# Diagnostics "After" Prognostics:

## Steps Toward a Prognostics-Informed Analysis of System Diagnostic Behavior

Eric Gould
DSI International
Orange, California USA
egould@dsiintl.com

***Abstract*—Although substantial effort has been spent developing new metrics for the evaluation of prognostic performance, relatively little attention has been directed toward ways in which existing systems analysis practices should be modified to incorporate knowledge from Prognostic Health Management. This paper discusses an approach to modifying system design assessments (such as Reliability, Testability and Maintainability) based on parameters provided within System Prognostic Requirements.**

***Keywords—Prognostics, Testability, Requirements, Metrics***

### I. INTRODUCTION

Over the last decade or so, the demand for increased prognostics within complex, critical systems has resulted not only in changes to how these systems are developed, but also to the way in which designs are analyzed as they are developed. In particular, system analysis practices that are affected by changes in Prognostic Health Management (such as Reliability, Testability or Maintainability analysis) must now either incorporate prognostic details into their calculations, pursue custom solutions to take prognostics into account, or ignore prognostics altogether.

This issue is exacerbated by the fact that much of the value in Reliability or Testability analysis can only be realized when design feedback is available relatively early in the development cycle. Because not only prognostic development, but also the evaluation of prognostic performance are, at this point in time, notoriously time-consuming, it is unlikely that information derived from formal prognostic performance metrics (such as those described by Saxena, et al [1]) can be incorporated into engineering analyses early enough to profitably impact system development and decision-making.

As an alternative, some projects have implemented custom solutions, modifying design-time engineering analyses to account for the expected impact of prognostics concurrently under development. There is, however, no standardized or officially sanctioned approach to accounting for prognostics within other system analyses. For each project, systems analysts (in consultation with the customer) must ask a series of questions. For example, diagnostic analysts must decide whether fault detection & isolation metrics should take full or partial credit for prognosed failures, or whether Testability analysis can be constrained to cover only the non-prognosed portion of the design. In either case, should prognostic horizon and/or accuracy be taken into consideration? If so, then how? Is the end user expected to always respond to prognostic notifications without questioning them, or will there be cases in which some sort of confirmation will be required before a maintenance action is performed? Should diagnostic analysis be consulted when determining the optimal areas in which to develop prognostic measurements or will only Reliability and Criticality considerations be involved in the selection of prognostic candidates?

This paper outlines an approach to incorporating prognostic considerations into Reliability, Testability and Maintainability analyses by representing expected prognostic behavior in terms derived from system prognostic requirements. We will first identify a small set of parameters that can be used to represent system prognostic goals and then demonstrate how several system prognostic requirements from current and recent development contracts can be represented using those parameters. We will then show how these parameters can be used to define prognostic behavior within ***eXpress***, DSI International's diagnostic engineering and analysis tool. Finally, we will discuss how these prognostic definitions can be used not only to modify the results of standard measures of diagnostic effectiveness (using fault detection and isolation metrics defined within IEEE Standard 1522-2004 [2] as a basis for the discussion), but also to inform simulation-based approaches to assessing the impact of different prognostic, diagnostic and maintenance strategies.

### II. SYSTEM PROGNOSTIC REQUIREMENTS

Because system prognostic requirements are relatively new to defense development projects—compared, that is, to system diagnostic and testability requirements, which have been around since the 1980s—it is perhaps not surprising that there has been a fair amount of variance in the definition of desired prognostic capabilities from one project to another. For this paper, in order to determine a set of parameters useful for satisfactorily representing system prognostic requirements, the specific wording in a half-dozen system prognostic requirement statements—collected from both current and recent projects—was examined.

The specific set of projects for which requirements were examined is, if not exactly random, then at least arbitrary. It should be mentioned, however, that a good number of these projects are or were contracted by the U.S. Army. Because of the extremely small sample size, the prognostic requirement statements examined in this paper may indeed promote U.S. Army concerns over those of other organizations; likewise, it is possible that the conclusions reached in this paper are, to some extent, only applicable to a limited range of prognostic implementations. Over time, as additional requirements are taken into consideration (or, perhaps, as a common practice for defining system prognostic requirements begins to emerge), some of this paper's observations may need to be revisited.

