Sustainment of Commercial Aircraft Gas Turbine Engines: An Organizational and Cognitive Engineering Approach

by

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ABSTRACT

Sustainment of commercial aircraft gas turbine engines in the form of maintenance, repair and overhaul (MRO) is a primary activity in the life-cycle of a modern commercial aircraft system. About forty percent of a typical air carrier's maintenance costs are due to engine MRO. As such, the MRO industry is constantly looking for opportunities to reduce costs and make sustaining aircraft over long lifetimes an affordable proposition for air carriers. Current MRO decision support tools focus on engine condition monitoring and fault diagnostic systems, and most of the existing literature has focused on developing algorithms for these systems. However, few researchers have suggested how to design a broader set of computer-based decision support tools to meet various other cognitive needs of the engine MRO community. Besides engine condition monitoring and fault diagnostics, other cognitive needs can be found in areas such as fault prognostics, maintenance planning, workscope generation and configuration management.

This thesis presents a novel cognitive engineering approach to creating a framework that more fully captures the decision support needs of commercial aircraft gas turbine engine maintenance, repair and overhaul (MRO) organizations. Using field studies of various airlines, engine MRO providers and engine manufacturers across North America, Asia-Pacific and Europe, the analyses presented offers a thorough understanding of these cognitive needs and the decision-making process in engine MRO. A set of preliminary recommendations are proposed for a design framework of new decision support tools for engine sustainment and how such tools can be implemented in future engine MRO operations.

Thesis Supervisor: Charles Coleman

Title: Boeing Assistant Professor of Aeronautics and Astronautics

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List of Acronyms and Abbreviations

ACARS	ARINC Condition and Aircraft Reporting System
AOG	Aircraft On Ground
BITE	Built-in Test Equipment
BSI	Borescope Inspection
CMC	Central Maintenance Computer
CTA	Control Task Analysis
CWA	Cognitive Work Analysis
DPCM	Diagnostic, Prognostic and Condition Monitoring
ECM	Engine Condition Monitoring
EEC	Electronic Engine Control
EGT	Exhaust Gas Temperature
EHM	Engine Health Management
EMM	Engine Maintenance Manual
EMP	Engine Maintenance Plan
EMS	Engine Monitoring System
ETOPS	Extended Twin-Engine Operations
FAA	Federal Aviation Authority
FADEC	Full Authority Digital Engine Control
FAR	Federal Aviation Regulation
FCU	Fuel Control Unit
FIM	Fault Isolation Manual
HMV	Heavy Maintenance Visit
HPC	High Pressure Compressor
HPT	High Pressure Turbine
IFSD	In-flight Shut Down
JAA	Joint Aviation Authority
JAR	Joint Aviation Regulation
LPC	Low Pressure Compressor

LPT	Low Pressure Turbine
LRU	Line Replaceable Unit
MAT	Maintenance Access Terminal
MCD	Magnetic Chip Detector
MEL	Minimum Equipment List
MFD	Multi-Function Display
MPG	Maintenance Planning Guide
MRO	Maintenance, Repair and Overhaul
MSG-3	Maintenance Standards Group 3
N_1, N_2	Spool speeds
	(N_1 – low pressure spool, N_2 – high pressure spool)
NGV	Nozzle Guide Vane
OEM	Original Equipment Manufacturer
PMA	Part Manufacturer Approval
RCM	Reliability-centered Maintenance
SOAP	Spectrometric Oil Analysis Program
TBC	Thermal Barrier Coating
VIGV	Variable Inlet Guide Vane
VSV	Variable Stator Vane
WDA	Work Domain Analysis

Chapter 1: Introduction

A key transportation system like the commercial aviation industry[1] inherently has a myriad of actors and stakeholders who are interwoven by a vast and multi-layered network of relationships and interactions. Such a large, complex infrastructure requires a continuous and concerted sustainment effort among all the system's actors in order for the system to function effectively, safely and reliably for very long (10-20+ years) lifetimes.

Sustainment – maintenance, repair and overhaul (MRO) and performance - is a primary activity in the lifecycle of a modern aircraft system. Without an effective sustainment infrastructure, operational wear and equipment obsolescence over time would severely degrade the performance of the aircraft. It would be increasingly difficult to operate the aircraft at its designed mission and rapidly rising operating costs would render this aircraft system too expensive to operate. Surveying across many aircraft systems over the last few decades, it has been estimated that two-thirds of the system's lifecycle cost is attributed to operations and sustainment. So it is no surprise that sustainment considerations are now firmly entrenched in the design and lifecycle model of modern aircraft, right from the drawing board onwards.

For a commercial aircraft system, sustainment is dominated by MRO as commercial aircraft usually do not receive performance upgrades or enhancements unlike military aircraft[2]. This thesis focuses on the MRO aspects of the sustainment of commercial aircraft systems. Much of the commercial aircraft MRO cost is initially borne by the airline and the MRO shops, and this cost is eventually passed on to the airline passengers. Effective MRO is essential for the airlines to meet stringent safety and reliability standards mandated by regulatory bodies and demanded by the general public, as well as

[1] The commercial aviation industry is defined here to be air carriers operating under Part 121 of the Federal Aviation Regulations (FAR) and their associated MRO and supplier networks.
[2] Military aircraft often receive mid-life performance upgrades and their mission capability is expanded to prolong service life. Commercial aircraft, on the other hand, have rarely seen changes in their performance except for noise hush kits or glass cockpits, and the only change in missions is freighter conversions.

to maintain the performance of the aircraft throughout its lifetime. Furthermore, the effectiveness of the airline's MRO operations directly affects its on-time departures and arrivals. Therefore, MRO is an integral part of the airline's business model[3].

Earlier research efforts by the Lean Sustainment Initiative[4] have focused on military aircraft systems. This thesis aims to shift our focus onto commercial aviation MRO.

Despite a growing recognition of the importance of maintenance in the aircraft lifecycle and more emphasis placed on maintainability (and lifecycle support) in the design of new commercial aircraft, there is still much room for improvement in the area of MRO for the commercial aviation industry. Table 1 illustrates the safety and economic impacts of aviation maintenance on the airline and the air transportation system.

It has been estimated that improvements in diagnostic technology can reduce these maintenance costs by at least 25% if not greater (Bowe, 2000). Diagnostic, prognostic and condition monitoring (DPCM) tools have been employed by airlines and MRO shops in their engine maintenance - to monitor engines, predict any impending failures and to troubleshoot any engine problems which arise. As described later in this thesis, these DPCM tools are a critical component of the engine MRO process. However, such maintenance errors and engine problems seem to suggest that these tools may not be performing as well as they are expected to perform.

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[3] Air freight companies and cargo airlines share essential the same business model and face the same MRO challenges as the passenger-carrying airlines.

[4] Lean Sustainment Initiative (LSI) is a collaborative partnership of U.S. aerospace MRO providers, the US Air Force and MIT, which is dedicated to improving the MRO industry. More details on LSI can be found at <www.leansustainment.org>.

Aviation Maintenance Errors
• 15% of worldwide accidents involve a maintenance system error
• 48,000 US flights dispatched each year with a maintenance error on board
• 20% of in-flight malfunctions are caused by maintenance errors

(Marx, 1999)

Maintenance Errors Cause	
• 20%-30% of in-flight shutdowns (IFSD)	$ 500,000 per IFSD
• 50% of flight delays are due to engine problems	$ 10,000 per hour
• 50% of flight cancellations are due to engine problems	$ 50,000 per cancellation

(Rankin, 2000)

Economic Size of Airline Line Maintenance	
Line maintenance problem	**Annual cost per aircraft**
Delays	$50,000
Cancellations	$60,000
High No Fault Found Rates	$30,000
High Repeat Fault Rates	$45,000
Excessive Spares	$15,000
Total	$200,000

(Bowe, 2000)

Table 1: Aviation Maintenance Facts

As modern commercial aircraft systems are made up of many complex sub-systems, it would be a challenging task to study the sustainment of all these systems. So, we have chosen to focus on the sustainment of one key system – the gas turbine engines. As an essential "bare-bones" system, the basic performance of the aircraft is highly dependent on the powerplant. A faulty engine grounds the aircraft, and aircraft downtime incurs severe penalties on the cost structure of the airline (see Table 1). The high cost of maintaining and repairing modern aircraft engines also heighten the need for reliable and accurate diagnostics, prognostics and overall maintenance management. It has been estimated that about forty percent of an air carrier's maintenance costs are due to engine MRO with another forty percent attributed to avionics and the remaining twenty percent divided between the airframe and internal sub-systems. Furthermore, the value of production of civil gas turbine engines was estimated at $17.5 billion in 2001, accounting for 88% of aviation gas turbines and 37% of all gas turbine engines (Langston, 2002). So, improvements in the sustainment of commercial aircraft gas turbine engines will have substantial impact on the overall gas turbine and airline industries.

In the case of aircraft engines, current MRO decision support tools focus on engine condition monitoring and fault diagnostic systems, and most of the existing literature has focused on developing algorithms for these systems. Although current DPCM tools in the market have sophisticated algorithms that can perform their individual functions well, there also has to be a good overall match between the tools and the end-user for the tools to be effective. Besides engine condition monitoring and fault diagnostics, other cognitive needs can be found in areas such as fault prognostics, maintenance planning, workscope generation and configuration management. Some tools for maintenance planning and fleet management are beginning to emerge.

Current tools can be improved by incorporating more end-user feedback and a thorough understanding of the entire MRO system into their development. For example, since DPCM tools are essentially providing cognitive support towards the MRO process, it is vital that the DPCM tools fit in well with the decision-making process of the user. The level of cognitive support provided by DPCM tools depend greatly on the tools' operating environments - the process, the people and the product being supported. So we need to thoroughly understand the MRO system, the people involved in MRO and how all the processes and decision-making is done, in order to develop effective DPCM and other cognitive support tools.

Through the implementation of effective computer-based decision support tools, airlines and MRO shops can shift to predictive maintenance, keep smaller inventories and reduce engine downtime. Therefore, maintenance and operating costs will be lowered over the aircraft's lifecycle and the system's overall effectiveness will be markedly improved.

The following are the three main objectives of this thesis:

1) Understand the key actors, interactions and system dynamics in the commercial aviation engine MRO system.
2) Survey the use of decision support tools in the engine MRO industry.
3) Propose preliminary recommendations for a design framework of future decision support tools for engine sustainment, using a cognitive engineering approach.

This chapter provides an introduction to the notion of sustainment for aircraft gas turbine engines and the importance of decision support tools in the aircraft engine MRO industry. Chapter 2 describes the methodology that is adopted in this thesis. Chapter 3 presents background information of the airline and MRO industries, while Chapter 4 describes how aircraft and engine MRO are organized and what processes are involved in these operations. A review of current and emerging engine DPCM tools and systems is presented in Chapter 5. Chapter 6 discusses why a cognitive engineering approach is used in this thesis and gives an overview of the Cognitive Work Analysis framework that is used in the later analyses. In Chapter 7, the MRO system is analyzed from a systems engineering viewpoint, focusing in particular on the interactions and processes between various actors in the MRO system. Results from the cognitive work analysis are also presented and discussed in this chapter. Chapter 8 provides a summary of the findings in this thesis, and offers recommendations for future research in this area of engine sustainment.

Chapter 2: Methodology

This chapter describes the methodology that was used in this thesis. Given the objectives of this thesis, the research work was split into three parts: an open literature review, industry field studies followed by two sets of analysis methods.

2.1 Open Literature Review

The research for this thesis started with a review of the open literature that has been written on aviation and engine MRO and associated decision support tools. It was found that the industry publications were an especially informative source on current market trends and industry practices. Existing technical literature on engine diagnostics, prognostics and condition monitoring was also reviewed.

2.2 Industry Field Studies

Most of the data gathered in this thesis was obtained by surveying the various airlines, OEMs, MRO shops and vendors of decision support tools. This method was chosen because of the importance of understanding current maintenance practices and the complex interactions that take place in the MRO system. Each actor in the MRO system has different requirements for their decision support tools. The field studies initially focused on the US domestic airline industry, and were later expanded to include other airlines, OEMs and MRO providers from Asia-Pacific and Europe.

(a) MRO Decision Support Tools and Vendors

Decision support tools are becoming popular in the aviation MRO industry. This study attempted to understand what the design considerations were in the development of these tools, and to what extent were these considerations owed to cognitive support and engineering. Often, these tools are not stand-alone products, and they are operated with a particular support infrastructure, which includes training and maintenance. We surveyed how each of these tools has been developed and their associated support infrastructure.

(b) Airlines

We surveyed the engine sustainment operations of major US, Asian-Pacific and European airlines, to understand what key considerations the airlines have with regards to engine sustainment. We also investigated how well decision support tools are integrated into the airline's operations, and the level of cognitive support they provide to the airline's flight crew and maintenance personnel.

(c) Maintenance, Repair and Overhaul Shops

There are some decision support tools for engine sustainment that are used to accurately diagnose engine problems and appropriate corrective repairs and overhauls are made. The needs and operations of MRO shops are different from that of the airlines. As such, it is likely that the decision support tools used by MRO shops would have different requirements and functions as compared to those installed on the aircraft or used by line maintenance personnel.

(d) Aircraft and Engine OEMs

Though the decision support tool users are generally the airlines and the MRO shops, the tools' effectiveness on the MRO system also depends in part on their impact on the aircraft and engine manufacturers. Sustainment considerations are included from the moment the aircraft or engine design is on the drawing boards. We looked at how decision support tools like DPCM (either developed in-house or by sub-contracted vendors) have been integrated by the engine manufacturer. As the engine and aircraft go into service, the manufacturers are constantly assisting in technical support, especially when the engine encounters problems in the field. Hence, we also examined the interactions between these manufacturers, the airlines and the MRO shops in the area of engine sustainment.

2.3 Analysis Methods

The analyses in this thesis were divided into two sections:

a) A modeling of the engine MRO system
b) A cognitive work analysis of the engine MRO system.

A model of the engine MRO system was first developed, to provide an understanding of the operational environment and the constraints involved. A stakeholder framework was used to identify the various actors in the engine MRO system. The key interactions and decision-making processes within the engine MRO system were identified and analyzed to determine where decision support tools can be most effective. Industry best practices were captured and the implementation of decision support tools for engine MRO is later discussed.

With all the data from the various open literature and field studies, the data transformation between various actors in each decision-making process was identified and tracked. Through a thorough understanding of the MRO landscape, a set of cognitive work analysis was then applied to determine how decision support tools can be designed to provide cognitive support to the actors in the engine MRO system. Current and future decision support tools are discussed and recommendations are made for a framework of future decision support tools.

Chapter 3: Background

To study the cognitive needs and the application of decision support tools in the commercial aviation industry, it is essential that we first identify the various actors and understand the landscape of the airline and MRO industry. We also need to understand how aircraft and engine maintenance are performed within the larger overarching regulatory and safety framework that governs all commercial aviation activities. In this way, we can then gain a good insight into how well decision support tools, in particular DPCM tools, can integrate with the MRO system and determine how much value they bring to the sustainment of the overall commercial aviation system.

This chapter provides the reader with a background on both the airline industry in general and also the commercial aviation MRO industry. Section 3.1 describes the key characteristics of the airline industry and how MRO affects the airline's operating costs. In Section 3.2, the key trends in the commercial aviation MRO industry are described along with a market forecast for the MRO industry.

3.1 The Airline Industry

This thesis initially looked at the U.S. airline industry as data and field studies were more easily accessible to the author. U.S. airlines account for 30%-40% of global air traffic and almost 45% of all commercial aircraft (Belobaba, 2002). Six out of the ten largest airlines in the world are U.S. "majors" and their annual revenue each exceeded $8 billion in 2001 (Air Transport World, 2002). However, given that the airline industry is a global enterprise, this study on engine MRO would be much more pertinent with a global perspective. Therefore, field studies were made with not only American but also Asian-Pacific and European airlines, OEMs and MRO providers.

Recent predictions on the future of the airline industry are optimistic, and this bodes well for the MRO market[5]. Table 2 shows the growth forecast by Strand Associates of the worldwide commercial jet fleet in various economic scenarios. The baseline was taken to be 14,898 aircraft in 2002.

Growth Scenario	Slow	Moderate	Fast
Fleet Size (in 2007)	18,846 (26.5%)	20,314 (36.4%)	21,029 (41.2%)
Fleet Size (in 2012)	21,534 (44.5%)	24,155 (62.1%)	25,256 (69.5%)

Table 2: Worldwide Commercial Jet Fleet Forecast (Jackman, 2002)

It is worthwhile to highlight some of the key characteristics of the civil aviation industry. Safety is the prerogative term here, and all MRO work is geared towards ensuring that the aircraft attains the demanded safety levels. Hence, it is important to note that the primary task of decision support tools is to enable maintenance personnel to make the proper maintenance decisions, in order to achieve the required safety levels of the aircraft and its sub-systems. For example, the goal of engine DPCM tools is to assist the maintenance personnel in accurately ascertaining the performance and safety of the engines that they are maintaining.

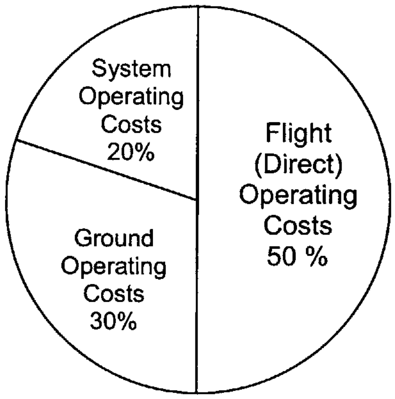
The civil aviation industry is also highly regulated[6] by the various national regulatory bodies like the Federal Aviation Authority (USA) and the Civil Aviation Authority (UK). Certification of tools, processes and people along with accountability of maintenance work are part and parcel of aircraft maintenance. Because of this regulatory inertia, it is estimated that the aviation industry will take ten years or more to incorporate the latest maintenance and DPCM technology across the board (Baldwin, 2002). Therefore, it is imperative that the development of DPCM and other decision support tools for aircraft

[5] At the time of publishing of this thesis, the global airline industry has undergone drastic changes especially in the U.S. domestic market in the last one year. However, forecasters remain optimistic that the airline industry will recover soon and continue to grow over the next 20 years (Boeing, 2002).
[6] Despite economic deregulation in the US airline industry, the maintenance aspects are still bounded by a large infrastructure of technical and procedural regulations.

engine MRO has to fit within this certification and regulatory framework, which would cover operating, reliability, accuracy and integrity of these tools.

Airlines are high-cost and high-revenue enterprises and are inherently less profitable than many other industries of similar size. With thin annual profit margins on the average of 1%-2% (up to 5% in best years), it comes as no surprise that airlines are always looking at ways to reduce their cost structure throughout their business model, including maintenance, repair and overhaul (Heimlich, 2002). MRO costs are particularly important to airlines because of the somewhat fixed cost nature of MRO. Passenger and cargo revenue fluctuate with the economic climate of the day. However, aircraft and engines, once procured and fielded, have to be continuously maintained regardless of the air traffic demand.

