DIAGNOSTIC MODELING AND DIAGNOSABILITY EVALUATION
OF MECHANICAL SYSTEMS

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ABSTRACT

Consideration of diagnosability in product design promises to increase product quality by reducing maintenance time without increasing cost or decreasing reliability. Methods for investigating the diagnosability of mechanical and electro-mechanical systems are described and are applied to the Bleed Air Control System (BACS) on the Boeing 747-400. The BACS is described and a diagnostic model is developed from the system Failure Modes and Effects Analysis. Emphasis is placed on the relationship between the system’s functions and its components. Two metrics for the evaluation of diagnosability and two metrics for the evaluation of component diagnosability are defined. These metrics emphasize diagnosing ambiguity and are combined with the probability of different system failures to weight the effects of each failure. Three modified systems are produced by reassigning functional components to another. The resulting effects on the system and component diagnosability are evaluated. We show that by changing these relationships system diagnosability can be improved without adding sensors or other components.

1.0 INTRODUCTION

Diagnosability, the measure of the ease of isolating the cause of a loss of functionality, can strongly influence the value of a product. Diagnosability investigation can be divided into diagnosability of individual components and diagnosability of systems of components. Diagnosability of a system can be further divided into system detectability, predictability, and distinguishability (Misra, et al., 1992). Detectability is a measure of the time that passes before the fact that a failure exists is recognized. Predictability is a measur
that will pass before a failure will occur. Distinguishability is a measure of the time required to determine which of a system's RUs is the cause of the loss of functionality. This research investigates diagnosability of components and distinguishability of systems to meet the need for the evaluation of diagnosability during design. These methodologies have then been applied to the bleed air control system for a Boeing 747-400 aircraft.

Poor diagnosability increases life cycle cost through additional maintenance time and cost. Poor diagnosability also decreases quality because the product cannot provide its intended functionality during the time the diagnostic is being performed. The issue of diagnosability has received considerable attention in the electronic domain, but research to improve diagnosability in the mechanical domain has been lacking even though diagnosability is a significant problem in many mechanical systems. A recent study by the Reliability Department at the Boeing Commercial Aircraft Group showed that the cost of unjustified removals (removal of a suspect component later found to be in working order) on the 747-400 aircraft was over $100 per flight hour, a cost that is equivalent to that of adding 8 tons of dead weight to the aircraft. This cost is a direct result of poor diagnosability with respect to the components that were removed. Further, fully one third of the components identified in the study were mechanical rather than electronic in nature. The total cost of poor diagnosability for this airplane will be even higher as the $100 per flight hour does not include the costs savings that could potentially be realized by reducing the time that mechanics spend on fault isolation. Another study by Boeing shows that the cost of downtime (direct cost plus loss of revenue) associated with the fault isolation task could be as high as $200 per flight hour. (Stander, 1982)
Traditionally, because diagnosability is considered after design (Yu and Biswas, 1992) problem in both electronic and mechanical systems are addressed by adding sensor-based automated diagnostic systems, (DoD, 1988; Jones, 1988; Kapur, 1988; Liu and Sheu, 1991). This additional hardware/software (as built-in test equipment (BITE) and automated test equipment (ATE)) is usually added to a system after diagnosability problems are discovered. Because these systems always add cost and complexity while decreasing reliability, we believe there is strong encouragement to consider diagnosability during the design of the product to keep the use of add-on diagnostic systems to a minimum.

It has been recognized that the quality of a product is determined to a great extent during the product's design, not during production (Ullman, 1992). The diagnosability of a product is also determined during the design phase. One reason fault diagnosis is not considered explicitly in the design process is that diagnosability is difficult for the designer to consider without actual data. Another reason is the lack of evaluation methodologies and metrics.

