# A Deterioration Model for Establishing an Optimal Mix of Time-Based Maintenance (TbM) and Condition-Based Maintenance (CbM) for the Enclosure System

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## ABSTRACT

Buildings comprise hundreds of assets, such as roofs and boilers, each of which has different durability expectations and therefore requires a corresponding maintenance strategy to sustain their performance and function over their respective service lives. Maintenance strategies can be classed into those that are time-based (TbM) and those that are principally condition-based (CbM). Whereas the former group of maintenance activities is carried out on fixed intervals, consistently over the service life of an asset regardless of its age, the latter is dependent, in part, on the emergence of distress-metrics that are empirically measurable at different life stages. CbM contemplates age and exposure conditions, is variable in its intervals and conditional in its implementation. Many maintenance manuals have offered a rudimentary approach to enclosure assets that is heavily focused on TbM principles with minimal consideration of changes to the TbM ratios with the passage of time.

This paper argues that the ratio of TbM to CbM (that is, the maintenance mix) should be aligned to individual assets and also adjusted at different stages over their respective service lives. To this end, the paper advances a multivariate deterioration model to identify the key milestones along the life of an asset and offers principles for a maintenance mix to guard against the risks of under-maintenance and the lack of credibility that arises when owners perceive an overly conservative program of over-maintenance based upon simplistic considerations of fixed interval maintenance. The multivariate deterioration model reveals insights for a reliability-centred paradigm for maintenance of enclosure assets.

**KEY WORDS.** Time-based maintenance; condition-based maintenance; maintenance mix; deterioration model; performance curve; survivor curve; probability of failure; consequences of failure; beyond economic repair; potential failure; functional failure; global maxima; global minima; local maxima; local minima.

## 1 INTRODUCTION

In the late-1990s, legislation was enacted in British Columbia mandating higher standards for the preparation of maintenance and operations manuals as part of the commissioning of all new construction projects and major rehabilitation projects. Over the past 15 years the authors have been involved in the preparation of several hundred Maintenance and Renewals Plans (MRPs) for a variety of building types in the residential, municipal and commercial sectors, in the Pacific Northwest, centred on Vancouver, Canada. Initially the MRPs were focused principally on the building enclosure system and were later expanded in their scope to include all other systems, such as mechanical, electrical, elevators and fire protection assets.

Drawing upon a database of 1651 buildings, it was established that the average MRP contained approximately 2,000 itemized maintenance tasks. A master library of these maintenance tasks had been developed through various means, including information extracted

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from hundreds of manufacturer product data sheets, literature reviews, and recommendations from various interdisciplinary consulting teams and service contractors.

In response to client feedback and empirical data from the field, the format and content of the MRPs went through numerous iterative changes to improve the quality of the maintenance instructions and maintenance intervals. The most common criticism from building owners has been that the maintenance schedules were "boiler plate", did not reflect local conditions and failed to recognize their budget constraints. Furthermore, many building owners complained that the MRPs advised on "what" needed to be done but not on "how" to do it.

The most challenging of the enhancements to the manuals was in finding an optimal balance (the maintenance mix) of TbM and CbM for varied enclosure assets at different stages in their respective lifecycles. As an example, the maintenance descriptions evolved from: "*Clean the roof gutters twice a year*" (TbM) to "*Inspect the gutters during early autumn and after inclement weather conditions. Depending on the proximity to trees and other vegetation, clean the gutters at appropriate intervals*" (CbM). Articulating these nuanced narratives was the easier of the technical challenges. The real heavy lifting occurred in developing a model to capture these ill-defined intervals that could be migrated into an overarching maintenance schedule.

In order for a maintenance 'plan' to be effectively bridged into a sustainable maintenance 'program' it is essential for the consulting team to recognize how owners: a) perceive the efficacy of enclosure maintenance intervals; b) manage long-range risk in the face of ill-defined maintenance schedules; and c) seek prioritization strategies to implement enclosure system maintenance within the constraints of limited budgets.

This paper explores the significant technical challenges in the preparation of meaningful building enclosure maintenance manuals (read: realistic and user friendly) that effectively empower the owners to self-sufficiency. The paper provides a means to capture "if-then" statements for non-predictive (stochastic) maintenance requirements, such as the delay-start cycle on events during the early life of an asset and predictive maintenance technologies during the mid-life of an asset.

### 1.1 Levels of Maintenance Manuals

Building maintenance manuals come in many shapes and sizes. For the purposes of this paper, a four-tiered classification of maintenance manuals is considered.

- *Level-1 Manual* – The most rudimentary of manuals, which contains a package of manufacturer's product data sheets, usually presented in a ring binder format.
- *Level-2 Manual* - These include the reference information in the Level-1 manual and also provide a summary table with itemized maintenance instructions for the more common routine maintenance tasks.
- *Level-3 Manual* - These contain all the information in a Level 2 manual and also include recommended fixed intervals (cycles) for the maintenance activities relative to the total service life of the asset.
- *Level-4 Manual* - These manuals go a few steps further and provide advice on matters such as the methods of maintenance (e.g. use of hot vs. cold water), the skill levels of the persons required (e.g. contractor, owner, consultant) and may also attach an estimated cost for the individual activities.

