# RELIABILITY CENTERED PREDICTION TECHNIQUE
# FOR
# DIAGNOSTIC MODELING AND IMPROVEMENT

by

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A diagnosability prediction metric is developed for system modeling of component failure rates and unjustified removals. The metric emphasizes ambiguity of system component indications as well as system structure. The metric is evaluated using historical data from the bleed air control system (BACS) on the Boeing 737-300. Four design changes are suggested based on improving system diagnosability by changing component functions, modifying indications, and adding or changing sensors. The resulting designs are compared via Boeing’s life cycle cost mechanism, DEPCOST model, based on cost improvements. It is shown that system improvements based on this prediction technique will increase the quality of a product since increased diagnosability decreases life cycle costs.

## 1.0 Introduction

The term quality, with respect to products, is broadening from a characteristic built into a system by the way it is manufactured to characteristics entirely inherent to the design process -- reliability and maintainability. A product is designed to achieve a given function and its quality is the degree to which it meets the functional specifications. Product failure is departure from these specifications. Emphasis on the consumer serves as the catalyst to bring about methodologies for increasing the degree a system meets its specifications through statistics and engineering. With the steady increase in complexity of systems, stringency of operating conditions, and positive identification of system effectiveness requirements, more and more emphasis is being placed on preventative maintenance, analysis, speedy repair, and replacement parts (Babb, 1973). These represent a major portion of system operating costs especially when each minute out of service is going to result in considerable financial loss for any high revenue-earning industry.

Diagnosability, the measure of the ease of isolating the cause of a loss of functionality, can strongly influence product quality through reliability and maintainability. Poor diagnosability can increase the cost of a product through increased maintenance down time which, in turn, decreases quality because a product, in general, cannot provide its intended function during this time (Clark, 1993). Improving diagnosability not only eases the diagnosis process--minimizing the total time of diagnosis, but the total cost of diagnosis is decreased in proportion to the above factors as well as in relation to the decrease in unjustified removals (removal of a suspect component later found to be in working order) of each Line Replaceable Unit (LRU)/Least Replaceable Assembly (LRA).

The historical unjustifiable removal rates of major components that are mechanical in nature average up to fifty percent higher than their failure rates. These inequities demand diagnosability metrics and methodologies to increase the quality of any mechanical system of today. Previous studies (Clark, 1993 and Wong 1994) present general methodologies which provide insight into the diagnosability of systems and suggest areas for design improvement, but focus mainly in the abstract. Previous work fails to address the issue of cost analysis of current and modified designs in a tangible way.

The objective of this research is to produce methodologies for the evaluation of diagnosability, a subset of maintainability, in the design and redesign phase of a product. A metric common to all mechanical systems enabling a prediction of the costs and, in turn, the quality of the product is developed. This metric can be used to accurately predict not only current, but modified system life cycle costs based on reliability and maintainability, or specifically, diagnosability. An analysis is presented of a real system that has experienced diagnosability problems and has iterated through redesign phases. The metric evaluated is Mean Time Between Unscheduled Removals (MTBUR) -- a function of both system structure and LRU failure rates.

The Bleed Air Control System (BACS) on the Boeing 737-300,400,500 aircraft was chosen as the analysis testbed for several reasons. Previous work (Clark, 1993 and Wong, 1994) utilized the 747-400 BACS, a subsequent iteration of the 737 BACS, so analytical comparisons can be drawn. The 737 BACS has a complete Failure Modes and Effects Analysis (FMEA) available which can be modeled through a Fault Tree Analysis (FTA). The system has a diagnosability problem evident in a large number of unjustifiable removals of LRUs. Also, the determining factor, cost, can be arrived at since a complete life cycle costing mechanism is in place for the system. The objective is to decrease cost by manipulating indication-LRU relationships without increasing complexity.

In the following section the BACS is described and modeled stating all analysis assumptions. Next, the method and metrics for prediction and design are derived using reliability mathematics for quantitative diagnosability analysis. The modeling equation arrived at is tested on the original design and, based on redesign for diagnosability potential, modifications are made to the system. The modifications range from dividing primary LRU functions differently to merely changing sensor types. The modified systems are then re-evaluated on the basis of diagnosability and ultimately cost. Finally, conclusions are drawn from the diagnosability analysis, recommendations are made for system changes, and direction for future research is laid out.