Previous work (Ruff, 1993) developed preliminary metrics and modeling methodologies for the evaluation of diagnosability during the conceptual phase of the design process. This work refines and extends the methodologies and metricsto the embodiment phase of the design process. Specifically, system modeling is done on conceptual, partially defined, and completely defined mechanical systems. This modeling uses the relationships between different failures that can occur in a system and the observations that indicate that a failure has occurred. From this modeling, four new metrics are defined for use in evaluation of both component diagnosability and system diagnosability.
To test this methodology it is applied to an electro-mechanical system identified as experiencing real problem difficulty in fault isolation. This system, the Bleed Air Control System (BACS) on the Boeing 747-400 aircraft, is chosen for this study for several reasons. The system diagnosability problem because one component, the Pressure Reducing and Shut Off Valve (PRSOV) has a high rate of unjustified removals. Also, a Failure Modes and Effects Analysis (FMEA) is available. The failure types and their effects on the system aids with the diagnosability evaluation. The BACS also gives a good framework in which to apply, evaluate, and test the diagnosability modeling methodology and diagnosability evaluation. The objectives for the BACS are to understand why it is hard to diagnose, change, and improve its diagnosability. This goal was accomplished by creating three slightly modified systems and analyzing them for system distinguishability. The results show that small changes in a system can affect distinguishability. The suggested metrics can be used to evaluate the magnitude of these changes.

In the following sections, the BACS is described, including major components and existing sensors. Next, techniques for system modeling are applied to the BACS. Changes in the model are made to make additional information available for an embodied system. Metrics for diagnosability evaluation are defined for both individual component and systems. On the basis of the diagnosability evaluation of the BACS, modifications to the system are made. The modified systems are then re-evaluated to determine the effects of the changes on the system's diagnosability. We conclude with observations on the methodology as applied to systems in both the concept and the phase of design, and discuss our plans for future work.
2.0 DESCRIPTION OF THE BLEED AIR CONTROL SYSTEM (BACS)

The BACS provides high pressure air for use in cabin air conditioning, engine starting, lower cargo compartment heating, icing, and deicing systems. It bleeds air from the eighth and fourteenth stages of the compressors on each of the 747's four jet engines. This air is routed through a heat exchanger where the bleed air is cooled with air from the engine air precooler, and then the air continues to the pneumatic manifold, as shown in Figure 1.

![Diagram of BACS system](image)

**FIGURE 1: BOEING 747-400 BLEED AIR CONTROL SYSTEM (BACS)**

The bleed air must be delivered to the manifold within specific temperature and pressure ranges. If the air was allowed to flow unrestricted, the manifold could be overheated or overpressurized. It is also important to be able to isolate the BACS on one engine from the others if that system fails. Valves are used to regulate temperature and pressure and to ensure that pressure is not lost through the BACS.
The High Pressure Shut Off Valve (HPSOV) restricts flow from the fourteenth compressor stage when the eighth stage pressure is adequate. There is a low pressure check valve (Check) to prevent air flow into the eighth compressor stage. The Pressure Relief Valve (PRV) which is before the precooler/entrair to ambient if the system becomes over pressurized. The Fan Air Modulating Valve (FAMV) controls the rate of cooling air flow through the precooler (Pclr). The Pressure Reducing and Shut Off (PRSOV), which is after the precooler, limits the air pressure supplied to the pneumatic manifold (Man). The PRSV also provides over temperature protection for the manifold by reducing flow if the bleed air temperatures are too high, and provides a checking function to prevent manifold pressure loss through the BACS. These components are interconnected with a series of ducts (Duct). For the purpose of this research, engine output was considered to be in one of two states: low output (idling on the jetway, for example) and high output (in flight).

The BACS currently has several sensors that are used to diagnose system failures. These sensors include analog readings of temperature and pressure between the precooler and the PRSOV, and the pressure at the pneumatic manifold. There are also switches that indicate when the PRSOV is closed when the PRV is open, and when the HPSOV is open.

3.0 Modeling of the Bleed Air Control System

For diagnostic evaluation during the design phase of product development, a system model is needed. In this section, we begin by defining the terms used in our diagnostic modeling of the BACS. We then will describe models for conceptual, partially defined, and fully defined systems. Information available at that point in the design process. In the model for a conceptual
system functions are mapped to parameters. Two extensions of this model are presented that use additional system information to give a more complete model. The indicator (system sensors) are included in the model of a partially defined system. The system failure from the FMEA, and varying system operating conditions are incorporated into the model for a fully de

3.1 Definitions

For the purposes of this paper we will, in general, use the description and definition of Ullman, 1992. The product is that artifact which we wish to design. The purpose of the product is to perform functions. The product is composed of a number of systems, each of which perform a sub-set of the required function. The systems are decomposed into a number of components. A component that can be replaced on the repair line is called a line replaceable unit (LRU), and for the purposes of this research it is considered the lowest physical level. A parameter is defined as a feature or specific measurable attribute of an LRU, component, assembly or system, such as a geometric or material property. Performance is the measure of function. An instantiated system will have an actual value for each performance definition as the performance measure (PM).

