Living RCM Certified®: A Continuous Reliability Improvement Process

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Video: https://www.youtube.com/watch?v=A03lqEKazgs

Abstract

The paper addresses a universal long-standing issue recognized by incomplete, inconsistent, or inaccurate recording of failure mode history in the EAM (Enterprise Asset Management) database. A maintenance organization requires accurate reporting of failure mode events in addition to relevant condition monitoring[1] data leading up to those events. Predictive reliability analysis (RA) makes use of both data dimensions. When the EAM database contains correctly captured failure mode event history maintenance engineers can then construct predictive decision models. Such models relate impending failure probability to influential condition data. Condition data is abundant and well structured. However, poorly recorded maintenance history hampers the use of condition data for verifiable and optimal decision making. The obstacle imposed by inadequate capture of maintenance events, called "age data", may be overcome by integrating a new data entry form[2] into the maintenance work closure procedure. The form illustrated in Figure 5, that can be operated entirely on MS Office suite, integrates with the EAM system thereby enabling the capture of analyzable failure mode events. The resulting data is analyzed and converted into *verifiable* continuously improving condition-based decisions. In a mine mobile equipment fleet, for example, a sufficiently large sample[3] of repetitive failure, potential failure, and preventive renewal instances, is likely to occur in a relatively short time horizon[4] for the purpose of analysis.

Keywords: Predictive Maintenance, PdM, Condition Based Maintenance

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[1] "Condition monitoring data" is also referred to as "condition data".

[2] See *Figure 5: Strategy visibility, history capture, and feedback form for Continuous Improvement* on page 7.

[3] See Appendix 1 Data Samples for Reliability Analysis for definition

[4] For example, six to eighteen months for a fleet of 10 trucks.

Acronyms

Acronym	Description
APMS	Asset Performance Management System – computerized system for building and managing an asset's maintenance / management plan.
BOM	Bill of Materials – Spare parts and consumables for the repair and maintenance of an asset.
EAM	Enterprise Asset Management – Refers to computerized system for storing an asset's engineering and maintenance information
OEM	Original Equipment Manufacturer
RA	Reliability Analysis – a diverse set of procedures for analyzing maintenance history with the purpose of developing physical, operational, or maintenance plan changes that will improve an asset's reliability.
RCM	Reliability Centered Maintenance – a process for developing an asset's maintenance / management plan.
RULE	Remaining Useful Life Estimate – the conditional mean time to failure of an item estimated from the current moment.
SME	Subject matter expert – Person with knowledge and experience with the asset class in question including technicians, operators, engineers, OEM representatives.

Contents

A Continuous Reliability Improvement Process

That continuous improvement flows from well captured maintenance history is axiomatic. Yet a systematic process for improving reliability by studying past maintenance related events can be elusive, despite a great deal of discussion on the subject.

