Canadian Forces T56 Engine Adaptive Maintenance System

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ABSTRACT

In 2005 the Canadian Forces (CF) approved the development of the T56 Adaptive Maintenance System (AMS). The AMS was developed to field innovative fleet management technologies for the CF's T56 fleet and to demonstrate life-cycle performance and cost improvements. It will result in a consolidated and revolutionary set of engine maintenance management capabilities for CF personnel at all organizational levels. In short, the AMS is driven to provide iterative work scope optimization tools to second and third-line engine maintenance to reduce CF costs, increase Time On Wing (TOW), and improve aircraft availability (lower cost per operating hour). AMS development can be divided into four mains areas: Cost Modelling, Reliability Centred Maintenance, Data Integration, and Performance Modelling. This paper will discuss the development and results of the AMS, including demonstrating its tangible benefits to the CF.

AMS Description and Capabilities

A traditional turbine engine repair / overhaul feedback system assesses problems found in engines and implements improvements into the build process. Unfortunately, the time it takes to obtain data and implement improvements or changes makes the learning-cycle excessively long as some CF T56's can remain on wing for almost a decade. By modelling system reliability, cost, and performance, a feed-forward capability can be incorporated. This shift will allows simulation of the effect of various risks and scenarios on T56 fleet reliability and cost in a theoretical sense, thus obtaining useful feedback while the engine is still on wing and in good health.

1.0 BACKGROUND

1.1 INTRODUCTION

For the past three years, the Canadian Forces (CF) has been working with Standard Aero to develop a tool that will assist the T56 Technical Authority (TA) with maintenance program decisions. The program was started for three primary reasons: 1) the CC130 is getting old, causing maintenance costs to increase; 2) the T56 feedback loop is over ten years long; and, 3) advancements in maintenance management technologies are now available that could be tailored for the CF.

It is no secret that the CC130 models flown by the CF are getting old. As with most aircraft, the cost of maintenance increases, and availability decreases as it ages. The technologies behind adaptive or predictive maintenance concepts have been rapidly developing over the last number of years. The CF has recognized that the current T56 maintenance program is not necessarily the best way of doing business, and has been pushing to develop a more progressive program.

In order to assess changes to the CF T56 maintenance program, a method to determine the effectiveness of the changes is required. In a typical feedback loop a baseline is known, a change is made, the new baseline is measured, the two baselines are compared, and a determination is made as to what is required from this point on. With the CF T56, there is an average of 9 to 10 years between visits to overhaul facilities; consequently the feedback loop would then be about 12 years long. A tool is required to give assurances in a much shorter time frame that the changes being made are worth making.

1.2 OBJECTIVES OF AMS

The goals of the Adaptive Maintenance System are to 1) reduce maintenance costs while increasing engine time on wing and aircraft availability; 2) develop an enhanced maintenance program for the T56; and 3) develop tools that would aide decision making and problem identification much faster than the current 10 year overhaul feedback cycle.

1.3 PLAN OF ACTION

In order to develop this program, the project was split up into four different streams. These streams included a number of sub-tasking that would be merged together to create a single program. The four streams are Reliability Models, Cost Models, Performance Models, and Data Integration. Each of these streams fed into the final group of tools or outputs of the program.

2.0 DEVELOPMENT “STREAMS”

2.1 RELIABILITY MODELS

Reliability studies were conducted on historical maintenance data to determine failure modes, which included analyzing primary failure indicators (PFI) and reasons for removal (RFR). In this context a failure refers to a part or component that is no longer able to function as designed. For the AMS program this included: actual part failures, damage beyond acceptable limits, hard life limits, and “soft” life limits (such as time between overhaul).

