Assumptions Inherent to Designing for PdM, CBM or RCM

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October 2018

For the purposes of this paper, the discussion shall specifically address the impact PdM, CBM and RCM on the replacement activities as opposed to other forms of adjusting, polishing, tuning, or cleaning, etc.

Although PdM, CBM and RCM promise to support a prioritized level of attention to Safety and Availability, their application must endure challenges in counter-opposite areas in Design Development intending to assure operational success or reduce Cost of Ownership. The collective performance in both the Design Development and the Sustainment lifecycles will determine if any combination of Predictive, Conditioned-based or Preventative Maintenance activities are most effective throughout the Product Lifecycle.

In pushing PdM's treasured "P-point" (Potential failure point) to the right as far as possible, the investment becomes directed to low-level specialty engineering methods and techniques. While any predictive and Conditioned-based Maintenance, or "CBM" ambitions for military programs can bask in incredible appeal at any time prior to asset delivery, they can become expensive endeavors that ultimately divorce themselves from financial accountability during the sustainment lifecycle.

Integral with PdM is the application of a CBM methodology that relies upon a means to detect and act upon the progression towards any specific failure(s) within a "time-window" or "failure horizon" prior to experiencing the failure(s).

Reliability-Centered Maintenance or "RCM" is a maintenance tactic premised upon the replacing of components in accordance with a schedule (time or distance, etc.). This schedule is derived from the determining of the independent "failure rates" for each component included in the subassemblies or system(s). While RCM offers a cheap alternative to diagnostics engineering on lower complexity or non-critical systems, it inevitably invites significant opportunity to force diagnostic errors inherent with the assumptions characterized in its approach.

More recently, articles written on the increased success of RCM are crediting such successes to the adoption of broadening the use of "lower-fruit level" CBM methodologies. The augmenting of RCM with specialized CBM practices is certainly a good next step for RCM, but it is still lugging around the same basic assumptions that prevent it from attaining maximum effectiveness.

***Initial* Eight Assumptions with RCM:**

1) Each individual component will fail independently
2) Each individual component will fail relatively consistently with its computed failure rate.
3) Must define the components before performing the RCM analyses.
4) Replacements are scheduled & performed in advance of "expected" failure(s).
5) Defining "Test Coverage" is unnecessary for RCM.
6) Fault Isolation effectiveness is predominately a sustainment endeavor.
7) The determining of "Fault Groups" is not an objective of the RCM discipline.
8) Historical or empirical data is effective at resolving similarly reported failures in the future.

<u>Arguments against the *Initial* Eight Assumptions with RCM:</u>

1) *Each individual component will fail independently*

   Ultimately, failure(s) occur when they occur regardless if RCM is performed or not. Additionally, dependent or independent failures may occur at any time regardless if the failures can be detected at any time prior to, or during the performing of any new testing activity.

   Multiple failure(s) may have occurred since the performing of the most recent test or maintenance activity. The assessing of the ability to detect or isolate multiple failure(s) is not a requirement for the delivery of many systems, which is unfortunate and assumes unnecessary risk. This requirement and/or procedural shortcoming ultimately becomes a significant contributor to the mis-isolation of failures as well as "masked" failures.

   Replacements may require the removal of non-failed components simply because the development of the design was unable to be influenced by diagnostics engineering for more effective detection and/or isolation. RCM is not concerned with the removal of failed or non-failed parts as much as it is concerned with performing the replacement procedure in accordance with its scheduled maintenance event.

   In specific applications, the airline industry has augmented RCM with "on-condition" inspections in an attempt to extend the component's replacement interval as described in its replacement "schedule", the inspections can be exclusive to the practice as stated in the procedure. However, this RCM "tactic" is beyond the scope of pure RCM simply because of its reliance upon CBM during the RCM intervals. This augmented practice is staring in a better direction, but it is still short of the promise land.

2) *Each individual component will fail relatively consistently with its computed failure rate*.