3.2 Conceptual Systems

In previous work, (Ruff, 93) the relationship between parameters and functions were used to evaluate diagnosability product in the conceptual phase of the design process. The model developed in this work for a hypothetical product is shown in Figure 2. The state of the overall system function (SF) is indicated by a number of performance measures (PM), with a
relationship between a performance measure and a parameter (P) shown by a solid line. The parameters are grouped into LRUs. In modeling the system, one starts with the parameter and uses system information to determine which performance measures they affect, moving from the bottom of the diagram to the top. This is the causal direction because the state of the parameter causes (determines) the performance measures. In performing diagnosis, one starts with a set of performance measures that are abnormal and uses the model (or experience) to determine which LRUs could have caused the failure, moving from the top of the diagram to the bottom. This is the diagnostic direction and the resulting set of suspect LRUs are called candidates. A highly distinguishable system is one that would have very few candidates for any possible set of abnormal performance measures.

![Diagram](image_url)

**FIGURE 2: CONCEPTUAL SYSTEM WITH VARIOUS PARAMETER-PERFORMANCE MEASURE RELATIONSHIPS**

For the BACS, the model shown in Figure 3. Ovals represent functions. When modeling a conceptual system, functions and sub-functions can be substituted for performance measures because the performance function can be used to discover failure in the system. Observation of the function is used as a performance measure; if a function is not being performed correctly at least
one of the line replaceable units that provides that functionality. The major system LRUs are represented by rectangles, and the relations the LRUs and sub-functions are indicated by the connecting lines.

![LRU Diagram](image)

**FIGURE 3: LRU-FUNCTION RELATIONSHIPS FOR THE BOEING 747-400 BACS WITH FUNCTIONS REPLACING PARAMETER MEASURES**

Careful examination of Figure 3 will show that each LRU has a unique set of affected sub-functions. It should then be a simple task to determine the faulty LRU given a set of PMs that are outside their design states. It is known, however, that the BACS is not easy to diagnose. This discrepancy results from the fact that a faulty LRU may not be indicated by all the functions it helps provide. If we change the nature of the relationships so that a faulty LRU could be indicated by any combination of its PMs being abnormal, the model will more closely simulate the actual system. This modification represents a major change in the assumptions about the relationships between the LRUs and the PMs, the possibility of more than one failure indication per LRU.

### 3.3 Partially defined systems
As the system design progresses, the additional information that becomes available can be used in the system model. Designers of the BACS included a number of sensors for use in obtaining information about the system. These sensors provide a different set of measures to use in the developing indicator.

We define the output of these sensors as the status of a LRU: PRV Open, PRSOV Closed and Hi Stage, and the performance measures of a function; Manifold Pressure and BACS Temperature Pressure. Because the function-LRU relationships are known (Figure 3), the performance measures are related to the LRU through the functions. In Figure 4, ovals now represent the six indicators, LRUs are shown as rectangles, and LRU-Indicator relationships are shown as lines.

![LRU-PM Relationships for the BACS](image)

**FIGURE 4: LRU-PM RELATIONSHIPS FOR THE BACS**

This model of the system uses more of the information about the system, but does not explicitly consider different failure modes and operating conditions.