Now, most of the requirements statements examined for this study include verbiage describing the purpose and desired implementation of the prognostics for that project. Aspects covered by these qualitative descriptions include 1) whether the prognostics shall be embedded in the system, 2) whether prognostics shall be automated or initiated, 3) whether prognostics shall be developed solely for the determination of mission-readiness or also for the optimization of logistics, 4) whether prognostics results shall be reported to the crew, maintenance technicians, and/or mission planners, and 5) whether prognostics shall consist solely of condition-based observations of failure precursors or whether it can also contain predictions based on the failure rates and stress histories of individual components. Although information of this type is essential for circumscribing the prognostic capability required for each project, it is not relevant to our current analysis; in the examples that follow, the requirements have been pared down to include only the information needed for a quantitative evaluation of a system's prognostics capability.

### A. *Prognostic Parameters*

The wording of each sample requirement statement was examined as if it were a template for the construction of future requirements, with the quantitative aspects of the requirement broken down into individual parameters. It was determined that five basic parameters were sufficient for describing any of the sample requirement statements:

- Scope – the set of possible failures to which a given requirement applies. Common scopes include mission critical failures, essential function failures, or failures that necessitate a system abort.
- Category – the set of prognoses to which a given requirement applies, such as embedded or sensor-based prognoses.
- Horizon – the time before failure that prognosis must occur. This can either be a fixed value (e.g., 72 hours prior to failure) or a calculated value, based on both the desired mission length and the corrective action time associated with each failure.
- Coverage – the percentage of failures in the specified scope that must be prognosed. This parameter can either be failure probability-weighted (so that there is greater credit for failures that occur more frequently) or non-weighted (so that all failures in the specified scope are counted equally).
- Accuracy – the desired confidence/correctness of the overall prognostic capability (typically defined as a percentage). In some requirement statements, Accuracy is bundled with Coverage as a single "percentage of failures prognosed" parameter.

### B. *Example Prognostic Requirements*

We will now briefly examine the individual prognostic requirements statements, parsing each statement into the related parameters and discussing any interpretive idiosyncrasies. Unfortunately, for most of these requirements, not only the names of the projects, but also the actual parameter values mandated by the requirement cannot be revealed; the examples in this paper have therefore been sanitized (and the values of parameters changed) to conform with these restrictions.

Also, a good number of the prognostics requirements were originally defined using threshold/objective format (with dual values provided for the coverage, accuracy and/or prognostic horizon). So that the following examples are as transparent as possible, all threshold/objective parameters have been simplified so that they are expressed as a single goal.

Finally, to facilitate discussion, the example prognostic requirements have been sorted into three groups, based on the terms that are explicitly called out within the requirement:

- Scope-Horizon-Coverage-Accuracy (SHCA)
- Scope-Horizon-Percentage (SHP)
- Scope-Category-Coverage (SCC)

Although other combinations of terms are certainly possible, these three groups provide sufficient variety for the current discussion.

#### 1) *Example 1 (SHCA):*

*Prognostics shall predict at least 80% of the mission critical failures 96 hours in advance of occurrence with 90% probability.*

| | |
|---|---|
| Scope: | Mission Critical Failures |
| Horizon: | 96 hours |
| Coverage: | 80% |
| Accuracy: | 90% |

This prognostic requirements statement has four parameters (SHCA) that collectively specify the expected behavior of the prognostics. Because it reads like a performance requirement—one that specifies the expected performance of a fielded system—greater "credit" should be given to prognosed failures that occur more frequently than to those that occur relatively infrequently. So, when calculated as an engineering metric, the prognostic coverage should be weighted by the failure probability of each individual failure. The overall coverage can thus be calculated by summing the failure rates of the failures in the scope that can be prognosed, divided by the sum of the failure rates for all failures in the scope (similar to the way in which failure-weighted fault detection numbers are calculated within most Testability analyses). Suppliers should, of course, verify this calculation method with their customers up front, since it can have a significant impact on the level-of-effort needed to develop the required prognostic coverage.