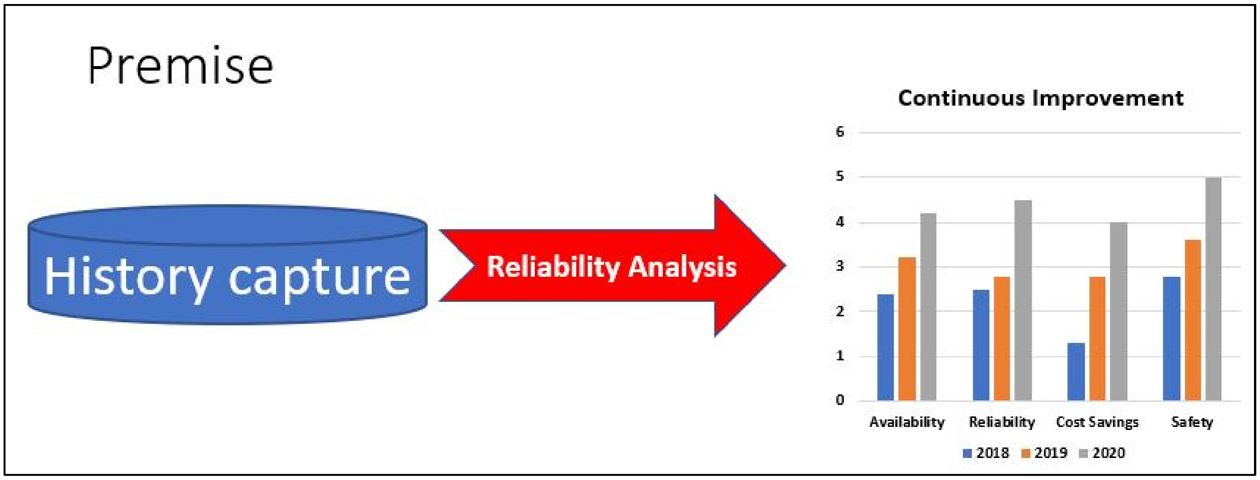

Figure 1: History Capture enables Continuous Improvement

In a nutshell continuous reliability improvement resulting from optimal predictive decisions depends on systematic reliability analysis (RA) performed on *adequately captured historical event data* in conjunction with the relevant monitored condition data[5].

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[5] Including vibration, oil analysis, sensor, and real time control (historian) data.

1. Maintenance History Tracking

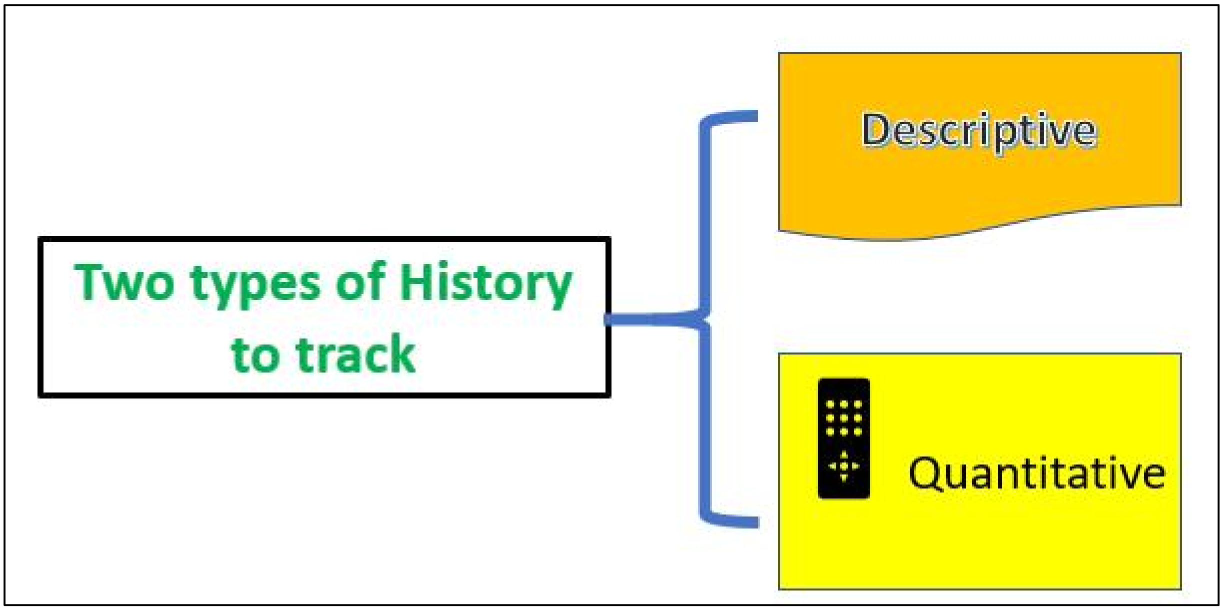


Figure 2: Two types of maintenance history tracking

Two types of history can be recorded and tracked:1) Descriptive, and 2) Quantitative. Engineers working in a maintenance setting typically analyze "Descriptive" history consisting of textual narratives, sketches, and photographs that document maintenance and operational problems encountered day to day. A subject matter expert (SME) reviews this information, then proposes and designs engineering or operational changes that will resolve the issue(s).