## 2.0 Description and Modeling of the Boeing 737-300 Bleed Air Control System

This section introduces the bleed air control system (BACS) including major LRUs and their indications. The scope of the analysis and all assumptions are explicitly stated for the system. Modeling of the system is accomplished with the use of a failure modes and effects analysis (FMEA) by Airesearch and maintenance manuals provided by the Boeing Company. Failure combinations are incorporated in similar fashion to previous research (Clark, 1993) for ease of comparison analysis and application of system metrics. Though the 737-300 is singled out in this research, all analyses and recommendations can be extended to the 400 and 500 models since they are exactly the same.

### 2.1 Description of the Bleed Air Control System (BACS)

The BACS consists of two identical sets (one per engine) of valves, controls, ducts, and a heat exchanger mounted in the engine nacelle area as shown in figures 1 and 2.

Figure 1. 737-300 BACS component location - left view

Figure 2. 737-300 BACS component location - right view

Each set of equipment automatically selects the engine bleed air supply from either the low-stage (5th stage) or high-stage (9th stage) bleed ports and regulates the pressure and temperature supplied to the air-using systems such as cabin air conditioning, cargo heating, and anti-ice.

Bleed air from the 5th and 9th stage compressors is routed through a heat exchanger, called the precooler, where it is cooled with air from the engine's fan. From the precooler, the air continues to the pneumatic manifold as shown in figure 3.

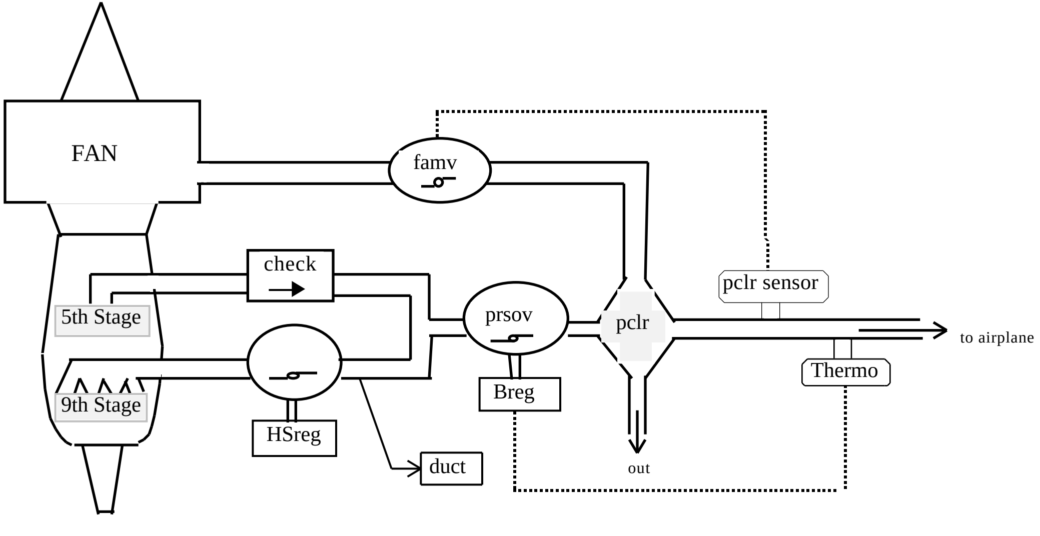

Figure 3. 737-300 BACS schematic

Since bleed air must be delivered to the pneumatic manifold within specific temperature and pressure ranges to prevent under/overheat and under/overpressure conditions, a number of valve and control systems are used for regulation.