Module-level reliability studies were conducted individually on the main engine modules: Propeller, Reduction Gear, Torquemeter and Power Section. These data were then combined to form a system level reliability model for the entire engine. The method employed in the AMS program development is shown in Figure 1 below. Once the necessary data were identified, collected, and validated, it was analyzed for PFI and RFR to determine failure modes. Results were initially examined as Pareto plots to highlight significant maintenance drivers (see Figure 2). The failure modes were also used to create Weibull curves for the generation of reliability block models, which were validated against historical data. These models then formed the backbone for the development of AMS forecasting and prediction applications. For example, the applications can run different scenarios to determine the effects of changes in a particular failure mode or of different maintenance policies on the overall system.

The reliability analysis phase of the AMS project has objectively shown where to prioritize reliability improvement efforts required to more successfully manage the T56 propulsion system. Thanks to the AMS project, the CF has a much clearer understanding of the top reliability drivers for the entire propulsion system and has subsequently taken action to address each one.

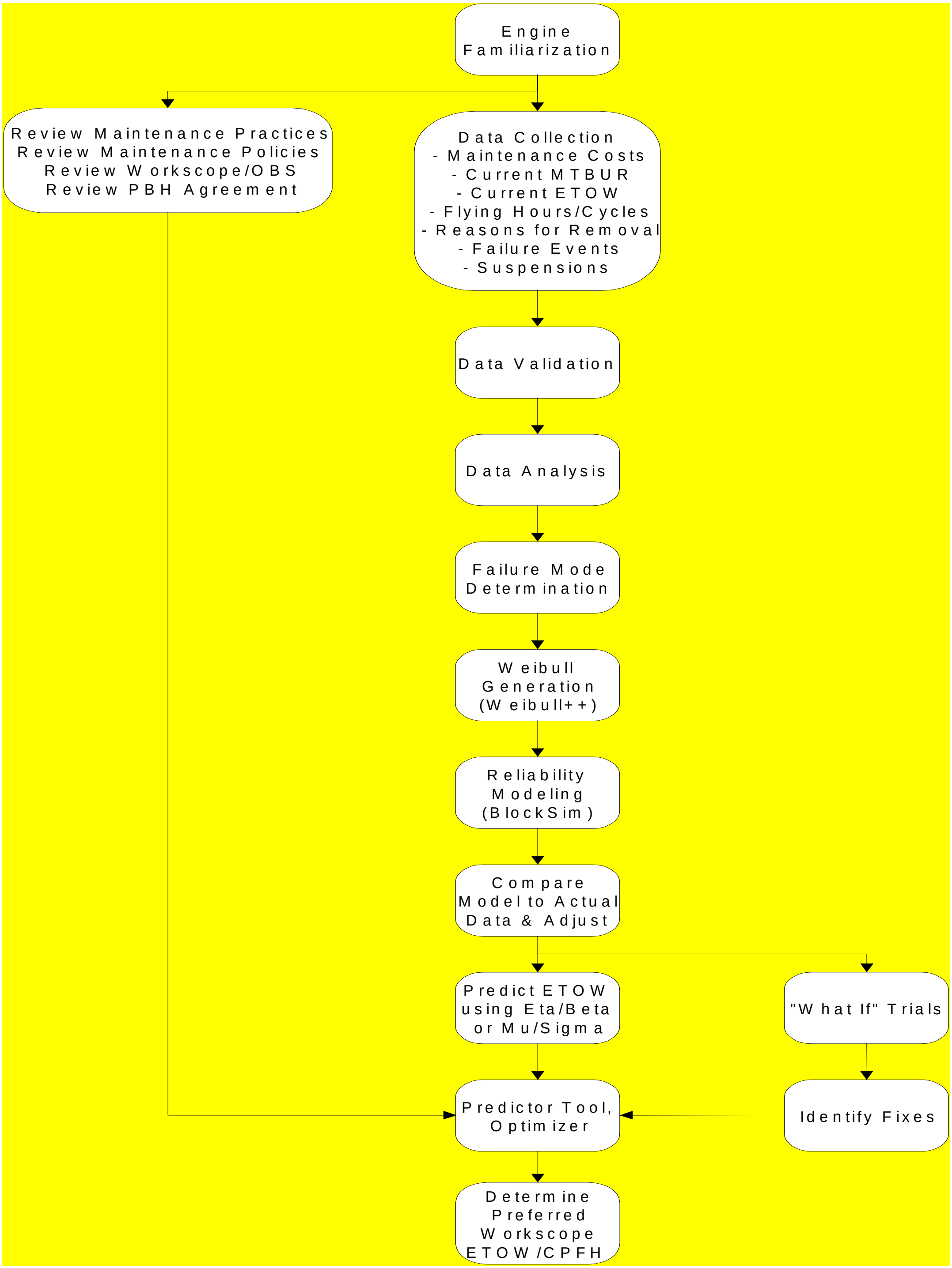

Figure 1 – Flow Chart for the AMS program Reliability Analysis (NOTE: OBS=Operating Build Spec., PBH=Power By the Hour, CPFH=Cost Per Flying Hour, MTBUR=Mean Time Before Unscheduled Removal, ETOW=Estimated Time On Wing)

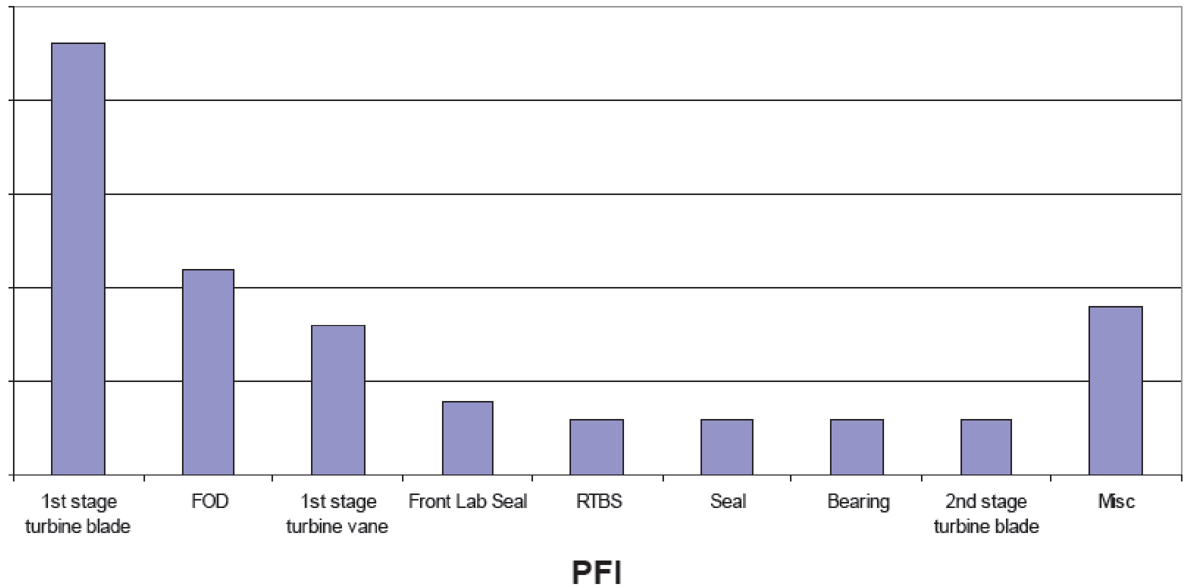

Figure 2 – Pareto of Primary Failed Item for T56 Power Section (NOTE: FOD=Foreign Object Damage, RTBS=Rear Turbine Bearing Support)

2.2 COST MODELS

As the reduction of cost is one of the main objectives of the AMS, the determination and prediction of cost is a key element of the program. Costing models were developed to support the AMS tools. The boundaries or selection of costs were restricted to include only those that would influence the T56 support program. Cost determination was therefore limited to the maintenance costs of the T56 engine systems drawn from field and depot level cost elements. The main cost elements are categorized as: fixed, variable, sunk, direct and indirect. The types of costs comprising each element include: time, consumables, part use, risk, and sunshine (unexpected internal component costs). The sources of cost data include maintenance service and support costs incurred during depot and field activities. Component reliability results were also incorporated for forecasting future cost estimates. The main cost elements are shown in Figure 3.