The majority of the maintenance manuals in British Columbia since the passage of the regulations in 1999 are considered to fall into Level-2 and Level-3.

## 1.2 Levels of Maintenance Articulation

The quality of the maintenance instructions vary dramatically between the MRPs offered by different consulting firms. The following Tables 1 & 2 illustrate the different levels of articulation of the individual maintenance tasks that have been found within different MRPs.

| Window Maintenance Task | Task | Interval | Scope | Method | Schedule |
|---|---|---|---|---|---|
| "Wash the windows" | Y | | | | |
| "Wash the windows twice each year" | Y | Y | | | |
| "Wash the vision glass of all the exterior inaccessible windows twice each year" | Y | Y | Y | | |
| "Wash the vision glass of all the exterior inaccessible windows with tucker pole and warm water twice each year" | Y | Y | Y | Y | |
| "Wash the vision glass of all the exterior inaccessible windows with tucker pole, soap and water in the Spring and Fall seasons | Y | Y | Y | Y | Y |

Table 1. Examples of different levels of TbM guidance offered in maintenance manuals

Table 2 provides a similar illustration of the different levels of articulation for a non-routine maintenance task that occurs at longer and varied intervals. Sealant inspections are generally considered a condition-based maintenance task.

| Sealant Maintenance Task | Task | Interval | Scope | Method | Schedule |
|---|---|---|---|---|---|
| "Inspect the sealant" | Y | ? | | | |
| "Inspect the sealant for signs of distress" | Y | ? | Y | | |
| "Inspect the sealant for signs of distress, such as cracking, debonding, … etcetera" | Y | ? | Y | | |
| "Visually inspect and test a representative sample of the sealant for signs of distress, such as cracking, debonding, …etcetera." | Y | ? | Y | Y | |
| "Inspect a representative sample of the sealant for signs of distress, such as cracking, debonding, … etcetera. Carry out localized repairs, as required. | Y | ? | Y | Y | Y |

Table 2. Examples of different levels of CbM guidance offered in maintenance manuals

The qualitative descriptions and qualifiers attached to the maintenance tasks can have a significant impact on the way in which the end user defines the scope of work, estimates the costs, establishes budgets, hires contractors and generally applies the necessary and recommended maintenance.

## 1.3 Distinguishing "Maintenance" versus "Care"

While care is, in some ways, synonymous with maintenance, it is helpful to draw a more careful distinction of these terms. Where maintenance can be considered to be the things that must be done to preserve an asset, care contemplates the activities that must be avoided in order not to jeopardize warranties and expose assets to extraordinary loadings. A CbM program will seek to determine the quality of maintenance and the potential lack of care of the asset by measuring the condition of the assets to assess whether they will fail during some future period. The following Table 3 provides some examples of the differences between maintenance and care of assets.

| **Maintenance**<br>(What operators must do) | **Care**<br>(What operators must not do; avoidance) |
|---|---|
| Cleaning, washing | Dripping, spilling |
| Lubricating | Bumping, gouging |
| Inspecting | Burning, grazing |
| Purging, flushing, extracting | Tearing, scraping |
| Scoping | Smudging, scuffing, soiling |
| Adjusting, re-aligning | Marking, tagging |
| Re-calibrating, refastening & re-torquing | Neglecting |
| Re-coating, re-finishing | Overloading, abusing |
| Swapping out | Blocking, encroaching |

Table 3. Examples of some maintenance and care guidelines that appear in manuals

For example, a maintenance instruction may state: *“Inspect the balconies”* whereas a care instruction may state: *“Do not extinguish cigarette butts on the balcony membrane”*. As a result of hundreds of condition assessments carried out of the 15 years of the study period, some assets have been found to be more susceptible to failure resulting from a lack of care rather than a lack of maintenance. Whereas insufficient maintenance can contribute to intrinsic failure of assets, a lapse in the necessary levels of care can result in extrinsic failure.