   Again, failure(s) occur regardless if they are specifically described in any design assessment product or in any published documentation – with or without the augmentation of scheduled CBM techniques (as identified above). While the approach of scheduling replacement activities certainly offers merit, it still is unable to avert attention to component failures not described in the inspection procedure nor capable of tested by the technician or equipment at the time.

   Every design places constraints on the diagnostic capability – particularly those designs not influenced for diagnostic effectiveness during the development process. When performing Diagnostic Engineering during the development process, RCM would benefit from new information that is otherwise unavailable or unknown.

   Diagnostic Engineering identifies the utility or restrictions of the design's characteristics and suggests design modifications for improving scope or value of the maintenance actions. In this regard, more of the designer's knowledge is captured within a collaborative development environment that is otherwise discarded. As a result, the planning or performing of any preventative maintenance activities are able to benefit from considering the diagnostic impact before or after the replacement procedure is performed.

3) *Must define the components before performing the RCM analyses.*

Since designing for RCM is unable to effective until after the replaceable components have been defined at a point after the functional design has been determined in the design development process, the opportunity for influencing the design for maximum diagnostic effectiveness is already marginalized. This slight delay yields a lost opportunity since the ability to describe the individual component failure rates, failure modes, or failure effects are dependent upon having decided the components to be included in the design. Furthermore, for any re-design or changes to the design, any defined components may be swapped with any other components and thereby cause the failure properties to be reworked beyond simply the swapped components in the design.

If, however, the components are initially described in functional form, where the failure modes and failure effects could be immediately represented as "functional failure(s)", this would provide a framework to describe the propagation of these functional failures across any other interdependent designs – thus observing the impact throughout the subsystem and system level of the design.

The exposing of the impact of interdependent functional failures in early design development is beneficial in a myriad of ways to improve the diagnostic integrity of the design, including:

- Hardware partitioning & optimal sparing
- Ranking infrequent & less critical failures to more frequent and critical failures
- Improved BIT design to address more effective diagnostic objectives/future technologies.

4) *Replacements are scheduled and performed in advance of "expected" failure(s).*

Since many failures occur when they occur, which may not be consistent with the frequency of our failure predictions, we still have to describe an effective "Run-To-Failure", "RTF" maintenance strategy. Independent of Diagnostic Engineering, RCM is unable to assess the effectiveness of an RCM versus RTF maintenance strategy during design development. Certainly, we can replace items in advance of failure, but for non-critical failures, this may increase cost of ownership without increasing safety, operational success or availability.

Complicating the validity of the assessment, RCM is unable to consider the impact of maintenance upon the future failures. This is essential if replacements are performed due to any other cause than a scheduled replacement activity, which will certainly occur. Additionally, when performing an RCM activity, we may cause more frequent replacements and more unscheduled replacements, due to either mis-diagnosis or lack of comprehensiveness of the fault isolation activity.

If replacements require the removal of "boxes", LRU's, WRA's, "fault groups" or "assemblies" due to the inherent design (or test) constraints of the fault isolation methodology or technology, non-failed components are also replaced that may still have considerable "Remaining Useful Life" (RUL). As such, the sustainment paradigm takes repeated cost hits from the inability to "manage" (by fault isolation) insipient failures in a non-ambiguous manner. This often leads to the *prematurely* replacement of components solely due to fault isolation weaknesses and happenstance.

When performing a retest and the LRU does not report any failures, how would the practice of RCM determine if the LRU is, "good" if it is unable to define what functions are actually being fully tested?

5) *Defining "Test Coverage" is unnecessary for RCM*

RCM is not typically concerned with the knowledge of "Test Coverage" during design development. When "on-condition" maintenance inspections occur as an augmentation of RCM, the approach inadvertently infers the limited use of "Test Coverage" in the sustainment paradigm. That said, RCM is defined during design development and relies upon a separate discipline (Maintenance Engineering) to determine the extent (scope and frequency) of the application of "on-condition" maintenance inspections.