### 3.4 Fully Defined Systems

After the system is completely defined and the LRUs well understood, the failure model for each LRU in each set of operating conditions are known. This
information can be used to expand the system model. In Figure 5, failure modes of each LRU are related to the indicators for high engine output conditions. The ovals again represent the six indicators. The rectangles now represent LRU failure modes. In addition to failures that will always affect certain performance measures, relations between failures that only sometimes affect a performance measure were found to exist (the former are solid lines, the latter as dashed lines). Each failure can now be broken down into time-
FIGURE 5: FAILURE-PERFORMANCE MEASURE RELATIONSHIPS FOR HIGH OUTPUT CONDITIONS FOR THE
747-400 BACS WITH FAILURES PLACED BOTH ABOVE AND
BELOW THE PERFORMANCE MEASURES BECAUSE OF
SPACE CONSTRAINTS

4.0 EVALUATION OF DIAGNOSABILITY

For diagnosability to be considered in the design process, there must be some method that can be used to determine what parts of a system are the source of diagnosability problems will be discussed. These metrics may be measures for improving embodied systems by addressing specific problems. To measure the relative diagnosability of systems will be introduced in 4.2. These metrics may be more useful for comparison of competing the design phase.

4.1 LRU Metrics

In order to create numerical measures for LRU diagnosability, terms must be defined. An indication is a set of abnormal performance measures that corresponds to a set of suspect candidates. After an examination of the failure-performance measure relationships, list of all possible indications and their corresponding candidate can be formed. This description of the system would read like a series of if-then statements for example, if performance measures 1, 2, and 5 are abnormal then C, E, and G are candidates. This type of statement would be created for all physically possible combinations of abnormal performance measure values.
The greater the number of times a certain LRU appears as a candidate the more trouble is to diagnose. For the BACS, the PRSOV is a candidate in about half of all possible indications. Because the PRSOV appears as a candidate often and has a high failure rate, the mechanic will often replace the PRSOV if the true cause of failure is not obvious. Equation (1) defines the percentage that have a certain LRU as a candidate, which is one measure of the diagnosability of the LRU.

\[ S_{LRU} = \frac{N_{LRU}}{n} \]  \hspace{1cm} (1)

S_{LRU} is the percentage of indications that have a certain LRU as a candidate, where \( N_{LRU} \) is the number of different indications that have a certain LRU as a candidate and \( n \) is the total number of different indications. The total of all of the S's for a system will be greater than or equal to 100% because there will always be one or more candidates per indication.

If a LRU appears as a candidate often, but in apparently small candidate sets, the diagnosability of that LRU may not be of great concern. The \( S_{LRU} \) for certain LRU is not the only measurement of diagnosability. In the BACS, the PRV is a candidate for many indications but often it is the only candidate and it does not seem to present the same diagnostic challenge as the PRSOV. This means that to identify a LRU that is difficult to diagnose, the difficulty of the diagnosis of the indication for which the LRU is a candidate must be considered. Equation (2) defines the average number of indications associated with a LRU, which is a measure of the difficulty of the diagnosis of the indications associated with a certain LRU.
\[ C = (n \sum_{i=1}^{n} C_i) \tag{2} \]

\( C \) is the average number of candidates, where \( C_i \) is the number of candidates for each indication, summed over the total number of different indications. A LRU will be the source of diagnosability problems if both its \( C \) and \( S_{LRU} \) are higher than other LRUs in the system. A LRU will have a high problem if the LRU has a high probability of failure compared to the other LRUs in the system. In order to make judgments about the diagnosability of a particular LRU, both its \( C \) and its \( S_{LRU} \) must be considered. Examples of \( C \) and \( S_{LRU} \) for the BACS are found in section 5.1.

### 4.2 System Metrics

Metrics designed to give a numerical value for system diagnosability can be divided into three groups: detectability, predictability, and distinguishability. Because of the high cost of unjustified removals, distinguishability as the greatest problem in most mechanical systems, and this section will concentrate on ways to measure it.

It has been suggested (Ruff and Paasch, 1993) that the maximum number of candidates for any indication is a measure of the distinguishability of a system. Although the maximum number of candidates is important, this metric does not tell the whole story, especially for a system with many different failure modes. A more complete look at a system includes the average number of all indications. The number of candidates for an indication affects the diagnosis time because more candidates means that potentially more LRUs must be individually inspected before the faulty LRU is found. Equation (3) defines the
A measure of distinguishability generally increases with the inverse of the average number of candidates for each indication and is bounded to range from zero to one,

$$D = \frac{\sum_{i=1}^{n}(1/C_i - 1/C)}{n(1/C)}$$  \hspace{1cm} (3)$$

$D$ is the distinguishability, $n$ is the total number of possible indications, $C$ is the total number of LRU's, and $C_i$ is the number of candidates for each indication. A distinguishability of one, or 100%, means that every possible indication would have only one candidate and diagnosis is trivial. A distinguishability of zero means that for any indication all LRU's in the system are candidates, and every LRU must be checked individually until the faulty LRU is discovered.