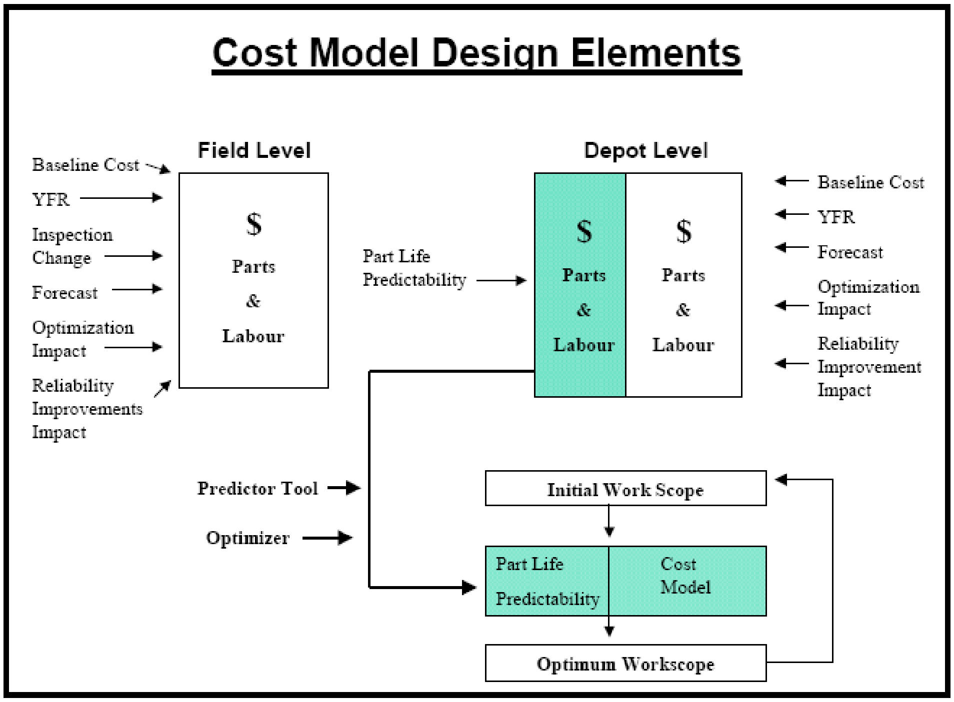

Figure 3 – Overview of Cost Model Design Elements (NOTE: YFR=Yearly Flying Rate)

Although the cost model will be used to support a number of purposes, the primary requirement is two-fold: to determine the costs associated with a given workscope (defined as a collection of maintenance activities carried out or planned) and/or to forecast the costs of planned or potential future expenditures such as modifications. A number of database tables, input requirements, and relationships were created to support the cost model. It is implemented as a set of database procedures. Basically it will calculate a cost given a set of predefined work items, such as an actual maintenance activity already carried out or a planned optimized workscope in order to provide that information to other applications of the AMS program.

2.3 PERFORMANCE MODELS

The performance models of the AMS mainly attempt to relate engine component geometry, especially that governed by overhaul build practices, to expected engine performance. Geometric studies were done on the reduction gear, compressor, turbine, and combustor. Additionally data on components fits and clearances were analysed to determine their affect on performance.

Specific build combinations were validated through engine testing. However, before doing so, an extensive investigation of the Standard Aero engine test cell was conducted. As a result, several improvements to the test cell were implemented that greatly improved data collection and back-to-back test repeatability.

2.3.1 Compressor

Past build data was analyzed to correlate specific clearances and part geometries to engine performance. For the compressor, rotor runout, case fit, blade condition, and stator vane condition were all considered. An optical scanner was employed to investigate the condition of new and used compressor airfoils. A data collection and analysis tool called the Performance Reasoner was developed to allow the individual effects to be summed in a probabilistic fashion. The Reasoner was subsequently validated using archived test data.

