Condition and Reliability Prediction Models using the Weibull Probability Distribution

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Abstract

Key to a successful building asset management plan is the ability to measure current condition and predict future condition and degradation trends over a specified planning horizon for each and every individual component-section present in a building. However, this ability poses a difficult challenge because of the vast array of different components, their material make-up, and type found in a building and because each has a different expected life and degradation curve. In addition, condition trends and service lives depend on the amount of preventative and corrective maintenance, including repair, invested during a component-section's lifecycle. Because of these variables, it is difficult to accurately project a condition-lifecycle trend for each individual component-section without a periodic inspection and a meaningful condition metric for measuring condition. This condition metric provides data for the lifecycle prediction process. However, condition data are most often very limited for any given component-section. This paper addresses the use of the Weibull probability distribution function with the data collected during component-section inspections to predict lifecycle condition and reliability over time. The prediction model is self-correcting using attribute information collected during both current and historical inspections to accurately project the unique lifecycle degradation trend for an individual component-section in a building.

Introduction

Recent requirements in civil infrastructure asset management have highlighted the need for improved methods, metrics, and tools to support maintenance, repair, and recapitalization decisions for both public and privately owned facilities (GAO 2003). The objective of these efforts is to minimize total lifecycle costs while maintaining facility condition and performance above specified levels. Lifecycle costs can be optimized by identifying, analyzing, and planning facility repair work in a timely fashion, before the penalty costs due to accelerated facility condition degradation is compounded. This requires knowledge of the relative condition and how that condition degrades over time. For decades, pavement management systems have existed to measure and predict condition for that specific infrastructure domain, but extending that science to building infrastructure management presents a completely new challenge. Currently, existing software applications allow the quantitative calculation of a condition index (CI) value for each component of a building based on an objective condition survey process (Uzarski and Burley 1997). This paper explores the use of this metric to track condition trends and project condition and reliability for the vast and diverse array of building components.

Building Component-Section Lifecycle

Buildings are complex assets comprised of several systems and components, and crossing several specialized civil construction disciplines. Because of this, a rigid hierarchical structure, such as the ASTM Uniformat II (U2) standard for building elements classification (ASTM 2002), is required. The U2 standard divides the building first into major assemblies aligned with the construction trade disciplines, then by building systems, and finally by the individual components that make up those systems. Each component can then be further divided into a component-section, which establishes component attributes based on material, type, age, and location. For example, a wall (component) may be constructed of masonry or wood. The different materials have different responses to their environment over time, have different service lives, and require different work actions at various stages in their lifecycle. As such, the basic management unit for building lifecycle asset management and condition tracking is termed the component-section.

Each component-section works interdependently with other component-sections to support the functions of an efficiently operating building. Each component-section 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 component-section can no longer serve its intended function sufficiently (Moubry 2002). It may also adversely affect the function or condition of other component-sections. This limit state occurs at a typical condition index value (CI equals approximately 40) as defined by the building component condition index scale. Due to the nature of their function, certain component-sections, such as structural columns, have a service life designed to correspond to the life of the facility. Other component-sections, 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 component-sections 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-section and the consequence of a failure, this corrective action may best be performed at or before reaching the failure state.

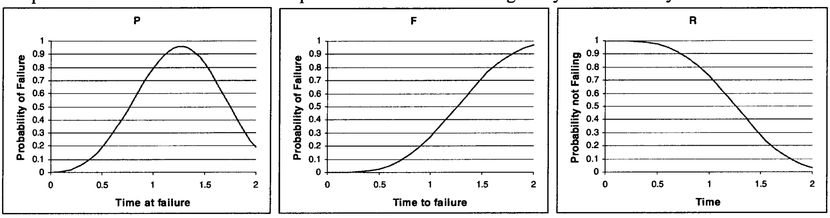
Predicting this failure state for a unique component-section in a building is difficult, because the true lifespan of a component-section is rarely known, when new. While a designer or manufacturer can provide a generalized idea of design life for a component-section, actual service life depends greatly on local environmental factors, use and abuse, and levels of routine maintenance accomplished. In addition, for many component-sections, simply defining what constitutes a failure state can sometimes be ambiguous. For instance, does a window component-section 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 component-sections and to different people. Instead, defining a quantitative failure state based on an objective condition index (CI) 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 component-sections, repair early in the lifecycle 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." Experience with the building component CI metric has shown that for a wide variety of components, the repair sweet spot falls in the CI equals 70-80 range. 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 lifecycle.

Reliability and Condition

Each building constituent component-section has a finite service life. This service life defines the lifespan for a component-section. Although a building component-section cannot last forever, its service life can be extended with proper operation, maintenance, and even repair. Likewise, a component-section'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-section and there is a limit to the certainty that its service life can be known at the time of construction or installation. Figure 1a shows the probability distribution for the time to failure for a hypothetical component-section. The design service life is the time in service at which the component-section 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-section 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 component-sections are published from different sources based on industry estimates. Unfortunately, unlike pavements, little data exist to describe the variances associated with each service life. In addition, because of the vast and diverse array of individual building components, a family analysis approach, common to pavement infrastructure, to predict condition and service life data is not applicable.