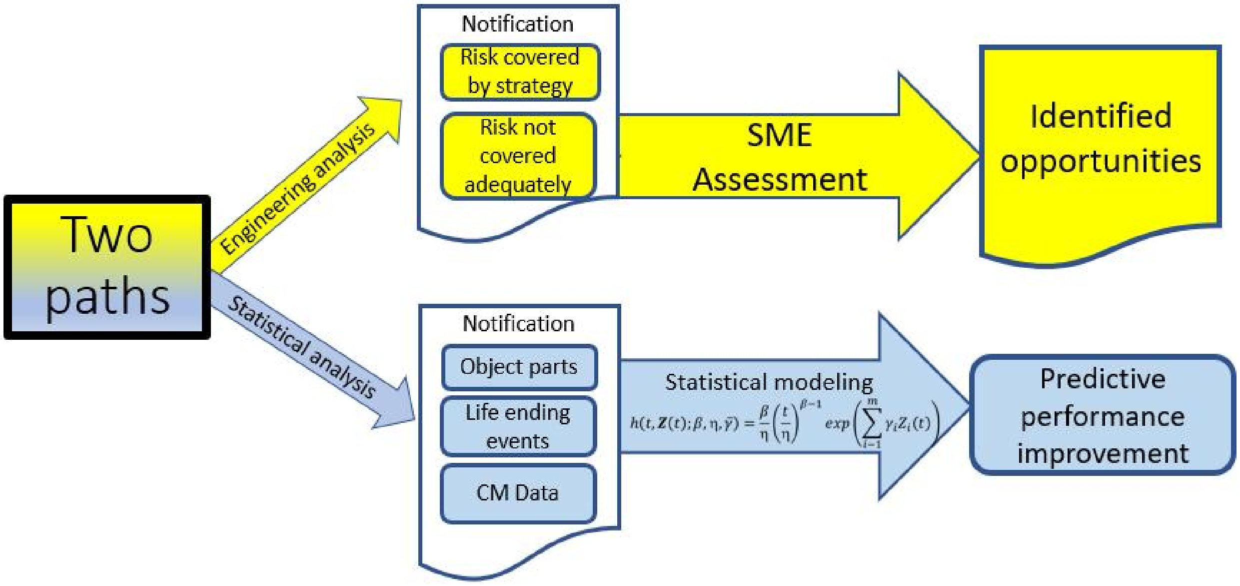


Figure 3: Two analysis paths

Maintenance engineers are less familiar with a second type of historical record, required for *quantitative* data analysis. Although powerful analytic tools and EAM database systems have long been available, this type of analysis is seldom performed successfully in the maintenance organization. The primary reason for the paucity of quantitative analysis in maintenance is well known. Failure mode event data having enough precision, completeness, and accuracy for purposes of analysis is generally unavailable in the EAM database. We propose a new data entry form (illustrated in Figure 5) that can ensure "analytic grade" data for reliability analysis.

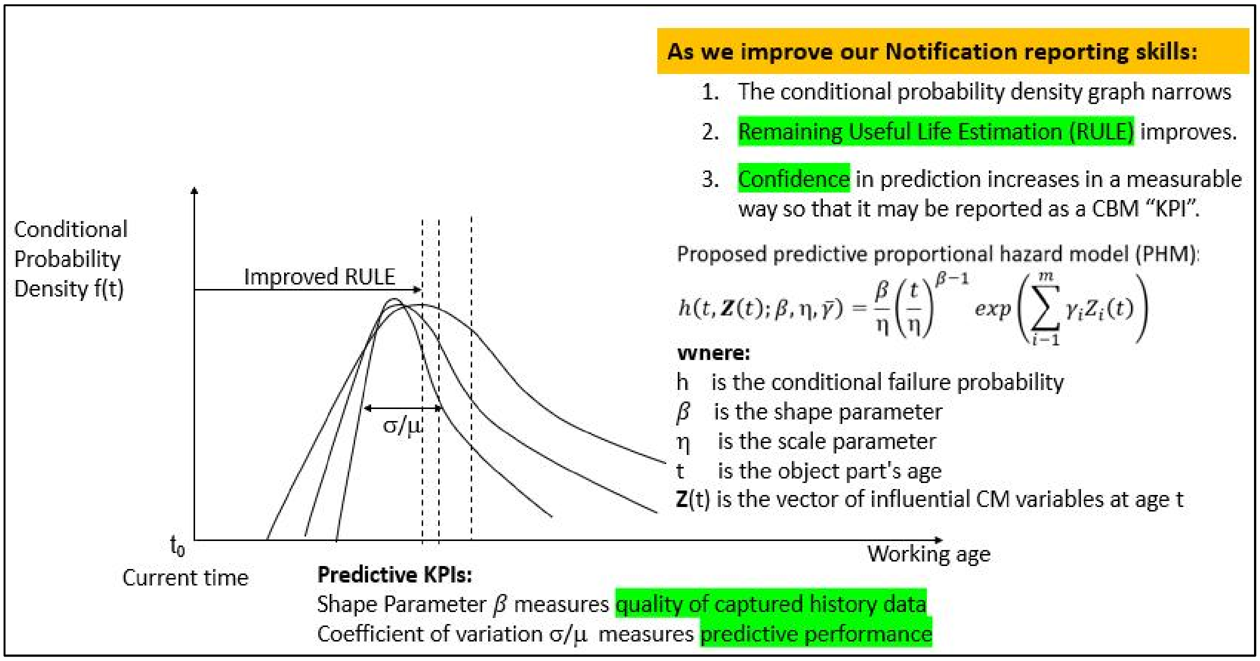
While the top path of Figure 3 represents the usual trajectory from field observation to opportunity, the lower path introduces a second avenue towards reliability improvement, particularly to Condition Based Maintenance (CBM/CM/PdM) programs. This second path allows failure mode event history to be correlated with condition monitored data in order to answer such questions as:

1. What is the actual predictive capability of a set of monitored data?

2. What are the monitored variables that are most influential to the probability of failure in an upcoming calendar or age interval?
3. What is the probabilistic relationship between those variables and an item's remaining useful life estimate or RULE?
4. What is the confidence with which a proposed predictive decision is taken?
5. What is the return on investment of a given predictive maintenance strategy?
6. How can predictive performance be measured?

A robust analytical approach towards answering these questions is illustrated in Figure 4.

2. Measuring and Improving Predictive Maintenance (PdM) performance



As we improve our Notification reporting skills:

1. The conditional probability density graph narrows
2. Remaining Useful Life Estimation (RULE) improves.
3. Confidence in prediction increases in a measurable way so that it may be reported as a CBM "KPI".

Proposed predictive proportional hazard model (PHM):

$$h(t, \boldsymbol{Z}(t); \beta, \eta, \bar{\gamma}) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} exp\left(\sum_{i-1}^{m} \gamma_i Z_i(t)\right)$$

wnere:

h is the conditional failure probability
β is the shape parameter
η is the scale parameter
t is the object part's age
Z(t) is the vector of influential CM variables at age t

Predictive KPIs:

Shape Parameter β measures quality of captured history data
Coefficient of variation σ/μ measures predictive performance

Figure 4: Predictive performance improves with maintenance reporting skills

Successful quantitative reliability analysis for predictive maintenance depends almost entirely on the reporting skills of the technician. The form of Figure 5 can assist in the development of such essential skills. Predictive improvement can be assessed using the Conditional Probability Density (CPD) relationship of Figure 4. CPD is like the well-known probability density function except that the origin is not positioned at age "0" when the item was new. Rather, it is the current moment in time, which is, of course, the moment at which a predictive decision must be made. The quality of that decision is measured in terms of confidence as reflected by the narrowness of the CPD curve's variability about the mean. The mean, by definition, is the object part's Remaining Useful Life Estimate or RULE.[6] Reporting the coefficient of variation σ/μ (the standard deviation divided by the mean) is a convenient way of tracking confidence in predictive decisions. The equation for hazard rate h shown in Figure 4 is known as the Cox Proportional Hazard Model [PHM) used routinely in actuarial risk assessment. The model predicts failure probability as a function of the object part's working age and the values of the relevant condition indicators at the current moment. The shape parameter β is influenced predominantly by (and thus is a measure of) the quality with which failure modes and their life ending events (FF, PF, or S) have been recorded in the field.[7] The parameters γ_i reflect the influence that each condition indicator bears upon the object part's failure probability in the upcoming period.