## 1.4 Distinguishing Time-based and Condition-based Maintenance

While TbM activities continue at the same intervals, regardless of the changing condition of the assets, CbM requires the owners and operators to appreciate the advancing age of the asset and to align the maintenance activities accordingly. Table 4 provides a comparison summary of the key attributes of these two maintenance classes.

| | **Time-based Maintenance** (TbM) | **Condition-based Maintenance (CbM)** |
|---|---|---|
| **Example maintenance task** | “Wash” the windows | Inspect the sealant and “repair as required”. |
| **Typical interval for the maintenance tasks** | Fixed - Twice per year over the life of the asset | Certain years but typically after an initial time lapse (i.e., delayed start) |
| **Qualitative vs. quantitative** | Quantitative | Qualitative |
| **Requires a deterioration model to set appropriate intervals** | No | Yes |
| **Requires diagnostic instrumentation to establish recommendations** | No | Sometimes |
| **Results in a prognosis on the remaining service life of the asset** | No | Sometimes |
| **Subjective judgement** | Sometimes | Almost always |
| **Scopes are typically 100%** | Yes. Clean all windows regardless of degree of dirtiness or the age of the windows. | Scopes are tied to findings, which can vary dramatically at different times in the life of the asset. |
| **Cost estimates are quantifiable** | All costs are measurable and can be known beforehand | Some costs are not known (other than anticipated by the model which can be statistically estimated) |

Table 4. Comparative matrix of some TbM vs. CbM attributes

A robust maintenance program includes both TbM and CbM tasks. The challenge is to establish the correct balance and to match the ratios to different assets at different stages in their respective lifecycles.

While a TbM approach works well with some assets, particularly those that are highly regulated for safety reasons, it is not appropriate for many assets that behave differently over time. Condition-based maintenance does not lend itself to a scheduling paradigm as it relies on condition statements, such as: "*If condition X arises, then carry out maintenance activity Y*".

## 2 THE NEED FOR A DETERIORATION MODEL

A deterioration model is essential for the development of a reliability-centred paradigm for the maintenance of assets. The model guides the maintenance mix in order to guard against the risk of under-maintenance and the lack of credibility that arises when owners perceive an overly conservative program of over-maintenance based upon simplistic considerations of fixed interval maintenance. The mix (ratio) of TbM and CbM varies across systems, across individual assets within systems, and at different times over the individual service lives.

Whereas the mechanical and electrical (M&E) systems provide schedules for the maintenance of nodes and runs (such as pumps and pipes), the enclosure system is focused on the lifecycle behaviour of surfaces and planes (such as coatings and roofs). The former is impacted principally by equipment run hours based on occupant loads and is generally predictive and grounded in hard-time concepts. The latter is impacted by variable exposure conditions that are not ubiquitous, are stochastic, and dependent on a combination of hard-time and soft-time principles.

Fixed-interval maintenance schedules provide for the necessary and sufficient maintenance of many of the tangible capital assets in buildings (such as compressors and boilers). These time-based maintenance (TbM) programs have been effectively developed within the M&E disciplines. For example, the maintenance of a pump will be prescribed at quarterly or annual intervals, which will generally remain consistent throughout the useful service life of that asset from the time it is placed in service until it is retired from service.

The building enclosure system, as an environmental separator, is subject to weathering principally from the environment and is subject to secondary and tertiary distresses from building occupants. The building enclosure system does not lend itself exclusively to fixed scheduling patterns and requires a maintenance mix that also includes "variable-intervals" and "floating-intervals" in order to advance realistic schedules.

Fixed-interval schedules are more readily incorporated into maintenance service agreements and it is therefore commonplace for buildings to have the majority of their M&E assets covered under a preventive maintenance contract. Since variable-intervals and floating-intervals are essentially performance-based requirements, they are not easily articulated in service agreements and are more difficult for facility owners and operators to synchronize with their facility schedules and budgets. It is challenging for owners to effectively anticipate the enclosure maintenance schedules when it is a moving target.

A deterioration model describes the process and mechanisms by which assets wear over time and pass through different stages of "failure". Key elements of the model include the following: the anticipated rate of deterioration of the asset; the path of deterioration; the milestones (or points or stages) along the deterioration path; the thresholds that define the beginning and end of each stage of deterioration; the different levels of risk exposure at stages along the deterioration path; and, the appropriate maintenance actions to take during the sequential condition stages. The models consider many variables that impact life, including: quality of maintenance; loadings, climate, latent and patent defects, operating conditions, service environment, etc. A literature review [1, 2, 3] reveals that there are numerous types of deterioration models that have been advanced over the years and these can be considered to fall into two broad groups:

- *Degradation Curves***.** These are also referred to as 'performance curves'. A graphical representation of the exposure and increasing deterioration of an asset, where the shape of the curve indicates the anticipated rate of deterioration of the asset and the length of the curve represents the service life of the asset.
- *Survivor Curves.* Also referred to as 'probability distribution curves' or 'retirement curves'. They are used to ascertain the probability of failure (PoF) of an asset during any particular calendar year and are derived from the statistical data on the functional failures ('F') of all the assets within a statistical population.

Figure 1 provides a conceptual illustration of these two types of deterioration models where the changing impact of asset exposure over the service life (degradation curve) and probability of failure at a particular age (survivor curve) are correlated over time.