2) *Example 2 (SHCA):*

*Prognostics shall accurately predict pending critical system failures that might occur in a 72 hour mission, early enough to allow corrective action before the unit begins the mission. Prognostics will provide coverage for 65% SA and 50% EFF at a 90% accuracy rate.*

| | |
|---|---|
| Scope: | System Aborts (SA) |
| Horizon: | 72 hours + corrective action time |
| Coverage: | 65% |
| Accuracy: | 90% |

| | |
|---|---|
| Scope: | Essential Function Failures (EFF) |
| Horizon: | 72 hours + corrective action time |
| Coverage: | 50% |
| Accuracy: | 90% |

Example 2 is a double requirement (it can be translated into two SHCA requirements with different scope/coverage values). Unlike Example 1, there is no indication whether or not the coverage parameters in Example 2 are to be weighted by failure probability. Once again, this aspect of the requirement should be ironed out between customer and supplier during early phases of the project.

Unique to this requirement is the fact that the desired Horizon of each prognosis is based on both a target mission length (72 hours) and the corrective action time associated with that prognosis. A failure is only considered covered if it can be prognosed far enough in advance that it can be corrected prior to beginning a 72 hour mission.

3) *Example 3 (SHP):*

*Prognostics shall detect and report 30% of all potential mission critical aborts 8 hours or greater before failure.*

| | |
|---|---|
| Scope: | Mission Critical Aborts |
| Horizon: | 8 hours |
| Percentage: | 30% |

This system prognostics requirement statement has three parameters—Scope, Horizon and a single percentage. It is an example of the requirements format that I have labeled SHP requirements. SHP requirements are very similar to SHCA requirements, the only difference being that the Coverage and Accuracy parameters have been conflated into a single term (Percentage). This gives the providers more flexibility in developing prognostics—for instance, the requirement in this example can be met if system prognostics are capable of predicting 30% of the failures in the scope (30% Coverage) with 100% Accuracy, the entire scope (100% Coverage) with 30% Accuracy, or various combinations of Coverage and Accuracy that collectively constitute 30% of the Mission Critical Aborts.

Even though the coverage is now part of an overall percentage, the analyst must still determine whether or not the coverage should be probability weighted. For this example, the way in which the scope is worded ("all potential mission critical aborts") might be interpreted to imply that all failures within the scope should be given equal weight (as always, the interpretation of each metric must be negotiated between customer and supplier).

4) *Example 4 (SHP):*

*Prognostics shall predict 60% of impending critical faults or failures within no less than 36 hours before mission failure.*

| | |
|---|---|
| Scope: | Critical Faults or Failures |
| Horizon: | 36 hours |
| Percentage: | 60% |

Not surprisingly, this SHP requirement is very similar to that in Example 3. The biggest difference (other than the scope) is the use of the word "impending"—which suggests that the calculation of coverage (and therefore of the Percentage term of the requirement) should be weighted by failure probability).

5) *Example 5 (SHP):*

*Prognostics shall predict an average of 90% of the expected failures for the next 120 hours of operation.*

| | |
|---|---|
| Scope: | All Expected Failures |
| Horizon: | 120 hours |
| Percentage: | 90% |

This is yet another example of the SHP format. Unlike the four previous examples, however the scope here explicitly consists of "expected" failures, so the coverage used to calculate the Percentage should most likely be weighted by failure probability.