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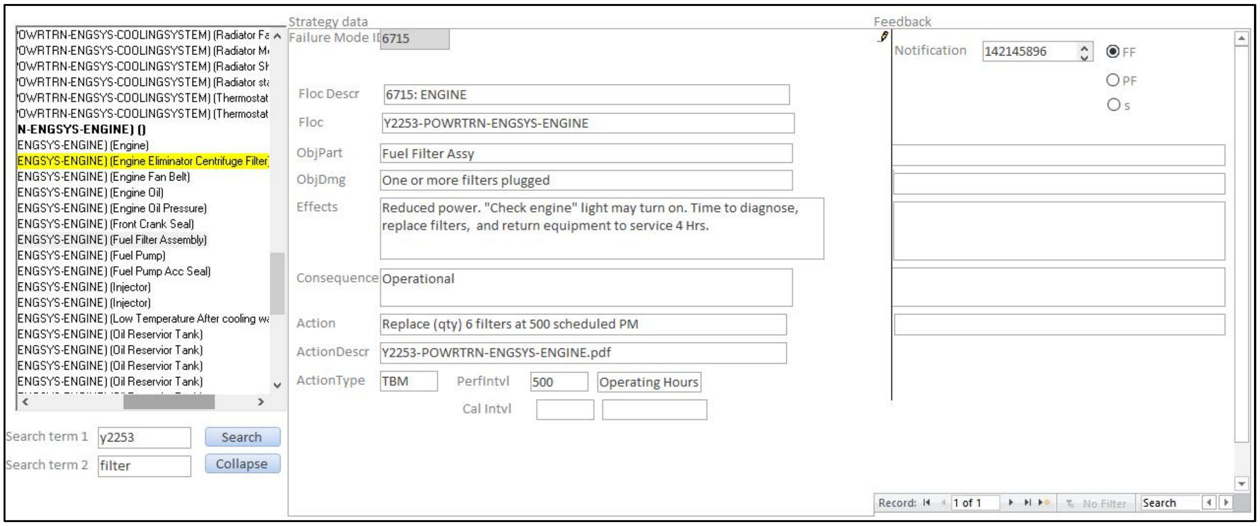
[6] Also known as the "Conditional Mean Time to Failure". For more information see: https://www.livingreliability.com/en/posts/the-elusive-p-f-interval/

[7] https://www.livingreliability.com/en/posts/defeating-cbm/

3. Strategy visibility, history capture, and feedback for Continuous Improvement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'OWRTRN-ENGSYS-COOLINGSYSTEM) (Thermostat
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N-ENGSYS-ENGINE) ()
ENGSYS-ENGINE) (Engine)
ENGSYS-ENGINE) (Engine Eliminator Centrifuge Filter)
ENGSYS-ENGINE) (Engine Fan Belt)
ENGSYS-ENGINE) (Engine Oil)
ENGSYS-ENGINE) (Engine Oil Pressure)
ENGSYS-ENGINE) (Front Crank Seal)
ENGSYS-ENGINE) (Fuel Filter Assembly)
ENGSYS-ENGINE) (Fuel Pump)
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Search term 1: y2253
Search term 2: filter

Strategy data
Failure Mode ID: 6715
Floc Descr: 6715: ENGINE
Floc: Y2253-POWRTRN-ENGSYS-ENGINE
ObjPart: Fuel Filter Assy
ObjDmg: One or more filters plugged
Effects: Reduced power. "Check engine" light may turn on. Time to diagnose, replace filters, and return equipment to service 4 Hrs.
Consequence: Operational
Action: Replace (qty) 6 filters at 500 scheduled PM
ActionDescr: Y2253-POWRTRN-ENGSYS-ENGINE.pdf
ActionType: TBM
PerfIntvl: 500 Operating Hours
Cal Intvl:

Feedback
Notification: 142145896
● FF
○ PF
○ s

Record: 1 of 1

Figure 5: Strategy visibility, history capture, and feedback form for Continuous Improvement

The data entry form of Figure 5 provides the basic foundation block for a Living RCM Certified®[8] continuous improvement process enabling predictive analytics along the lower path of Figure 3. The form consists of three window panes for use by technicians when recording their notification / work order data observations. The leftmost pane contains the asset RCM[9] tree view. The leaf nodes represent failure modes. When a leaf node is selected in the tree view the corresponding mitigating strategy will appear in the center pane. The technician assures himself, in the light of the center pane's revealed object part, effects, and strategy, that the selected node precisely represents the observed failure mode whose occurrence he should record. He does so in the rightmost frame. That pane *requires* selection of an "Ending Event" corresponding to each failure mode (object part) renewed during work execution. The ending event, one of functional

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[8] A closed-loop process for ensuring analytic grade data needed for predictive policy modeling and for continuous improvement of the RCM knowledge base.

[9] Based on the SAE JA1011 structure or other hierarchical representation of the asset's failure modes.

failure (FF), potential failure (PF) or suspension (S)[10] is a prerequisite for subsequent reliability analysis. Analysis requires precision in failure mode and ending event selection. Fortunately, errors or misunderstandings will be unlikely using this form given the visibility and completeness of the center pane's contextual information. An EAM transaction will update event history regularly from the form's underlying database.