During takeoff, climb, and most cruise and hold conditions, the pressure available from the 5th stage is adequate to meet the requirements of air supply used. During descent, approach, landing and taxi conditions 9th stage bleed air is required. The selection of the bleed supply is controlled by the high-stage valve (HPSOV) and the high-stage regulator (HSreg) setting. The HPSOV is responsible for regulating and shutting off the flow of 9th stage engine bleed air in conjunction with signals from the remotely located HSreg which selects the proper bleed air stage as necessary to satisfy system requirements. The low pressure check valve (Check) permits the flow of 5th stage bleed air and prevents higher pressure air from the 9th stage from back flowing into the 5th stage. The pressure regulator and shutoff valve (PRSOV) limits bleed air to a predetermined pressure level for the system. Secondarily, the PRSOV works in conjunction with the 450°F thermostat (Thermo) as a flow modulating valve to limit downstream temperature within a maximum upper temperature band based on signals from the Thermo. A remotely located bleed air regulator (Breg) works with the PRSOV to control the output pressure to a maximum and incorporates an overpressure switch which activates the PRSOV to close in the event of extreme bleed pressure. The precooler control valve (FAMV) controls the flow of fan cooling air to the bleed air precooler (PCLR). The FAMV modulates in response to pneumatic control pressure signals from a remotely located precooler control valve sensor (PCLRsen) to maintain bleed air temperature downstream of the precooler within a specified range. The PCLR vents excess air to ambient as do the HPSOV and PRSOV by incorporating pressure relief valves to provide additional actuator relief in the event of transient overshoots. All components are connected by a series of ducts (duct).

The 737 BACS currently has five sensors, or indications, that are used to diagnose system failures. These indications include 1) above normal readings on an analog pressure gauge 2) below normal readings on an analog pressure gauge 3) bleed trip off light illumination 4) low cabin pressure on an analog pressure gauge, and 5) low cabin temperature on an analog temperature gauge. All subsequent analysis refer to these indications in the predeeding numerical order, e.g., bleed pressure hi & bleed trip off equals indication 13.

## 2.2 Scope and Assumptions of BACS Analysis

The valves, controls, ducts, and systems making up the BACS and described in the previous section (parenthetically denoted) are considered LRUs which can be replaced on the repair line as the lowest physical level of replacement. Each LRU provides a function for the system that can be measured. The five indications listed provide the performance measures of each LRU individually and collectively depending on the mode of operation of the system. An example is the HPSOV providing pressure to the system measured by the analog pressure gauge on the pilot’s overhead panel. The LRU, HPSOV in this case, is directly associated with an indication, pressure in this case. The LRU to indication relationship is causal in direction.

Each indication, though, does not necessarily imply a causal relationship to an LRU unless only one LRU could have possibly caused the indication--a distinguishability of one (Clark, 1993). The process of diagnosis is one of determining the set of parameters,or LRUs, of a system that have parameter measures, or indications, that fall outside the desired (or necessary) design values. This indication to LRU relationship is diagnostic in direction, and the resulting set of suspect LRUs are called candidates.

The scope of BACS model is to define the LRU/indication relationships in such a way as to incorporate all LRUs and indications in the system as well as all modes of failure of each LRU. Successful completion of the model allows for systematic changes to be incorporated and analyzed. Assumptions are made to simplify the analysis and to provide consistency with a real system.

As opposed to previous research, this analysis incorporates all operating conditions of the aircraft at once since the information from all engine output conditions is realistically available to maintenance personnel. To move beyond the trivial, proper electrical power is assumed to be available to the system, a failure that has no indication associated with it is not considered, and an indicator failure is not considered since the flight crew can establish its validity. Failure of circuit protection is not considered. Valve port leakage and external leakage are not considered.

Only one LRU failure at a time is considered, i.e., mutually exclusive, though an analysis technique for dependent LRU failures (passive) is developed. All ducting is considered to be one LRU. The failure rates experienced based on the FMEA and Boeing's Dependability Cost (DEPCOST) model are in the same proportion as those predicted. Failure modes obtained from the FMEA for the BACS are the only failure modes considered. Maintenance is performed in accordance with established maintenance procedures and by personnel possessing appropriate skills and training.

Inputs to the BACS model are obtained through design standards and engineering judgment if not stated explicitly by the Airesearch FMEA or Boeing publications.