Distinguishability defined above does not take into consideration the likelihood of each diagnosis being performed. If a certain indication is hard to diagnose, it may be of little concern if the indication is very unlikely to occur. Emphasis needs to be placed on the diagnosis tasks that will need to be performed most often. Equation (4) defines the measure for distinguishability that, again, generally increases with the inverse of the average candidate for each indication. But this measure is weighted so that the indications that are most likely to occur are given the most consideration,

$$WD = \frac{\sum_{i=1}^{n} P_i (1/C_i - 1/C)}{(1/C) \sum_{i=1}^{n} P_i}$$  \hspace{1cm} (4)$$
WD is the weighted distinguishability, where C is the total number of
the number of candidates for each indication, and \( P_{i} \) is the probab
indication. Equation (5) gives the definition of \( P_{i} \).

\[
\begin{align*}
    P_{i} &= 1 - \prod_{\text{candidate}} (1 - PC) \\
    \text{(5)}
\end{align*}
\]

PCj is the probability of failure of each of the candidates for a given indication.
There will be a corresponding \( P_{j} \) for each possible indication. The weighted
distinguishability will vary from zero to one, like the unweighted
distinguishability if the probability of all indications is equal, the weighted
result will equal the unweighted result. If the probabilities are not equal, the
second formula weighs the indications according to how often the diagnosis of
each would be performed. Although weighted evaluation requires more
information, it will give a better idea of the differences in diagnosis time that
would be required for different systems.

Both the weighted and unweighted distinguishability metrics can be applied to
the model of the system at any of the three levels of abstraction discussed in
section 3.0. These values, however, can only be compared with values for other
systems that provide the same overall functionality and are at the same level of
abstraction. Examples of unweighted and WD for the BACS are found in section
5.2.2.

5.0 BACS DIAGNOSABILITY EVALUATION

All 4 of the previously defined metrics can be used to characterize
diagnosability. The LRU metric, \( S_{LRU} \), is used to find LRU's that
contribute highly to diagnosability problems. The distribution of systemsub-
functions can be changed to improve the diagnosability of components. To evaluate diagnosability on a system level, one of the system metrics must be used. These system metrics can be used to compare competing designs that provide the same function, evaluate the effects of changes to a system. In this section, LRU diagnosability is evaluated on the BACS and small changes are made to the system. The system metrics, D and WD, are used to evaluate the effects of the changes.

5.1 LRU Evaluation

The metrics introduced in section 4.1 allow the designer to find which system are the source of diagnosability problems. For the BACS, if the PRSOV is a diagnostic challenge because it has a high rate of unjustified removals. The diagnosability of the PRSOV can be compared to the diagnosability of other LRU’s by using the metrics. The metrics can be applied to a system model of the three forms discussed in section 3.0. Values for SLRU and are shown in Table 1 for the BACS in the concept form (from LRU-function relationships in partially defined form (from LRU-PM relationships) and the fully defined model for high and low output conditions. The line replaceable units are listed in alphabetical order. PC is the probability of failure for one hour of operation for each of the LRU’s.
TABLE 1: COMPARISON OF DIAGNOSABILITY OF BACS LRUs BASED ON CONCEPTUAL, PARTIALLY DEFINED, AND FULLY DEFINED SYSTEM MODELS