Without Diagnostics Engineering playing an integral role with RCM, "Test Coverage" is effectively dismissed. At this point, RCM essentially becomes a contributor to the deploying of a segregated and independent maintenance philosophy.

6) *Fault Isolation effectiveness is predominately a sustainment endeavor.*

Fault Isolation Effectiveness is essentially dismissed and not typically a concern of RCM during design development. This practice has traditionally been a major contributor to such symptoms of ineffective sustainment as "No-Fault Found" (NFF), "Can Not Duplicate" (CND), "Re-Test OK's" (RETOK) and a host of other cost drivers resulting from inaccurate or unnecessary replacement activities.

RCM is designed around a requirement to schedule replacements of components before a failure is detected or before a critical failure may result from combined non-critical failures. The discipline requires the identification of the lowest level failure modes for any specified "component(s)" within that design and the resulting "failure effects" for each level of the design architecture (e.g. MIL-STD 1629A).

Although the FMECA provides a method to describe the detection method(s) for the observance of any (impending or "hard") failures, there is no requirement for the Reliability Engineer to include any restrictions upon that detection method as may be constrained by the integration of any other design along with other designs to be integrated into a hierarchical systems design. The assumption is that the required FMECA product is an independent level of the design and once delivered, it is accurate to its independent piece of the systems' design.

The troubles with the lack of concern for "Fault Isolation Effectiveness" is that it is a symptom of employing anti-collaborative design development processes. Sure, Systems Engineers will argue that the Fault Isolation is being performed "as required" and by another discipline – typically Maintenance Engineering or as an "aside" by other dedicated Reliability Engineers. Surprisingly, to some traditionalists, this is not an acceptable answer in today's environment. However, this is a core competency of high-end Diagnostics Engineering.

Fault Isolation Effectiveness should be able to be fully performed in any aspect of the operational and support environment. This is another giant step beyond traditional Health Monitoring expectations that merely "sense" a failure. If using a high-end "Health Management" capability, performing "diagnostic reasoning" on-board can avert costly false mission aborts and diffuse uncorroborated system false alarms. However, this is a high-end Diagnostics Engineering competency that needs to be worked in full integration with all RAMS design AND sustainment activities.

7) *The determining of "Fault Groups" is not an objective of the RCM discipline.*

The determination of "Fault Groups" is just not an endeavor performed with traditional RCM. Diagnostics Engineering, on the other hand, determines the constituency in each Fault Group simply by determining the design's inherent "Test Coverage" at any level of the design. Going a step further, the "Fault Groups" for any BIT, will differ as determined by the "Test Coverage" of the BIT (via embedded and/or Health Monitoring/Management).

For on-board operational Health Management, the objectives of "Safety" mitigation is prioritized over any other operational objective. As such, the identification of the Fault Groups are secondary concerns and can be immediately determined as based upon the "Test Coverage" of any of the BIT as corroborated with any other BIT during any mode of operation, if high-end Diagnostics Engineering is performed during design development.

If the diagnostic "Test Coverage" is unknown or under-developed during design development, the determining of Fault Groups at that initial operational level is an uncertainty. Likewise, any ensuing maintenance activity beyond the on-board remediation (if any) will begin at a compromised starting point that has dismissed a full pallet of diagnostic conclusions otherwise available. Regardless of the capability of Automated "Test" Equipment, a thorough testing of any pulled replaceable units (LRU's, WRA's, etc.) are commenced with LCN-savvy, but otherwise simplified Fault Code Entry Points unfortunately dismissive of much broader diagnostic certainty.

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8) *Historical or empirical data is effective at resolving similarly reported failures in the future.*

Historical or empirical data "may" be effective at resolving similarly reported failures in the future. If the constraints of (operational) Diagnostic capability continues to permit the pulling of "non-failed" components along with or without "failed" components, even augmented with on-condition RCM, the schedule is already compromised. The use of empirical data to influence future "testing" and "fault reasoning" sequencing or tactics on future maintenance activities can be harmful as well as helpful. How would we "know" if we replaced "all" of the (assumed) failure(s) at that next level of repair?