If the variance for the time from component-section construction or installation to failure were known, the statistical probability of that component-section failing at a given year in its lifecycle could be defined. The cumulative failure distribution, Figure 1b, then relates the probability that the component-section will fail at or before a given year. The inverse, Figure 1c, represents the reliability, measured by the probability that the component-section will meet or exceed performance standards at a given year in its lifecycle.



Figures 1a. Failure in year t 1b. Failure before year t 1c. Performs past year t

The model assumes that the condition state measured by the CI and the reliability state are proportionally similar. Both are defined below.

Condition

The physical condition state relates the general health of a building component-section. Physical degradation of the component-section due to normal aging, excessive or abusive use, or poor maintenance can cause a reduction in the component-section's ability to perform as required. In BUILDER® EMS (BUILDER 2005) for example, condition is measured in absolute terms by the use of a condition index metric. The condition index uses a scale of 0-100 with 100 defining "Defect Free" or pristine condition. The lowered condition state is caused by distresses observed during a structured, objective, and repeatable inspection. These distresses have an adverse affect on the component-section's ability to perform. Through a "deduct value" process based on the distress types, severities, and densities present, a condition index is computed. It can be assumed that, when new, a component-section condition index is 100 (i.e. Defect Free).

Reliability

Reliability is the statistical probability that a component-section will meet or exceed performance requirements for a given length of service life. For most building component sections, it is a function of the amount of time a component has been in service. In general, condition and reliability are related as follows:

- Condition and reliability are maximum (100) at or near the start of the service life,
- Condition and reliability approach the minimum state (0) asymptotically,
- Condition and reliability deteriorate unless corrective action is performed, and
- As condition deteriorates, reliability likewise decreases.

Condition Prediction Model Requirements

In order to have a robust condition prediction model, the following methodologies are proposed:

- Model is seeded with reasonable initial assumptions, and "self-corrects" based on collected information,
- Model automatically adjusts the expected service life based on an inspection generated condition index,
- Model takes into account the inspection date and type when calibrating the prediction trend,

- When repair work is completed, model adjusts the prediction trend, and
- Model takes the type of repair work into account when projecting the predicted condition trend.

Weibull Probability Distribution

The Weibull cumulative probability distribution function is used to model the condition lifecycle curve. The Weibull statistical distribution represents the probability of time to failure of a component-section in service. It has natural boundary conditions which abide by the assumptions discussed above, and takes the shape of a classical condition deterioration curve. The resulting mathematical condition prediction model is:

$$C(t) = a \times e^{-(t/\beta)^{\alpha}} \tag{1}$$

Where:

C(t) = component-section condition index as a function of time
t = time, in years, since component-section was installed or constructed
e = exponential
a = parameter, initial steady state component-section condition index
β = parameter, service life adjustment factor
α = parameter, accelerated deterioration factor

Initial Model Seeding

The first step of the self-correcting prediction model process uses initial general assumptions to compute the parameters a, α, β which describe the shape of the condition lifecycle trajectory. When the component-section is new or there are no inspection data the only lifecycle information available is the installation or construction date for the component-section (at which the assumed CI is 100) and the expected service life (at which assumed CI equals some terminal value at end of service life). The model must also be seeded with a degradation factor. An example is illustrated in Figure 2 with an example 30 year service life. The actual degradation factors can be set individually for each component-section based on historical trends, if known. If unknown, any reasonable values may be chosen because the model will self-correct once inspection data are collected.

These assumptions initialize the prediction model when no other information exists. Each assumption results in a data point which is a function of component-section time in service and condition. The three model parameters are then solved using those data points to describe the shape and trajectory of the component-section lifecycle curve.

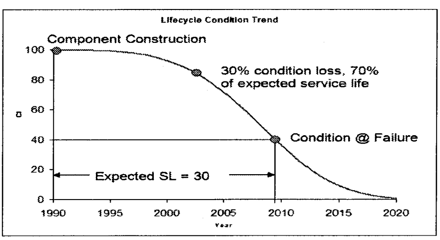


Figure 2. Example Initial Lifecycle Condition Trend

Calibration with Inspection Information

The initial model seeding described above may be reflective of a typical component-section, but they do not account for the unique reliability or behavior of a specific individual component-section present in a specific building. Therefore, as time progresses and the component-section ages and degrades, it becomes important to assess the component-section condition at various points during the lifecycle to compare and calibrate the expected condition with the actual observed condition.

As the component-section progresses farther into its lifecycle and more inspections are performed, these historical inspections form the shape of the observed and projected lifecycle 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. Figure 3 illustrates how collected inspection data are used to readjust the expected service life and lifecycle curve. As more data are added, the better the model becomes tailored and unique for any given component-section. Figure 3 also illustrates how the expected service life shifts.

Weighting of Historical Inspection Data

After several inspection points are collected, the model begins to accumulate information about the behavior of the component-section's condition over time. However, some inspections and data points are more accurate than others depending on the inspection type done, the level of inspection detail, and the inspection date. The condition prediction process takes these factors into account when adjusting the model.