<table>
<thead>
<tr>
<th>Component</th>
<th>PC x 10^3</th>
<th>Conceptual $S_{LRU}$</th>
<th>Conceptual C</th>
<th>Partially Defined $S_{LRU}$</th>
<th>Partially Defined C</th>
<th>Fully Defined Hi Output $S_{LRU}$</th>
<th>Fully Defined Hi Output C</th>
<th>Fully Defined Lo Output $S_{LRU}$</th>
<th>Fully Defined Lo Output C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check</td>
<td>0.21</td>
<td>0.08 1.00</td>
<td>0.00 --</td>
<td>0.03 2.00</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duct</td>
<td>1.16</td>
<td>0.23 1.33</td>
<td>0.14 3.43</td>
<td>0.11 2.75</td>
<td>0.17 3.75</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FAMV</td>
<td>5.19</td>
<td>0.23 2.67</td>
<td>0.14 3.57</td>
<td>0.13 2.80</td>
<td>0.03 4.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HPSOV</td>
<td>1.91</td>
<td>0.23 1.67</td>
<td>0.14 3.43</td>
<td>0.08 1.67</td>
<td>0.22 3.13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Man</td>
<td>1.16</td>
<td>0.08 1.00</td>
<td>0.02 4.00</td>
<td>0.11 2.25</td>
<td>0.11 1.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pclr</td>
<td>1.16</td>
<td>0.08 3.00</td>
<td>0.63 2.03</td>
<td>0.31 2.33</td>
<td>0.25 2.78</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRSOV</td>
<td>11.23</td>
<td>0.54 1.86</td>
<td>0.63 2.51</td>
<td>0.50 2.10</td>
<td>0.39 2.36</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRV</td>
<td>3.81</td>
<td>0.08 3.00</td>
<td>0.14 3.43</td>
<td>0.34 1.31</td>
<td>0.42 1.13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The metric values show general agreement for all three levels of abstraction. For example, the PRSOV has a high $S_{LRU}$ (0.54, 0.63, 0.50, 0.39) relative to the other LRUs, and the FAMV has a high C (2.63, 3.57, 2.80, 4.00) relative to the other LRUs in all three evaluations. Because the metric values show agreement, it is assumed that the diagnosability valuation of a system in its conceptual phase will provide a good estimation of the diagnosability of a fully defined system. Because the values for the fully defined system use an amount of known information, they will be used for the discussion of BACS LRU diagnosability.

The three different metrics, PC, $S_{LRU}$, and C, combined show why the PRSOV has a high rate of unjustified replacements. The PRSOV has the highest $S_{LRU}$ for both sets of operating conditions combined with a relatively high C. This poor diagnosability combined with a probability of failure that is much greater than that of any other LRU may cause the mechanic to replace the PRSOV whenever the actual failure becomes difficult to locate.
Diagnosability is a quantifiable aspect of a LRU. There are different metrics that can be evaluated from information that already exists in the FMEA for a defined system, or LRU-function relationship for conceptual systems. The sources of diagnostic hurdles can be discovered, and the problem can be identified. The results of the LRU evaluation provide direction for the designer in modifying the system for increased diagnosability.

5.2 System Evaluation and Modification

The metrics introduced in section 4 allow a designer to compare the diagnosability of systems and LRUs. In this section, the current BACS and the modified versions will be evaluated for diagnosability. Changes are made only to the distribution of functions between LRUs, and only one change is made in each of three modified systems. There are no changes in the location of the LRUs. These systems are described in section 5.2.1. The results of the diagnosability evaluation of the systems appears in section 5.2.2.

5.2.1 Description of Modifications

The PRSOV causes trouble with fault isolation because under any operating condition the PRSOV contributes to the performance of many functions and therefore affects many performance measures. For this reason, failures in the PRSOV can easily be confused with failures in many other LRUs. The PRSOV is the focus of all three modification because it is difficult to diagnose and has a high probability of failure. The problem can be addressed by removing a function from the PRSOV and giving that function to the receiving LRU. The receiving LRU could already contribute to the performance of the function being
considered, so that the end result is removal of one of the LRU-performance measure relationships. This simplification of the system makes diag

One function that the PRSOV shares with many other LRU's is the "control combined temperature" function. For this function is moved from the PRSOV to HPsov. Assuming the air from the low pressure port is never hot enough to overheat the system, the HPsov could be used to protect the system from overheating by restricting flow from the high pressure port.

For system B, the temperature control function of the PRSOV is moved to the PRV. For this case, the PRV would vent bleed air out of the system before the precooler if the temperature after the precooler was too high. The PRV would be a better choice for receiving function from the PRSOV than the HPsov because, in the original system, the PRV is less often confused with the PRSOV than the HPsov.

The third variation of the BACS, system C, involves removing the control function of the PRSOV. In this proposed system, the pressures are regulated directly at the high and low pressure ports instead of downstream of the precooler. This change requires the low pressure check valve with a more complex pressure control valve, but it preserves the number and location of LRU's and sensors.