The most universal and capable ATE is always going to be limited by the diagnostic integrity of the design – and as constrained by each integrated level of the system design.

In any environment where empirical data is used to leverage an RCM maintenance philosophy, a strict adherence to consistency must be performed throughout the Product Lifecycle, else the empirical data becomes more and more circumstantial. The schedule and quality of performance of RCM for such purposes must be held to a very high level of competency and regularity, which is atypical of its application without Diagnostics Engineering.

Whether using RCM, CBM and/or PdM as a maintenance strategy, the ability to assess which sustainment strategy (or balance of strategies) would be the most effective for any particular system is dependent upon establishing a canvas that can instinctively perform, by simulation, a myriad of comprehensive assessments. Too frequently, these strategies have been worked and developed for programs in accordance with political partnering and economic support rather than from the merits of assessing their independent or interdependent effectiveness by the performing of an operation support simulation.

However, if using the vast capabilities of high-end Diagnostics Engineering, the assessment of the effectiveness of any maintenance philosophy can be traded during design development quite effectively and essentially seamlessly in a collaborative PLM environment. But not without first establishing the diagnostic capability of the operational design at a time when influencing the design development so the sustainment objectives can be achieved effectively by average-skilled personnel.

While in design development, we may discover that the development of specialized sensors may typically accompany the promise of delivering on the application of high-end PdM techniques and technologies. The catch is that, while sensor development and algorithm refinement are integral to gaining the precision in measuring of the failure progression at the lowest level of the design, the approach typically omits the inclusion of an equally precise and interdependent means that is capable of assessing the merits of the technology in terms of the sustainment objectives.

In addition to the design level, such product assessments must also be performed at the "integrated" systems level" throughout the product development of the design. Such assessments would require the consideration of all other co-developed (internal or external design) subsystems that will be integrated into the full (asset level) system design.

However, while being charmed with the low-level, discipline-specific vernacular, we must not lose sight of the single most important omission that inferred within the elegance and promise of PdM, CBM, RCM or any supporting Maintenance activity.

What we should be seeking throughout any serious PLM endeavor is the ability to validate the Diagnostic capability at not just the design level, but also at the subsystem or integrated system design. In this manner, we will discover which functions or failures can be detected in any particular independent design contained within the asset – and precisely those that we are unable to detect at any other integrated system level(s).

Furthermore, to secure the utility of the investment into PdM for such high fidelity for any low-level capability, it requires equally capable higher-level attention. Otherwise, we could not be certain which functions or failures are detectable at any level of the design hierarchy, for any given mode of operation – without maintaining equal diagnostic precision at the highest system level. At this point, we can ask more thought-provoking questions as, "Have we accounted for any lack of detection at the systems level in our design assessment products, including the FD/FI/FA, FMECA or FTA?"

If we are considering the investment into more advanced techniques to establish tighter failure horizons, accuracy or confidence in Physics of Failure (PoF) ambitions, such as HALT or HASS, etc., then we need to *know* if we can *uniquely* assess the failure progression as well as the failure(s) in a myriad of operational modes.

Ubiquitously, those involved in PdM or any form of CBM endeavor too often dismisses the value of being able to validate the diagnostic capability of the full and operational asset. Instead, the activity dives into low-level discussions and swims in a pool of its disciplinary-specific vernacular. Such low-level focus is a result of the customer or systems integrator "assuming" that the diagnostics is a given characteristic in any large, complex or critical system as an output from their traditional design processes. Wrong - that couldn't be any further from reality. The revelation for those folks is that PdM, RCM, Corrective ("Run-To-Failure", "RTF") or Opportunistic Maintenance strategies ultimately rely of the diagnostic integrity of the entire integrated and fielded/deployed or operational asset. If Diagnostics Engineering is *not* a specifically required activity, investment into more alluring approaches for sustainment are simply not going to be as effective as promised.