MRO forms a significant portion of the airline cost structure. According to Belobaba (2002), a typical airline cost structure can be represented by Figure 1. Using Form 41 data from the U.S. Department of Transportation (DOT), the maintenance cost of a typical Boeing 757-200 in 1999 was $590 per flight hour. This accounted for 23% of flight (direct) operating costs, which in turn was approximately 50% of total operating costs. These percentages reflect typical data for a US major airline. Our field studies found that Asian-Pacific and European carriers also share similar cost structures, with maintenance costs being a leading cost center.



Flight Operating Cost (FOC)
- All costs related to aircraft flying operations
- Including pilots, fuel, maintenance and aircraft ownership

Ground Operating Costs
- Servicing of passengers and aircraft at airports
- Includes aircraft landing fees and reservations/sales charges

System Operating Costs
- Marketing, administrative items
- Includes in-flight services and ground equipment ownership

Boeing 757-200 (1999)	**Cost per flight-hour**
Crew	$ 489 (19%)
Fuel	$ 548 (22%)
Maintenance	$ 590 (23%)
Ownership	$ 923 (36%)
Total FOC	$ 2550

Figure 1: Typical Aircraft Cost Structure (Belobaba, 2002)

Although the aviation industry, and in particular the aircraft design/manufacturing and MRO sectors, are seen to be predominantly engineering in nature, we should not fail to realize that the first and foremost function of the commercial aviation industry is to essentially provide a transportation service. As a service industry, the activities and functions of all the actors in the commercial aviation system have to be geared towards achieving this service of flying passengers and cargo around the world, meeting passenger and cargo demand and ultimately meeting customer satisfaction. Therefore, commercial aviation MRO should be viewed as an industry that supports this goal. After all, if poor maintenance causes flights to be delayed or cancelled, passengers will be discouraged to fly with that airline. Under-performing airlines would lead to detrimental ripple effects on the MRO providers. Therefore, one of the underlying implications for MRO is to have effective decision support tools that can help provide timely maintenance, which would meet the customer's expectations in terms of safety and on-time departures and arrivals.

3.2 The Commercial Aviation MRO Industry

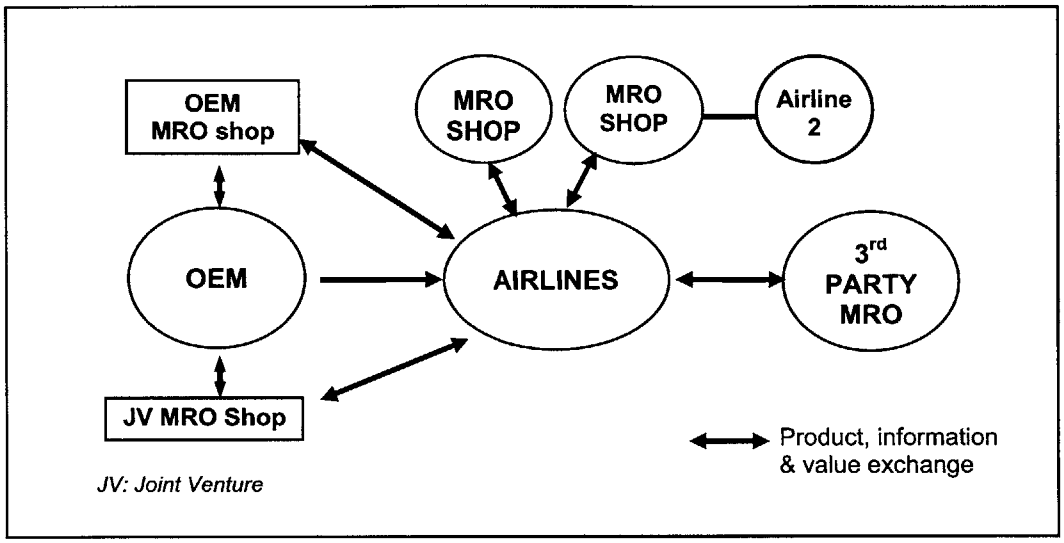


Figure 2: Commercial Aviation MRO System

Figure 2 illustrates a simplified schematic of the complex and multi-layered commercial aviation MRO system. The three main groups of actors are the airlines, the original equipment manufacturers (OEMs) and the third-party (independent) MRO providers. For the purposes of this thesis, the myriad of suppliers who provide various aircraft components to all the airlines, OEMs and MRO shops have been omitted from this schematic. Aircraft components (products), maintenance records and component data (information) are exchanged between the three main actors and the value streams are as shown.

In the traditional airline business model, most major airlines with medium to large fleets conduct their own line maintenance at their own airports and set up line maintenance stations at strategic destinations in their network. These airlines have built up significant maintenance infrastructure, comprising of their own hangars and MRO shops at their hub airports where all their aircraft are sent for heavy maintenance. Smaller airlines would typically out-source all their maintenance to either other larger airlines or third-party MRO providers. MRO was purely in the domain of the airlines and third-party providers. The OEMs were responsible for manufacturing the aircraft and components and were not involved in the lifecycle support except for providing technical information and spare parts.

However in the last decade, many airlines have changed their business models. There has been a major expansion of the OEMs into the MRO sector and aftermarket, especially in the airframe and engine MRO sectors. The OEMs see the potential economic opportunities in the MRO market over the lifecycle of each aircraft system, which would enable them to continue receiving some revenue long after their products had been manufactured and fielded. As many airlines nowadays are shifting their attention back to their core function of flying passengers and its associated in-flight services, they have out-sourced their MRO operations to either a third-party or to the OEMs (e.g. Southwest Airlines). Hence, OEMs have taken advantage of this monumental shift in the industry, and stepped in to fill the growing demand for external MRO providers. In particular, the three largest engine manufacturers (General Electric, Pratt & Whitney and Rolls-Royce) have been very active in recent years in expanding their share of the engine MRO market.

OEM expansion into the MRO market has triggered the resurgence of MRO alliances. Once an isolated European phenomenon in the 1970's with KSSU (KLM, Swissair, Sabena and UTA) and Atlas (Air France, TAP, Lufthansa, Alitalia and Sabena), the MRO alliances these days are not limited to just among the airlines. As illustrated in Figure 2, MRO alliances come in the form of airline to airline, third-party to airline, OEM to airline and all variations in between[7]. These alliances aim to improve efficiency through the sharing of capabilities, shop and hangar space and manpower, and alliance partners are able to penetrate into new markets around the world. In the engine MRO sector, the three major engine OEMs have invested in several alliances with airlines and third-party engine overhaul shops especially in the Asia-Pacific and European markets. The added benefits also include closer positioning of MRO services to key customer regions. As one OEM notes, "People want to see their engines in the shop…so we need to be near customers" (Murray, 2002).

[7] For more details on MRO alliances, see Chandler (2001).

The OEMs enter the MRO market with significant advantages over the airlines and third-party MRO shops. These advantages include not only the full technical knowledge base of their products, but also the benefit of co-locating repair facilities within their manufacturing plants and easy access to spare parts and tooling. In the case of gas turbine engines, the OEMs have also simultaneously developed their own DPCM tools and have packaged these tools with various other aftermarket services as a complete maintenance package for the airlines. These tools have the benefit of having their associated sensors being incorporated into the engines right from the start and can offer much easier implementation than those tools being offered by independent DPCM vendors. Furthermore, an engine OEM has the added benefit of being able to gather data from its global fleet of engines across many airlines, whereas airline and third-party MRO shops are limited to their own fleet and shop data respectively. With more data, OEMs can offer better diagnostic and prognostic services and provide more effective part repairs and engine maintenance (Tegtmeier, 2002). Therefore, it has become a growing challenge for independent DPCM vendors and especially third-party MRO shops to compete with the OEMs. Fortunately for the airlines, several of the OEMs have formed alliances with them and there is a fair amount of collaboration and joint development of maintenance processes and DPCM tools to improve overall maintenance (Chandler, 2001). Moreover, airlines are able to focus more on their flight operations and passenger services, and leave all the maintenance work with the OEMs.

Some airlines with excess MRO capability have realized that they could spin off their MRO operations to become profit, rather than cost centers. These airline maintenance subsidiaries are particularly popular among European and Asian-Pacific carriers (e.g. Lufthansa Technik, Air France Industries, SIA Engineering Co., Hong Kong Aircraft Engineering Co.). One benefit of keeping their MRO in-house through independent operations or MRO alliances is that these airlines are able to maintain a tighter control over their maintenance operations. In turn, their maintenance schedules can be more in-tuned with their flight operations, resulting in greater system productivity and effectiveness. Hence, we find that certain air carriers have become strong players in the MRO world with several competing with the growing OEM alliances head-on.

The resulting impact on the implementation of decision support tools in this complex landscape is that to be effective in today's MRO world, these tools now have to simultaneously meet the cognitive needs and be integrated into the maintenance infrastructure of multiple maintenance organizations. As these MRO alliances continue to grow and be both vertically and horizontally integrated, supporting maintenance tools like DPCM also have to be modified likewise to the changing operational environment.

The airline industry is moving towards becoming a commodity-like market, as price differentiation becomes much more important to passengers than the actual flight service itself. An increasing proportion of passengers are more content at purchasing the lowest airfares and are less concerned about which airline they fly or how good the in-flight service is. In such a market where "everything" comes down to costs, airlines are compelled to reduce their operating costs in order to maintain their profit margins and remain competitive. The aviation MRO industry also has to play its part in reducing MRO costs. As Ruffles (2000) aptly points out, "the primary driver in both the civil and the military sectors will be to reduce the cost of acquiring, operating and supporting the product [engines] throughout its life". Hence, the MRO market will soon be dominated by MRO providers and parts suppliers who can provide the lowest lifecycle cost to the market (Baldwin, 2002). Companies that develop decision support tools are also compelled to offer the most economical IT solutions to the airlines and MRO providers. However, it should be noted that in the aviation industry, the minimal safety standards are always ensured regardless of the costs.

MRO Market Value and Forecast

In 2001, the MRO market was valued at $37.8 billion (Jackman, 2002). The market can be categorized into 4 major sectors:

1) Heavy maintenance visits and major modifications or retrofits (HMV/Mods)
2) Engine overhaul
3) Line maintenance
4) Component overhaul

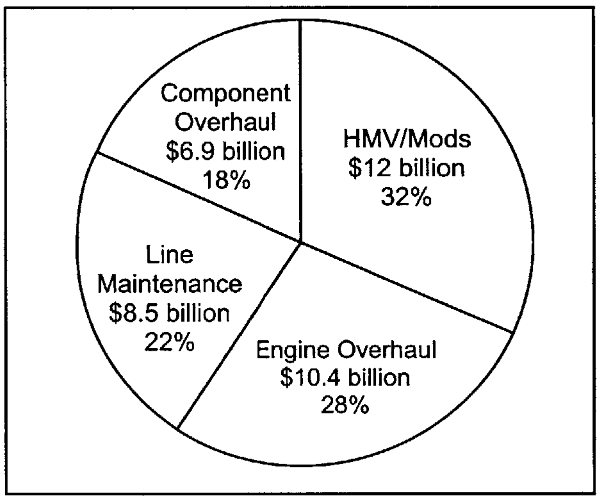


Figure 3: Commercial Aviation MRO Market in 2002 (Jackman, 2002)

Based on the fleet forecasts shown in Table 2, the MRO market is expected to recover to 2000-2001 levels by 2004. 3%-6% growth is forecasted, varying by region. Above average growth is expected in the Asia-Pacific region, given the continued burgeoning growth of air travel there. Depending on the economic scenario, the 2007 MRO market could be valued between $44.8 billion and $50.8 billion (see Table 3).

Growth Scenario	Slow	Moderate	Fast
Annual Growth (2002 - 2007)	3.5%	5.2%	6.1%
Annual Growth (2007 - 2012)	2.7%	3.8%	4.0%
Average Growth (2002 - 2012)	3.1%	4.5%	5.0%
Market Value (in 2007)	$ 44.8B	$ 48.7B	$ 50.9B
Market Value (in 2012)	$ 51.1B	$ 58.7B	$ 61.6B

Table 3: MRO Forecast for 2002-2012 (Jackman, 2002)

With the downturn in the economy and weak air traffic demand, the MRO market will continue to see difficult times in the next two years, though the long-term future still bodes well. Given the current global downturn of the airline industry, it is pertinent now, more than ever, for airlines and MRO providers to invest in more effective maintenance and DPCM tools, which would help reduce their maintenance costs in the long run. More effective maintenance will also improve airline performance and ultimately raise customer satisfaction and increase passenger traffic. These early investments might be an extra cost burden in the short-term, but their significant benefits in terms of better predictive maintenance and fewer inventories would quickly repay their initial investments (Murray, 2003). With optimism that the airline industry will recover and air travel will continue to grow, it would be prudent for the MRO industry to continue investing in more effective DPCM and other maintenance decision tools.

Chapter 4: Aircraft and Engine Maintenance, Repair and Overhaul

In this chapter, the organization and processes involved in aircraft and engine MRO are presented. Section 4.1 describes how maintenance fits into the airline's organization and the maintenance processes that are practiced in the airline industry. Section 4.2 covers aircraft engine MRO. A brief overview of aircraft gas turbine engines and the common faults and failure modes is presented, along with the MRO processes that try to maintain the engines in airworthy condition. The engine MRO shop is described thereafter, followed by an introduction to the decision support tools that are used in engine MRO.

4.1 Aircraft MRO

4.1.1 Airline Maintenance Organization

A typical airline is organized along four main divisions – commercial, engineering, flight operations and general administration– as shown in Figure 4.

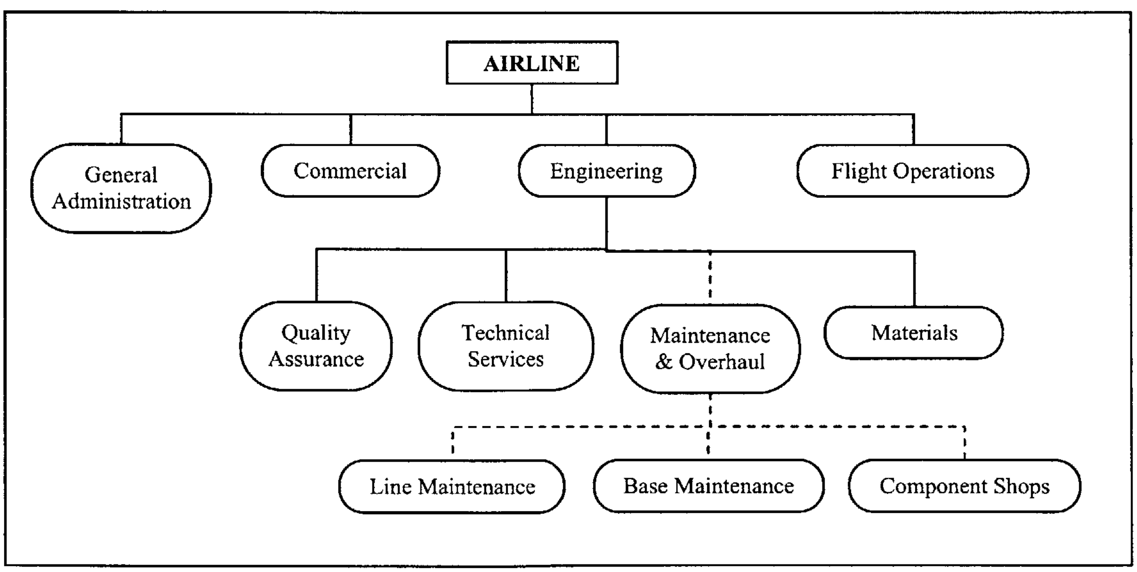


Figure 4: Airline Organizational Structure

The Commercial division represents the customer-end of the airline, which includes marketing, ticketing, reservations and passenger services (e.g. airport terminal staff). This group makes the business decisions with respect to maximizing revenue, so any flight delays or cancellations due to maintenance has to be reviewed. Flight Operations represents the flight crew and flight attendants. The usual corporate functions like finance, public affairs and human resource fall under General Administration.

The Engineering division provides technical support to the airline. Quality Assurance is responsible for ensuring quality standards are maintained throughout all airline functions and that the airline is always in compliance with the regulations as an air carrier. Materials is responsible for providing the necessary aircraft spares and keeps an inventory of the regularly used and critical components. Technical Services provides the engineering support, primarily for maintenance and aircraft purchasing and modification. It is mandated, by civil aviation regulations, to ensure that all the aircraft are maintained to the required airworthiness standards. To achieve this, technical service engineers follow OEM guidelines to determine when an aircraft (or engine) has to be maintained and what workscope is required for each maintenance visit. They are not authorized to perform any maintenance work. Maintenance control and planning is also carried out by this department, who work closely with line maintenance and airline operations controllers to coordinate aircraft maintenance events.

Actual maintenance work is performed by a separate Maintenance and Overhaul department. This can be an internal organization, a separate subsidiary of the airline, or a third-party MRO provider depending on the airline's business strategy for aircraft maintenance. Airlines usually have their own line maintenance personnel to take care of their aircraft at the airport gates. Line maintenance is typically contracted out to local providers at line stations overseas. Base maintenance and the component shops perform depot-level MRO. These include the powerplant section and the engine overhaul shop. For airlines that out-source their maintenance work, their base maintenance and component repair and overhaul responsibilities are fulfilled by third-party MRO providers. In such cases, the airline's technical service engineers would still have the responsibility to ensure that their out-sourced maintenance work complies with all the aviation regulations.

4.1.2 Aircraft MRO Processes

As certain items of the aircraft structure and its systems deteriorate during flight operations, it is necessary to assure that the aircraft and its system designs remain airworthy. Maintenance is the action necessary to sustain or restore the integrity and performance of the aircraft (Hessburg, 2001). Aircraft maintenance covers a broad spectrum of activities[8], including inspections, overhauls, repairs, preservation, and replacement of parts such as to conform to the standards stipulated in the aircraft system's initial certification of service. In the FARs, maintenance is typically referred to as "continuing airworthiness". Because they have been designed to optimize performance and minimize operating costs, commercial aircraft have to be maintained at very high standards throughout their operational life. All aircraft systems have to produce optimum performance, otherwise the aircraft's overall flight performance will be degraded. This, in turn, compromises on flight safety and also raises operating costs (e.g. inefficient engines cause higher fuel consumption).

Aircraft maintenance is mandated and regulated through civil aviation regulations like the U.S. Federal Aviation Regulations (FARs) and the European Joint Aviation Regulations (JARs). These regulations specify the conditions that deem an aircraft system to be airworthy and safe. All aircraft MRO processes are stringently regulated and documented. Any new MRO process, equipment or personnel has to be pre-approved by the regulatory authorities. This rule would also apply to new MRO decision-support tools.