### 2.3 Modeling of the Bleed Air Control System (BACS)

Failure mode information is available from the FMEA conducted on the 737-300 BACS including probability assessments for each mode of failure. Mean time between failures for each LRU is available from a completed DEPCOST model based on historical data and maintenance reviews for the system as well. Since an LRU can fail in several ways, a "sometimes" indication developed to exhibit relations between failures and indications that only sometimes promote failure indications. The fault tree analysis model of the BACS shown in figure 4 incorporates both always and sometimes relations depicted as solid and dashed lines, respectively. Due to space constraints the LRU failures (rectangles) are placed both above and below the indications (ovals).

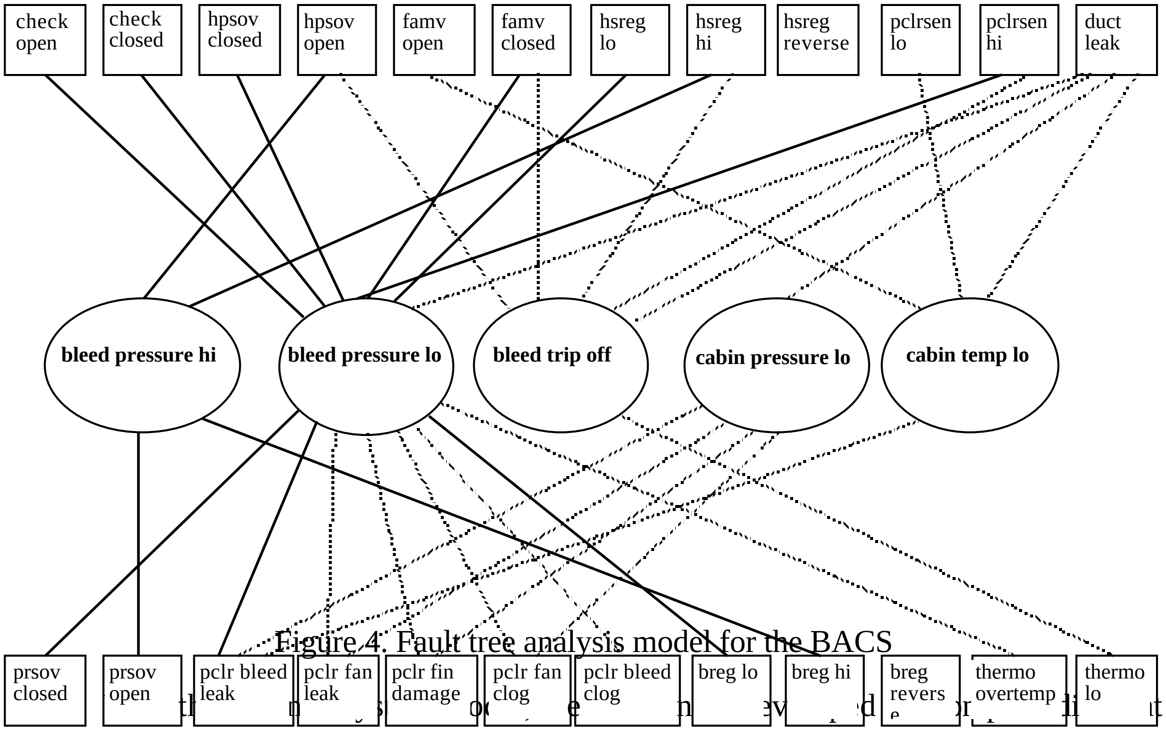

Figure 4. Fault tree analysis model for the BACS

systems that perform the same function by totally different designs or by reassigning LRU-indication relationships. Defining a prediction method to determine mean time between unscheduled removals (MTBUR) leads to a redesign methodology based on diagnosability. Incorporating these prediction metrics into the life cycle costing mechanism DEPCOST model, total diagnosability cost savings can be discovered.

## 3.0 Diagnosability Metrics

For diagnosability to be considered in the design/redesign process, there must be some way to predict how system changes will affect system parameters for comparing competing designs with respect to diagnosability. A methodology based on the prediction technique must be arrived at for use in determining what parts of the system should be changed to improve diagnosability.. A prediction metric based on unjustified removals and time is introduced in this section.