The effect of the three modifications on the LRU-PM relationships is shown in Figure 6. Modifications are evident when compared to Figure 4. For system A, the PRSOV-temperature relationships are removed. No new relationships are added because the function is moved to the HPsov, which already had a temperature relationship. System B also removes the PRSOV-temperature relationship. Again, there are no relationships added because a PRV-temperature relationship already exists. For system C, the PRSOV-pressure
relationship removed but a low pressure check valve-pressure relationship must be added.

![LRU-PM Relationships Diagram](image)


### 5.2.2 Results

Diagnosability evaluation was performed on both the original system and the modified systems. Important measures of diagnosability are the percent of indications for the PRSOV, the average number of candidates for each different PRSOV failure indication, the unweighted distinguishability, and the weighted distinguishability. These are shown in Tables 2 and 3 for high and low engine output conditions.
TABLE 2: COMPARISON OF ORIGINAL AND MODIFIED SYSTEM AND LRU DIAGNOSABILITY FOR HIGH ENGINE OUTPUT CONDITIONS

<table>
<thead>
<tr>
<th></th>
<th>( \mathbf{S_{\text{PRSOV}}} )</th>
<th>( \mathbf{C_{\text{PRSOV}}} )</th>
<th>( \mathbf{D} )</th>
<th>( \mathbf{WD} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present System</td>
<td>0.50</td>
<td>2.1</td>
<td>0.68</td>
<td>0.58</td>
</tr>
<tr>
<td>System A</td>
<td>0.42</td>
<td>1.9</td>
<td>0.73</td>
<td>0.61</td>
</tr>
<tr>
<td>System B</td>
<td>0.22</td>
<td>2.1</td>
<td>0.70</td>
<td>0.54</td>
</tr>
<tr>
<td>System C</td>
<td>0.12</td>
<td>2.0</td>
<td>0.82</td>
<td>0.72</td>
</tr>
</tbody>
</table>

TABLE 3: COMPARISON OF ORIGINAL AND MODIFIED SYSTEM AND LRU DIAGNOSABILITY FOR LOW ENGINE OUTPUT CONDITIONS

<table>
<thead>
<tr>
<th></th>
<th>( \mathbf{S_{\text{PRSOV}}} )</th>
<th>( \mathbf{C_{\text{PRSOV}}} )</th>
<th>( \mathbf{D} )</th>
<th>( \mathbf{WD} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present System</td>
<td>0.39</td>
<td>2.4</td>
<td>0.75</td>
<td>0.50</td>
</tr>
<tr>
<td>System A</td>
<td>0.21</td>
<td>2.3</td>
<td>0.73</td>
<td>0.59</td>
</tr>
<tr>
<td>System B</td>
<td>0.19</td>
<td>2.0</td>
<td>0.81</td>
<td>0.53</td>
</tr>
<tr>
<td>System C</td>
<td>0.12</td>
<td>2.0</td>
<td>0.81</td>
<td>0.71</td>
</tr>
</tbody>
</table>

Examine the results for system A, it appears that system diagnosability has improved. The drop in the percent of indication for the PRSOV (0.50 to 0.42 and 0.39 to 0.21) means that it is suspect less frequently. The number of candidate for the PRSOV (2.1 to 1.9 and 2.4 to 2.3) means that when the
PRSOV is a suspect, it is easier to diagnose [in the system weighted distinguishability (0.58 to 0.61 and 0.50 to 0.59) suggest that the improvement in PRSOV diagnosability has improved the diagnosability not just moved the problem to another area. The improvement is, however, small. The effect of the change made for system B is much different from the change made for system A. The percent of indications for PR than halved for both operating conditions (0.50 to 0.22 and 0.39 to 0.19). A similar gain in system diagnosability would not be expected however because of the mixed results for weighted distinguishability (0.58 to 0.54 and 0.50 to 0.53). The change in system B eliminated the PRSOV indications which few candidates were involved. The remaining difficult to diagnose indications which have the PRSOV as a candidate dominate the distinguishability. A common theme for the first two modified systems is a large drop in the percent of total indication for the PRSOV without a similar increase in system distinguishability. This means that the PRSOV is suspectless often, but when it is suspect it is more difficult to diagnose. The reason for this effect is that distinguishability is based on the number of candidates for each indication and the elimination of indication does not affect it. "Temperature out of range" is common to many of the PRSOV indications that involve few candidates, so the elimination of this function eliminates this possibility, but does not improve the diagnosability of the system.