[8] Maintenance does not include servicing – which is the replenishment of consumables need to keep an aircraft in operating condition (e.g. cleaning, fueling, catering and lavatory servicing).

There are broadly two categories of aircraft maintenance:

(a) *Scheduled maintenance*

The airlines typically draw up a scheduled maintenance program for each fleet type based on the tasks and time intervals recommended by the OEM and the approved by the regulatory authorities in the Maintenance Planning Guide (MPG). These include periodic inspections of on-condition parts, replacements of life-limited parts and various maintenance checks.

Maintenance checks are planned programs of varying length based on the life of the aircraft (Confidential source A, 2003). For a typical Boeing 747-400, the maintenance checks would be:

(i) Layover/overnight checks – A quick inspection of the aircraft's general condition (check is done typically every 3-5 days).

(ii) A checks – Performed overnight at line maintenance. These checks involve external inspections and limited system checks for critical systems like emergency equipment and the use of BITE[9] for troubleshooting of any faults detected (every 2,000 flight hours or about 4 months).

(iii) C checks – Hangar visits focused on detailed checks of individual aircraft systems and thorough inspections of specified components. Some structural inspections and minor cabin restoration are also performed. C checks are completed in 3-5 days (every 6,200 flight hours or about 12 months).

(iv) D check (or HMV[10]) – This is a major overhaul of the aircraft, including detailed inspections of the airframe with all interiors and paintwork removed. Major structural repairs for corrosion and fatigue cracks, as

[9] BITE: Built-in test equipment
[10] HMV: Heavy maintenance visit

well as major modifications are performed. A HMV usually takes about one month (after 30,000 flight hours).

Conservative airlines that we interviewed preferred to use a more rigorous letter check system at shorter intervals. Although it is more costly to perform more frequent inspections and replacing components that still have some remaining life in them, the airline can "buy insurance" against future failures. This also leads to a more scheduled maintenance system, which facilitates manpower and inventory planning. This conservative approach is followed until a more accurate prognostic system is available to the airlines.

(b) Unscheduled maintenance

Unscheduled maintenance refers to maintenance that occurs on a non-routine, ad-hoc basis. These would include resolution of pilot-reported anomalies ("squawks") or aircraft damage due to domestic/foreign objects (D/FOD). Due in part to the very complex nature of aircraft systems and the highly regulated maintenance environment, there are frequent service bulletins (SB) issued by the OEMs and airworthiness directives (AD) issued by the regulatory authorities which must be complied. These SBs and ADs often call for special inspections, repairs and replacements, which could possibly cause the affected aircraft to be taken out of service or the grounding of a particular fleet type at an unscheduled time. Unscheduled maintenance also occurs because of faults or anomalies found during scheduled maintenance, which would require a longer than intended aircraft downtime.

Aircraft MRO is conducted primarily at 3 types of locations:

1) Ramp/ Flight line (at the airport gate) – line maintenance
2) Hangar – base maintenance
3) Component shops

Line Maintenance handles the aircraft while it is in revenue service. They ensure that the aircraft is airworthy before and after each flight. The line maintenance environment is flight schedule driven, and there is often limited time available to perform the required maintenance work. Furthermore, resources like parts and tooling are often limited at line maintenance stations. BITE is usually used during quick inspections and relatively simple fault isolation procedures. Certain component modules known as Line Replaceable Units (LRU) can be replaced at the flight line with relative ease and these LRUs use BITE to tell the line mechanics if they had been properly installed. Malfunctions affecting airworthiness are either repaired or deferred according to the aircraft's minimum equipment list (MEL), which allows the aircraft to fly safely with certain faulty but less-critical equipment on-board until it reaches the next maintenance base or its next scheduled maintenance visit. The MEL is created by the aircraft OEMs and approved by the regulatory authorities. Condition monitoring tools are great assets to line maintenance as they provide the mechanics with added warning time of the aircraft's condition and what needs to be fixed, before the aircraft actually arrives. Hence, DPCM tools that are implemented at line maintenance have to be quick, easy to process and reliable. For many airlines, the ACARS[11] (Aircraft Communications, Addressing and Recording System) system is used for data reporting during flight operations between the aircraft and ground monitoring stations (e.g. maintenance control centers and the OEMs).

Base Maintenance and the component shops handle the aircraft or component (e.g. engines) when it is taken out of service. Base maintenance performs the majority of the scheduled inspections and also completes the heavy checks. It also performs modifications and repairs, clears deferred maintenance items, and incorporates service bulletins and airworthiness directives. The component shops repair and overhaul components that have been removed from the aircraft. For example, there are engine overhaul shops which repair, refurbish and overhaul aircraft engines and auxiliary power units (APUs), and various other shops that focus on aircraft systems like avionics,

[11] ACARS is provided by ARINC Incorporated. For more details on ACARS, the reader is referred to ARINC at <www.arinc.com.>

hydraulics, pneumatics, environmental control systems (ECS) and emergency equipment (e.g. life rafts, fire extinguishers). Diagnostic tools are used in base maintenance and the component shops to repair faulty components. Usually the faults have been broadly identified at the line before the parts are sent over. However, more detailed troubleshooting and analysis are needed in order to put in place the appropriate repair scheme. Links between the diagnostic tools and the available repair schemes would greatly aid in faster and more efficient overhauls.

Maintenance Processes

With the advent of large commercial airliners like the Boeing 747 in the late 1960's, there was a need to develop a structured approach to the design of large preventive maintenance programs. This led to the creation of the initial maintenance steering group document (MSG-1), which was based on reliability-centered approaches and was applied to the Boeing 747 aircraft. The objective was to develop a scheduled maintenance program that "assured the maximum safety and reliability of which the equipment was capable and also provided these components at the lowest cost" (Mobruay, 1997). MSG-1 has been revised over the years. The current version, MSG-3, contains guidelines that are used to develop and refine maintenance programs for all major types of civil aircraft (Air Transportation Association, 2001).

According to Hessburg (2001), there are three recognized processes used in the airline industry to define maintenance: hard time, on-condition, and condition monitoring.

"Hard time" is a life-based concept and it assumes that reliability decreases with operating age. Hard time would be suitable for components that have a very predictable failure rate and have definite life limits (e.g. metal fatigue). The life of these components is defined as either a fixed time or number of operating cycles (one flight cycle consists of takeoff-cruise-landing, regardless of flight time). The major disadvantage of hard time is that component failure is actually difficult to predict, because the operating conditions can vary tremendously between each fielded component. Hence, components in each aircraft would actually deteriorate at different rates. Sometimes components are removed even through they were not close to failure, while at times component failure could be accelerated beyond the normal rates for instance by extreme flight conditions. It becomes a very costly proposition to use life-limited parts (LLP) because either their maximum potential operational life is not realized (at the point of removal), or failures occur earlier than expected. Hence, there is now a general consensus within the aviation industry to shift to a more reliability-centered maintenance process. Hard time is now limited to very few safety-critical life-limited parts like compressor discs, which are removed when their life is near expiration regardless of their actual physical condition.

The prevailing process nowadays is On-Condition Maintenance. Instead of predicting hard time failure wear-out points, repetitive inspections or tests are made to detect potential failures. The OEMs would specify a certain standard of performance for the component to be airworthy. These inspections and tests would call for the removal or repair of the particular component "on the condition" that they do not meet these defined standards. On-condition maintenance is driven by the reliability-centered approach guided by MSG-3, where it is generally agreed that aircraft components have been designed to high reliability rates and any failures can be detected through these regularly scheduled inspections.

The third and newest process is known as Condition Monitoring. This process has been applied to components that show deterioration over time. The condition of the component is monitored, observing its deterioration towards the failure mode. Various statistical and physics-based approaches are used to trend this deterioration. Condition monitoring is gradually replacing on-condition maintenance for large aircraft engines. More details on condition monitoring, with respect to aircraft engines, are presented in the subsequent chapters. The goal here is to achieve a level of *predictive maintenance*, whereby the component failure can be predicted and prevented in time before failure actually occurs. This calls for advanced condition monitoring and prognostic tools, which is one set of decision support tools that we focus on in this thesis. With better condition monitoring and prognostics, impending failures are identified early thereby avoiding major failures and unnecessary loss of aircraft availability to the airline's schedule. Costly repairs and replacements of expensive components can also be avoided. This form of predictive maintenance also reduces the amount of inventory that has to be stockpiled. Instead the inventories "can be paired down to the right number of the right parts in the right places" (Baldwin, 2002).

The future of aircraft MRO is in predictive maintenance. There has been a concerted industry effort to apply condition monitoring beyond engines to include for example hydraulic and structural systems. In the near future, the latest maintenance support tools will be developed, not only for engines, but also for these other aircraft systems.

4.2 Engine MRO

4.2.1 Aircraft Gas Turbine Engines

In this thesis, we focused on the sustainment of high bypass turbofan engines, which are used on most large commercial airliners. Examples of contemporary engines of this class are the General Electric GE90, Pratt & Whitney PW4000 and Rolls-Royce Trent series. We have chosen to focus on these engines, instead of smaller turboprops and piston engines, for the civil aviation industry because they are the most expensive to maintain and incur a large financial burden on airlines. The MRO setup requires large capital investments to build overhaul shops, manufacture tooling and ground equipment, and provide spare parts. As such, improvements in engine MRO efficiency will bring the most savings to airlines for this class of engines.

This section presents an overview of a typical aircraft gas turbine engine layout and components, and a brief description of how such an engine operates and the interactions between the different engine components. A high bypass turbofan engine, typical of most large airliners (with the exception of the Concorde), has four main sections as shown in Figure 5. Air enters the engine through the inlet, which streamlines the air flow. A large fan compresses the air, with some of the compressed air entering the low pressure compressor (LPC) while most of the air is bypassed outside the engine core. The core flow is further compressed by the LPC and the high pressure compressor (HPC). Both the LPC and HPC have stages of rotating blades (rotors) and stator vanes which increase the air pressure by turning the flow and decreasing air velocity. The compressed air is then burned with jet fuel in the combustor, adding energy to the core flow, which raises the gas temperature to about 2000F. The high pressure turbine (HPT) and low pressure turbine (LPT) extract energy from the hot gases through stages of nozzle guide vanes (NGV) and rotors, which convert thermal energy of the air into kinetic energy of the rotors. Energy extracted from the HPT drives the HPC through the high pressure shaft, while the LPT drives the LPC and fan through the low pressure shaft. The combustor and HPT are usually referred to as the hot section. The core flow and bypass flow are ejected at the exhaust nozzle at high velocities. The total change in momentum of air flow produces a forward thrust force.

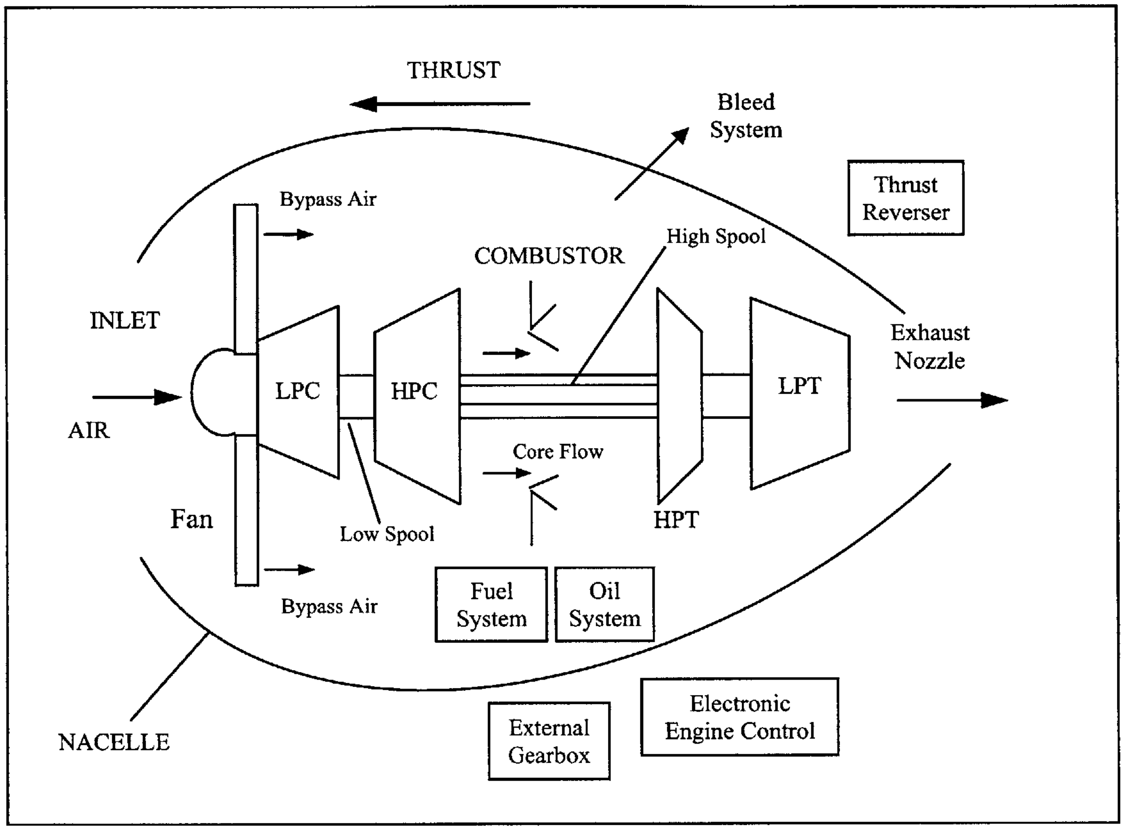


Figure 5: Schematic of a Turbofan Engine

A two-spool engine is depicted in Figure 5. Some engines have three spools, with an additional low-pressure turbine driving only the fan. Shaft rotation speeds are denoted by N_1, N_2 (and N_3) for the high pressure and low pressure shafts respectively. The shafts are supported by several bearings which are housed in bearing compartments. A pair of thrust reversers is attached to the nacelle. These deflect the exhaust flow forward, which acts as a braking force during aircraft landing.

There are several accessory systems that keep the engine functioning safely and efficiently and meet its secondary functions. The fuel system delivers fuel from the aircraft's fuel tanks to the combustor through a network of fuel lines. It also regulates the fuel flow through the fuel control unit (FCU). Fuel is also used to cool the lubrication oil. The oil system lubricates the shaft bearings and also removes heat from the turbomachinery. The newer generation engines are equipped with an electronic engine control (EEC) system which collects sensor data and then optimizes the engine for the thrust setting required. An external gearbox extracts mechanical power through a secondary drive shaft. The gearbox drives pumps for the oil, fuel, hydraulic and pneumatic systems and also drives an electrical generator. A portion of the air flow is extracted (bleed flow) by the bleed system to supply air to the aircraft cabin's environmental control system (ECS)[12]. For a more detailed understanding of the principles and components of a gas turbine engine, the reader is encouraged to refer to Kerrebrock (1992), Mattingly et al.(1992) and Treager (1996).

4.2.2 Engine Faults and Failure Modes

Aircraft gas turbine engines are subjected to a wide range of component faults, failure modes and sometimes complete engine failure. Our study found that the most common engine problems encountered were:

1) *High exhaust gas temperature (EGT):* EGT is measured at the rear of the HPT. A high EGT is often caused by a malfunction in the fuel flow or turbine cooling system. This would lead to thermal failure of hot section components like burnt or cracked HPT blades and nozzle guide vanes and deterioration of the combustion chamber lining.

2) *Vibrations:* Excessive engine vibrations are usually due to rotor imbalances, misaligned rotating parts and bearing failures. For airline operators, vibrations are considered excessive when they become uncomfortable for the passengers (though they are almost always well within the engine's safety limits). The

[12] Refer to Appendix A for a breakdown of each engine module.

vibration source has to be located and rectified. Rotors have to be re-balanced and any failed bearings must be replaced.

3) *Compressor surge:* Instabilities in the compressor cause the air flowing over the compressor blades to stall, resulting in a reversal of the core flow. The air is forced out of the inlet, sometimes accompanied by visible flames. If the instabilities do not self-correct, then the engine might have to be shut down. Compressor surge usually causes some mechanical damage, and maintenance is required to minimize the occurrence of surge.

4) *Bearing Failure:* Bearings start to wear and spall because of fatigue and wear. As bearings spall, there is more friction on the bearing surfaces. This causes vibrations and weakens the bearing supports. To prevent excessive vibration and structural failure, the bearings have to be replaced early on before the defects grow.

5) *Wire Harness Failures:* The wire harness that is wrapped around the engine casing comprises many control wires that connect the EEC to various sensors and actuators. Harness shearing or wire chaffing is a common occurrence, which leads to corrupt or lost signals.

Other common engine problems include foreign object damage (e.g. birdstrikes), fuel and hydraulic leaks and abnormally high fuel or oil consumption. The reader is referred to Tumer & Bajwa (1999b), Treager (1996) and FAA (2000) for more information on engine faults and malfunctions.

4.2.3 Engine MRO Processes

Aircraft engines are kept on-wing for as long as possible to maximize their revenue-making potential. Most engines nowadays stay on-wing for up to seven years. On-wing maintenance is performed by line maintenance mechanics. This is usually in the form of scheduled inspections and the occasional changing of line replaceable units. Some nacelles are built specially to open sideways so that mechanics can easily access the hot section. The engine is removed off-wing only when on-wing maintenance is not possible, such as when the engine has to be disassembled to access the hot section components. Engine disassembly/assembly, part repairs and overhauls are done at the engine overhaul shop.

Condition Monitoring

Condition monitoring is used in the maintenance of aircraft gas turbine engines. Parameters such as altitude, Mach number, thrust level setting, inlet pressure and temperature, spool speeds N_1 and N_2, combustor pressure, exhaust gas temperature (EGT), fuel flow and vibration levels are measured periodically and plotted against time. These parameters, coupled with oil sample (e.g. SOAP[13]) analysis, are compared against known specific deterioration trends. These trends have been derived either from exhaustive developmental testing by the OEMs, modeled through physics-based approaches, or are based on the operator's experience. This method is known as trend analysis. Trend analysis has proven to be quite successful in detecting predictable failure modes (Treager, 1996). Accurate identification of incipient failures is thus possible, thereby allowing economical repair before the occurrence of extensive costly damage. Condition monitoring is most beneficial with high cost items such as engine components. Based on this approach, aircraft-on-ground (AOG) incidents due to engine problems are quite rare. This results in very reliable aircraft dispatch and on-time arrival rates.

[13] SOAP: Spectrometric Oil Analysis Program

Advanced diagnostic, prognostic and condition monitoring (DPCM) tools offer the remote automation of this tedious process and better engine maintenance management. These tools are able to run complex algorithms to ascertain the actual condition of the engine. Data from a family of engines can be collated and analyzed for common failure modes.