Simulation Summary Report

Simulation:	Run to Failure	Sched. Maint. (tight)	Sched. Maint. (loose)	Prognostics
Failure Statistics				
Likelihood of Loss of Operation	100% at 1,280 hours	100% at 1,360 hours	100% at 1,680 hours	100% at 1,520 hours
Likelihood of Loss of Equipment	100% at 1,440 hours	100% at 1,760 hours	100% at 2,000 hours	100% at 1,920 hours
Likelihood of Loss of Life	62.098% at 4,000 hours	61.537% at 4,000 hours	62.612% at 4,000 hours	61.904% at 4,000 hours
Prognostic Statistics				
Critical Failures Prognosed	N/A	N/A	N/A	4.787 (27.007%)
Critical Failures Not Prognosed: Loss of Operation	2.780 (15.694%)	2.828 (20.004%)	2.800 (26.677%)	2.787 (15.721%)
Critical Failures Not Prognosed: Loss of Equipment	14.255 (80.486%)	10.622 (75.143%)	7.015 (66.830%)	9.480 (53.484%)
Critical Failures Not Prognosed: Loss of Life	0.677 (3.820%)	0.686 (4.853%)	0.682 (6.493%)	0.672 (3.788%)
Maintenance Statistics				
Corrective Maintenance	54.646 (100.000%)	51.753 (87.637%)	46.943 (72.724%)	50.747 (90.984%)
Scheduled Maintenance	N/A	7.301 (12.363%)	17.607 (27.276%)	N/A
Maintenance due to Prognostics	N/A	N/A	N/A	5.029 (9.016%)
Replacement Statistics				
Replacements due to Item Failure	42.157 (77.146%)	39.143 (66.283%)	34.320 (53.168%)	38.130 (68.362%)
Replacements due to Diagnostic Ambiguity	12.489 (22.854%)	12.611 (21.354%)	12.623 (19.556%)	12.618 (22.622%)
Replacements due to Prognostics	N/A	N/A	N/A	5.029 (9.016%)
Replacements due to Scheduled Maintenance	N/A	7.301 (12.363%)	17.607 (27.276%)	N/A
Remaining Useful Life Per Replacement	1,392.812 hours (3.164%)	1,507.617 hours (5.347%)	1,634.176 hours (9.279%)	1,480.756 hours (6.409%)
Remaining Useful Life Per Early Replacement	2,222.812 hours (4.791%)	2,322.021 hours (7.652%)	2,418.948 hours (12.072%)	2,287.480 hours (9.290%)
Cost-Related Statistics				
Wasted Item Cost	274.53	680.85	1,162.97	392.29
Wasted Item Cost due to False Removals	274.53 (100.000%)	279.49 (41.050%)	276.79 (23.800%)	279.03 (71.130%)
Wasted Item Cost due to Prognostics	N/A	N/A	N/A	113.25 (28.870%)
Wasted Item Cost due to Scheduled Maintenance	N/A	401.36 (58.950%)	886.18 (76.200%)	N/A
Cost of Extra Replacements	105.24	399.31	694.67	133.24
Cost of Extra Replacements due to False Removals	105.24 (100.000%)	109.74 (27.483%)	105.26 (15.152%)	110.55 (82.965%)
Cost of Extra Replacements due to Prognostics	N/A	N/A	N/A	22.70 (17.035%)
Cost of Extra Replacements due to Scheduled Maintenance	N/A	289.57 (72.517%)	589.41 (84.848%)	N/A

The expected values will evolve throughout the Sustainment Lifecycle – depending on Maintenance mix PdM, CBM, RCM.

Then, what is the good news? Well, *all* of these maintenance philosophies (PdM, CBM, RCM & RTF) need to be balanced in terms of (the same four goals) Safety, Availability Operational Success and Cost of Ownership. All can be simulated once the diagnostic integrity of the operational asset(s) is captured, assessed, validated and cross-validated with the design data from all contributing design disciplines and teams.