**Degradation Curves** **Survivor Curves**

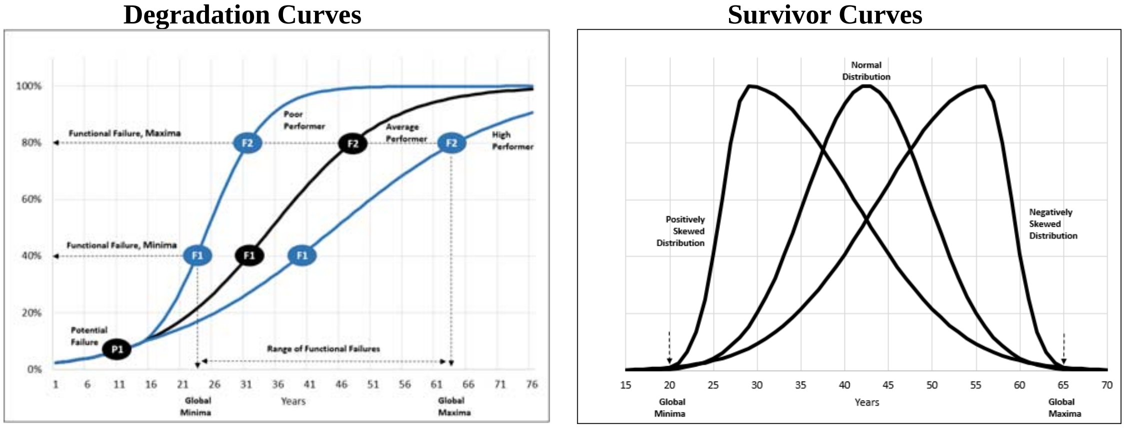



Figure 1. Conceptual representations of degradation curves (left) and survivor curves (right).

Table 5 provides a summary of some of the key attributes of these two types of deterioration model.

| | Degradation Curves | Survivor Curves |
|---|---|---|
| Primary source of knowledge | Empirical data | Statistical data |
| Principal value of the model to asset owners/operators | What do we do over the life of the asset? | When should we prepare for the end of life of the asset? |
| Purpose | To establish practices to achieve the full service life of an asset. | To avert the consequences of failure (CoF) that arise upon functional failure ('F') of an asset. |
| Curve elements | Delta; slope; points of inflection; potential failure; functional failure; local maxima; global minima; local minima, global minima; average performers, high performers; poor performers; leading, lagging and coincident indicators. | Skewness; kurtosis; mean; median, mode; standard deviation; left modal; right modal; dispersion; local maxima; global maxima; local minima; global minima; probability of failure; sample size; statistical population; dataset. |

Table 5. Comparison of key parameters of two types of deterioration models.

## 2.1 The Degradation Curves

The deterioration path is represented using a logistic function also known as a sigmoid function. The graphic is asymptotic to two points, where 0% and 100% have been selected to represent the outer limits of asset wear.

The degradation curve comprises three general classes: ‘average’ performers; ‘poor’ performers and ‘high’ performers. These are statements on the results of a single asset when compared to all other assets of the same class. The multivariate deterioration model contemplates two distinct stages, each of which is established by failure thresholds to identify the start and end of each stage.

- *Potential Failure (‘P’)* – The point in the deterioration process when it is first possible to detect whether a “failure” is occurring, or is about to occur. This will depend on the quality of the diagnostic technologies, such as infrared thermography or the testing protocols such as pull adhesion test. Potential failures do not signal that an asset must be replaced. Rather, they are leading indicators of the months, years or decades before the end of life of the asset.
- *Functional Failure (‘F’)* – The point in the deterioration process when the density of deficiencies (and/or significance of deficiencies) has exceeded an acceptable level, where acceptable is defined by the owners and/or industry standards.
- *P-F Interval* –The failure development period from potential failure (‘P’) to functional failure (‘F’) where the owner has the opportunity to take action to monitor performance through failure modes and effects analysis (FMEA), and thereby anticipate and avert the consequences of failure. The P-F Interval was coined by Moubray [2] and has been extensively referenced in the reliability engineering and facility management literature.

The multivariate deterioration model requires that domain experts develop a protocol to rate distress indicators (leading, lagging and coincident) that are most likely to affect the performance of a specific asset type and indicate the proximity to ‘F’. The two types of distress-based indicators that are contemplated in the multivariate deterioration model are as follows:

- *Direct Distress-Indicators* – A failure that impacts the critical component of the asset and will affect the timetable for functional failure (‘F’). For example: an unrepaired blister in the membrane may result in a leak (‘F’).
- *Indirect Distress-Indictors* – A failure that impacts a non-critical component of an asset and will not necessarily affect the timetable of functional failure. For example: corrosion of the cap flashing (sheet metal coping) at the perimeter parapet of a roof.