Besides electronic data acquisition, engine maintenance is also performed manually through borescope inspections and magnetic chip detectors (MCD). Inspection ports have been built around the engine's outer casing for mechanics to examine potential failure areas such as the compressor and turbine blades, and the combustion chamber lining. The oil system not only provides lubrication for many engine components, but it also serves as an effective yet simple diagnostic tool. A common component failure is spalling of the bearings, where small pieces of bearing material are worn out and chip away. This causes the bearings to increase in friction, which over time changes the bearing stiffness (causing rotor imbalance and loss of structural rigidity) and generates excessive heat between the bearings and the rotating engine components. As the oil system runs through all these bearings and rotating parts, the metal chips get picked up the oil. MCDs are placed strategically along the oil path to pick up these metal chips. Location of the various metal chips and subsequent material analysis allows the mechanic to pinpoint where the chips came from (often different sets of bearings are made of slightly different materials to ease identification of these metal chips). Borescope inspections and MCDs, complement the DPCM tools, by allowing the mechanic to confirm the failures before repair work is performed. They are also an important manual back-up to the electronic sensors (an important factor in a fail-safe environment like aviation).

Fault Isolation Procedures

At the flight line, line maintenance mechanics use prescribed fault isolation procedures in the Fault Isolation Manual (FIM) to troubleshoot any aircraft or engine fault. When a fault is detected, a fault message number is displayed on one of the multi-function displays in the cockpit or on a Central Maintenance Computer (CMC) for a Boeing 747 or a Maintenance Access Terminal (MAT) for a Boeing 777. The mechanic then looks up the appropriate page in FIM. The FIM gives a procedural checklist, which is a tedious and time-consuming process. It was found to be highly circumstantial and not flexible in actual use. There was little direct linkage between the parameters measured the on-board engine monitoring system and the FIM. More logic can be built into the procedure, based on the actual engine data. If the faults are serious enough that they cannot be isolated in time or require immediate attention, then the aircraft has to be grounded and the engine removed for more thorough maintenance.

Different operators have different requirements for their engines, mainly due to their aircraft routes and cycles, and their business models. For operators which have long maintenance cycles, they need engines with a long on-wing time. Small low-cost airlines on the other hand are more concerned with low-cost shop visits. For airlines which fly long trans-Pacific and trans-Atlantic routes, their engines need to have a low-fuel consumption to attain maximum range. For corporate aircraft, their owners typically look for maximum safety, reliability and near perfect dispatch rates – they want to fly whenever they need to, and costs are less of a concern. In fact, "the longest time on-wing is not the most cost-effective because engines have an optimum on-wing time, after which subsequent shop visits can explode" (Tegtmeier, 2002). Therefore the engine maintenance program and the DPCM tools used have to take into account these different requirements, in order for maintenance to be effective not just in the technical sense but also economically for the operator.

One drawback of shifting to more automated condition monitoring is the need for better sensors. The sensors on today's engine were designed to support automated engine control, not to report on the state or health of the engine. The signals from these sensors are used by either hydromechanical controls or newer electronic engine control units to run the engine as efficiently as possible. So, it is possible that current DPCM tools which rely on these sensors are not able to capture all the data that they need. However, more instrumentation in the engines cost money and further complicates the engine design. More sensors would also lead to increased maintenance, since these sensors are subjected to the same extreme heat and pressures as other engine components.

In the near future, it is envisioned that MRO of aircraft engines will reach levels of predictive maintenance such that engines become "smart" enough to "know exactly what their condition is, what help they will need and when they will need it" (Canaday, 2002).

Differences between aircraft and land-based gas turbine engines

DPCM tools have also been extensively developed for land-based gas turbines[14], which are used in electric power generation (Boyce & Latcovich, 2002). Maintenance management systems are also available for land-based gas turbines (Bently Nevada, 2003). These tools have been fairly successful in maintenance of these power plants. However, there are significant differences between aircraft and land-based gas turbines, both in their system design and their operational requirements. Aircraft gas turbine engines are typically run at higher temperatures and make extensive use of lightweight and highly temperature resistant exotic materials, which are expensive to maintain and difficult to repair. Land-based gas turbines are run continuously for long periods at fairly constant power output levels, whereas aircraft gas turbines are constantly put through numerous cycles each day. The cyclic nature of operations results in undesirable cycle fatigue on many engine components. Maximum power is applied at each takeoff, which is usually at least twice as much power as required during cruise flight. Furthermore, aircraft engines face several demanding operational constraints. Only the highest safety levels are demanded of aircraft engines. Quick turnaround times and cost implications of engine downtime imply fast, reliable and effective engine maintenance. These operational and technical differences place unique demands on aircraft engine DPCM and other maintenance decision support tools. Hence, different decision support tools have to

[14] This excludes aero-derivative gas turbines, which were initially designed for aircraft use but later modified for land-based power generation. These tend to be more expensive than conventional land-based gas turbines and are somewhat over-designed for their power generation. However, the different operational environment makes these aero-derivative engines different from aircraft engines.

be developed solely for aircraft gas turbine engines, which will provide the unique cognitive support that is needed.

Changing the Engine MRO Landscape

In recent years, the engine MRO industry has seen several key changes in the business strategies of both airlines and the MRO providers. It is worthwhile to understand how these changes alter the MRO decision-making process and their implications for decision support tools.

The biggest trend of all has been the out-sourcing of maintenance work by many airlines, including their engines. By out-sourcing their maintenance, airlines do not have to invest resources in maintenance infrastructure, inventory and maintenance personnel which used to cost a large proportion of their operating budgets. Fixed contracts lead to a stable cost model. This seems to work well for low-cost airlines and smaller regional and domestic operators with small aircraft fleets. However, there are several concerns with out-sourcing the airline's MRO. A lack of oversight may lead to quality assurance issues for third party maintenance work (this can be particularly problematic because airlines are required to be responsible for ensuring their aircraft's airworthiness under their FAR 121, or equivalent, air carrier status). It would also be more costly to fly aircraft and ship components to overseas MRO shops. Furthermore, there may be difficulties with certifying foreign MRO providers.

On the other hand, there are some airlines who believe MRO is one of their core competencies and wish to retain their in-house MRO capabilities. This is especially so for major airlines with large fleet sizes. In-house MRO capabilities offers airlines tighter control over the quality standards of the maintenance work, better integration between maintenance planning and operational requirements and overall synergy between the airline and its maintenance division. Airlines with excess MRO capability have transformed MRO into profit centers by in-sourcing MRO work from other airlines and forming joint venture MRO shops with OEMs.

These MRO-capable airlines will be the ones that can most successfully implement new decision support tools that are proposed in this thesis. This is because as MRO is in-house, there is a thorough understanding between MRO and the airline's operational environment. Cognitive engineering approaches would suggest that new decision support tools for MRO be designed with a strong ecological emphasis which considers the tools' operating environment and the MRO provider's organizational nature. Hence, these MRO-capable airlines offer the optimal proving ground for these new decision support tools. Nonetheless, these new decision support tools will also reap significant benefits for non-MRO capable airlines and other MRO providers (including the OEMs) through more effective management planning tools. The out-sourced MRO providers can also use better diagnostics and prognostics to more accurately predict engine downtime and then charge the appropriate service fees for the out-sourced work. This will help airlines paint together a more realistic picture of the expected downtime of their engine fleet and the associated MRO costs.

Since engine parts are expensive and the economic downturn has reduced maintenance budgets, it is not surprising that part repairs have become more popular instead of complete overhauls. As one engine component shop notes, "operators are continuing to look for reduced repair costs, along with the longevity of the repair once it's reinstalled in the engine" (Tegtmeier, 2002). Increased emphasis on part repairs implies that engine diagnostics have to be further improved. To apply the correct part repair schemes, the diagnostics must be able to analyze down to the component level, including the physical state or condition of the component. As OEMs and independent repair shops develop new repair schemes, the technology used can also be transferred to new diagnostic systems.

The third trend has been a shift towards engine maintenance cost per hour (MCPH) agreements (Aircraft Technology, 2001). These MCPH arrangements are now a regular occurrence between airlines and engine OEMs. Airlines either pay a fixed annual fee for their engine maintenance (regardless of the amount of work) or pay a pro-rated cost for the amount of hours their engines had flown. This can be considered a radical change from the traditional MRO arrangements of cost per maintenance hour. With fixed revenues from these MCPH agreements, the impetus on the OEMs is to limit the amount of maintenance work and increase the profit margin from the fixed revenue. One way is to design even more reliable engines (which might be difficult to improve on). The second way is to develop more accurate and reliable engine prognostics and fleet management tools that can predict how much maintenance work each engine requires. Then the MCPH price can be set accordingly and the OEM will have greater certainty in its profit model. Thus, not only do airlines want to improve their own engine fleet management, the OEMs also now need to worry about managing their global engine fleets. Hence, the engine OEMs are actively developing engine prognostics and fleet management tools for this very purpose. We believe that with the OEMs driving such advances in these decision support tools, the OEMs would also modify and spin-off the same technology for airline users.

4.2.4 Engine MRO Shop

The engine MRO shop operates much like a manufacturing plant, with the notable exception that no new parts are actually being manufactured. Figure 6 shows a typical engine repair and overhaul process, based on the engine MRO shops that were studied.

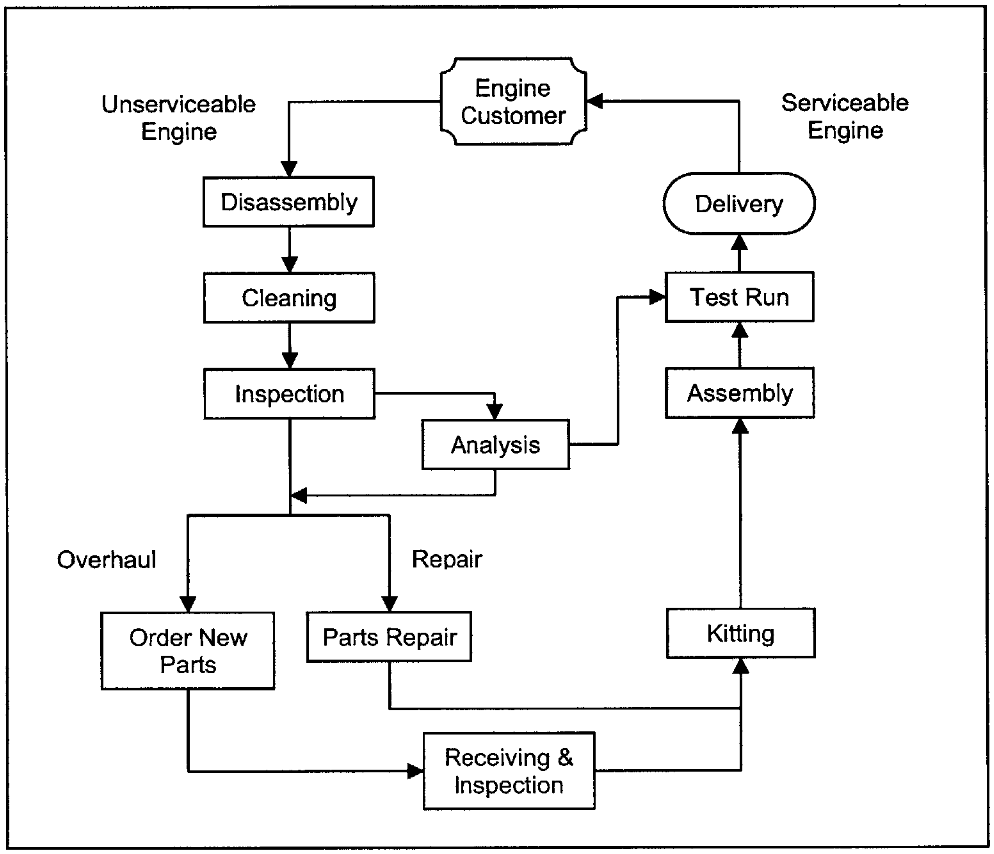


Figure 6: Engine Overhaul Process (Adapted from Mohammed et al, 1996)

The shop floor of engine MRO shops is either organized by process or by engine type. Some shop floors have engines that move around the shop in an assembly line style with all the disassembly/assembly done at one place regardless of engine type. Once the engine is stripped, it is sent to the various module centers. The other type of shop floor has engines of the same type grouped together in one location and a team of mechanics would specialize on all MRO processes for that particular engine type.

Engine subassemblies and components are first cleaned to remove dirt and oil, before they are inspected for damage against specified damage tolerances. Engineering analysis is sometimes needed to ascertain the faulty components. Faulty components are either repaired or replaced. New parts are either obtained from the shop's inventory or have to be ordered from suppliers. The new parts and repaired old parts are put together with the rest of the engine during the kitting process. Once all the parts are in place, the engine is fully kitted and ready to be assembled. After the engine is assembled, it is put through a series of test runs in the test cell to ensure that any malfunctions had been rectified and the engine is serviceable again.

Depending on the size and scale of the engine shop, it may have several types of non-destructive testing (e.g. fluorescent penetrant inspection, eddy current testing) and part repair facilities. It may also have one or two test cells if the engine shop does the assembly process. The three major engine OEMs have built up a distributed network of overhaul and part repair shops, which has been found to be more cost-effective. Overhaul shops are located near major customers while there is usually only one specialized repair shop for each major component (rotor blades, discs etc.) in the network.

The hot section components are replaced most often during each shop visit like the HPT airfoils, combustion case liners and the HPC discs. These frequently needed parts are difficult to manufacture, have long lead times from the suppliers and are too expensive to keep in the inventory. Hence, improvements in engine prognostics especially for the hot section can help the shop's material planning and lower inventory costs.

The most important performance indicators for the engine MRO shop are turnaround times and cost. The current turnaround time for a major overhaul of a large high bypass turbofan engine is approximately 90 days (Confidential source B, 2003). Much of the cost comes from the spare parts, especially the hot section components. The goal is to restore the engine to a serviceable status in the shortest time possible at a competitive price to the customer.

4.2.5 Decision Support Tools for Engine MRO

Information Technology (IT) or computer-based tools have become increasingly popular in the MRO industry (Murray, 2003). In particular, IT-based decision support tools have been available since the 1970's with the implementation of engine monitoring systems (SAE, 1981 & SAE, 1988). Nowadays, there are full DPCM tools offered by the engine OEMs and several other independent vendors (Canaday, 2002).

Other IT tools have been developed to provide engine mechanics with limited electronic versions of workscopes, job cards, engine maintenance manuals, illustrated parts catalogs and maintenance records. Such tools covered in our study were found to be mostly on-line or CD-ROM based database libraries which the human user could reference. However, they did not have the capability to aid the engineer or mechanic in deciding which tasks to include in the workscope or which engine records were the most pertinent in a particular situation. Several researchers like Baker (1997), Liening and Blount (1998) and Knotts (1999) have also suggested how knowledge-based systems can increase the cost-effectiveness of aircraft MRO processes. These works can be integrated with a cognitive engineering approach as proposed in this thesis to develop decision support tools for the MRO industry.

IT developers are beginning to move away from focusing not just on supporting the technical side of MRO (e.g. DPCM tools) but also on supporting the overall MRO process. Configuration management, equalized maintenance, supply chain management and maintenance planning are where the latest IT systems are targeting (Baldwin, 2002).

Table 4 lists some examples of existing decision support tools for engine MRO. Most of these tools have seen widespread use by many airline operators, while some of the newer products are beginning to be used in the MRO industry. Engine diagnostics has been the mainstay for such IT-based systems. In recent years, OEMs and independent developers have begun to shift some of the attention towards predictive maintenance and engine MRO management. The analysis presented in Section 7.2 aims to recommend how these emerging decision support tools can be enhanced to provide more effective cognitive support to their users. In addition, functions as yet untapped by existing tools are also recommended in Section 7.2.

Function	Decision Support Tools	
	Name	**Developer**
Engine DPCM	*Remote Diagnostics*	GE Engine Services
	Compass	Data Systems & Solutions
	ECM II	Pratt & Whitney
	eCM 2.0	SmartSignal
	ICEMS	Scientific Monitoring Inc.
MRO Management	*eMaintenix*	Mxi
	Impresa	Avexus
	Airplane Health Management (AHM)	Boeing

Table 4: Some Examples of Existing Decision Support Tools for Engine MRO (Canaday, 2002 & Baldwin, 2002)

Before such IT-based decision support tools can be implemented, there are some obstacles that have to be first cleared. The major obstacles are the procurement costs and software maintenance and certification of the new IT system. These tools have to bring in an adequate return on investment based on the cost savings and increases in efficiency as a result of using these tools. They have to be customizable to a certain extent, to meet the unique operational requirements of each airline. These tools also have to be able to integrate seamlessly with the airline's current operational procedures and IT systems.

As with any other IT system, software maintenance can be a never ending arduous task, as the software has to be continuously updated with new codes and data. In the case of safety-critical software like engine DPCM systems, the need for accurate, reliable and the most updated software codes would require a high degree of software maintenance.

Hence, extra manpower resources and a robust software maintenance plan are required to ensure that the IT system is updated and reliable.

The third, and in the author's opinion, the largest obstacle for IT-based decision support tools is in meeting certification and regulatory requirements. Our study found that there are currently no regulations that directly pertain to decision support tools. For engine DPCM systems, the only regulation that the system indirectly had to adhere to was in ensuring the engine was always airworthy whenever the DPCM system did not detect a fault (e.g. FAR 33). Some attempt has been made in the military sector for a formal certification process of engine monitoring systems (Matchett, 2001), but none thus far to our knowledge in the civilian sector. As with other safety-critical systems, there would be issues over accountability between the human user and the DPCM system should an engine-related accident occur. Without any existing guidelines or regulations, a disagreement over whether the human user or the automated system is at fault would remain a debatable, open question. Certification of various classes of decision support tools will command a common high standard of reliability, accuracy and safety in these tools. Without a certification process, such standards between competing tools can differ widely. Given the trend of out-sourcing MRO and in particular engine condition monitoring, many airlines now have foreign OEMs or independent DPCM service providers. If DPCM tools are to be certified and regulated, then local regulatory authorities would be in a dilemma over jurisdiction of these foreign companies[15]. The fact that no such certification or regulations yet exist (even though DPCM systems have been available for 20+ years) does highlight the difficulties regulatory authorities face in this emerging field of MRO. Nonetheless, this author believes that some form of certification process or regulation is sorely needed in this area, bringing these IT tools into the same overarching regulatory framework as for every other process, equipment and personnel in the MRO system.

[15] In the aviation MRO industry, all MRO processes, equipment and personnel have to be audited and certified by the local civil aviation authorities. IT-based engine DPCM tools should be no different.

In this thesis, we explored all these areas of the engine MRO process whereby decision support tools can aid the human worker, as well as described how such tools can be developed through a cognitive engineering approach.