Attributed by Boeing as the "single most important input" in the DEPCOST model, Mean Time Between Unscheduled Removals (MTBUR) has been targeted by this research as the overriding prediction parameter of diagnosability. For an aircraft system, MTBUR is defined as the average number of unit flight hours occurring between unscheduled removals of an LRU. Mathematically, it is the inverse of the LRU removal rate. Reliability mathematics and labor time are the key contributors to the derivation of the predicted MTBUR based on LRU failure rates and system structure.

Though the normal distribution is capable of describing most mechanical part lives, the scheduled maintenance overhaul and replacement times are assumed to be within the middle portion of the famous bathtub curve describing system life. Therefore, the exponential distribution of is used in all subsequent analysis--assuming a constant, or near constant, failure rate. The structure of a system is most readily evaluated in terms of times to complete maintenance actions. The assumption of constant working conditions in the context of human factors as well as proper experience and training are made. The analysis also assumes a certain degree of maintenance technician knowledge prior to diagnosis based on the principle of optimum checking order (minimizing time and the chance of replacing the wrong LRU).

From a generic FMEA a fault tree analysis model can be assembled to include the failure rate of not only the LRU, but also the mode in which it fails. Therefore, a particular failure indication rate can be assessed by summing the failure rates of all LRUs with a common indication:

$$\sum_{i=1}^{n} failrateLRU_i \Big| ind_j = failrateind_j \qquad (1)$$

given $ind_j$ is the common indication. Since maintenance technicians work in the diagnostic direction, this indication failure rate is a necessary starting point.

An LRU will be removed in one of two conditions: failed or not failed. Removal in the failed condition can be predicted directly from the reliability of the LRU and is justified. Removal in the not failed condition, or unjustified removal, is a function of the probability of detecting the wrong LRU and the time it will take to repair it as well as how often the other LRU candidates for that indication fail. Equation (2) defines the prediction metric for total MTBUR of an LRU.

$$MTBUR_{tot} = 1 \big/ \left( 1 / MTBUR_{un} + 1 / MTBUR_{J} \right) \qquad (2)$$

$MTBUR_j$ is the mean time between justified unscheduled removals of an LRU and is equal to the MTBF of that particular LRU. $MTBUR_{un}$ is the mean time between unjustified unscheduled removals defined by the mean time between failures of all other candidate LRUs ( $MTBF_{n-i}$ )divided by the probability of detecting the particular LRU in question ( $PD_i$ ):

$$MTBUR_{un} = {MTBF_{n-i}} \big/ {PD_i} \qquad (3)$$

where $PD_i$ is defined by

$$PD_i = {PC_i \left| ind_j \right.} \big/ {\left( LLHPR + SLHPR \right)} \qquad (4)$$

where $PC_i \left| ind_j \right.$ is the probability of a particular LRU failing in a mode that incites a given failure indication (generated from $failrateLRU_i \left| indication_j \right.$ ), LLHPR is the line labor hours per removal of the particular LRU, and SLHPR is the shop labor hours per removal of the particular LRU. Both time variables are retrieved from maintenance log books and historical data.

For a complete prediction of the total MTBUR of a particular LRU in a system, equation (3) is inverted for each indication to find the unjustified removal rate and then added to the others to find the total unjustified removal rate of the particular LRU. The total unjustified removal rate is then inverted to find the total $MTBUR_{un}$ which is applied to equation (2). MTBUR predictions are found in the next section.

## 4.0 Application and Evaluation of MTBUR Prediction Metric

The procedures introduced in the previous sections allow the designer to accurately model an existing system to shed light on which LRUs are a source of diagnosability problems. The designer can also incorporate system changes and see precisely how time and cost are affected. For the BACS, the PRSOV is a known diagnostic challenge due to its historical high rate of unjustifiable removals. Previous work (Clark, 1993) suggests a comparison of metrics such as $\bar{c}$ (the average number of candidates for a given failure) to identify components, like the PRSOV, with potential diagnosability problems and then an application WD (weighted distinguishability) for modified systems to see if an improvement is achieved. Application of the MTBUR prediction metric allows for an immediate evaluation of not only which LRUs pose a threat to diagnosability, but which improvements in diagnosability are feasible.