6) *Example 6 (SCC):*

*The System shall have prognostics on greater than or equal to 25% of all LRUs/LRMs that can cause an Essential Function Failure.*

*The System shall have sensor-based prognostics on greater than or equal to 10% of all the LRUs/LRMs that can cause an Essential Function Failure.*

| | |
|---|---|
| Scope: | LRUs/LRMs that can cause an EFF |
| Category: | All Prognostics |
| Coverage: | 25% |

| | |
|---|---|
| Scope: | LRUs/LRMs that can cause an EFF |
| Category: | Sensor-Based Prognostics |
| Coverage: | 10% |

These two requirements are in SCC format, which differs from that of the previous examples in several ways. First of all, the system's prognostics capability is divided into two sets—sensor-based prognostics and non-sensor-based prognostics (the prognostic category for the first requirement consists of all prognostics, whereas the category for the second requirement limits the calculation to only sensor-based prognostics).

A second difference is that these requirements have no Horizon parameter. The reason for this is that these were not intended to be stand-alone requirements, but rather constraints supplied in addition to a statement in SHP format (Example 5) that constituted the primary prognostics requirement for that project. That requirement (Example 5) not only specifies the desired prognostic Horizon, but is also worded in such a way that the specified percentage would be based on the *weighted* prognostic coverage of the system. This is important because, in the Example 6 requirements, coverage is expressed in terms of repair items (LRUs/LRMs) that result in an EFF, rather than the EFFs themselves. If these were stand-alone requirements, then the resulting prognostics would not necessarily address the most frequent or the most critical failures.

Although possibly counter-productive if issued by themselves (perhaps resulting in resources being wasted on the development prognostics for areas other than those that need it most), the two requirements in Example 6 nevertheless serve two purposes when issued in conjunction with a primary SHCA or SHP requirement. First of all, by splitting up prognostics into multiple categories, they can be used to assure that sufficient attention is paid to a desirable subset of the overall prognostic capability (sensor-based prognostics, in this example). Equally important, they specify that prognostics must be developed on a certain minimum percentage of the system's repair items (repair items with at least one failure that could result in an EFF). The primary prognostics requirement (e.g., Example 5) forces prognostics to be developed for the most frequent, most critical failures. The SCC requirements, on the other hand, force prognostics to be developed over a substantial subset of the system hardware (rather than only for a handful of relatively critical and relatively unreliable components).

## III. Prognostic Definitions in ***eXpress***

We will now take a look at how prognostic definitions are defined within DSI's diagnostic engineering tool ***eXpress***. There are several reasons why support for prognostics has been added to a tool that is used primarily for the creation, assessment and optimization of system diagnostics. First of all, as a tool designed for system-level analysis, ***eXpress*** already has the infrastructure in place to perform an analysis of system-level prognostics. Data from individual prognostic definitions are compiled across the entire system to produce overall measures of prognostic effectiveness—measures that can be easily compared to system prognostic requirements to determine contract compliance.

A second advantage to modeling prognostic measurements within ***eXpress*** (one that is directly related to the focus of this paper) is that the Reliability, Testability, and Maintainability evaluations performed within ***eXpress*** can now reflect the expected performance of systems for which mission readiness is assured using prognostics (as we shall see, there are multiple ways in which these evaluations can take prognostics into consideration). Moreover, diagnostic procedures developed within ***eXpress*** can be optimized based on the assumption that prognostics will be employed.

For example, prior to developing prognostic sensors, ***eXpress*** analysis can be used to determine the set of failures for which prognosis is most desirable (taking into consideration not only the criticality and frequency of failures, but also how successfully the system can diagnose and remediate the failures without prognostics). Later, if the bottom line changes and you need to reconsider the value of developing some of the more expensive prognostic sensors, you can easily reevaluate the PHM performance that would be achieved if the system were to not have those sensors.

A third advantage of adding prognostic definitions to an ***eXpress*** model is that this information can be easily exported for analysis within an external tool. For example, **STAGE** (DSI's simulation-based analysis tool) is currently being enhanced to support prognostics within case studies that compare different combinations of health management approaches. This will allow PHM analysts to evaluate different "cocktails" of diagnostics, prognostics and preventative maintenance to determine which combinations are most effective not only from the perspective of mission readiness, but also supportability and cost effectiveness.