Chapter 5: Engine Diagnostics, Prognostics and Condition Monitoring

Engine diagnostic, prognostic and condition monitoring (DPCM) systems are one example of decisions support tools for engine MRO. The first Aircraft Gas Turbine Engine Monitoring Systems guide was published by the SAE in 1981 (SAE, 1981). This document provided the first-ever guidelines on how to design and implement engine monitoring systems. Since then, DPCM systems have been extensively developed and fielded and have become an invaluable tool for engine MRO. This chapter describes the current state of DPCM systems and provides an overview of some of the techniques that are behind DPCM systems.

5.1 Current State of Engine Diagnostics, Prognostics and Condition Monitoring

Current engine DPCM systems have proven to be quite effective in providing early warnings of existing or impending engine failures, which help airlines avert unexpected major engine failures and reduce flight delays due to engine maintenance. One DPCM system provider has estimated that its DPCM system can save airlines $10 per engine per flight hour. This might seem small but multiplied by the decrease in delays and cancellations and the numerous flight hours, this could save the airlines up to $100 per flight hour for each engine (Baldwin, 2002). Most of these systems are currently offered by the engine OEMs as part of their aftermarket package with the airlines, which also includes spare parts and on-site/on-wing technical support. There are a few independent DPCM providers who have been offering similar services as well. The predominant approach has been performance-based trend analysis, with increasing automation in the data acquisition and trend analysis methods.

These systems have become well integrated into the engine maintenance process. Some airlines have developed their in-house expertise to monitor their own engine fleet using various OEM or independent DPCM systems. Other airlines with less maintenance or engineering capability pay the OEMs or DPCM system providers a certain price for the DPCM service, whereby their engines are monitored externally and the airlines are informed of any required maintenance actions. DPCM systems are used as "system initiators", which alert the engine analyst to any possible engine problems and this starts the maintenance process. If the DPCM system stays quiet, then the analyst would assume that all the engines are performing normally and no maintenance is required. This is the current form of condition monitoring being practiced. Most of these DPCM systems are based on a trend-analysis approach (described in the next section). Results are presented in either graphical or text formats. An engine analyst uses the results of the trend analysis to hypothesize what the engine problem is and then issues an inspection to the line mechanic to confirm the detected engine fault. Once the fault is confirmed, the appropriate maintenance is carried out.

The latest engine DPCM systems utilize online portals to provide real-time information for their users. Engine analysts can pull up electronic engine records and observe the trend history of each engine. Electronic alerts are also issued through this online portal.

Though DPCM systems have been fairly successful, some operators have highlighted several problems with the current systems. There is a lack of user customization of the user interface. These systems are often standardized packages which do not offer the flexibility to cater to each operator's own operational requirements. The only customization available in earlier generation DPCM systems allows the operators to set the threshold alert levels. Notification systems were also not as real-time as frontline engine operations would desire[16]. There is also no relation yet between the diagnostics and the repair schemes, which would be an invaluable feature for maintenance engineers.

Our study found that there were two main criteria that airline operators place on engine DPCM systems. Accuracy and reliability is the most important metric. The DPCM system has to be accurate and false positives must be minimized. Because of the

[16] Emerging DPCM systems are able to alert their users through e-mail, pagers, cell phones, personal digital assistants (PDA) and other wireless communication devices.

potential costs and downtime if an engine fault is detected, the airline cannot afford any false alarms. Airline operators also seek versatile and adaptable DPCM systems that can be used on various engine types without much modification. In particular, for airlines that have mixed engine fleets, a DPCM system that can be used across different OEM engines would be most desirable. Such a multi-OEM system would fulfill the need for just one DPCM system, instead of separate systems for each OEM engine type. Moreover, airlines can save money on system infrastructure and less user training is required.

As DPCM systems are continually upgraded and expanded, future features will include advanced gas path monitoring, oil and vibration monitoring, oil debris monitoring and near real-time fault resolution (Heath, 2000). Engine DPCM technology will also be extended in the future to support the condition monitoring of the rest of the airplane, including the auxiliary power unit (APU), hydraulic systems and airframe structures.

Engine DPCM tools can be categorized into three types, namely in-flight (onboard systems), ground-based and for the MRO shop. In-flight DPCM tools are integrated into the overall flight management system so that the flight crew is notified of any engine malfunctions. These have to be very quick alert systems and highly safety-driven. Ground-based systems are typically used by the airline's line maintenance for engine condition monitoring and parameter trending. The third category is the diagnostic-intensive systems which are required in the engine MRO shops. It is useful to note the different requirements among these three categories of engine DPCM tools, which are supporting different cognitive needs. These differences are highlighted in Chapter 7.

5.2 Methods and Algorithms

Current engine DPCM systems employ a variety of statistical, physics-based, neural-network and other methods to determine the condition of the engine system. We have classified these methods into two broad categories: condition monitoring and trend analysis, and emerging technologies (e.g. artificial intelligence-based, model-based etc.).

5.2.1 Condition Monitoring and Trend Analysis

Traditional trend analysis is based on engine monitoring systems which collate and trend engine parameters like exhaust gas temperature (EGT), engine pressure ratio (EPR), spool speeds, fuel flow, vibration levels and oil temperature and pressure (Barwell, 1988). When the engine experiences a fault or failure mode, certain parameters would deviate from their "normal" values. Patterns of normal and abnormal parameter trends have been correlated to particular engine failure modes (Treager, 1996). In older DPCM systems, the human user has to manually match the actual trends to patterns that are based on his/her own experience or "textbook" patterns. This is a tedious and difficult task, even more so for users that have to monitor large fleets.

A more advanced form of trend analysis is employed by newer DPCM systems, which are able to model the deterioration trend of these parameters based on statistical data (Brochu, 2002). For example, it is statistically known how the EGT margin (difference between actual EGT and the limiting failure temperature) varies with the number of cycles of a particular engine. These deterioration trends give the expected value of each parameter according to the life of the engine. Comparing the actual values with the expected values yield residuals or deviations. These residuals form certain patterns that can be correlated to known engine failure modes. The user can set threshold values to trigger an alert if the residuals are significant enough. The actual diagnostics using fault pattern matching and physical inspections remains a manual process.

The latest emerging DPCM systems are designed to automate the trend analysis and pattern matching. A library of fault patterns is established which the automation can compare. These fault patterns are derived from a large database of engine data gathered from development tests and in-service experience. The DPCM system will match the actual pattern with this fault library in order to identify the overall state of the engine.

One disadvantage of these statistically-based methods is that they require a large enough collection of engine data in order to have meaningful statistical analysis. These methods may be quite useful for older engines with large fleets and many years in the field. However, this does not work well with brand-new engines even though some developers have used data from the engine's test and developing phase. Hence there is great dependence on the in-service history of the "fleet leader" – the first set of engines that are put into service. Furthermore, current data trending techniques do not offer good insight into the actual causes of the failures. The failure modes are concluded in general terms (e.g. HPT failure, bearing failure) but the data trends cannot pinpoint the failed component. Physical inspections are still needed to complement the trend analysis. Perhaps data from physical inspections can be merged with the trend analysis, to produce a more detailed an informative diagnosis.

5.2.2 Emerging Technology

The latest research initiatives in engine DPCM methods have been surveyed by Tumer and Bajwa (1999a) and Li (2002). There has been a great deal of effort in developing algorithms for more accurate, robust and faster engine condition monitoring and diagnostics. Several new techniques include physics-based models and artificial-intelligence based methods.

Physics-based approaches use models of the actual engine cycle and air flow to determine how faulty components like chipped compressor blades would change the performance of the engine (Baig and Sayeed, 1998). Although these methods provide better diagnostic and prognostic capabilities, a very thorough understanding and analysis of the engine and sufficient sensor instrumentation is required. Actual engine design specifications have to be combined with theoretical design data. Furthermore, the DPCM systems have to incorporate significant computing capability to model the air flow. Given that space, weight and cost are important design considerations, it is a challenge to incorporate these types of DPCM systems into the engine itself.

Artificial intelligence based methods like neural-network and genetic algorithms have also been studied (Kobayashi and Simon, 2001). These allow the DPCM systems to develop its own database from the engine's service history, and they are able to self-diagnose the engine based on what it has learned. Such self-learning methods do not require prior knowledge of the engine. Hence, given enough learning data, these systems can be applied to almost any engine. This is a key benefit for airline operators who can use these systems across multi-OEM engine fleets. However, such DPCM systems would need an extensive learning period and training data before they can become operational and effective.

Research in recent years on engine DPCM systems has been largely focused on "improvements of reliability, accuracy, computational efficiency of the diagnostic systems" (Li, 2002). However, as aptly suggested by Tumer and Bajwa (1999a), "a more specific goal is to develop a means to use engine monitoring systems to help with engine maintenance decisions". One main purpose of this thesis is to offer recommendations on how to achieve this very goal.

Chapter 6: Cognitive Engineering Approach

Previous research efforts by both academia and industry in aircraft engine MRO has been largely focused on the physical processes involved. This thesis advocates a new approach to the understanding and modeling of the engine MRO system through a cognitive engineering viewpoint. As cognitive engineering is a relatively new concept, this chapter first presents an introduction to cognitive engineering in the context of complex sociotechnical systems such as the engine MRO system. A framework, using cognitive engineering principles, known as Cognitive Work Analysis is then described. This framework is used in the analyses presented in the next chapter.

6.1 Introduction to Cognitive Engineering

This thesis uses a novel cognitive engineering approach to the analysis and design of decision support tools for engine MRO. Since decision support tools are fundamentally providing cognitive support to human users, we believe that a cognitive engineering approach can offer new insights into how decision support tools can best meet the needs of the human users.

Cognitive engineering is concerned with the analysis, design and evaluation of complex sociotechnical systems (Vicente, 1999). Complex sociotechnical systems consist of several layers, as shown in Figure 7.

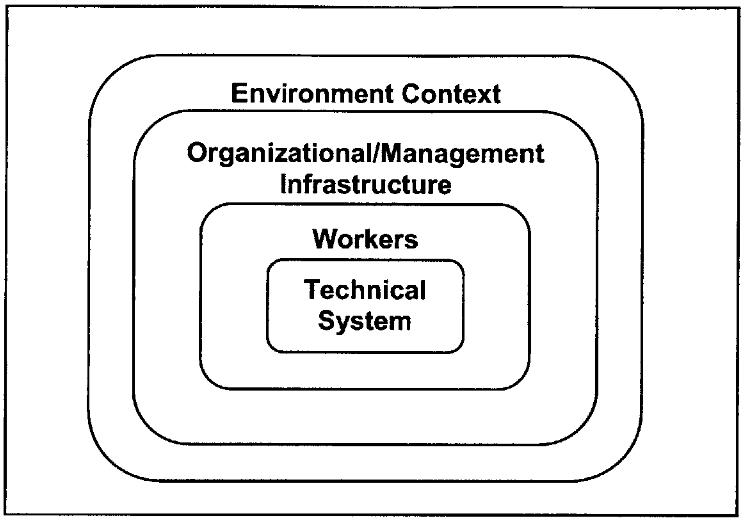


Figure 7: Various layers of a complex sociotechnical system (Vicente, 1999)

The fundamental philosophy of cognitive engineering is that we consider an ecological approach to the system, rather than only focusing on the technical aspects. Traditionally, many disciplines have viewed the technical core to be their whole system. However, operating experience has shown that there are in fact other layers of the sociotechnical system that also need to be addressed. The workers, organizational infrastructure and the environmental context are just as important as the technical core for the successful functioning of the system. The commercial aviation MRO system is no different.

The technical core corresponds to the aircraft or engine that is the hardware being worked on and the engineering design, maintenance and diagnostics that is associated with the hardware. Mechanics, engineers, pilots and other airline and MRO personnel are the workers in this system. Airlines, OEMs and MRO shops all have their own business models to meet, which drives their organizational and management infrastructure. It can be shown that business decisions are always coupled with technical decisions in the MRO industry. The regulations and public concerns for aviation safety form the overarching environmental context that aviation MRO is subjected to.

Table 5 shows how the engine MRO system can be considered, according to Vicente's (1999) definition, as a complex sociotechnical system.

Characteristic	Engine MRO System
Large Problem Spaces	Many engines in the fleet. Infinite possibilities of engine faults and failure modes. Large information space
Social	Airlines, OEMs and MRO shops are large organizations.
Heterogeneous Perspective	Airlines, OEMs and MRO shops all have different objectives. Workers have varying backgrounds and knowledge.
Distributed	Geographical spread of aircraft and engine across the world. Mechanics are spread out at various line stations along the airline network.
Dynamic	Long downtime for engine MRO.
Potentially High Hazards	Catastrophic failure if the engine is not maintained properly or if faults are not addressed in time.
Many Coupled Sub-systems	Engine modules are coupled. Airlines, OEMs and MRO shops have coupled interactions.
Automation	Automated engine condition monitoring, diagnostics and other decision support tools.
Uncertain data	Imperfect sensors, non-regular data sampling
Mediated Interaction	Not possible to physically check all engines. Have to use remote sensors.
Disturbances	External factors like FOD, birdstrikes, human error, new regulations, political and social factors.

Table 5: Engine MRO as a Complex Sociotechnical System

In the case of decision support tools, a cognitive engineering approach would suggest that these tools allow the end user to "finish the design". In other words, the decision support tool allows the user to customize the final interface to suit his/her own operating environment. There are many ad-hoc, unanticipated situations in engine MRO. Each failed engine always brings a unique problem. Hence the decision support tool must be able to adapt to changing environments and requirements. To do this, we need to first understand the cognitive needs of the tool's user and design the tool to meet those needs.

For example, engine DPCM tools have proven their effectiveness at detecting and identifying engine failures. However, the engine analyst using these tools does not always receive the information he/she needs to confirm the diagnosis and then propose a suitable mitigating action. Delivering the right information at the right time is a key factor in determining the effectiveness of engine DPCM tools (and in fact all decision support tools). This is where cognitive engineering can be best applied.

A cognitive engineering approach has been found to be useful in analyzing complex sociotechnical systems like nuclear power plants (Mumaw et al. 2000) and in the design of aircraft instrument and display systems (Dinadis & Vicente, 1999 & Namidian et al, 2002). This thesis will extend the application of cognitive engineering away from process control and aircraft instrumentation, and into the sustainment field.

6.2 Cognitive Work Analysis

We will use the Cognitive Work Analysis (CWA) framework described by Vicente (1999) to analyze the cognitive needs of an MRO organization and how decision support tools can best meet these needs. The CWA framework was first proposed by Rasmussen et al (1994) as a formative approach to work analysis. This was found to be well suited to the work demands of complex sociotechnical systems. In Vicente (1999), CWA was used in the process control environment. Though MRO is quite different from process control, the CWA framework is still valid for this application since we have earlier shown that MRO is also a complex sociotechnical system.

CWA focuses on identifying technological and organizational requirements that need to be satisfied if a device is going to support work effectively (Vicente, 1999). It provides an integrated framework for us to cover both the ecological and cognitive considerations in our work analysis. There are five steps in the CWA framework: Work Domain Analysis, Control Task Analysis, Strategies Analysis, Social Organization and Cooperation and Worker Competencies. .

1) **Work Domain Analysis**

The first step is to describe the work domain. In our study, the main work domain is the engine MRO system. Different actors in the engine MRO system will have a different abstraction of their own sub-work domain. For example the airline CEO would consider just the airline as his work domain. An engine MRO manager would consider the airline's maintenance division as his work domain, while an engine analyst would view his work domain to be solely the aircraft engine.

The work domain can be represented by an abstraction-decomposition space (Figure 8). This space is a combination of the decomposition hierarchy (part-whole links) and the abstraction hierarchy (means-ends links). Each cell is a different but complete representation of the same work domain only at a particular abstraction and decomposition level. This model represents the possibilities for action in this work domain.

	Total System	Subsystem	Functional Unit	Subassembly	Component
Functional Purpose					
Abstract Function					
Generalized Function					
Physical Function					
Physical Form					

Figure 8: Abstraction-Decomposition Space (Vicente, 1999)

For each work domain, the various abstraction and decomposition levels will be described using the abstraction-decomposition space. Means-ends links will also be mapped to show the relationships between the cells. The abstraction hierarchy is useful for coping with unanticipated events. Since maintenance is frequently unpredictable in the engine MRO domain, the abstraction hierarchy fits well for our purposes.

The work domain analysis will help us determine what models and information requirements are needed for each work domain. The means-ends links define the system's functional structure and also implies the relationships between variables that are to be measured or controlled.

2) Control Task Analysis

Control task analysis identifies the requirements for each situation encountered in the work domain. We choose to focus on the work requirements for expert performance. Since we want to design decision support tools to aid worker performance, it seems logical that we should design tools that can produce the same levels of performance as expert workers. Hence, novice workers can benefit from these expert-level support tools. One of the underlying goals is to have workers in the engine MRO, regardless of their initial skill level, to be able to produce expert performance through these decision support tools.

A decision ladder, developed by Rasmussen (1974), shown in Figure 9 is used to break down a control task into a series of information-processing activities.