The current 737 BACS design is the testing ground for the MTBUR prediction metric in section 4.1. Section 4.2 applies design changes to develop several redesigns of the system and an evaluation based on MTBUR changes and cost savings is presented along with recommendations.

### 4.1 Application of MTBUR prediction to the original 737 BACS

Only active/independent failures will be analyzed which make up the vast majority of unjustifiable removals (over 90%). From the fault tree analysis model of Figure 4, the metrics from section 3.0 can be applied for each LRU to arrive at a predicted MTBUR. Using the DEPCOST model for historical values of each LRUs MTBUR, an evaluation of the prediction metric may be accomplished. Table 1 includes values of historical versus predicted MTBUR.

| LRU | HISTORICAL | PREDICTED |
|---|---|---|
| HPSOV | 36018 | 38931 |
| PRSOV | 5394 | 6789 |
| PCLR | 65758 | 76841 |
| duct | 11000 | 11827 |
| FAMV | 16421 | 27123 |

| | | |
|---|---|---|
| CHECK | 309102 | 319140 |
| HSreg | 10985 | 15659 |
| PCLRsen | 15168 | 24106 |
| Breg | 11607 | 16700 |
| Thermo | 13799 | 89645 |

Table 1. Historical versus predicted MTBUR

Several LRUs (HPSOV, Breg, and duct) had no MTBUR listed. Based on engineering judgment, these LRUs were assigned an MTBUR equal to twice their historical mean time between failures (MTBF). Other omitted items include the Shop Labor Hours per Repair (SLHPR and spares cost of the Breg and HPSOV which are estimated at values of similar equipment (HSreg and PRSOV values, respectively, varying slightly due to complexity differences). The predicted values fall within approximately twenty percent of the true values with the exception of the 450°F thermostat. This anomaly could be explained by organizational factors outside the scope of this research, e.g., direction from higher levels because of low spares cost, ease of maintenance, least SLHPR, or merely politics, since the LRU should last much longer based on its failure rate.

Not only are predicted MTBURs and costs within an acceptable range of historical values, but order is preserved with respect to both candidates for diagnosability problems and cost drivers. With this information, the choice of LRUs and functions for redesign can be easily made.

Using the DEPCOST model directly, a comparison of cost *and* MTBUR can be accomplished by viewing figure 5. This figure is constructed by modifying the MTBUR input column of the DEPCOST model to reflect predicted values of MTBUR. The 450°F thermostat is extracted from subsequent analysis due to the assumed organizational factors mentioned earlier as well as the LRU impotency with respect to overall cost savings compared to all other LRUs in the system. Since no passive failures are addressed in this research one would anticipate a higher predicted MTBUR and therefore a lower cost than the historical values.

Figure 5. DEPCOST model of predicted MTBURs

### 4.2 System Modification and Comparison

All redesigns are based on not only diagnosability improvements, but also on cost savings since cost is always the common denominator. Four design modifications are studied and evaluations for each based on feasibility given. The benchmark for all design comparisons is the original design using predicted values of MTBUR for continuity.

#### 4.2.1 Change 1--Remove Pressure Function from PRSOV

Like the temperature control function, the pressure control function of the PRSOV is shared by other LRUs. In this case, the pressure is regulated directly at the high and low pressure ports instead of at the junction of the two just prior to the precooler. This change requires the check valve to be replaced by a control valve. Also, the Breg must then be moved to the new control valve to monitor downstream pressure and signal a bleed trip off indication in the event of an overpressurization.

Based on benchmark MTBUR and cost, change 1 increases the MTBUR for the PRSOV by 51 percent, decreases the MTBUR for the check valve by 79 percent, and slightly decreases the MTBUR for the Breg. Since the check valve is converted to a control valve, the failure rate of its counterpart control valve, the HPSOV, is assigned to the check valve bringing its MTBUR down exponentially. Since the check valve is more resistant to cost change than the PRSOV due to labor time and ambiguity, overall cost is in favor of the PRSOV. The cost savings for this system change is on the order of 8 percent--a significant amount based on the size and complexity of an aircraft system.