Table 6 provides a comparative matrix to further illustrate the fine distinctions between direct- and indirect-distress indicators.

| **Attributes** | **Direct Failures**<br>Intrinsic | **Indirect Failures**<br>Extrinsic |
|---|---|---|
| Example(s) of failure | Blister in a membrane | Degranulation of the cap sheet |
| Causes | Physical, chemical | Occupants, contractors, lack of care, etc. |
| Location | The critical element of the assembly | The secondary and tertiary elements of the assembly |
| Impact on BER and ‘F’ | Yes | Sometimes |
| Controllable by the owners | Marginal | Yes – full control |

Table 6. Significance of direct and indirect failures of an asset

Weighted factors can also be developed, where appropriate, to rate the severity (such as ‘low’, ‘medium’, ‘high’) of the distress- metrics of potential failure.

### 2.2 The Survivor Curves

The survivor curves represent the functional failure distributions of all the assets in a statistical population and are classified into three broad groups based on the relative skewness and dispersions of the probability distributions.

- *Normal Distribution* – Also referred to as the ‘bell curve’. The modal year and the average asset life are the same, thus producing a symmetrical curve. Half of the assets are retired prior to the average life and an equal amount are retired after the average life term is reached.
- *Positively Skewed Distribution* – An asymmetrical distribution with left modality where the greatest number of asset retirements occurs prior to the average service life. There is a long tail to the right of the mean.
- *Negatively Skewed Distribution* – An asymmetrical distribution with right modality where the majority of the assets in the group last longer than the average life but they will be retired over a relatively short period of time. There is a long tail to the left of the mean.

Within these three distributions there are numerous degrees of skewness. The varying levels of risk at the different stages along the survivor curve are evaluated with the following three concepts.

- *Probability of Failure (PoF)* – The likelihood, based on realistic forecasts, that an asset will reach functional failure (‘F’) in a particular calendar year. PoF can be expressed in a variety of linguistic or numerical scales relative to a particular year. For example: failure is ‘impossible’, ‘remote’, ‘probable’, or ‘likely’.
- *Consequences of Failure (CoF)* – The impact (such as physical, financial and/or legal) of an asset reaching functional failure (‘F’), which is measured relative to the following two entities: the building and the stakeholders of the buildings. CoF can be expressed as linguistic variables (say, ‘catastrophical’, ‘critical’, ‘marginal’, and ‘negligible’) or numerically (say, 1-100).
- *Minimas and Maximas* – With references to the entire statistical population of all the assets within a given population, global maxima and global minima refer to the failures of the outermost of statistical outliers. Local maxima and minima are the statistical outliers of a specific dataset or a specific asset on a specific building. For example, the roofs in a local area (say, the City of Vancouver) relative to the same roof types across a broader geographical region (say, North America).

Where the local minima correlates with the earliest potential date for functional failure (‘F1’), the local maxima represents the likely last date for functional failure (’F2’) of a single asset within its population group. Further insight into the window of time between F1 and F2 provides the means by which the authors advance a multivariate deterioration model that builds upon Moubray’s P-F Interval [2] and couples this with the Iowa survivor curves [3]. The multivariate deterioration model in this paper is therefore referred to as the ”**Extended P-F Interval**”.

## 3 THE MULTIVARIATE DETERIORATION MODEL

The multivariate deterioration model contemplated in this paper is comprised of several interacting elements that arise from superimposing one curve over the other, where the survivor curve(s) are the backdrop of the model and the degradation curve(s) occupy the foreground. These correlations are represented conceptually in Figure 2, followed by a more granular presentation in Figure 3.