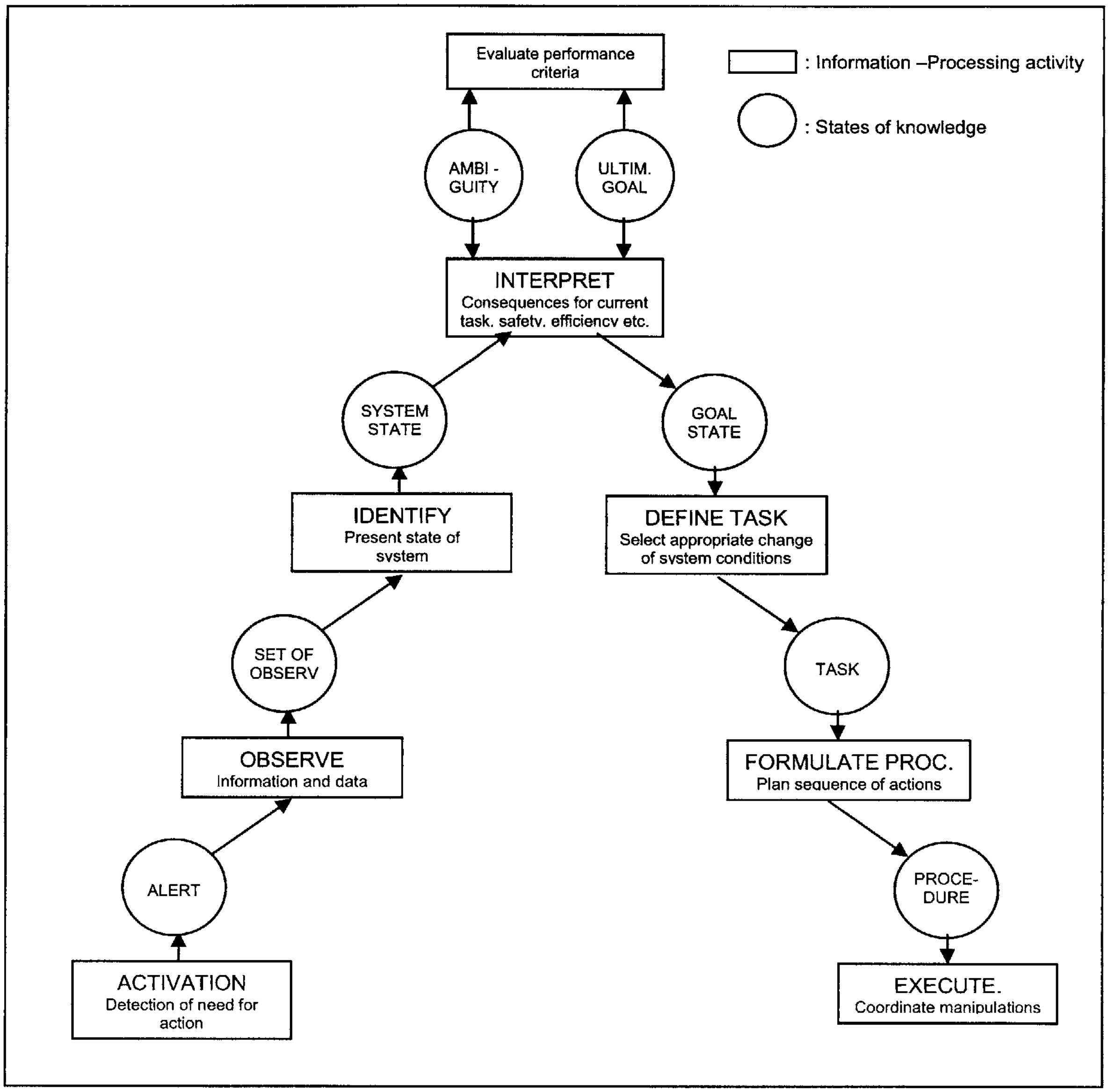


Figure 9: Decision Ladder (Vicente, 1999)

This decision ladder is a template for modeling the control tasks that have to be accomplished in each operating mode of the engine MRO system. A separate control task analysis will be made for each operating mode. Not all the steps have to be followed in this linear sequence and the order can be changed depending on the task. Expert workers are able to skip steps by taking shortcuts between information-processing activities and states of knowledge.

The control task analysis can tell us what goals must be pursued and what the constraints are. Procedures and control structures can also be developed from the decision ladder. We aim to model what the information processing sequence is for the each operating mode so that we can identify which steps in the operating procedure can be supported by decision support tools. We also want to identify any shortcuts for our expert level decision support tool. It is envisioned that the decision support tool can help the worker perform these shortcuts regardless of the worker's skill level, and at the same time help the worker understand how and why these shortcuts are made.

3) Strategies Analysis

Strategies Analysis uses information flow maps to describe how each information-processing activity can transform an initial state of knowledge to a final state of knowledge. Information flow maps describe what information inputs and outputs are required and how all that information is processed. These information flow maps can serve as templates for designing decision support tools.

It is our goal to automate (wherever possible) the most resource-intensive aspects of each strategy. If properly designed, the decision support tool can reduce the time spent for each strategy and also increase the effectiveness. At the same time, the human worker is not overburdened and is able to accomplish many more tasks.

4) Social Organization and Cooperation Analysis

This fourth step in the CWA framework deals with how the social and technical factors in the system can work together to enhance the overall performance of the system. Using any of the above three modeling tools, roles are allocated to different actors and the organizational structure is created. For our purposes, we identified which roles can be allocated to automation and which roles to the human workers. The automated roles would form the functionalities of that particular decision support tool.

5) Worker Competencies Analysis

The final step in the CWA framework analyzes what competencies an ideal worker should exhibit. The Skills, Rules and Knowledge taxonomy is used to classify various human work behaviors. Once the worker competencies are identified, an ecological interface design (EID) approach can be used to determine the best user interface between the system and each worker.

Based on the information gathered in our field studies, this thesis will explore the first three steps of the CWA framework: work domain analysis, control task analysis and strategies analysis. The remaining two steps of the CWA framework require a more in-depth set of field studies of the interactions among the system's actors and their interfaces with automation systems. Therefore, it is proposed that future researchers will follow-up this thesis in these two areas, to complete the cognitive work analysis of the engine MRO system.

Chapter 7: Analysis

In this chapter, two sets of analyses are presented. Section 7.1 describes an organizational analysis of the engine MRO system followed by a description of the key interactions and processes that take place in this system. Section 7.2 shows how the Cognitive Work Analysis (CWA) framework is applied to this particular work domain. The results of the CWA are then used to suggest how decision support tools can be developed for engine MRO.

7.1 Engine MRO System

Before we can perform the cognitive work analysis, we first had to create a thorough model of the engine MRO system. The actors in the engine MRO system are first identified, and then the key interactions and decision-making processes are discussed.

7.1.1 Engine MRO System Stakeholders

The first step is to identify the various actors in the engine MRO system and how they are related to the system and to each other. We used the Enterprise Stakeholders framework proposed by Murman et al. (2002) to identify these actors as shown in Figure 10.

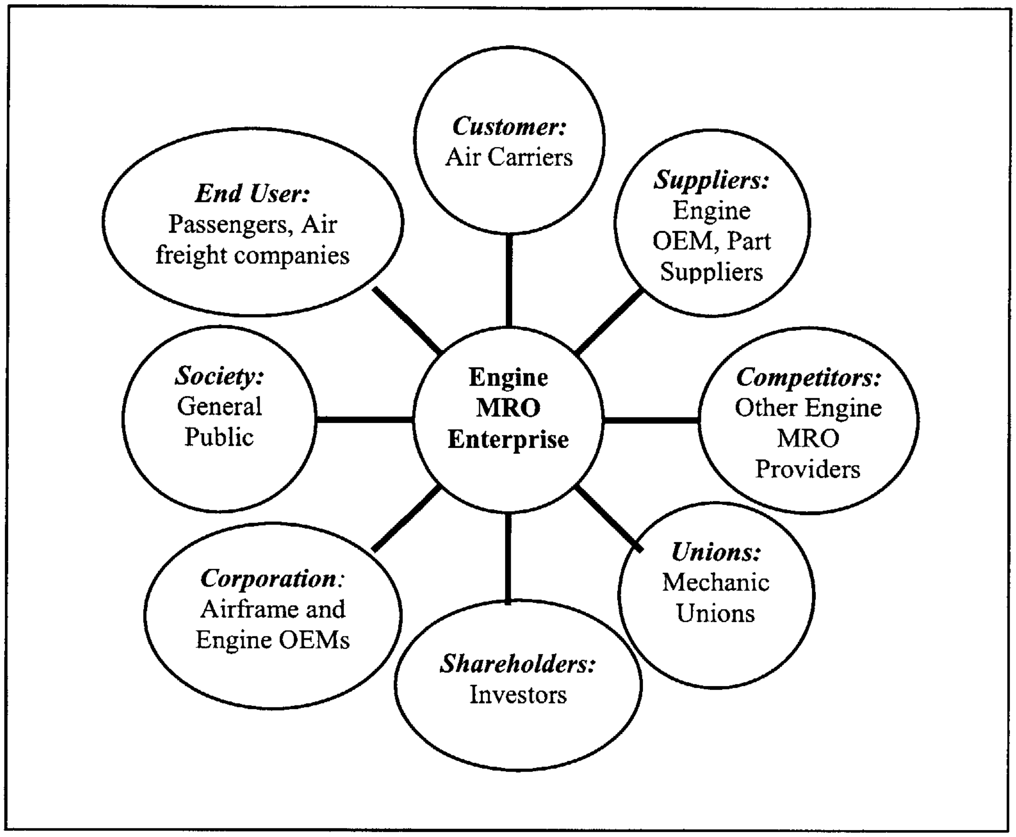


Figure 10: Stakeholders of the Engine MRO Enterprise

This framework allows us to illustrate the value of improvements in engine MRO to these stakeholders, in particular the benefits brought about by computer-based decision support tools. We can also model how these stakeholders are affected by various decisions made in the engine MRO system.

Customer: Air Carriers

The air carriers are constantly seeking the cost-effective solutions for their engine maintenance. In turn, the engine MRO provider has to meet the customer's demands for high reliability and fast turnaround times at minimum cost to the customer. If air carriers can have better engine management and planning tools, then they can revert to predictive maintenance strategies.

End User: Passengers, Air freight

Poor engine maintenance leads to grounded aircraft, flight delays and cancellations, and many disgruntled passengers. Airlines would lose their passenger revenue if they have a poor maintenance reputation. Improved DPCM tools can improve engine maintenance and increase on-time departure rates, which will boost passenger revenue and increase passenger satisfaction with the airline's service.

Suppliers: Engine OEMs, Part suppliers

Many suppliers involved in the engine MRO system. Part suppliers include the engine OEMs and the PMA[17] suppliers. Improvements in inventory planning would help part suppliers to better meet the demand for the right spare parts at the right time.

Competitors: Other engine MRO providers

The engine MRO market is highly competitive. This is most apparent in the large civil turbofan engine sector with the three major OEMs actively expanding their MRO network while some airlines are starting to in-source work from other airlines.

Society: The general public

Since engine MRO has a direct effect on flight safety, there is always the utmost emphasis on ensuring the highest quality of workmanship in engine MRO. Better condition monitoring and prognostics can increase the public's confidence in flight safety, which could increase passenger traffic and airline revenues.

[17] PMA: Part Manufacturer Approval – FAA certified independent engine part supplier. PMA parts are built to the same specifications as the original product by the OEM, but PMA parts have been found to much cheaper than purchasing from the OEMs.

Unions: Mechanics Unions

The labor unions for the mechanics and engine shop personnel may oppose the wide-spread implementation of decision support tools if these tools start to replace jobs. However, if the tools can be demonstrated to relieve workloads and improve worker efficiency, then the unions would be favorable to these tools.

Shareholders: Investors

Engine MRO is performed either by airlines themselves or out-sourced to an engine OEM, independent engine MRO shop or to a joint-venture provider. For each organization, very large financial capital is needed to setup and provide MRO services (e.g. tooling, inventory, training etc.). The financial risks are large. So the engine MRO enterprise is compelled to generate enough revenue to balance the large costs. New decision support tools described in later sections can help increase revenue and lower costs.

Corporation: Airframe and Engine OEMs

With improved decision support tools for engine MRO, airlines can realize greater efficiencies in their MRO operations and have lower MRO costs. This will boost productivity of the overall airline industry. Airframe and engine OEMs can then benefit from the increased profitability in the commercial aviation industry through more sales of aircraft and engines.

7.1.2 Interactions and Processes

Figure 11 shows how typical front-line maintenance operations are organized.

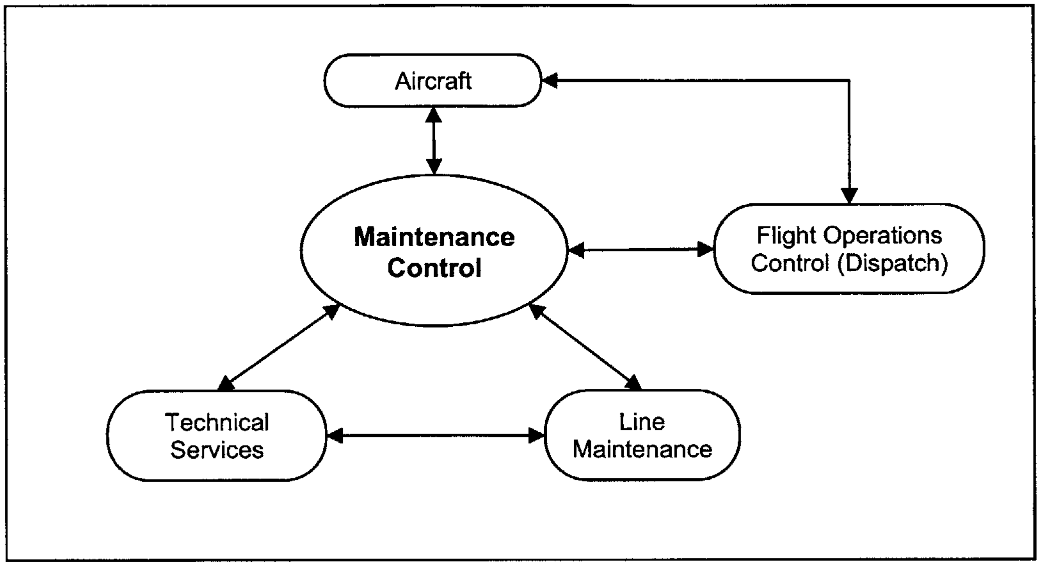


Figure 11: Front-line Maintenance Operations

There is a maintenance control center which is typically co-located with the airline's flight operations control center. Whenever there is a maintenance problem, maintenance control would coordinate the maintenance event. Maintenance problems can arise from either pilots reporting an in-flight malfunction (known as a flight deck effect – FDE) or technical service engineers recommending an unscheduled maintenance event (e.g. an alert from the engine condition monitoring system).

If the aircraft is still en-route when an FDE occurs, pilots would communicate with maintenance control to determine the severity of the malfunction. At the same time, the dispatchers are advised of the aircraft's status. Maintenance controllers are usually experienced mechanics or engineers who are very familiar with the fault codes on the CMC[18] and fault isolation manuals. Once the malfunction is identified, the pilots would be advised to land immediately (severe malfunction) or be allowed to continue on to their

[18] CMC: Central Maintenance Computer

scheduled destination. Line maintenance at the aircraft's destination is notified of the malfunction and is prepared to fix the problem during the aircraft's layover. Technical service engineers are on-hand to assist in fault diagnostics and workscope generation.

For the engine MRO case, the engine analyst would alert maintenance control when the DPCM system has detected a fault. At the same time, the analyst would issue an inspection (and workscope) for the line maintenance mechanics at the aircraft's destination. Maintenance control would coordinate with the flight operations control center to minimize disruptions to the flight schedule. If the fault cannot be rectified within the aircraft's turnaround time, then spare aircraft may be diverted to substitute the AOG[19].

Each link in Figure 11 represents an information flow between the various actors. These can be interpreted as communications or data links. Decision support tools can tap onto these links to provide seamless information exchange. The main problem here is transferring the right information between the engineers, controllers and mechanics. Workscopes, aircraft downtime and required resources have to be communicated precisely. Engine removal plans also have to well coordinated to minimize schedule disruptions.

A typical decision process when an engine system has failed is shown in Figure 12.

[19] AOG: Aircraft On Ground (refers to the situation where an aircraft that is originally scheduled to fly is unexpectedly grounded usually for maintenance reasons)

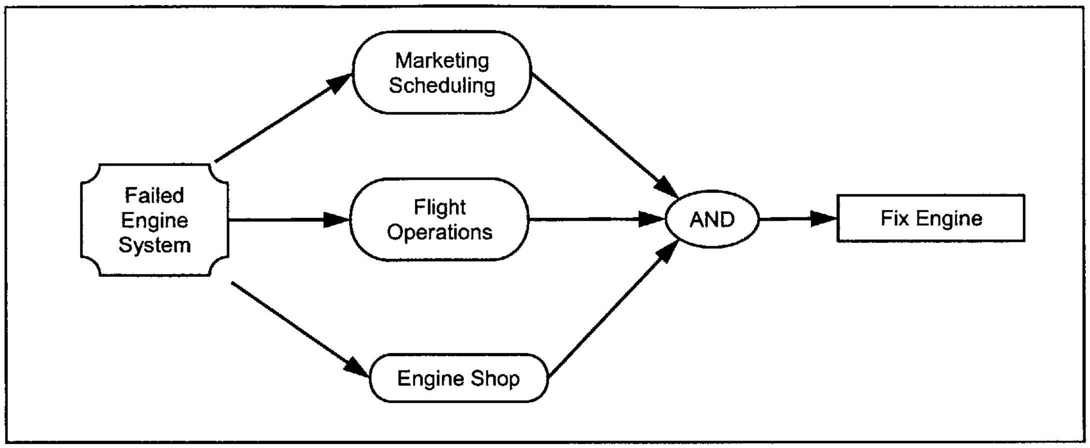


Figure 12: Airline Decision Process for a Failed Engine

Firstly, the aircraft with the failed engine (or impending failure) has to be grounded for the duration of the engine change. The aircraft can be grounded provided it is not scheduled to fly. For busy markets with high demand, Marketing would be reluctant to lose any aircraft. Flight operations has to release the aircraft from service, while other aircraft are diverted to make up for the grounded aircraft. Finally, there has to be capacity at the engine shop to accommodate the failed engine. Once all the criteria are fulfilled, then an engine can be removed and fixed. The engine MRO planning strategy described later addresses how a decision support can be developed for this purpose.

Short-haul vs. long-haul

Our study found that most US domestic carriers did not follow the process outlined in Figure 12. Instead, aircraft are grounded immediately without hesitation based on safety grounds (a "fly-fix-fly" approach). With shorter routes and a more frequent schedule, domestic carriers can afford to have their passengers transferred to the next available flight using adequate backup aircraft. Short and frequent flights lead to higher flight cycle rates for domestic aircraft, which accelerates the aircraft's ageing. On the other hand, for Asian-Pacific international carriers, the marketing and scheduling are much stronger drivers in the MRO decision process. Because long-haul flights are less frequent (often with no alternative flights on same-day) and garner more revenue, international carriers place a greater emphasis on high aircraft dispatch rates and there are severe economic implications if a flight is cancelled or delayed. Flight safety is still the most important criteria. However, these airlines have to weigh the economic penalties and they would try to defer maintenance as long as possible. This note is another example of how operational constraints can be as important, if not more, than the technical constraints. Hence, future decision supports tools need to take into account such operational differences between various airlines.

Figure 13 shows how decision support tools can be implemented throughout the engine MRO system. Decision support tools are required by all actors in the system. It is essential for the actors to have their information systems linked together through data transfer links, so that information like engine diagnostics, workscopes, repair schemes and work schedules can be transferred seamlessly. With up-to-date synchronized information, each actor is able to make faster and more informed decisions.