The feasibility of this design change can be approached from two directions. The number of LRUs remains constant, and hence the complexity does not increase nor do the functional requirements change drastically. Even the relationship of the Breg is not significantly altered since it was remotely located from the PRSOV anyway. Yet, considering the limited amount of space available in this particular system, any change in size and complexity at the LRU level could be restrictive, i.e., making the check valve a control valve. Also, keeping the bleed trip off functional relationship with the PRSOV requires an additional control line from the Breg.

For an original design for future aircraft (737-600,700,800...) change 1 is a feasible and logical design to address the unjustifiable removal problem, but a “quick fix” for current aircraft it is not.

### 4.2.2 Change 2--Add PRSOV Closed Sensor Light

Using an existing design modification based on the 747-400 BACS design, a PRSOV closed sensor light/indication is added to the system to arrest the unjustifiable removals of at least that particular LRU. Since 70 percent of the PRSOV failure modes are in the closed position, this modification promises significant impact.

Basically, this modification entails simply adding a limit switch type sensor to give the aircraft crew, and thus troubleshooting personnel, an indication when the valve is in its closed position (indication 6 for analysis). Thus, if an indication 2 (bleed pressure low) occurs without an indication 6 (PRSOV closed) then a PRSOV failure can be discounted. This decrease in ambiguity of indication 2 (below normal analog pressure gauge reading), which is the most ambiguous, should aid in overall system diagnosability.

Based on the benchmark, MTBUR of the PRSOV increases by 34 percent and all other MTBURs increase slightly as well with the exception of the check valve’s decreasing slightly because of the system metric dynamics (the ambiguity of the check valve’s only indication, 2, mandates an increase in false detections of low failure rate LRUs with a decrease in number high failure rate candidates). Overall cost savings is approximately 7 1/2 percent.

This modification exemplifies the age old battle between BITE and increased weight and complexity. Modern sensors have a reliability of at least an order of magnitude above that of the parent system and weigh as little as a dime, yet even the slightest increase in weight and complexity can substantially increase cost in terms of fuel and assembly hours--especially for aircraft systems. From the human factors standpoint, there is a point of diminishing returns on information available to crewmembers in the form of indications, but since this indication is continuous and can be recorded, reaching that point from this indication is doubtful.

Since so many system variables comprise fuel saving strategies, the cost benefit seems to be in favor of increased weight based on the amount of savings this change produces. Even in this particular system, there is always enough room under the cowling for “just one more sensor”.

### 4.2.3 Change 3--Add Indication 3 to PRSOV

Targeting the PRSOV once again, the function-indication relationship is modified to decrease the ambiguity of indication 2 in much the same way as adding a sensor.

Some type of relationship with existing indications or LRUs and the PRSOV is sought after because of the high failure rate of the PRSOV in the closed position. Considering the bleed trip off light illuminates whenever a bleed trip occurs and a bleed trip closes the PRSOV in the case of overheat or overpressure, an association is already in place. Merely running the bleed trip off light (indicator 3) wire from the PRSOV closed position instead of the overheat/overtemperature probes which currently signal the indication not only reduces the ambiguity of indication 2, but maintains system integrity by changing no functions and adding no sensors. This modification simply changes the PRSOV failed closed indication from indication 2 to indication 23.

The MTBUR for the PRSOV increases by 29 percent and increases slightly for the HSreg, duct, Breg, HPSOV, and PCLR primarily due to the decrease in ambiguity of indication 2 which these LRUs share. All other LRU MTBURs decrease slightly due to associations with both indications 2 and 3 (except for the check valve whose MTBUR decreases for the same reason stated in section 5.2.2) which the PRSOV is now associated with. The overall cost savings for this modification is almost 6 1/2 percent.

This modification seems very feasible due mainly to its simplicity. According to Boeing publications the bleed trip off light is incited by an overpressure (>180 ± 10 psi) at the inlet of the PRSOV which is monitored by an overpressure switch inside the remotely located Breg. The indication is also incited by an overheat (>490°±10°F) out of the precooler which is monitored by an overheat switch just downstream of the precooler. This change would replace two wires running from the switches with one wire running only from the PRSOV to the bleed switch off light. A drawback would be an apparent need to install a limit switch sensor in the PRSOV to monitor its position and relay the message to the indication, therefore adding a sensor like change 2 but not decreasing the ambiguity as much as a separate indication might.