2.3.2 Turbine & Combustor

Past build and performance data for the turbine module were mined and correlations derived for specific geometries. Some dimensions that were investigated included the axial positioning of the turbine rotor, blade untwist, nozzle guide vane condition, combustion liner fit and tip clearance. These correlations were added to the Performance Reasoner and validation testing carried out. Overall, it was found that the Performance Reasoner was capable of successfully explaining over 50% of engine performance variation. This represents a significant advance and it is believed that as the underlying correlations are improved this number will increase.

2.3.3 Fits & Clearances

An in-depth study of the basic fits and clearances of tight tolerance components such as blades and vanes was carried out. It showed areas where data collection is weak and that regression analysis proved to be the foremost method of drawing conclusions from the data. The study revealed insights into blade tip grinding and aerofoil inspection techniques.

2.4 DATA INTEGRATION

The three main data sources for the AMS are:

- the CF aircraft maintenance records database called Automated Data for Aircraft Maintenance (ADAM),
- the engine configuration and life limited component database, which is the T56 Parts Life Tracking System (PLTS), and
- third line or depot maintenance information from the Standard Aero production database (SA SQL).

The data warehouse brings together the sources of information into single integrated location. It consists of over 50 relational data tables that describe different aspects of aircraft and engine maintenance. The data tables can be separated into groups according to functionality.

The warehouse requires regular updating, which is done both manually and automatically. This allows both ease of updates and capacity to validate data before it becomes part of the warehouse. It is maintained through two main applications: the bulk data loader to automatically enter large volumes of fleet data and the database population utility to add/modify/delete individual records. These data are then used throughout the AMS program as inputs to the various analysis tools.

3.0 OUTPUTS

3.1 MAIN ANALYSIS TOOLS DESCRIPTIONS

3.1.1 Workscope Optimizer

The workscope optimizer determines an “optimized” work package for depot repair or overhaul activity based on the analysis of trade-offs between factors such as reliability, performance, and cost. In general, the optimizer will be used to establish a workscope to minimize cost per flying hour; however, it may also accommodate such priorities as maximum time on wing, highest performance, or minimum turn-around-time. Figure 4 shows a sample output screen from the Optimizer.