### *A. Tests and Prognoses*

In ***eXpress***, test definitions are normally used to represent diagnostic knowledge. Each test definition specifies the coverage of a corresponding real-world test or measurement—the specific functions or failure modes that should be exonerated (removed from suspicion) or indicted (called into suspicion) when that test passes or fails. Tests are organized into different test sets so that they can be easily selected as groups to support different diagnostic case studies.

Prognostic measurements are represented in ***eXpress*** using a special type of test definition—basically, a test definition to which prognostic parameters have been attached. The coverage for each prognosis is represented the same way as it would be for a diagnostic test—the only difference being that the coverage represents the specific functions or failure modes for which failures can be predicted using prognostics. Like tests, prognostic measurements are also organized into sets. When a project has prognostic requirements that utilize the Category parameter, then the individual measurements should be grouped into different sets by category. Analysis can then be constrained by simply selecting the sets that correspond to the desired prognostic categories.

### *B. Prognostic Terms*

For each prognostic definition included in an ***eXpress*** model, the analyst specifies one or more Horizons, each accompanied by three variables—Confidence, Correctness and Accuracy—that collectively describe the expected behavior of the given prognostic measurement at that Horizon (Fig. 1).

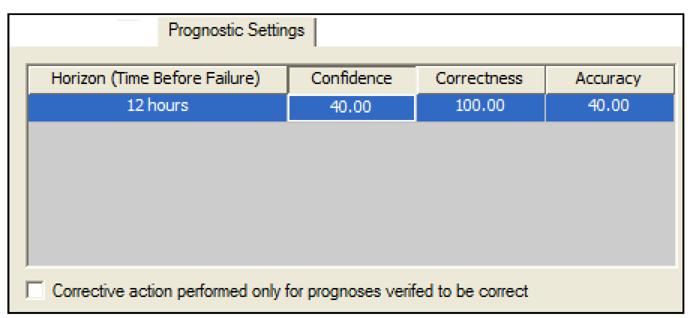


Figure 1. Prognostic Settings in ***eXpress*** (single horizon)

The value of the specified Horizon is similar to the Horizon parameter within a prognostic requirement—it represents a time interval before failure that the given prognosis might occur. The Confidence represents the likelihood that the given prognosis will predict the covered failure(s) at or before the specified Horizon (time before failure). When multiple Horizons are specified within a single prognostic definition (Fig. 2), then the Confidence and Horizon pairings represent the likelihoods of predicting failures at different points in time. Note: it is expected that Confidence increases as the Horizon decreases—in other words, that predictions become more confident as one approaches the time of failure.

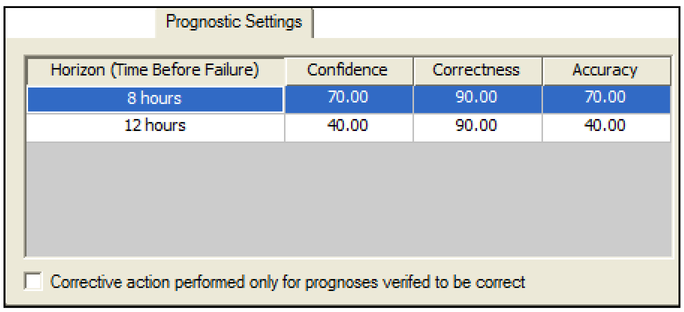


Figure 2. Prognostic Settings in ***eXpress*** (multiple horizons)

The Correctness variable is used to represent the expected percentage of prognoses that are correct (i.e., not *too early*). Within ***eXpress***, the concept of *prognostic correctness* is intentionally fuzzy (the analyst, for instance, does not specify how early is too early). By default, the Correctness setting affects neither the prognostic nor diagnostic analysis performed within ***eXpress*** (more about this later). The Correctness value is included not so much to inform the analyses performed within ***eXpress*** as it is to help categorize simulated prognoses within tools like **STAGE**.