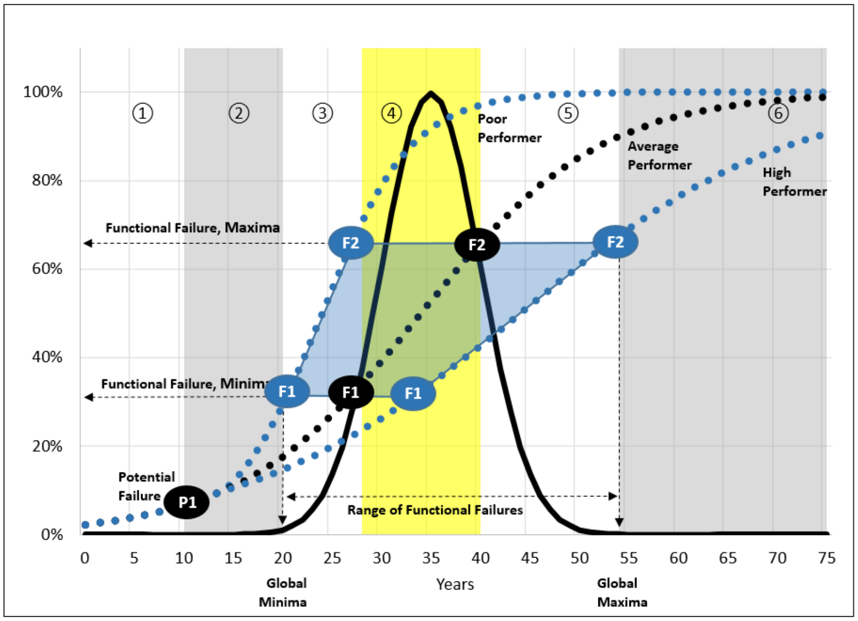


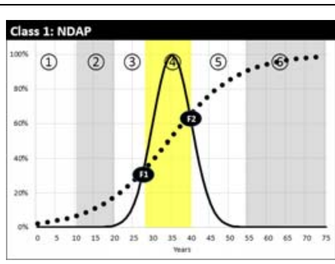
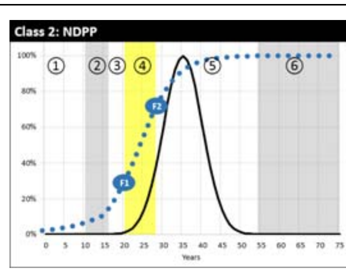
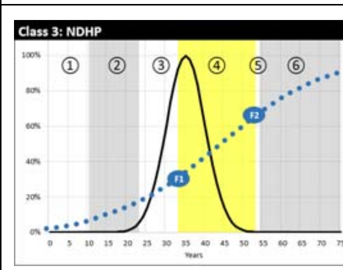

Figure 2. The multivariate deterioration model represented using a normal distribution to conceptually illustrate the correlations between this type of survivor distribution and three different degradation rates.

This overlay provides insight at the intersection points and at the relationships (distances) between the points. Recognizing the different lifecycle behaviours of assets and local performance characteristics, the multivariate analysis has identified nine scenarios (or classes), which are listed below.

| **Classes** | **Class Title** |
|---|---|
| Class 1: NDAP | Normal distribution with 'average' performing asset |
| Class 2: NDPP | Normal distribution with 'poor' performing asset |
| Class 3: NDHP | Normal distribution with 'high' performing asset |
| Class 4: PSAP | Positively skewed distribution with 'average' performing asset |
| Class 5: PSPP | Positively skewed distribution with 'poor' performing asset |
| Class 6: PSHP | Positively skewed distribution with 'high' performing asset |
| Class 7: NSAP | Negatively skewed distribution with 'average' performing asset |
| Class 8: NSPP | Negatively skewed distribution with 'poor' performing asset |
| Class 9: NSHP | Negatively skewed distribution with 'high' performing asset |

Table 7. Nine deterioration-and-probability scenarios under the multivariate model

These nine classes are represented graphically in the following array where the first group are based on the normal (symmetrical distribution) followed by the positively and negatively skewed distributions.

<table>
<tr><th></th><th>'Average' Performers</th><th>'Poor' Performers</th><th>'High' Performers</th></tr>
<tr><td>Normal Distribution</td><td>
</td><td>
</td><td>
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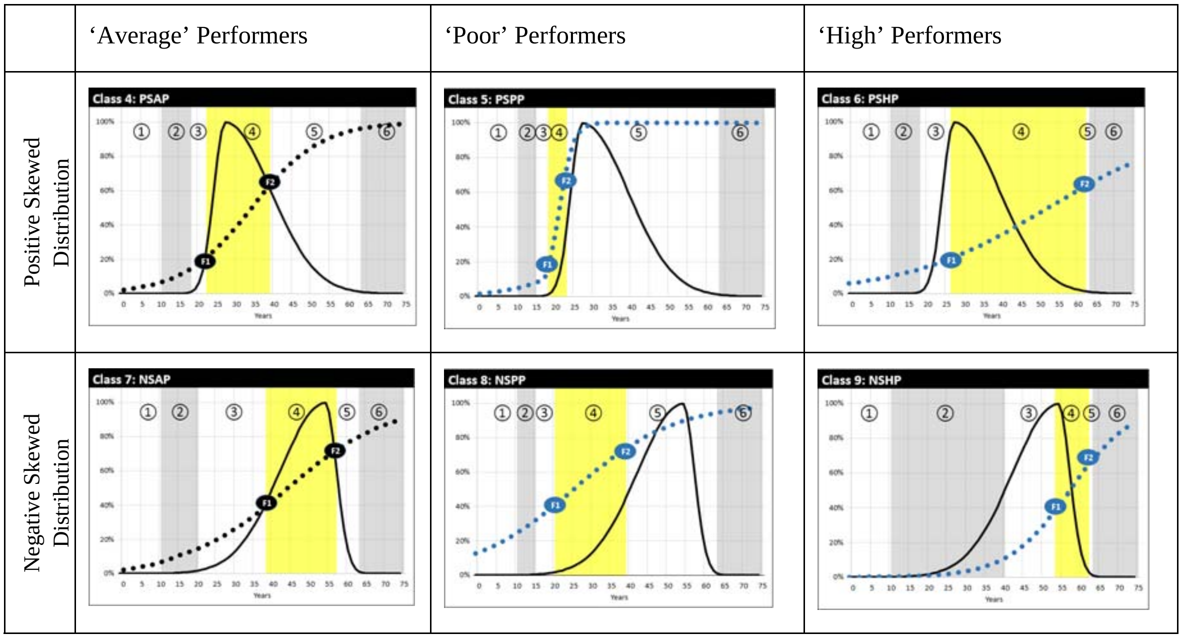


Figure 3. Matrix of the nine classes within the multivariate deterioration model.

