enough, its condition reaches some limit or failure state at which the exterior envelope components can no longer serve its intended function sufficiently [Moubry, 2002]. It may also adversely affect the function or condition of other components. Due to the nature of their function, certain building components, such as structural columns, have a service life designed to correspond to the life of the facility. Other components, such as a roof surface, can have a projected lifespan much shorter than the life of the facility. Periodic repair or replacement of the various components is needed to restore condition and performance capabilities, as well as that of the building as a whole. Depending on the criticality of the component and the consequence of a failure, this corrective action may best be performed at or before reaching the failure state.

Predicting this failure state for a unique component in a building is difficult, because the true lifespan of a component is rarely known, when new. While a designer or manufacturer can provide a generalized idea of design life for a component, actual service life depends greatly on local environmental factors, use and abuse, and levels of routine maintenance accomplished. In addition, for many components, simply defining what constitutes a failure state can sometimes be ambiguous. For instance, does a window component fail when the vapor barrier is breached, it is no longer operable, a window pane breaks, or some other criteria? This failure state could have a different meaning for different components and to different people. Instead, defining a quantitative failure state based on an objective condition index metric [Uzarski and Burley, 1997] provides a more consistent definition of component failure.

The failure state is rarely the most efficient point when corrective action should be performed. For many components, repair early in the life cycle can extend life and avert expensive damage caused by accelerated degradation later. The point at which minor corrective action is most efficient is termed the "sweet spot." Performing repairs at the sweet spot can result in penalty cost savings from major repair or replacement due to costly critical failure consequences later in the life cycle.

To determine the necessary major repairs and component replacements for a building's envelope, and to justify the timing of that work to optimize the savings per repair dollar invested, a model composed of exterior envelope components is first defined for each building structure. This classification is based on the ASTM Uniformat II hierarchy [ASTM International, 2002] and includes the following components:

- Wall Structure and Insulation
- Wall Finish/Façade
- Windows, Doors
- Fascia, Soffit, Awning, Canopy, etc.
- Envelope ventilation components

Each component in the building model also has assigned attributes based on its material, type, age, and location. For example, a window component may be made of metal, vinyl, or wood. 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 the basic unit for building life cycle asset management and condition tracking.

CONDITION ASSESSMENT

The concept of condition is not easily quantifiable the way explicit physical properties such as force, mass, and velocity are measured. In order to measure condition, a scale is defined that correlates to varying degrees of qualitative condition descriptors, as shown in Table 1. The science and considerable research in the CI approach is in creating the 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. Each distress has a specific definition and visual cues that must exist. In addition, each distress has one of more levels of severity, which indicates how it affects a building system's operational, mission, and life safety capabilities. For example, as the primary barrier between exterior and interior environments, the exterior building components that make up this system are susceptible to several modes of deterioration including:

- Water/Moisture Damage
- Material Cracking/Spalling
- Deteriorated Mortar
- Settlement/Expansion/Contraction
- Efflorescence/Staining
- Disintegration/Erosion/Chipping
- Corrosion/Abrasion/Indentations/Punctures
- Warping/Swelling/Rotting/Insect Infestation
- Mold/Fungus Growth
- Deteriorated Sealants/flashings
- Failed Moisture/Vapor/Thermal barriers

Condition Index	Definition
100-85 Good	Slight serviceability/reliability reduction overall to component.
85-70 Satisfactory	Component serviceability/reliability is degraded but adequate.
70-55 Fair	Component serviceability or reliability is noticeably degraded
55-40 Poor	Component has significant serviceability or reliability loss.
40-25 Very Poor	Unsatisfactory serviceability or reliability reduction
25-10 Serious	Extreme serviceability or reliability reduction
10-0 Failed	Overall degradation is total.

TABLE 1 – CONDITION INDEX DESCRIPTION

During an EMS condition assessment process, a trained building technician records the presence of all observable distresses present for the exterior envelope. 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.

In order for this process to work, an extensive collection of deduct values must exist for each distress. A panel of subject matter experts was assembled from facility managers, engineers, inspectors, maintainers, and technicians to develop the deduct sets. During extensive surveys, each panel expert was presented with combinations of a distress, severity, and affected density, then asked to provide a rating between 0 and 100 based on the condition descriptors associated with the CI scale. Plotting the survey results of deduct values versus density, a graph was obtained for each distress severity. These graphs are the deduct curves that form the foundation for the EMS Condition Index models.