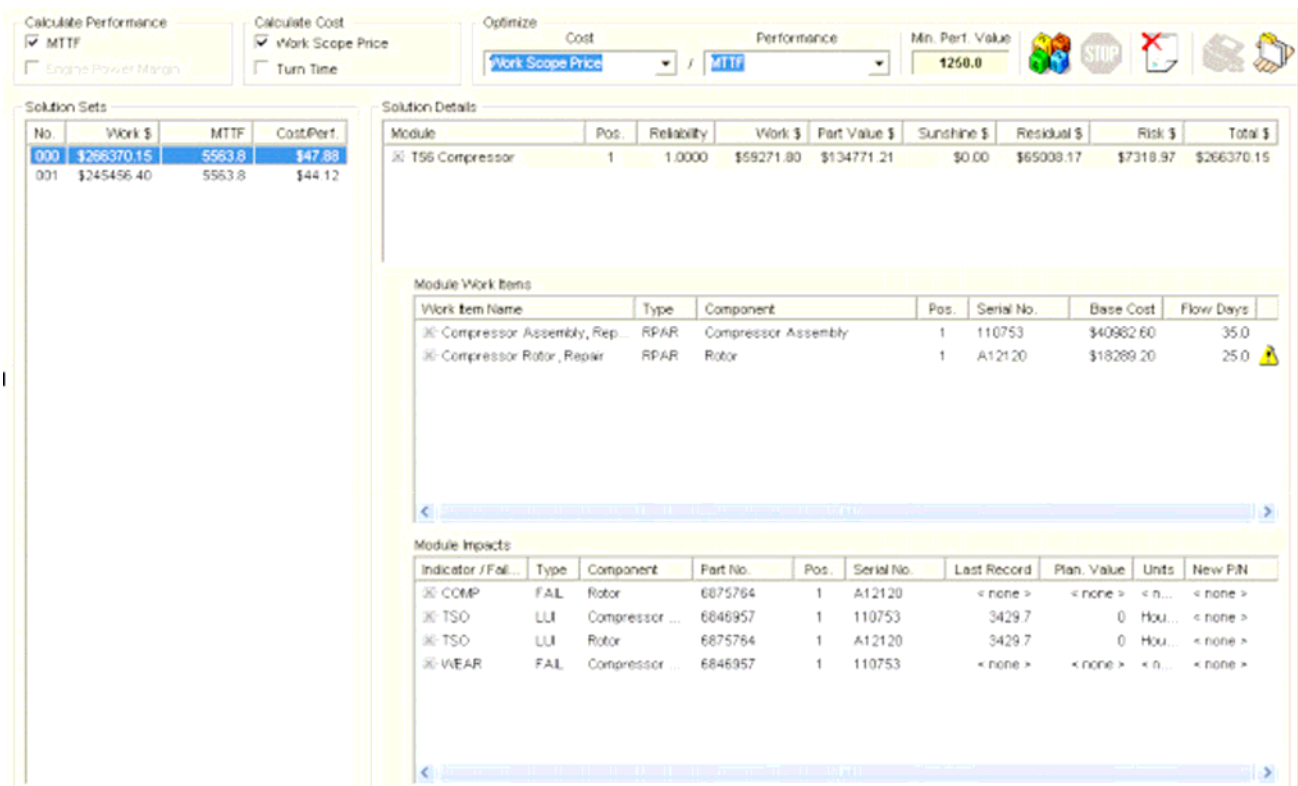

Figure 4 – Workscope Optimizer Tool – Sample Output

3.1.2 Fleet Fly Forward Simulator (F3S)

By incorporating the cost models, performance models, and reliability models, the F3S system can analyse effects on the fleet such as a change to the maintenance program. The F3S mimics actual engine behaviour by drawing on reliability data in the failure distributions, which are then embedded into a Monte Carlo simulation to project when an engine is due for maintenance. Then the F3S uses the workscope optimizer to simulate an optimal repair and estimates the new time on wing. The F3S repeats these steps for each aircraft in the fleet for the selected time frame to provide an overall fleet level assessment. The simulation will give the expected changes to the average TOW, cost per flying hour, and availability. Figure 5 shows an example input screen.