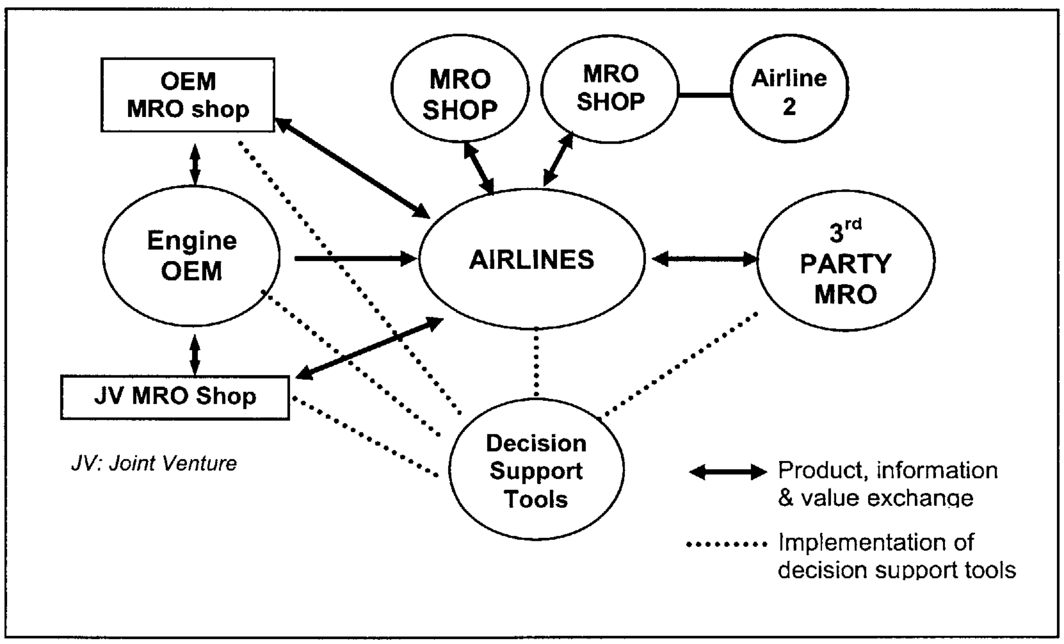


Figure 13: Decision Support Tools in the Engine MRO System

Current decision support tools have been developed separately for each actor. These include diagnostic tools, supply chain management tools, resource planning systems etc. Perhaps if these tools can be linked, then the information exchange can be faster, more accurate and yield overall improvements in efficiency throughout the engine MRO system.

Figure 14 illustrates the importance of having an integrated system of decision support tools between the airline, its engineering and maintenance departments and the MRO shop(s). The decision tools that are proposed in the next section can be modules of this integrated system. More details about the links between various decision support tools will be discussed in the strategies analysis section.

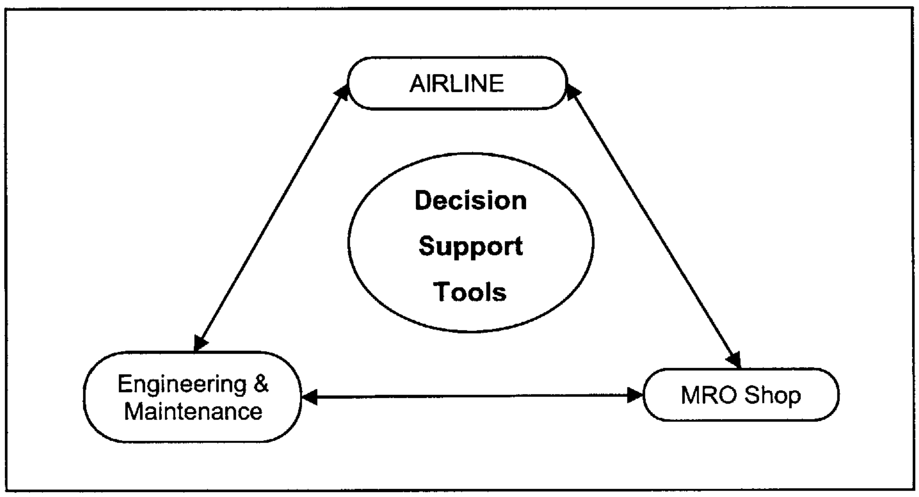


Figure 14: Integration of Decision Support Tools into the MRO Process

Figure 15 shows how the MRO organization can be divided into three tiers. Each tier has a different abstraction of the engine MRO system and the actors in each tier have different cognitive needs. The top tier comprising senior management has high-level overviews of the MRO system. At this level, financial information like costs and revenue are more important than details about the engine failure. However, the engine failure translates to repair and overhaul cost which raises the maintenance cost. Hence, the airline's senior management still see the effects of the engine failure, but at a different abstraction level. Senior management is also interested in the long-term, overall business model of the airline. Middle management like the engine MRO manager and planners have to consider both short-term and long-term views of the system, taking into account the technical, financial and logistical aspects of the system. The maintenance controllers, engine analysts and engineers form the links between the middle management and the mechanics. They have to translate both technical and operational information between these two tiers. For these actors, detailed knowledge of the engine state and the resources and tasks needed to rectify the engine problem are most crucial. They are the "frontline" decision makers, who often have to make immediate decisions that have severe safety-critical consequences. The actual maintenance work is done by the mechanics at the shop floor and the flight line. At this cognitive level, current detailed engine information is the most important. Mechanics primarily need to know how to rectify the current engine problem, what workscopes and job tasks to follow and what results are expected.

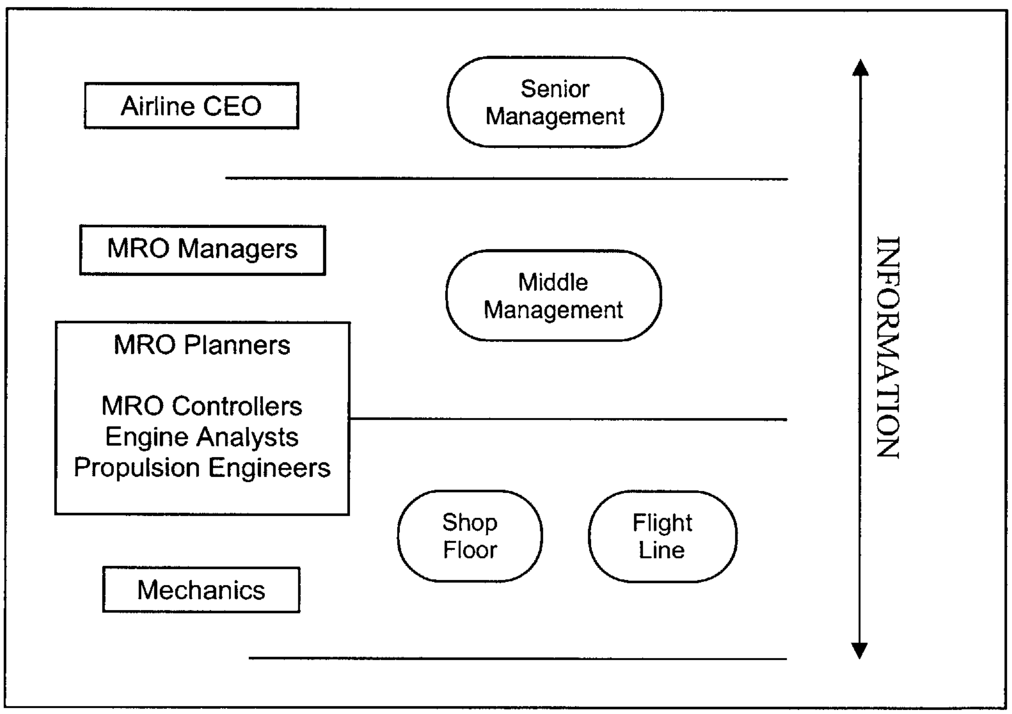


Figure 15: 3-Tiered MRO Hierarchy

Information is exchanged up and down these three tiers. For efficient information exchange between each level of the organization, the various decision support tools must be compatible and the information has to be transformed to cater to the different cognitive levels. Hence, we have identified three different types of cognitive needs, for which different decision support tools are suggested using CWA.

7.2 Cognitive Work Analysis

Based on our field studies, we used Rasmussen's and Vicente's Cognitive Work Analysis (CWA) framework to analyze the cognitive needs of various actors in an engine MRO organization. At the same time, we investigated the use of decision support tools (e.g. engine DPCM) in this work domain and explored which areas of engine MRO can best be supported by such tools.

Our analyses followed the first three steps of the CWA framework: work domain analysis, control task analysis and strategies analysis. The fourth step, social organization and cooperation analysis, relates to role allocations and organizational structure. Aspects of role allocations were incorporated with the first three sets of analyses. Decision ladders (from cognitive task analysis) and information flow maps (from strategies analysis) were used to highlight which roles have been allocated to computer-based tools and which roles are allocated to various human actors. Organizational analysis and the fifth and last step of CWA, worker competencies analysis, are recommended for future research. These steps would involve a more detailed and lengthy study of interactions among the human actors in the MRO system and also between human users and their automation systems, so as to recommend suitable organizational structures and to develop ecological interface designs.

The CWA framework was found to fit very well with the cognitive processes of the MRO actors that were studied. Different actors were thought to have different cognitive needs, and this hypothesis was verified by the different work domains and decision ladders for each actor. Various strategies for each set of control tasks (e.g. diagnostics, prognostics or workscope generation) were identified through field observations and feedback from MRO personnel. Through each set of work abstraction-decomposition space, decision ladder and information flow map, the preliminary design for a decision support tool for each actor can begin.

7.2.1 Work Domain Analysis

The first step in identifying the cognitive needs of the engine MRO organization is to perform a set of work domain analyses for the different actors in the engine MRO system. We have chosen to focus our analyses on the following key actors:

1) Airline Chief Executive Officer (CEO)
2) Engine MRO manager
3) Engine MRO shop manager
4) Engine analyst (or propulsion engineer)

These four sets of actors were so chosen to represent four abstraction levels of the engine MRO system. Though the largest group of actors in the engine MRO system, the engine mechanics, is not in the above list, our field studies found that the engine mechanics operate at a similar abstraction level as the engine analyst or propulsion engineer. These actors are the front-line workers of the engine MRO system who are faced with engine maintenance decisions on a daily basis. Hence, the cognitive needs of the engine mechanics will be discussed together with the engine analyst and propulsion engineer.

The main objective in this section is to illustrate how the engine MRO system as the work domain is viewed differently by different actors. As such these actors face a different decision-making process and their cognitive needs have to be supported by different decision support tools.

7.2.1.1 Airline CEO

The airline CEO utilizes the highest level of abstraction of the engine MRO system in managing his/her airline. Figure 16 below shows the work domain for the airline CEO. The CEO's main function is to ensure the airline carries out its core functional purpose, which is to fly passengers and freight safely at a profit. To meet this functional purpose, the airline has to both meet and generate passenger and cargo demand.

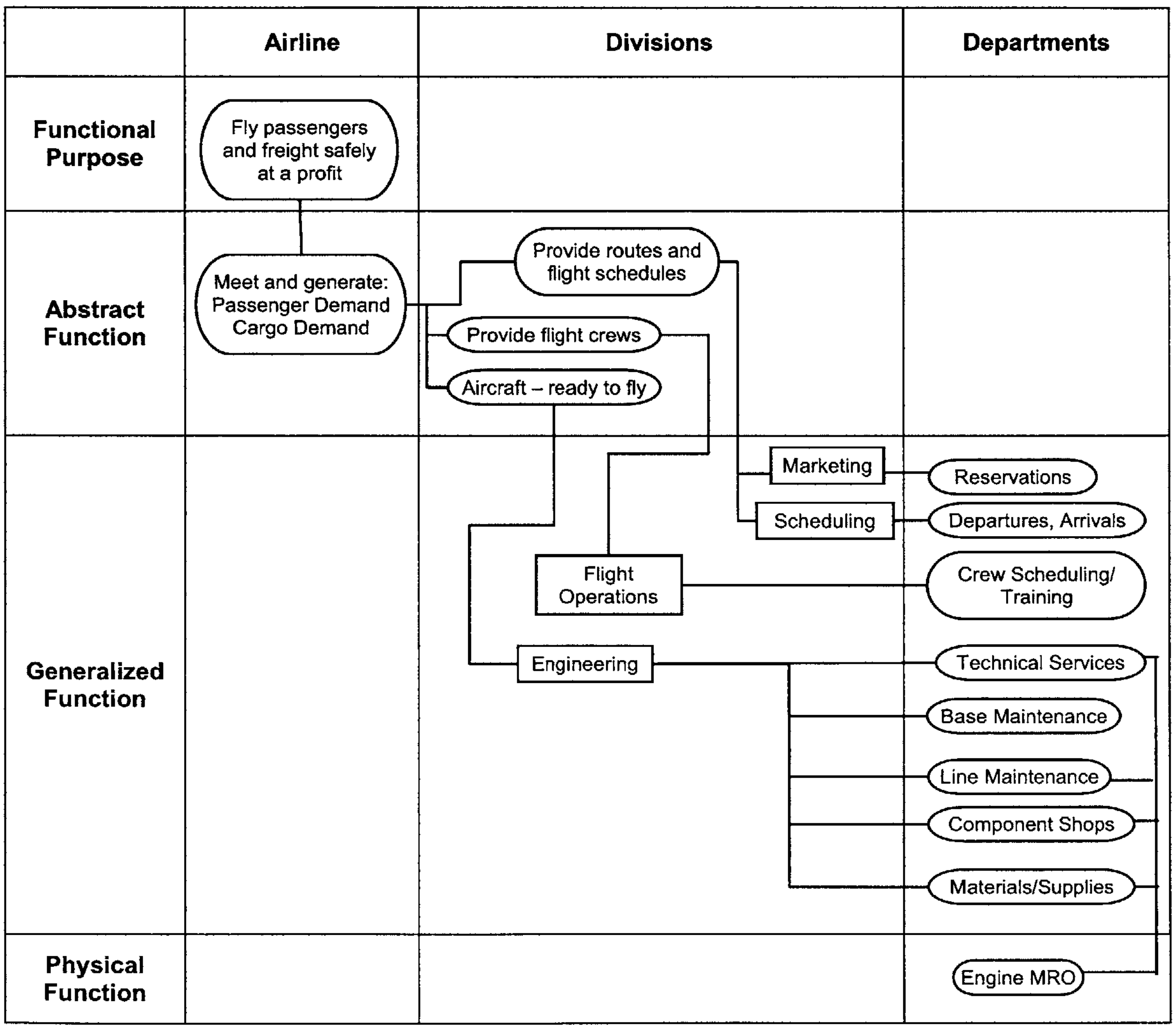


Figure 16: Airline CEO's Abstraction-Decompostion Space

The airline organizational structure (see Figure 4) is a typical example of functional decomposition as the airline's three main divisions can fulfill three sub-functions. The

Commercial division provides the routes and flight schedules to meet the customer's demands, through its Marketing and Scheduling functions. Flight Operations provides the pilots and flight attendants, and coordinates frontline flight operations of the airline's aircraft fleet throughout the airline's network through an operational control center.

The third sub-function of providing serviceable (i.e. ready-to-fly) aircraft is undertaken by the Engineering division. As described earlier in this thesis, the technical services, maintenance and materials departments fall under this division. Engine MRO is identified as a physical function in this abstraction-decomposition space.

Using this mapping of the work domain, the airline CEO is able to explicitly relate engine MRO to the airline's core functions through the means-ends links shown above. Not only does this mapping show the importance of engine MRO (and maintenance in general) to the airline, it also serves as a useful tool for the CEO to manage the airline's financial resources, especially in the current downturn of the airline industry. Suppose there are limited funds available for engine MRO. Instead of cutting the engine MRO budget, the CEO can implement cost-cutting measures at the Materials department (e.g. keeping a smaller inventory). Since Technical Services is linked to engine MRO, perhaps the technical service engineers can improve their engine prognostics or cut-back on non-crucial engine workscopes. This is an example where the CEO can use this mapping of his/her work domain to more effectively manage the airline.

Figure 16 can be used as a template to create an airline CEO's "dashboard" for airline management. This dashboard can show the performance indicators of each airline function and department, including engine MRO. These performance indicators could include revenue counters, running expenditures, on-time departure rates, aircraft and engine turnaround times and current value of inventory. Through the means-ends links shown in Figure 16, functional relations between different airline departments can be more explicitly represented. Thus, the CEO would be able to easily visualize how each airline department is performing and identify where the strong and weak links are within the airline organization.

If engine MRO or all maintenance is out-sourced to external MRO providers, this dashboard can also be used to track how well the external MRO providers are meeting the airline's expectations and operational requirements (e.g. MRO costs, on-time engine deliveries from the shop). This can also be applied to other out-sourced functions such as in-flight catering and ticketing (e.g. Internet-based travel agents).

Such a decision support tool would be able to support the cognitive needs required of the CEO in managing the airline. To our knowledge, such a management tool has not yet been implemented by the airlines in our study.

The downstream effect of this upper management tool on engine MRO is that the airline's management can link MRO expenditure (and maybe profits if there is in-source work) to the airline's overall business model. Such financial transparency would compel engine MRO providers to actively reduce their costs in order to provide competitive and affordable MRO services to the airlines.

Various other decision support tools, which are described later in this chapter, can be linked directly or indirectly to the CEO's dashboard. Thus the maintenance-side of the airline can be integrated into the overall airline management system and decision-making process.

7.2.1.2 Engine MRO Manager

The engine MRO manager oversees all engine MRO activity, ensuring that all the airline's engines are functional and are of the appropriate safety levels. Since MRO is a cost center for the airline (at least for its own engines), the engine MRO manager aims to minimize the cost of engine MRO. Figure 17 shows the work domain of the engine MRO manager.