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%. 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.

CONDITION PREDICTION

The Condition Index metric is a reliable gauge of an asset's localized condition at the time of the assessment. It can be used to compare expected conditions based on an assumed service life to actual measured conditions. The service life of a building envelope component reflects the average expected time that a component will perform as required in service before a replacement is needed. Initially, each building component has an expected condition deterioration trend, which relates the projected condition index metric of the component as a function of its time in service.

Although a building component cannot last forever, its service life can be extended with proper operation, maintenance, and even repair. Likewise, a component's service life can be significantly decreased by environmental factors, abusive operations, or lack of maintenance. Because of these factors, a wide service life range can exist for a given component and there is a limit to the certainty that its service life can be known at the time of construction or installation.

The design service life is the time in service at which the component has the greatest probability of failing, but in actuality the true service will be unique for each. Depending on the service life variance within a unique component type, there is probability that the actual life could be more or less than the design service life. Design service lives for a wide range of building components are published from different sources based on industry estimates. Unfortunately little data exist to describe the variances associated with each service life.

As a result of this uncertainty, the periodic inspections are performed to measure the actual in service condition index of the component based on the distresses that are observed. This condition assessment process results in a measured condition index which is used to calibrate the condition deterioration trend based on inspection observations [Grussing, 2006]. As the component progresses farther into its life cycle and more inspections are performed, these historical inspections form the shape of the observed and projected life cycle curve. Actual historical condition degradations trends are then used to accurately model the behavior of the component condition and reliability profile. The initial industry average estimate of expected service life is re-adjusted based on information about how the component is actually degrading.

As more data are added, the better the model becomes tailored to a unique building envelope component. In addition to predicting the future condition of a component, this model provides the basis for calculating the extended service life that results when a corrective work action is performed by corrective repair or total replacement of the component.

IDENTIFYING CANDIDATE WORK REQUIREMENTS

The Condition Index describes the absolute condition of a building component on 0-100 scale (Table 1). It also establishes a means to compare all building component conditions on a relative scale. A condition standard specifies a threshold CI value for a component or a group of components (such as the exterior envelope system) to establish a target condition below which corrective action becomes an option. Because not all components in a building are required to be maintained at the same standard level, multiple condition standards may exist. A policy based on organizational goals and accepted risks will then identify which components should be maintained at a high condition and which can be maintained at lower condition levels. These standards can be selectively applied based upon several attributes of the components, such as the type of building or building system the component resides in, and the effect of component failure on mission. Since the exterior envelope system is deemed a critical system, it was given a relatively high condition threshold standard correlating to a Condition Index of 80. When a building envelope component deteriorates to this level, it becomes either a candidate for corrective repair or component replacement.

Corrective repair improves the condition of the exterior envelope component and is usually initiated sometime prior to failure. Corrective repair is different from a major overhaul or component replacement because it does not usually correct all component distresses. Some minor and inherent distresses will remain part of the component until it is completely replaced. Therefore, after a repair is completed, the model assumes the CI value is improved to 95 (out of 100), which relates to a full restoration of serviceability on the CI scale, but not necessarily a pristine condition. The model also assumes that the condition deterioration rate at a given condition index level are the same before and after a repair. Therefore, corrective repair essentially shifts the condition life cycle curve to the right, thus extending service life. Figure 1

shows the projected condition index plotted versus time for the typical building window component. The discontinuity at time, time = 20 years, represents a corrective repair event.