Continuous improvement of the maintenance strategy itself may be routinely accomplished by considering a technician's on-the-spot observations during work execution. Text input areas in the third "Feedback" pane adjacent to each text box in the strategy pane encourage and provide a channel for the technician to suggest changes or additions to strategic information such as Object Part, Object Damage, Failure Cause, Effects, Consequences and Mitigation. Such valuable information fed back by the technician in an "RCM-like" way drives incremental strategy improvement so that the maintenance plan can better respond to observed reality.

A generally recognized management principle suggests that motivation increases[11] when we allow strategic decisions to be influenced by the employees who are most directly involved. RCM practitioners have documented increased credibility and effectiveness of the maintenance plan when it is influenced by technicians and operators.[12] The form's feedback pane enables and encourages this approach.

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[10] A renewal for any reason other than (potential or functional) failure.

[11] https://www.forbes.com/sites/mikekappel/2018/04/04/how-to-encourage-employee-involvement-in-decisionmaking/#36cbfc526561

[12] Moubray, RCM lI, Industrial Press 2nd edition Appendix 3. Human error

Declaring a failure mode's life ending event (in pane 3) can be challenging. Operational context[13] is a decisive factor when recording the event as one of functional failure FF or potential failure PF. Fortunately when completing the form’s third pane, given that the relevant facts are fresh, ensuing discussion among engineers, supervisors, and technicians will lead in a natural way to organizational standards for the consistent capture of event data. For example, when a certain function, say “To contain”, has been lost, this by definition would be reported as a “failure” when leakage rate exceeds a standard. But is it a potential failure PF or a functional failure FF?[14] The function in some contexts might be less critical, and, consistent with the equipment's strategy, the consequences of the failure may have been minimal. We might, in such a case, record the event as a *potential* failure. The identical seal failure in some other circumstance could be a *functional* failure *if* significant operational, maintenance, safety, or hidden[15] consequences were incurred. Declaring a failure as “functional” or “potential”, then, is context dependent. The foregoing thought process, if repeated with each notification closure will naturally result in the acquisition of analyzable data in addition to continuous knowledge and strategy improvement. The equipment strategy's "Effects analysis" should be updated when necessary in the rightmost "Feedback" pane to reflect significant new insight and associated logic in the declaration of functional and potential failure.

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[13] Likely effects of the failure mode on reliability, availability, and readiness

[14] Although reliability analysis requires only the declaration of failure regardless of whether it is a PF or FF, the distinction will allow the organization to track potential failure detection effectiveness as a key performance indicator of any predictive maintenance tactic.

[15] The detection and confirmation of a hidden failure, for example the failure of a safety device or backup system, should always be recorded as “functional failure” since the consequences are by definition (i.e. “The failure would not normally be detected were it not for the failure finding tactic.”) always incurred.

The data entry form of Figure 5 by using only the available tools within the Microsoft Office suite can be easily tested without excessive organizational disruption and expense usually incurred when introducing new external software applications.

4 EAM Catalog Profiles and APMS Synchronicity

Maintenance improvement initiatives in quantitative RA will likely be impaired when there is no enforcement of a one-to-one relationship between the EAM catalog profile object parts displayed as drop-down choices in the work closure form and the failure modes identified in the RCM derived strategy stored in the APMS[16]. Table 1 illustrates an example of a general problem:

Table 1: Lack of Synchronicity between EAM Catalog Profiles and RCM Strategy

Identified Object Parts in the APMS / RCM knowledge repository	**EAM Object Part at the same functional location**
Left Front Idler Roller Assembly	Adjuster Bolting
Right Front Idler Roller Assembly	Bushing
	Cap
	Idler
	Pivot Shaft Bearing
	Roller
	Seal
	Shaft
	Track
	Bogie Major
	Bogie Minor
	Crawler Shoe
	Drive Tumbler
	Equalizer Bar
	…

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[16] Asset Performance Management System e.g. Meridium.

We note that the catalog profile in column 2 is a more detailed listing of object parts than what had been uncovered during the development of the APMS equipment strategy. Often, the failure modes identified in an RCM analysis are a relevant subset of the EAM catalog profile list. But the RCM analysis can often include object parts *not* identified in (or expressed *differently* from) those in the catalog profile. The reasons for such discrepancies are historical. EAM catalog profiles were generated with the intent of strict corporate control over the dropdown lists of choices available to the technician. Since different plants have similar assets and operating processes a common lexicon for describing symptoms, object parts, object damage, and so on would help direct central engineering resources towards resolving common problems across the organization.