Overall, this design mentality is logical. Scrutiny reveals that complexity is even reduced if the bleed trip off light signal wires are removed from the Breg overpressure and overtemperature switches. Of course, a modification like this may take more hours of overhaul than desired. In addition, even though indication 2 decreases in ambiguity, indication 23 increases in ambiguity. In light of the above discussion, change 3 promises to be a sound design.

### 4.2.4 Change 4--Add PRSOV & FAMV Stuck Sensors

The final modification of this analysis incorporates a “stuck” sensor for both the PRSOV and FAMV. This modification essentially eliminates all unjustifiable removals of the two least diagnosable/highest cost drivers in the pneumatic system.

Both the PRSOV and FAMV incorporate butterfly-type valves for their operation so a sensor placed on the axis of the valve could monitor any movement, or lack thereof. Complexity is not increased to a great extent and added weight does not seem to threaten feasibility.

Based on the benchmark once more, all LRU MTBURs realize a rather tremendous increase: PRSOV 65 percent; PCLRsen 54 percent; FAMV 25 percent; and all others over 3 percent. The overall cost savings is over 16 percent.

This change is recommended over all other changes due to its simplicity and ease of retrofitting current aircraft designs. Information from the Boeing company and the Federal

Aviation Administration (FAA) implies bigger cost savings realized on sensor-based modifications rather than complete component overhaul do to certification practices. Change 4 of the BACS MTBUR based research analysis possesses the confident expectation of most cost-benefit and least retrofit time loss. A summary of modification results based on predicted diagnosability cost including spares provisioning is shown in table 2.

| *Original design cost = $122,258* | | |
|---|---|---|
| **DESIGN** | **COST** | **% SAVINGS** |
| Change 1 | $112,443 | 8.0 |
| Change 2 | $113,085 | 7.5 |
| Change 3 | $115,343 | 5.7 |
| Change 4 | $102,334 | 16.3 |

Table 2. Cost analysis of modifications.

## 5.0 Conclusion

The growing life cycle cost dependency of quality products is prompting design engineers to meet product specifications with diagnosability as a major ingredient. This research has addressed diagnosability analysis for mechanical systems quantitatively by means of LRU-indication relationships. These relationships, along with structure which is defined by maintenance time, essentially determine the diagnosability of a system. As system LRU functions and indications are modified, diagnosability also changes based on the reliability of each LRU and the ambiguity of each indication. The MTBUR of each system LRU is a direct measure of diagnosability. A generic metric was developed to predict LRU MTBURs for any system made up of several LRUs that give some indication of failure. The MTBUR of a particular LRU is directly related to the probability of detecting that particular LRU and its time to repair given a failure indication including other LRUs. The value of MTBUR for each LRU can be compared to that of other LRUs to determine which ones present a diagnostic challenge. System changes based on this information can then be made to decrease the cost of diagnosability.

The MTBUR prediction metric was applied to the 737 BACS to determine system improvements. LRU evaluation presented the PRSOV and FAMV as primary candidates for diagnosability improvement. The life cycle costing mechanism, DEPCOST model, was used to evaluate system cost based on the diagnosability parameters of unjustified removals, spares cost, and maintenance time. Four design changes were suggested and analyzed based on MTBUR, cost, and feasibility. These redesigns modify LRU indications by optimizing current indications or by adding sensors to strategic LRUs. Evaluations of the redesigns revealed an improvement in diagnosability directly impacting the cost of the system.

Quality through diagnosability cannot be neglected in today’s marketplace. The MTBUR prediction serves as an indespensible design tool for analysis of system redesigns, sensor reallocations, and the developement of system fault isolation procedures. The relationships of diagnosability developed here can be directly compared with other common design decision-making variables such as manufacturability and ease of assembly in the arena of life cycle costing. The optimal result of lower life cycle costs increases throughout the design process since the prediction model becomes more accurate as the system is refined. The direction of future research is expected to address the structure of designs explicitly in terms of maintenance hours. This will especially enhance prediction techniques of systems with a lack of historical data.

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