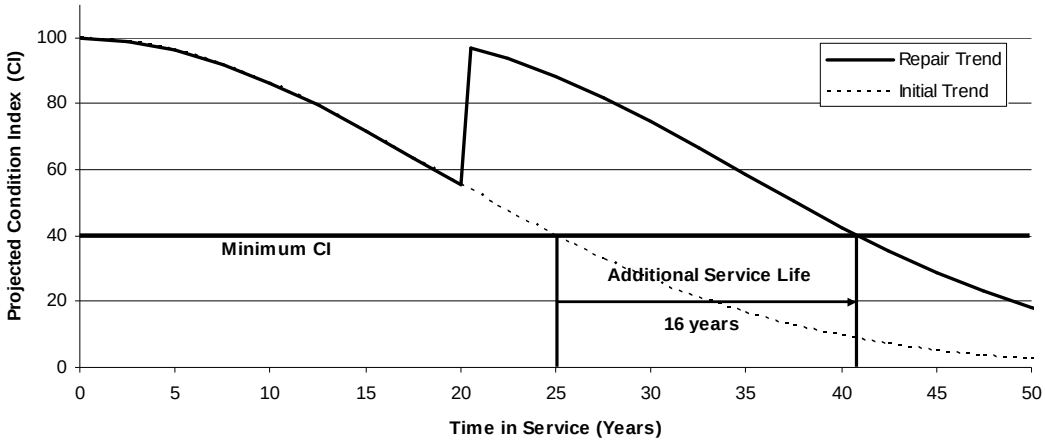

FIGURE 1 - COMPONENT CONDITION PREDICTION TREND FOR METAL WINDOW EXAMPLE

Based on the definition of the CI scale, functional component failure occurs when the CI falls to approximately 40, which establishes a performance threshold limit for the model. For the un-repaired component life cycle model, CI = 40 when the time in service equals the expected service life. For a component that has been repaired, the improved condition results in additional service life, as illustrated by Figure 1. Thus, the benefit of repair allows the deference of capital renewal required by component failure.

Eventually, however, a component will likely require complete replacement. In the condition life cycle model, complete component replacement essentially resets the component service life clock and the component CI is restored to its maximum (CI = 100).

PRIORITIZING WORK

Typically, the total estimated costs for all corrective work item candidates will exceed the authorized budget. Hence, a ranked work item list is necessary. This ranking should reflect the importance of both the building and component and the potential return on investment (ROI) for doing work at the specified time plus other variables. In so doing, an objective prioritization scheme must be based on the priorities of the organization and the risk associated with investment alternatives.

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 envelope component and repair criteria which can be related to importance measures. For example, one objective is accomplishing the most cost efficient work candidates. In this case, the main prioritization criterion is the calculated ROI metric. Another, sometimes competing objective, is repairing the most important component based on mission criticality. Here, the different measures associated with building use type, building criticality, and component criticality are prioritization criteria. By assigning relative weights to the different measures and objectives, a consistent and

repeatable importance score is calculated for each work item, which is then used to rank work items and establish the funding cut line based on the budget.

CONSEQUENCE ANALYSIS

A long term maintenance, repair, and capital renewal plan for an organization can involve a portfolio of hundreds of buildings all at varying condition states. This plan may seek to identify building envelope work requirements over a five to ten year horizon. With the numerous assets involved, optimizing a strategy that incorporates current user requirements, budget constraints, and future performance sustainment can be a difficult challenge. Using a structured business process framework, and component degradation analysis, different investment decision scenarios can be explored, and consequences can be evaluated over a long-term horizon.

One such automated consequence analysis tool is the IMPACT simulation model [IMPACT, 2008] used in conjunction with the BUILDER® Engineered Management System [BUILDER, 2008]. This model simulates the annual fiscal cycle of work planning/executing and displays building, system, and component conditions up to ten years into the future. Model inputs include the real property inventory, condition information and deterioration trends, current work projects, budget projections, and user defined standards, policies, 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 completed and deferred and 6) updates the component inventory database to reset the cycle for each year in the simulated budget plan.

A simulation was performed for the building envelope system for a subset of Army buildings. The result is a projected condition response of the portfolio of assets over the duration of the scenario horizon (Figure 2).