Each of these classes represents a different scenario of exposure conditions affecting the in situ assets and corresponding condition-based maintenance practices. The following table includes two brief examples of how different types of enclosure assets may be considered to fall into these classes under different exposure conditions and maintenance regimes.

| Examples of Enclosure Assets | Survival rates of the statistical population | Degradation with adequate maintenance | Degradation without adequate maintenance |
|---|---|---|---|
| 2-ply SBS roof | Normal distribution | Class 1: NDAP | Class 2: NDPP |
| Painted Wood siding | Positively skewed distribution | Class 4: PSAP<br>Class 6: PSHP | Class 5: PSPP |

Table 8. Examples of two assets under the multivariate deterioration model

If painted wood siding is not regularly subject to recoating cycles, which protects the substrate, the asset may be deemed to have deteriorated from an "average" performer to a "poor" performer. Determination on whether a specific asset is exhibiting characteristics of an 'average', 'poor' or 'high' performer is identified by the condition-based maintenance cycles.

## 4 SIX PHASES IN ALIGNING THE MAINTENANCE MIX

Drawing from the intersection points on the degradation curves (empirical) and survivor curves (statistical), the multivariate model suggests that there are six distinct phases in the maintenance program over the life of an asset. While the length of the six phases vary dramatically within each the nine classes the attributes of the phases are consistent.

| Advancing Maintenance | Attributes, example and strategic considerations for the maintenance team |
|---|---|
| **Phase 1:**<br>*"Too early to tell"* | The first stage in the life of an asset is typically dominated by routine maintenance activities, principally cleaning tasks. This is also coupled with preparations for warranty reviews to detect any warrantable construction defects. |

| | |
|---|---|
| | Under normal operating conditions and aside from any warranty defects, signs of potential failure ('P') should not be present. Or, the potential failures, cannot be detected with current diagnostic technology or test protocols. |
| **Phase 2:**<br>*"The emergence of potential failures"* | As the asset starts to advance in age, it become susceptible to potential failures ('P'), which are the leading indicators of the eventual functional failure ('F'). Phase 2 therefore represents the start of the P-F interval. For example, the perimeter cap flashing (coping) on a roof may exhibit signs of surface corrosion, which suggests potential failure where intervention practices (such as touch-up painting) can help to avoid active leaks if the corrosion were to allowed to deteriorate to an eventual discontinuity in the surface of the flashing (coping). Phase 2 therefore requires the first shift in maintenance practices. |
| **Phase 3:**<br>*"Getting past global minima"* | The 3rd phase begins when the survivor curve indicates that the earliest functional failures ('F') have ever been recorded against the statistical population (i.e., the global minima). For example, a population of 1500 2-ply SBS roofs in the City of Vancouver may indicate that the earliest recorded failure occurred at year 12. It is at this phase that the owners are able to ascertain whether their asset is an 'average', 'poor' or 'high' performer relative to other assets of the same population. An understanding of the asset performance rating provides a critical piece of information to adjust maintenance practices to help the asset achieve its full life potential. |
| **Phase 4:**<br>*"Getting to local maxima*" | This phase represents a significant window of opportunity for the management team. Based upon the data from the statistical population, it is the phase in which functional failure ('F') of the asset is now likely. The maintenance team endeavours to get the local asset to local maxima (F2). In the path from F1 to F2, the asset managers will reach point where equilibrium can no longer be achieved through continued reinvestment and the owners should pursue a path of renewal or redevelopment instead. An asset is considered to be beyond economic repair (BER) when it is more cost effective to replace the asset than it is to repair it. BER is often defined when the density of deficiencies has exceeded a threshold established by domain experts or regulatory standards. BER arises before functional failure. The asset stewardship program starts to shift from maintenance planning to renewal planning. |
| **Phase 5:**<br>*"Striving for global maxima"* | If the asset has managed to reach phase-5, then the team may be fortunate to seek the current global maxima or to set a new global maxima. For example, the management team may find that the asset on their building is achieving a level of performance that exceeds the service life tables in the published literature. |
| **Phase 6:**<br>*"Finding a new global maxima"* | This phase is outside the bounds of the global maxima of the statistical sample and is unlikely to occur until new technological advances are made. Alternatively, the asset is significantly deteriorated and therefore not performing its intended task. |

Table 9. The six phases of the multivariate deterioration model

While the boundaries of the six stages are not always clearly demarcated, particularly in the absence of data on the condition of the assets, the owners and operators can look to the model to provide guidelines. The following table provides a summary of the maintenance mix within each phase.