The mathematical Weibull model has only three parameters or degrees of freedom to define the condition lifecycle curve. However, with the initial installation or construction date, the expected service life date, and several inspections collected, more than three data points exist. The model uses regression analysis to fit the prediction curve through data points by minimizing the sum of squares residual error. Each point is also associated with a weighting factor that modifies its residual error. The more accurate the data point, the higher the weighting factor and the more affect it has on the adjusted model. Also, the adjusted prediction curve always passes through the last known condition index point.

Factors that affect the weighting values for a data calibration point include the component-section installation or construction date certainty, the time (in years) since the previous inspections, the inspection type of inspection (distress survey or direct rating) (Uzarski 2004), and the change in CI value between inspections.

Scheduling Inspections

The proposed model above illustrates how important inspection scheduling is in the condition prediction process. The quantitative BUILDER® inspections provides the information for self-correcting the model based on actual conditions. The prediction model is always most accurate in the time near a well trusted data point, such as in the case of a recent inspection. As time passes and that inspection becomes dated, the predicted condition becomes less certain. Depending on the predicted condition, the certainty of that predicted value, the consequence of prediction error, or the amount of service calls or trouble tickets, it may be time to schedule another inspection. This new inspection once again verifies and self-corrects the predicted condition model.

The proposed prediction model process provides a way for efficiently scheduling inspections and justifying the benefits. Since inspections cost money and require personnel resources, performing inspections at selected times in the lifecycle, based on need and not the calendar, efficiently allocates these resources.

Calibration when Work is Performed

In addition to adjusting the condition model based on inspection information, corrective repair work has an effect on the future condition trend. If the projected condition drops below a designated acceptable level or standard, component-section repair or replacement may be necessary. If a repair is performed, then the deterioration model experiences a step function increase at the time of repair which raises the CI up to an assumed value of 95. Since it cannot be assumed that the component-section has been repaired to a "Defect Free" condition (CI=100), a reduced CI is used. If a quality control inspection is performed on the work, the actual CI value, including 100, is used in the model. To predict the component-section condition trend response after repair, the established pre-repair degradation trend is extended (see Figure 4). The model also takes into account the age of the component-section at the time of repair when determining the new degradation rate. Generally, the older a component-section is at the time of repair, the faster the post-repair degradation will be when compared to the pre-repair rate, but there are exceptions. Thus, multiple repairs cannot extend the life of a component-section indefinitely. Eventually, component-section replacement will be required. Replacement will reset the service life clock. Of course, as discussed above, inspections will be periodically conducted on the repaired component-section which will adjust the lifecycle curve.

When the component is replaced with an identical component-section (replacement "in kind"), the prediction model takes the characteristics of the replaced component-section's degradation trend to initialize the new component-section condition prediction model.

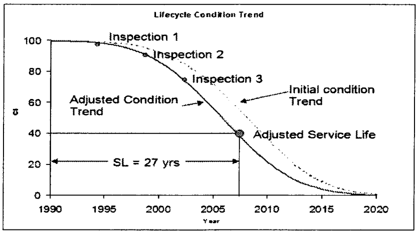


Figure 3. Lifecycle Condition Trend after Inspection Data Calibration

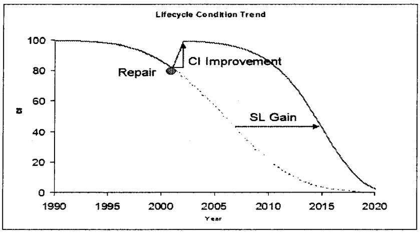


Figure 4. Lifecycle Condition Trend after Corrective Repair

Conclusions

The measurement and prediction of future facility component condition trends is essential to a reliability-centered building lifecycle management program. However, with the large number of dissimilar building components in a building portfolio, and the lack of detailed models to describe the response in service to each of these individual components, predicting condition performance for a building is quite a challenge. 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 proposed model described above provides a feedback loop to self-correct individual lifecycle trends for a wide variety of building components based on periodic objective assessment observations. In addition, corrective repair work performed during the lifecycle of a component-section is factored into the lifecycle trend analysis. This reliability/risk-based condition prediction model provides the basis for optimized planning of both inspection resources to refine the condition trend as required, and repair and recapitalization resources to plan corrective work at the appropriate time in the component-section lifecycle.

References

ASTM International (2002). Standard Classification for Building Elements – Uniformat II, ASTM E 1557-02.

BUILDER (2005). BUILDER Engineered Management System, http://dwww.cecer.army.mil/td/tips/product/details.cfm?ID=64&TOP=1

GAO (2003). Changes in Funding Priorities and Strategic Planning Needed to Improve Condition of Military Facilities, www.gao.gov.

Moubray, John. (2002). Reliability-Centered Maintenance, Industrial Press Inc., New York.

Uzarski, D.R. and L.A. Burley. (1997). "Assessing Building Condition by the Use of Condition Indexes," proceedings of the ASCE Specialty Conference Infrastructure Condition Assessment: Art, Science, Practice, pp.365-374.

Uzarski, D.R. (2004), "Knowledge-based Condition Assessment Manual for Building Component-Sections" U.S. Army Construction Engineering Research Laboratory. (Distributed with BUILDER® software)