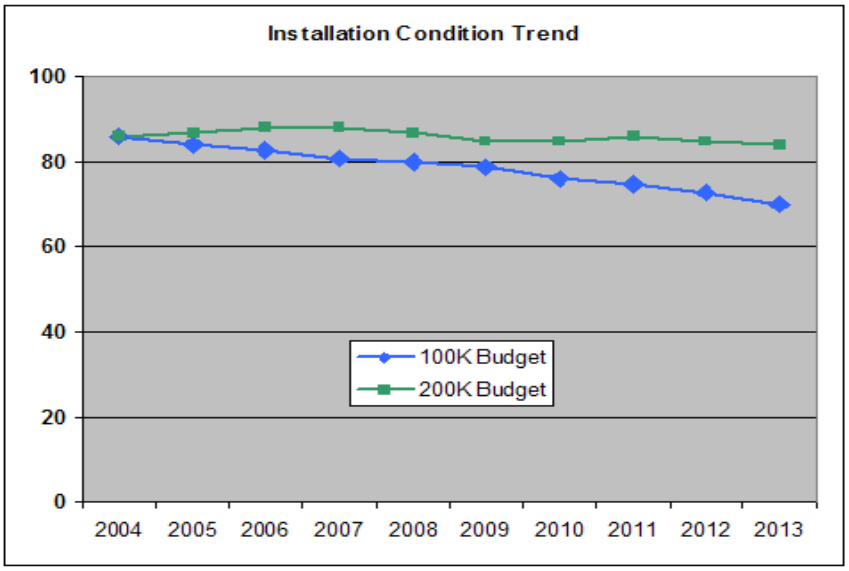

FIGURE 2 – IMPACT SCENARIO CONDITION TREND

In addition, the M&R backlog due to deferred work requirements is estimated for each year in the plan (Figure 3). In this example, raising the M&R investment in the building envelope for the subset of buildings from $100k annually to $200k annually had a profound effect on the condition and backlog over the planning horizon. This gives facility managers and decision makers the ability to see the effects of budget and policy on the condition of facility assets over time, and adjustments can be made accordingly to maximize performance and return on investment.

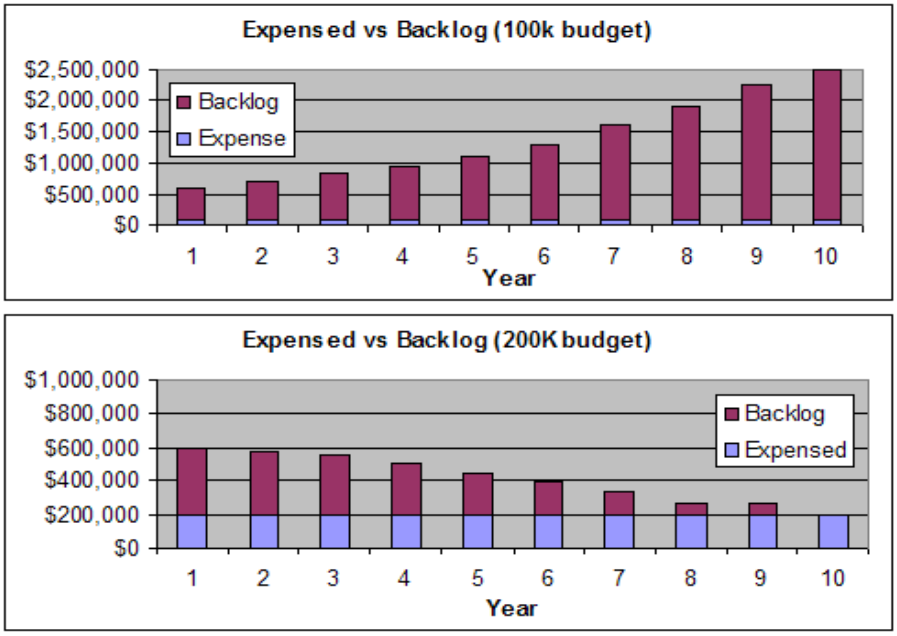

FIGURE 3 - M&R BACKLOG UNDER DIFFERENT FUNDING SCENARIOS

CONCLUSIONS

Fundamental to any successful facility infrastructure investment strategy are the objectives to 1) minimize life cycle ownership costs, 2) maximize facility performance, and 3) manage risk. Because of the critical nature of the building envelope, which serves as the primary barrier between interior and exterior environments, performance and risk are key factors when managing its condition and life cycle repairs. The process described herein provides the framework and decision support to help facility managers achieve these objectives. A distress-based condition assessment process is standardized, affordable, and results in a Condition Index metric that provides performance-based information about condition state, condition prediction trends, and remaining service life that are objective, consistent, and meaningful across a large set of buildings. The measurement and prediction of future facility component condition trends is essential to a reliability-centered building life cycle management program. Current models and industry estimates of component service lives rarely account for the local conditions of use, maintenance, and environmental factors, making the condition prediction for an individual asset less accurate. The CI establishes the foundation for risk-based condition standards, component reliability projections, and work planning and timing, and presents a rational and streamlined approach to work generation, work estimation, financial analysis computation, and prioritization.

Finally, the consequence analysis routines provide the critical ability to evaluate the effect of infrastructure investment policies against the fundamental strategic objectives. This supports proactive and accountable building infrastructure management for exterior envelope systems.

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