| | **TbM Activities** | **CbM Activities** |
|---|---|---|
| **Phase 1** | Routine maintenance on fixed intervals in accordance with the instructions in the maintenance manual. Primary focus is cleaning on seasonal cycles. | Minimal to no CbM is required other than field sampling as part of the warranty reviews to identify any construction defects. Although failure mechanisms have not yet emerged, or are not yet detectable through available technologies, the team |

| | | |
|---|---|---|
| | | should consider the types of predictive maintenance techniques and technologies to be used as the assets move into Phase 2. |
| **Phase 2** | Routine maintenance activities on fixed intervals. | Assemble the team of qualified experts to perform periodic field testing and diagnostic technologies to identify the leading indicators of potential failure (‘P’). Establish intervention strategies to avert functional failure (‘F’). |
| **Phase 3** | Routine maintenance activities on fixed intervals. TbM intervals are revisited and adjusted based on condition findings. | Additional CbM activities are introduced to start determining whether the asset can be graded as an ‘average’, ‘poor’ or ‘high’ performer. Average performers will require maintenance on standard intervals, high performer indicate that some maintenance can be pared back. The poor performers, on the other hand will require increased attention and investment. |
| **Phase 4** | TbM intervals are informed by the results of the condition findings. | The CbM activities have now been aligned to the assets based on their performance grades and the overall maintenance program has matured. The asset can continue to be monitored and intervention until the expected local maxima of functional failure (‘F2’). Begin the process of obtaining pricing for asset renewal and appropriating funds in the replacement reserve account. |
| **Phase 5** | Since the asset is now beyond economic repair, TbM is reduced to minimal levels (except in the case of statutorily regulated assets). Evaluation should only be considered to establish renewal requirements. | Since the asset is now beyond economic repair (BER), minimal CbM is performed, except to mitigate the risk of collateral damage until renewal of the asset. |
| **Phase 6** | Outside the current bounds of the global maxima of achievable asset service life | Outside the current bounds of the global maxima of achievable asset service life |

Table 10. Evolution of the maintenance mix across the six phases of the deterioration model

The deterioration model is one of the tools within the overall maintenance and renewals program. Table 11 provides an outline comparison of the multivariate model applied to three enclosure assets.

| **Deterioration Model Parameters** | **Urethane** (*Short life asset*) | **SBS Roof** (*Medium-life asset*) | **Glazing** (*Long life asset*) |
|---|---|---|---|
| Typical service life | 15 years | 25 years | 40 years |
| Examples of potential failures (‘P’) | Blistering, penetrations, gouges (care) | Delamination, degranulation of cap sheet; ridging | Sealant adhesive/ cohesive deterioration; warping |
| Examples of CbM methods to detect ‘P’ | Visual | Visual; thermal; exploratory openings | Visual; water testing; smoke testing |
| Local minima/maxima | Years 5/20 | Years 12/28 | Years 25/50 |
| P-F Interval | Years 3-15 | Years 5-25 years | Years 10-40 |
| ‘F1’-‘F2’ Interval | Years 10-15 | Years 18-25 | Years 25-40 |

Table 11. Application of the Extended P-F Interval to three different enclosure assets

## 5 FURTHER DEVELOPMENTS OF THE DETERIORATION MODEL

This paper has provided the outline of a multivariate asset deterioration model, which requires further development on numerous fronts.

- *Degradation Curves* – Domain experts, particularly those who work on failure modes and effects analysis (FMEA) and other branches of reliability engineering, should continue to establish and refine the libraries of leading, lagging and coincident indicators and the efficacy of different PdM technologies and field testing protocols.
- *Survivor Curves* – The existing suites of observed life tables must be incorporated into a broader longitudinal study on the retirement dispersions of different types of assets, in different regions, in different exposure conditions and under different maintenance regimes. The aggregation of larger statistical population of data is needed in order to refine the skewness, kurtosis and dispersions of the probability distributions.
- *Minimas and Maximas* –The private sector should be encouraged to share information on the local maximas/minimas of the assets under their stewardship and industry associations need to publish and disseminate this data for peer review. Aggregation of larger data sets will help to refine the maintenance strategies at the transition points between the six phases of the deterioration model and further industry understanding of the windows between ‘F1’ and ‘F2’.
- *Beyond Economic Repair* – Further work is necessary to quantify the density of deficiencies that can be more objectively used to establish that an asset has reached the end of its ‘useful service life’. These densities will vary based on the risk tolerances of different types of buildings and the risk profiles of different owners groups. To this end, further quantification is needed on the consequences of failure of different types of assets.
- *Total Cost of Ownership* – Calculation of the costs associated with maintenance at each of the stages of the model will provide useful insight into the cost impacts of different maintenance programs. Building owners need clearer quantification of the relative merits of preventive maintenance (PM), corrective maintenance (CM) and predictive maintenance (PdM) programs.

The multivariate model requires mindful integration of engineering to provide empirical data for the degradation curves, actuarial science for statistical data to the survivor curves, and facility operations to provide data on the efficacy of different diagnostic technologies and maintenance practices.

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