The pressure regulation function is common to many of the PRSOV indications that have a high number of candidates. Removal of this function from the PRSOV in system C has a dramatic effect on diagnosability. The percentage of indications that have the PRSOV as a candidate decreases just as it did for systems A and B (0.50 to 0.12 and 0.39 to 0.12 for system C), but for this
system, the higher candidate PRSOV indications and the system weighted distinguishability numbers show a noticeable increase for both high and low output conditions (0.78 and 0.50 to 0.71). System C is the most distinguishable of the four systems because the PRSOV is not only suspectless often, but it is easier to diagnose when it is suspect. For the weighted distinguishability calculations, the probability of HPSOV failure was u of the (lower)probability of check valve failure because the check valve has been replaced by a pressure control valve similar to the HPSOV.

5.3 Summary

Using the system model that was developed for this investigation, the LRU s that contributed greatly to system ambiguity were identified. Changes were made to the system with the least diagnosable LRU in mind to make fault isolation easier. After each change, the diagnosability of the modified system was evaluated. It was demonstrated that small functional relationships between LRU s in a system can make diagnosis more efficient. It can also be seen that careful examination of the indications can help determine which functions should be moved, and where they should be moved.

6.0 CONCLUSION

A diagnostic modeling methodology was described for a system at stages in the design process, and applied to a conceptual system, a defined system, and an embodied system. This methodology is based on relationship between a system's functions and its LRU s. The way that the overall function is divided among the LRU s determines the diagnosis system. For a conceptual system, diagnosability is investigated by r
system's LRUs to conceived performance measures, which may simply loss of certain functions. As the system becomes more defined, sen may replace loss of function as the set of performance measures. Fo completely defined systems, the LRU failure modes for each set of o conditions are related to the performance measures.

After the system model was complete, a set of metrics for numeric of diagnosability were introduced for LRUs and for systems. A LRU's diagnosability will depend on the percentage of possible indications the LRU is a candidate($S_{LRU}$), and the average number of candidates f indications for which the LRU is a candidate. These measures tell how oft the candidate must be diagnosed and how difficult the diagnosis is be performed. The diagnosability of a system will depend on the a number of candidates for each indication (D). This value can be we place the most emphasis on indications that are most likely to occur.

After the model and the metrics were developed, they were both a BACS. The results of the LRU evaluation showed that the failure of o the PRSOV, is difficult to diagnose. The PRSOV is involved in approxim of all possible BACS indications and has a high average number of c This information suggests that poor diagnosability is the reason that is involved in many unjustified removals.

Once the source of the diagnosability problem was located, hypoth changes were made to the system to attempt to improve the diagno Three modified Bleed Air Control Systems were suggested and evalua modified systems did not change the overall system function, the n LRUs, the location of LRUs, the number of sensors, or the location of modifications dealt with the reassignment of function only. The res
evaluation showed that changes in LRU-function relationships can change the diagnosability of the system. Although these modifications show promise in improving the diagnosability, the effects of these modifications on overall system reliability, and assembly have not been fully considered.

This research has provided insight into the diagnosability of the BAC systems. Suggested paths to follow to improve the BACS system diagnosability, metrics and the modeling methodology presented are generalizable and applicable to other systems. These systems have only two requirements for system maintenance, which can range from simple to complex, and the systems must give some indication of LRU failure.

Ideal concurrent engineering methodology would consider all aspects of the life cycle of a product. The common metric for design evaluation would be metrics presented here. The cost of diagnostic effort through the diagnosis does not have an actual unit of cost. To establish the relationship between distinguishability and diagnostic cost for an embodied system would require knowledge of time, material, and equipment costs required to isolate a single LRU for every LRU and failure mode. With this information, decisions affecting diagnosability could be directly compared to the other life cycle costs such as manufacturability or reliability. This is the direction we expect this research to take.

8.0 REFERENCES