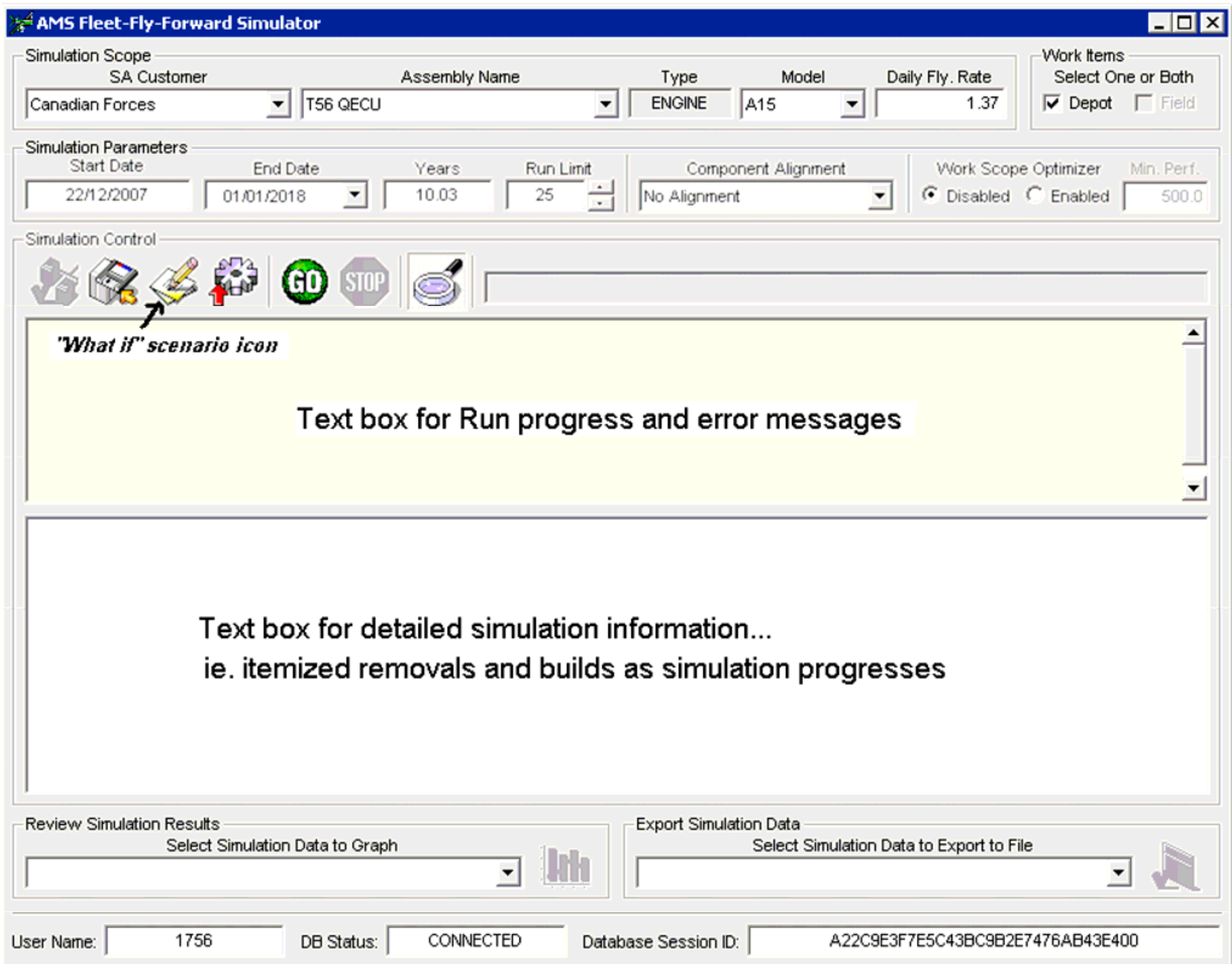

Figure 5 – F3S User Interface Screen

3.2 EXAMPLE OUTPUTS

The following example results associated with this project occurred either as a result of the data analysis needed to create the models or as a result of exercising the models.

3.2.1 Miscellaneous Results

In completing the various studies and sub-projects of the AMS program a number of areas for improvement were identified, these included:

- Test Cell Improvements – as described above, due to the requirements for additional engine testing, several improvements were made to the Standard Aero test cell improving repeatability, data capture, and vibration assessment.
- Planet Gear Optimization – analysis of T56 Reduction Gear Box (RGB) failure data revealed that an infant mortality failure mode exists. Investigation confirmed that all overhaul processes were within

allowable tolerances. It was postulated that the failure mode could be caused by the stack-up of build tolerances throughout the overhaul process. Geometric and finite element models of the RGB main drive elements confirmed that allowable tolerances resulted in a small percentage of RGBs with excessive stresses in key rotating elements. One result, based on the RGB studies, found that if the angular location of the planet gears was optimized this would reduce premature gear wear. This improvement is being introduced during depot level maintenance of the CF RGB.

- Compressor Rotor Inspection System (CRIS) / Laser System (rotor centring) - a capacitance probe system for improved compressor rotor centring together with a blade tip laser measurement system was developed from the compressor build study. Its implementation will improve the compressor build process and thus compressor performance.

3.2.2 Significance of Propeller Reliability.

The T56 engine and 54H60 propeller are not managed together as a single system, but as two individual systems. The creation of a single propulsion system reliability model highlighted the fact that the propeller's overall reliability is approximately half that of the engine. Moreover, it showed that the propeller (and not the engine) is the leading driver of T56 propulsion system on-wing removals.