The calculated Accuracy value corresponds to the Accuracy parameter within a prognostic requirement. Unlike the other two values used to describe a given Horizon (Confidence and Correctness), the Accuracy variable is not defined by the analyst, but rather calculated automatically by the software. By default, the Accuracy for a given Horizon is equal to the Confidence specified for that Horizon. There is a checkbox at the bottom of the Prognostic Settings panel that, when enabled, changes how the Accuracy is calculated.

The checkbox labeled “Corrective action performed only for prognoses verified to be correct” is used to specify that a given prognosis is not only independently verifiable, but will be verified before corrective action is performed. As an example, think of the brake pads on an automobile. As the pads wear past a given point, they begin to squeal when the breaks are applied—an intentional design characteristic that allows the owner of the car to identify when the pads need to be replaced. We could say that the squealing of the brake pads is a condition-based prognosis of a pending failure. Now, imagine that, when your brakes start to squeal you inspect the pads and see that there is plenty of life left—the squeal came *too early* (car owners can confirm that this false squeal is actually a fairly common occurrence). Would you still replace the pads? If so, then—from a purely pragmatic standpoint, the Accuracy of your prognosis would be equal to your Confidence that it prognosis would occur prior to failure. If, however, you only replace the pads when they have truly worn down (when the prognosis was correct), then the accuracy of your prognosis must be adjusted down to account the possibility of these false squeals.

So, when this checkbox is enabled, the calculated Accuracy is equal to the product of the Confidence and Correctness percentages (Fig. 3). Accuracy then represents the likelihood that the prognosis occurs early enough (Confidence), but not too early (Correctness).

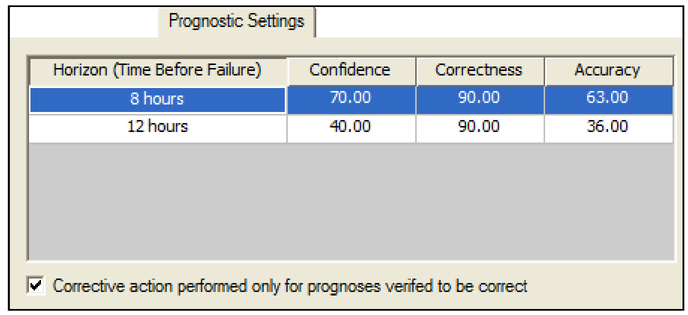


Figure 3. Accuracy calculated using both Confidence and Correctness

Rather than specify the Probability Distribution Function (distribution curve) that represents the likelihood of a prognosis occurring over time, the analyst enters one or more Horizons that specify the likelihood of a prognosis occurring at different points in time. This approach allows analysts to account for prognostics within Reliability, Testability and Maintainability analyses before the specific behavior of each prognosis has been identified (this is essential if these analyses are to impact the decisions made during the development of the design). The analyst can initially create prognostic definitions using Horizon and Accuracy values taken directly from contracted prognostic requirements (assuming, initially, that each individual prognosis will act in accordance with the requirements for the overall system). The Horizon, Confidence and Correctness values can then be adjusted as additional information about specific measurements becomes available, with additional Horizons being added to represent the likelihood of a prognosis occurring at different intervals prior to failure.

Prognostic Scope is specified not within the individual prognostic definitions, but rather by controlling the portion of the design over which analysis is performed. Within ***eXpress***, subsets can be hierarchically defined in terms of failure modes, functions or replacement items. To assess prognostic coverage of System Aborts, the analyst defines a subset of the design containing all failure modes that can result in System Aborts, and then generates prognostics within a study whose scope has been constrained to that subset. All prognostic and diagnostic analyses will then be calculated across the selected scope.

As one would expect, the overall system prognostic capability is then calculated based on the Coverage, Horizon and Accuracy of the individual prognostic measurements in the selected category, the relative failure probabilities of the covered failure modes, and the specified Scope of the analysis.