That reasoning is not incorrect, but a problem arises in the *detail* and *depth* required in day to day practice. Catalog profile lists were influenced primarily by engineering, BOM, and OEM maintenance manuals. When developing the catalog profiles, erring on the side of *greater* depth and *more* detail was considered conservative and thus desirable. However, when setting up the catalog profiles, scant attention was paid to the complexity of matching real situations encountered in the field to long lists of selection choices. The equipment strategy, on the other hand, was built with the benefit of SME and front-line experience using a structured RCM or similar process that addressed the *reasonably likely* failure modes, their effects, and consequences at a practical level of detail. Discrepancies in detail and depth such as those illustrated in columns 1 and 2 of Table 1, given their separate origins and processes, are not surprising.

Indeed, history capture in maintenance has generally suffered from a lack of guidance in determining just how much detail and depth are required. The solution is neither obvious nor consistent across the multitude of situations encountered daily. How should we establish practical standards for data capture that will satisfy the demands of reliability analysis and continuous improvement without excess, often unwieldy, detail and depth?

There are a variety of ways to deal with discrepancies such as those illustrated in the table. Each situation would depend on the maintenance and operational context. For example, if an item is routinely discarded or sent to a contractor for rebuild, and, if the frequency and consequences of failure are tolerable, the technician should not be required to parse the list of its internal object parts. In other words, that level of detail imposed by the catalog profile will not support corporate maintenance objectives for that asset in its operational context. In such circumstances, and upon discussion with the supervisor and/or SME, a “follow-up activity” can be proposed to eliminate or hide extraneous information and reassign the item itself as the “object part”.

An object part may be renewed as a result of failure (or suspension) but the part may not be listed in the catalog profile. Here too, an appropriate follow-up activity might be initiated by using the proposed form (Figure 5) to recommend adding that object part. Conversely, the form accommodates the situation where an object part may fail but that risk was not anticipated by the initial RCM analysis. Or, the effects and consequences evident to the technician during maintenance were not adequately described in the analysis. Each work closure is, using the proposed form, an opportunity to correct and improve the RCM knowledge base and EAM catalog profile.

Common to some of these problems is the structural difference between catalog profile and equipment strategy. In the RCM structure an object part and object damage are bound to each other as a combination[17]. This limits the number of choices for selection to about 6 or 7 on average. The catalog profile, on the other hand generally does not constrain the object damage when an object part has been selected. The number of choices can grow to the product of the size of each list. For example, if there are 12 choices for object part and 16 choices for object damage the number of permutations to be considered when populating the notification history tab expands to 192. Such "choice overload" discourages the care required for recording "analytic grade" failure mode event data.

Lack of synchronicity between the EAM lists and the RCM knowledge base contradicts several goals in maintenance knowledge management. The ramifications have yet to be fully explored but can be addressed by a continuous improvement initiative based upon the strategy visibility and feedback functionality of the form illustrated in Figure 5. Summarizing some of the hidden issues:

1. Lack of synchronicity between the two "knowledge" sources (RCM knowledge base versus EAM lists) detracts from the credibility of both.
2. Lack of consistent guiding principles as to depth and detail tends to confuse users, for example technicians, who are not sure which source is the "single source of knowledge".
3. Lack of a systematic process[18] for gradually and continuously synchronizing the two sources impedes quantitative reliability analysis. Reliability analysis requires

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[17] A failure mode can be thought of as a sentence consisting of three grammatical segments: noun (Object part), action phrase (failure mechanism), and "due to" clause (failure cause). The depth at which to identify the Object part and whether specifying the specific mechanism and cause adds value will depend on context.

[18] Such as that enabled by the form of Figure 5

that failure mode instance reporting follow strict but simple rules that can be easily enforced.

5. Conclusion

This paper identified the problem of incomplete information in the maintenance process that impedes reliability analysis needed for predictive performance. We proposed a simple data entry form based on the MS Office tool set used in conjunction with existing EAM user interface that resolves the data inadequacy problem. We also described a robust analytical approach for predictive modeling that becomes available to the maintenance engineer upon implementation of the proposed process for attaining analytic grade event data.