The data also showed that propeller leaks are especially troublesome and that resolution of this problem will reduce system removals significantly. While the system manager was aware of this persistent problem, its significance to overall system health was not apparent.

The reliability data also highlighted the fact that the propeller valve housing is another major removal driver. This complex hydro-mechanical system controls the propeller through all phases of operation. The data showed that many of these systems are replaced and subsequently found to be out of adjustment when returned to the depot.

The CF has launched an initiative to address these propeller issues. An on-site refresher training program has been launched to specifically address leak and valve housing issues. The CF has also launched a study into the viability of replacing the existing valve housings with an electronic version.

3.2.3 Control System Troubleshooting

During the data analysis phase, it was found that one third of engine accessories are removed with no fault subsequently being confirmed when the accessories are routed to the depot. This finding confirmed suspicions that technicians have difficulty troubleshooting the engine control system. This finding initiated a separate project under which an advanced, case-based reasoning system was populated with control system fault cases. The system is undergoing a trial at a Canadian air base.

3.2.4 RGB Removals for Vibration

The AMS data analysis found that several RGBs per year are removed for high vibrations and that subsequent testing at the depot has been unable to find a problem with any of these units. Consequently, a study was conducted to determine if off-the-shelf systems exist that could improve the ability of the depot to diagnose RGBs. An in-line oil analysis system and two advanced vibration-monitoring systems were evaluated in a depot trial using actual RGBs. The study showed that the systems' ability to detect and diagnose faults without the benefit of historical trend information is limited. Since the reliability data showed that the operational and financial cost of RGB vibrations is modest, it was decided to suspend work in this area until other, more appropriate, technologies are available.

3.2.5 Fleet Future Posture

The CF has started the retirement of selected CC130 aircraft. To assess retirement and management strategies for the fleet going forward, twenty-four scenarios were evaluated using the F3S. The cost and reliability impact of each scenario was evaluated and plotted. Some of the results of this study are:

- A well-developed retirement strategy for the propulsion system can reduce operating cost per hour by over 30%. Matching engines to aircraft and pro-actively adjusting sparing levels have major effects on support costs.
- Adopting a flexible approach to engine workscoping during retirement will result in significant savings. Instead of overhauling engines, specific, lower cost workscopes should be employed to see the engines safely through to their projected retirement date.
- Engines that have seen extended service in Southwest Asia appear to have different rates of wear and performance deterioration. For this reason, a further study is underway to determine if the underlying failure distributions for this subset of engines is different than the remainder of the fleet. The fleet model will be rerun as needed to validate the original findings.

3.2.6 First Stage Nozzle Guide Vanes (NGV)

The engine manufacturer has introduced an improved 1st stage NGV with better cooling. The expected benefit is a longer service life; however, the new NGVs cost significantly more. The AMS tools were used to evaluate the benefits of this upgrade over the remaining life cycle of the fleet. The failure distributions and cost relationships in the F3S were modified to reflect the performance of the new NGVs and scenarios were run. The F3S showed that little or no benefit was gained by upgrading the entire fleet. The model showed that maximum benefit would be gained by only upgrading those engines that would remain in service the longest. This recommendation is being adopted.

4.0 CONCLUSIONS

The AMS project has improved the management framework of the entire CF T56 propulsion system. Strategic reliability drivers have been identified and projects are underway to address them. Less time is spent managing issues that may have only limited impact on cost and reliability. The AMS has provided the CF with the ability to quickly and objectively make management decisions based on reliable determination and prediction of the life cycle performance of the fleet. Enhancements to the AMS are underway to improve its speed and add additional models of other areas such as parts supply, production and shipping times to be included in the scenario evaluations. This will allow the models to be used to optimize the entire T56 support system. In short the AMS will continue to provide ever greater insight into CF T56 fleet activities.