Of course, the real value of incorporating prognostics into a diagnostic engineering model (like those created in ***eXpress***) is not so much to facilitate the prognostic analysis itself as it is to develop, assess and optimize diagnostics (as well as improve the design's inherent ability to support diagnostics effectively) based on the assumption that a given level of prognosis can and will be achieved.

## IV. Prognostics-Savvy Testability Analysis

There are numerous design analysis practices that rely on knowledge of the diagnostic capability of the system in question—Testability, Maintainability and System Reliability analyses come immediately to mind). For the purpose of this paper, however, we will concentrate on the first of these practices—Testability Analysis, since this is the one most explicitly concerned with a system's diagnostic capability. A discussion of the impact of prognostics upon Maintainability and System Reliability analyses (although these two practices are based on the system diagnostic capability to the same extent as is Testability) will be deferred until another time and place. More specifically, the following comments will focus on the quantitative assessment of system Testability (fault detection and isolation), rather than the collection of low-level design practices that fall under the label Design for Test.

As of yet, there has been little or no public discussion of how the existence of prognostics should be reflected within testability analyses. DSI, however, has been either active or passive participants in several large-scale projects in which ***eXpress*** was used to analyze the diagnostic capability of a system that also includes prognostics. Note: Although the prognostics capability described in the previous section of this paper has been only recently added to the ***eXpress*** software, equivalent analyses could previously be performed in the tool using various workarounds (although each had its limitations).

To date, DSI has witnessed three very different approaches to accounting for prognostics within testability analysis. One approach is to *include* prognosed failures in the diagnostic analysis. Under this approach, prognosed failures are credited towards the systems fault detection and isolation requirements. In a second approach, prognosed failures are *excluded* from the diagnostic analysis, with testability being calculated across the remaining portion of the system. The third approach has been *ignore* prognostics when evaluating diagnostics—calculating the testability metrics as if prognostics had not been developed. As with all calculations used to satisfy contract requirements, the selected approach to accounting for prognostic knowledge (or assumptions) within testability calculations should be based on supplier/customer consensus.

### *A. Including Prognostics within Diagnostic Analysis*

When the results of prognostics are included in a system's diagnostic analysis, then the metrics used to calculate system testability (both fault detection and isolation) must be modified to also include prognosed failures. This does not change the equations or algorithms used for calculating these metrics, but rather the set of data over which they are calculated.

Under this approach, assessments of the fault detection capability of a given system would be expanded to include both prognosed and diagnosed failures. In IEEE Std. 1522-2004, the two metrics used to evaluate a system fault detection capability—Percentage of Detection and Expected Percentage of Detection [3]—would be calculated not across the possible diagnoses of the system in question, but across all diagnoses *and* prognoses. For failures that cannot be collectively prognosed & diagnosed with 100% confidence, the probability of diagnosis/prognosis must be updated accordingly to reflect the less-than-complete coverage of those failures.

Fault isolation calculations would also be expanded under this approach, so that they too account for prognosed failures. In IEEE 1522, the main fault isolation metrics—Percentage of Isolation, Expected Percentage of Isolation and Expected Ambiguity Group Size [4]—would, under this approach treat prognoses as if they were fault groups isolated by the diagnostics. When a given failure can be prognosed with less than 100% confidence, then (if that failure, when it occurs, can be diagnosed), the failure probabilities associated with that failure—in both the prognosis and the ambiguity group isolated by diagnostic—must be updated to reflect the accuracy of the prognosis. For example, if a specific failure can be prognosed with 80% confidence, then 80% of the associated failure probability should be allocated to the prognosis and 20% to the diagnosis (this is important so that the resulting statistics reflect the lower likelihood that actual failures will be isolated ambiguously when a system is at least partially maintained using prognostics).