Appendix 1 Data Samples for Reliability Analysis

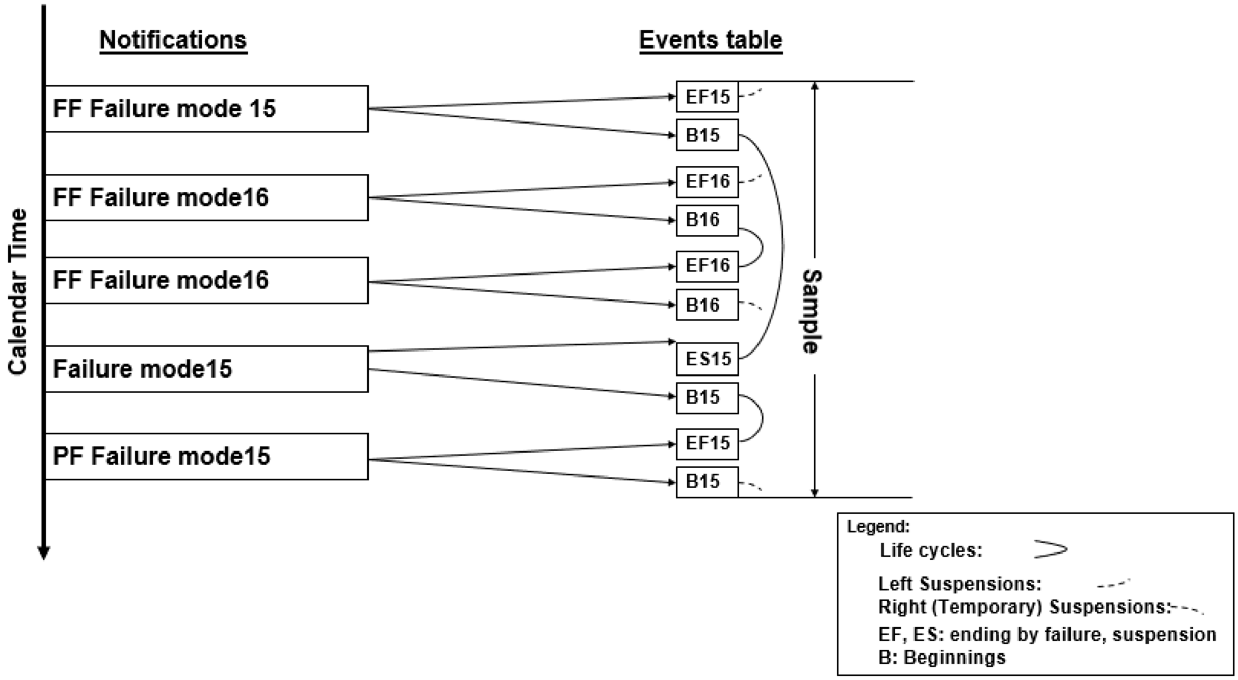

Figure 6: Sample Extraction for Reliability Analysis

The sole purpose of captured (quantitative) history data, specifically, the renewal of object parts, is to provide reliability engineers with the ability to perform RA on a data sample depicted graphically in Figure 6.

A sample is bounded within a calendar window. Data “points” are the lifetimes of failure modes occurring entirely or partially within that window. The lifetimes included in a sample are represented by the arcs shown on the right-hand side of the figure. Each arc connects two events, a beginning event B with an ending by failure EF or an ending by suspension ES.

RA, in its basic sense, is the “counting” of the arcs in the sample. Each failure mode’s age at its life ending event will have been recorded through the maintenance history capture process. The dashed arcs represent suspended lifetimes, which are the lifetimes that occurred partially outside the sample window. Suspended data contributes to the uncertainty of an analysis. RA software algorithms manage the uncertainty associated with suspensions so that confidence in a decision can be stated and thereby considered by stakeholders.

The EAM system can track an asset’s working age in calendar or in operational hours (or in any other units considered to be proportional to the accumulated stress on the asset). RA software calculates the age of a given failure mode (i.e. an object part) at the moment of an event. The working age of an object part at the time of its life ending event is used by the reliability analysis algorithm to develop the predictive model.

It is important to emphasize that RA requires, not only an object part’s life duration but also each failure mode instance’s life ending event. Current EAM procedures do not explicitly record object part life ending events. A failure mode instance can end with one of three events: 1) Functional failure (FF), 2) Potential failure (PF), and 3) Suspension (S). A Suspension is the renewal of an object part for any reason other than failure. Often maintenance history databases do not distinguish Failure from Suspension. Reliability engineers, consequently, cannot develop policies based on a reliability analysis with the degree of confidence necessary for their adoption in an equipment's age based or predictive strategy. At best, a Suspension is often assumed to be a Failure. Such an assumption results in low confidence and overly pessimistic maintenance decision making.