When worked in a collaborative design development with Diagnostics Engineering, we will be able to answer many questions not previously whispered, such as:

- How did we balance PdM (predictive) with RCM (preventative) and RTF (corrective) & how does it work to our LORA. How does the proper mix impact either of the four goals - over time - considering the impact of a maintained system?

- How does any mix of these capabilities increase availability without increasing cost of ownership above a certain threshold?

- How will any mix of maintenance actions impact our Mean Time Between Unscheduled Maintenance (MTBUM) or the Mean Time Between Critical Failures (MTBCF), Operational Aborts, “Diagnostic” False Alarms and/or any RAMS metrics?

Simulation Summary Report

Simulation:	3000 hours (w/o Prev. Maint.)	5000 hours (w/o Prev. Maint.)	8000 hours (w/o Prev. Maint.)
RAM-T Metrics			
Reliability	0.97681	0.96994	0.96584
Mission Length (for Reliability)	2.50 hours	2.50 hours	2.50 hours
Inherent Availability	0.98858	0.98464	0.98144
Operational Availability	0.86473	0.81982	0.78728
Mean Logistics Delay Time (MLDT)	24.00 hours	24.00 hours	24.00 hours
Mean Time to Repair (MTTR)	106.369 minutes	104.042 minutes	103.988 minutes
Mean Time to Replace (MTTR)	75.854 minutes	72.613 minutes	71.774 minutes
Mean Time to Isolate (MTTI)	30.515 minutes	31.428 minutes	32.214 minutes
Fault Detection	96.70%	94.72%	94.26%
Fault Isolation to 1 Item	92.50%	92.30%	92.18%
Fault Isolation to 2 Items or less	92.51%	92.30%	92.19%
Fault Isolation to 3 Items or less	92.51%	92.30%	92.19%
False Alarm Rate (from diagnostics)	0.959%	0.829%	1.035%
Failure Statistics			
Failures	28.358	61.306	111.532
Unique Failures	26.690	43.852	57.350
Total Percentage of Possible Failures	12.187%	20.024%	26.187%
Diagnostic Statistics			
Detected Faults	27.422 (96.699%)	58.070 (94.722%)	105.134 (94.264%)
Non-Detected Faults	0.936 (3.301%)	3.236 (5.278%)	6.398 (5.736%)
Faults Isolated to Fault Group of Size 1	25.366 (92.502%)	53.596 (92.296%)	96.914 (92.181%)
Faults Isolated to Fault Group of Size 2	0.002 (0.007%)	N/A	0.004 (0.004%)
Faults Isolated to Fault Group of Size 4 or Greater	2.054 (7.490%)	4.474 (7.704%)	8.216 (7.815%)
Diagnostic False Alarms	0.272 (0.959%)	0.508 (0.829%)	1.154 (1.035%)
Replacement Statistics			
Removals	35.044	74.700	135.462
True Removals	27.422 (78.250%)	58.070 (77.738%)	105.134 (77.611%)
False Removals	7.622 (21.750%)	16.630 (22.262%)	30.328 (22.389%)

The expected values will evolve throughout the Sustainment Lifecycle – depending on Maintenance Events & Philosophy.

The customer or the OEM must be in a position to welcome discussions that include such questions as described in the paragraph above – and dozens more. The OEM should be able to answer all of those inquiries with confidence and should be able to speak to the expected value of RCM within the context of the designs’ diagnostics constraints and within the maintenance philosophy as required by the program. The path to be in such a confident position will be with those who discover the value of Diagnostics Engineering.

Related Topics:

Evaluate PHM as an Integrated System Capability

Diagnostic Assessment of BIT and Sensors

Accounting for PdM in the FTA Assessment Product

Video Links:

Integrating Diagnostics and Reliability

Designing for Effective Sustainment

Diagnostic Validation