When prognostic considerations are to be incorporated into a testability analysis, the specific Horizon (or range of Horizons) allowed must be explicitly specified. Not only should prognostic measurements that fall outside the specified Horizon(s) be excluded from the calculations, but (for prognostic definitions with multiple Horizons), the Accuracy should be drawn from the largest acceptable Horizon within the specified range.

### *B. Excluding Prognostics from Diagnostic Analysis*

When the results of prognostics are excluded from a system's diagnostic analysis, then corresponding testability metrics must also be modified. Once again, this is a question of changing the set of data over which the metrics are calculated, rather than changing the actual calculation itself.

Under this approach, fault detection and isolation statistics are calculated over the non-prognosed subset of the system model. Not only are all failures fully covered by prognostics removed from this subset, but the relative failure probabilities must be reduced for those failures that are partially covered by prognostics (that is, covered with less than 100% accuracy). The resulting, non-prognosed subset of the designs constitutes the portion of the system over which diagnostics is expected to be performed. If all failures within the subset can be detected, then the fault detection capability of the system is 100%.

It is important that analysts and customers both understand that the exclusion of prognosed failures from diagnostic analysis does not in any way imply that the resulting testability numbers will improve. FD/FI numbers may go either up or down when prognosed failures are excluded from the analysis.

If, for example, all prognosed failures are also detectable (failures that, when they occur, can be detected by diagnostics), then the relative percentage of detected failures will decrease when the prognosed failures are excluded from the analysis. Likewise, if prognosis is capable of predicting mostly failures that can be unambiguously isolated when they occur, then the exclusion of prognosed failures will result in less attractive fault isolation numbers. On the other hand, if some prognosed failures can only be isolated in ambiguity with other items, then the fault isolation numbers may improve when those failures are excluded from the testability analysis.

### *C. Ignoring Prognostics within Diagnostic Analysis*

It is sometimes "decided" to ignore prognostics altogether when developing, assessing and optimizing a system's diagnostic capability. In many cases, this decision may have been unconscious, with analysts simply generating metrics in the same way as they would if the system had no prognostics. In other cases, diagnostic engineers may have chosen to ignore prognostics because they do not have faith that the specified parameters (Horizon, Accuracy or Coverage) can be achieved. Or there might be concerns that a given project may not fund the development of prognostics through to completion. Since, if the analyst's fears were to be realized, the burden would then fall on the diagnostics (and diagnostic engineers) to pick up the slack, the only "responsible" approach would be to analyze diagnostics as if the system were to have no prognostics. Unfortunately, this approach could also result in redundant optimization, with time and resources spent improving diagnoses that simply will not occur if prognostics are developed as planned.

Perhaps the most effective way out of this stalemate would be to specify multiple diagnostic requirements within contracts for those systems that also have prognostic requirements. Diagnostics should be required to unambiguously detect and isolate critical failures regardless of whether or not those failures can be prognosed. Troubleshooting procedures for less critical failures, on the other hand, might then be developed, assessed and optimized under the assumption that prognostics have been successfully developed and perform up to contracted levels.

## V. Conclusions

There are currently no real guidelines for the calculation of diagnostic-related metrics for systems whose critical failures are covered by prognostics. Not only have approaches not yet been standardized, but many of the alternatives have not even been discussed in a public arena. Existing standards describing diagnostic analysis—such as the IEEE Testability standard (IEEE Std. 1552-2004)—do not yet explicitly account for prognostics in any way. As a result, diagnostic analysis tools like ***eXpress*** are forced to address this issue using multiple, non-standardized approaches in an attempt to "cover all the bases."

As more systems are equipped with embedded prognostics, questions about the relationship between prognostics and diagnostics are likely to become even more prominent. A common practice will begin to emerge, with subsequent efforts at standardization. Until such a time, however, it is important that the relationship between prognostic and diagnostic analysis remain in flux, that previous methods for assessing diagnostic-related behavior remain in question, and that suppliers, customers and the companies that supply their tools remain in dialog.


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[4] *Ibid*., p. 23-24.