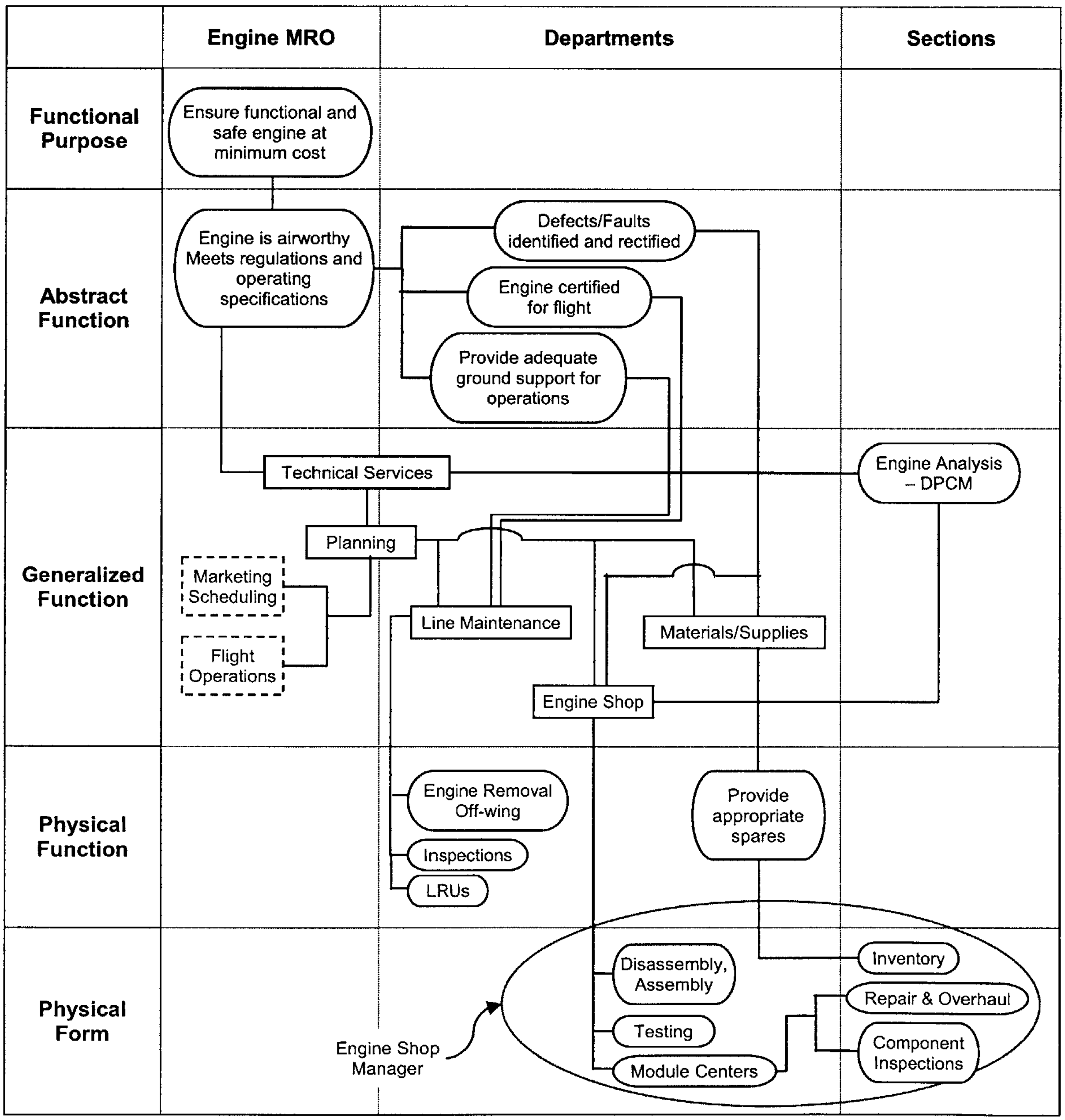


Figure 17: Engine MRO manager's abstraction-decomposition space

This work domain represents the various system components and functions that the engine MRO manager has to interact with to achieve his/her functional purpose.

For the engine to be airworthy and meet regulations and operating specifications, three functions have to be fulfilled. Any defects or faults have to be identified and rectified, the engine has to be certified as airworthy before each flight and adequate ground support must be provided during flight operations. The engine MRO manager has several departments at his/her disposal: propulsion engineers (under technical services), maintenance planners, line maintenance, materials and the engine MRO shop.

Propulsion engineers perform engine analysis (e.g. diagnostics, prognostics and condition monitoring) to identify engine faults and propose appropriate mitigating actions and maintenance processes. Line maintenance personnel are tasked to provide the ground support while engines are in-service and to certify each engine is airworthy before takeoff. They also perform on-wing inspections and quick maintenance using LRUs[20]. The engine shop handles most of the engine MRO while the materials department provides the appropriate spares to rectify the engine fault.

Maintenance planners have a very important role, as they plan the engine maintenance schedules and organize manpower and other resources to meet the maintenance tasks. As noted earlier on, the actual engine maintenance schedule not only depends on the technical reasons (e.g. engine failure) but is also constrained by commercial and operational factors. So in reality, the maintenance planner needs an information interface with marketing, scheduling and flight operations.

The engine MRO manager faces a tough challenge of incorporating information provided by each group of workers and deciding which maintenance decisions work best to meet the overall goal of the engine MRO portion of the airline. For example, the planners may schedule long maintenance intervals because aircraft are scheduled to fly throughout the

[20] LRU: Line Replaceable Unit

network before returning to the maintenance base after a long time. On the other hand, the propulsion engineers may recommend more frequent maintenance intervals because certain engines were found to have below average reliability. Hence, the engine MRO manager has to balance these constraints and manage all these resources effectively to produce functional and safe engines at minimum cost.

We can use Figure 17 to develop a tool to assist the engine MRO manager in making these various decisions. There are currently several tools available in the market that support some the functions described above (see Table 4 for some examples). For instance, several diagnostic and condition monitoring tools like SmartSignal's *eCM* or DS&S' *Compass* are adept at identifying engine faults, while Mxi's *eMaintenix* package is geared towards maintenance planning. However, engine MRO managers that were surveyed are looking for an integrated decision support tool that either comprehensively covers all these cognitive needs or links together the various current tools. This tool would then be able to provide the engine MRO manager with a complete and concise picture of his/her work domain. Such a decision support tool is most vital in unanticipated engine fault management situations, where the engine MRO manager has to make quick and prudent decisions to rectify the engine fault with minimum downtime and minimum overall cost.

7.2.1.3 Engine MRO Shop Manager

The next key decision maker we looked at was the engine MRO shop manager. As shown in Figure 18, the functional purpose of the engine MRO shop is to provide engine MRO services at a profit[21]. This implies that the engine shop has to meet the demand of the customer (or parent airline) for safe and functional engines at the fastest turnaround times possible.

The engine shop manager has a different operating constraint from that of the airline's engine MRO manager. The airline manager is concerned with immediate mitigating actions for faulty engines and flight safety. The engine shop, however, deals with more long-term decisions since minor engine repairs may take a week and full engine overhauls several months. Flight safety is also not a factor, since all the engines the shop deals with are already deemed to have failed in some way and have already been removed from service. This difference in urgency, and others, suggest that a different design philosophy has to be used for designing a decision support tool for the engine MRO shop.

The various departments of the engine shop aim to meet the three main functions of the shop, which are to identify and rectify any engine faults, perform the repair and overhaul process and to certify that the engine is restored to serviceable status after the re-work has been completed.

[21] This definition would be modified for internal airline engine shops which aim to minimize their costs instead of making profits.

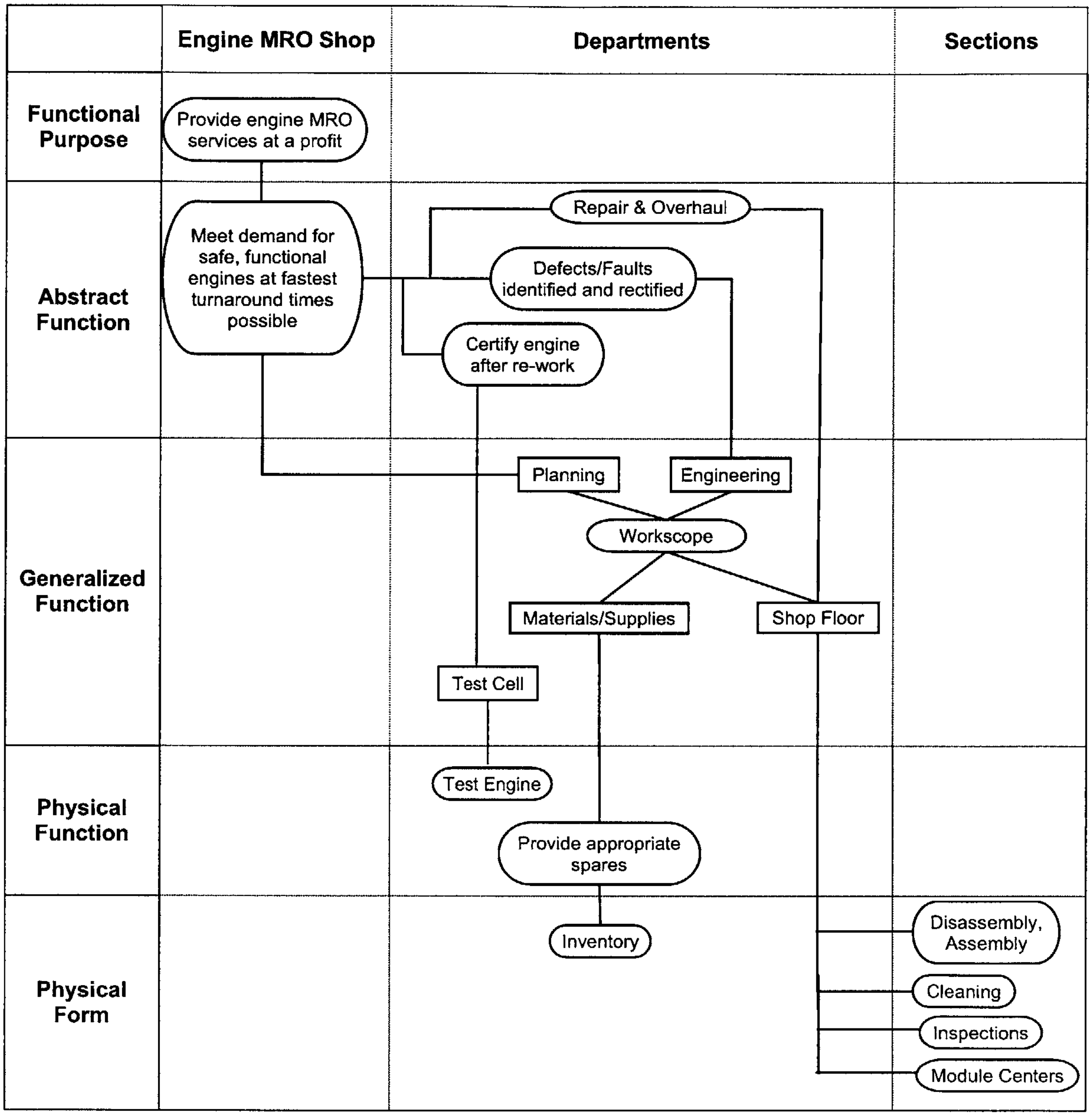


Figure 18: Engine MRO shop manager's abstraction-decomposition space

Decision support tools for the engine shop manager can be most effective by supporting the planning and engineering functions. These two functions combine to generate workscopes for the shop floor personnel to carry out the repair and overhaul process. These workscopes help the materials department to keep the appropriate engine spare parts in the shop's inventory.

7.2.1.4 Aircraft Gas Turbine Engine

The smallest decomposition level of the engine MRO system is the aircraft gas turbine. The engine is the work domain of the engine analyst and propulsion engineer. Before we perform a work domain analysis for these actors, it would be useful to first analyze the engine itself. The following analysis can be used to design an engine diagnostic, prognostic or condition monitoring tool for the engine analyst.

Figure 19 shows an abstraction hierarchy for an aircraft engine system. This model uses five levels each of abstraction and decomposition. The engine can be decomposed into the following levels:

1) Total system – the engine system
2) Subsystems – engine modules (e.g. fan, compressor, turbine and combustor)
3) Functional units – main assemblies of each engine module (e.g. rotors and cases)
4) Subassemblies (e.g. rotor discs and bearing compartments)
5) Components – individual parts (e.g. blades, bearings, pumps and valves)

<table>
<tr><th></th><th>Total System (Engine)</th><th>Subsystem (Modules)</th><th>Functional Unit</th><th>Sub-assembly</th><th>Component</th></tr>
<tr><td>Functional Purpose</td><td>Provide thrust
Supply mechanical power
Supply bleed air</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Abstract Function</td><td>Conservation of mass and energy</td><td>Mass-energy topology</td><td></td><td></td><td></td></tr>
<tr><td>Generalized Function</td><td></td><td>Processes involved in the engine such as compression, expansion and combustion</td><td>Process of turning the fan, compressing and expanding the air, burning the fuel</td><td></td><td></td></tr>
<tr><td>Physical Function</td><td></td><td></td><td></td><td colspan="2">Support functional unit processes
Ensure smooth and safe operation</td></tr>
<tr><td>Physical Form</td><td></td><td>Layout, form and location of modules</td><td></td><td colspan="2">Physical location, shape, size, physical condition of components</td></tr>
</table>

Figure 19: Abstraction Hierarchy for an Aircraft Engine System (adapted from Namidian et al, 2002)

At the functional purpose level, the engine system has to fulfill its three main design purposes:

1) Provide thrust for the aircraft
2) Supply mechanical power that is converted to electrical power and to drive accessory systems like hydraulics and pneumatics
3) Supply bleed air to the aircraft's environmental control system (ECS)

The work domain analysis presented here is similar to that used by Namidian et al (2002). The abstract function level of the engine system corresponds to mass and energy conservation laws. An example would be the thrust supplied by engine, which is a resultant force derived from the forward and aft forces generated by the compressors and turbines. At the generalized function level, we would model the processes involved in achieving the functions of each engine module and functional unit such as compression/expansion of air and combustion. These generalized functions are described in Figure 20, and they are closely related to the physical functions of the modules and functional units.

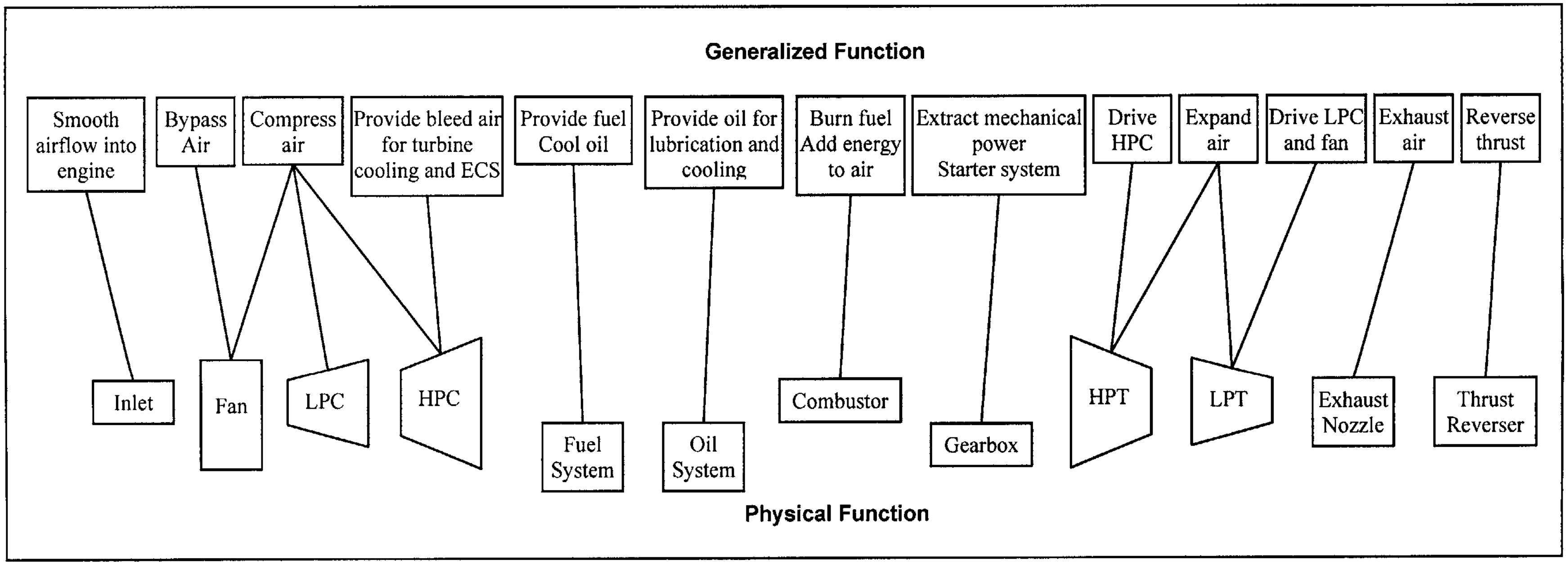


Figure 20: Means-ends mappings between adjacent levels of the engine abstraction hierarchy (adapted from Dinadis & Vicente, 1999)

At the physical function level, we would model the physical processes required to achieve the purpose functions of each component, subassembly and module.

A diagnostic, prognostic and condition monitoring (DPCM) tool can be developed using such a work domain analysis (WDA) of the engine. This WDA can help model how the different engine components interact and behave during normal operations and under various failure modes through the means-ends and topological links between each engine component. Current DPCM tools already employ well-proven algorithms to monitor and diagnose engine faults and failure modes. However, these diagnostic methods are usually based on physical processes and there is less emphasis on the linking the engine modules through their means-ends relationships. DPCM tools can use such means-ends linkages to present a more cognitively useful diagnosis to the human operator, by illustrating how one faulty component can lead to another component failure and as a result cause an overall engine malfunction or failure. If DPCM tools employ a more cognitive approach, using a WDA, we believe that fault overlaps and compound failures as a result of multiple faults occurring at the same, can be better understood and presented to the engine analyst.

7.2.1.5 Engine Analyst

For airlines that use engine condition monitoring systems, their engine analyst's view of his/her work domain – the engine – is very much based on the user interface and outputs from that condition monitoring system. To the engine analyst, the engine is effectively a "virtual" system represented by various sensor variables. Hence, most of the information that the engine analyst knows about his/her fleet of engines is based on the "lens" provided by the condition monitoring system. Therefore, it is imperative that the user interface and the sensor variables are delivering an accurate and useful perception of the engine's state to the analyst. The engine can be modeled according to its sensor variables, as shown in Figure 21.

The monitoring variables used by current DPCM tools are shown above in Figure 21. As DPCM and sensor technology develop, it is envisioned that more engine parameters can be monitored and used in detecting and identifying engine faults. With more information available, the engine analyst will be better poised to understand how, why and where the engine failed. Some suggestions on other variables are listed in Figure 21.

However, increasing sensor instrumentation has its difficulties. Sensors like thermocouples and pressure probes have been generally less reliable than many of the engine components. Because of the harsh operating environments and the delicate nature of these sensors, sensor failure has been one of the frequent failure modes. Furthermore, more sensors would lead to more sensor cables to the electronic engine control (EEC), increasing the complexity of the wiring routes and the external wiring harness. Sensors, of the required accuracy and sensitivity in a gas turbine engine, are expensive to manufacture which would then raise the cost of these engines, which would not be a favorable proposition for many airlines.

Therefore, there will have to be a trade-off between increased engine instrumentation and the increase in maintenance and cost of these extra sensors.

	Total System (Engine)	Subsystem (Modules)	Functional Unit	Subassembly	Component
Functional Purpose	Desired settings: - thrust level - power uptake - bleed air for environmental control system				
Abstract Function	Thrust Power generated Bleed flow Thrust specific fuel consumption				
Generalized Function		Fuel Flow EPR EGT margin			
Physical Function		Spool speeds: N_1, N_2 Vibration levels of fan and spools	Stage pressures/ temperatures Oil pressure/ temperature Bleed duct pressures		
Physical Form			Fuel Quantity Oil Quantity	Trim Balance	VIGV/VSV positions[22] (Bearing state) (Blade temperature) (Amount of TBC left)[23] (Component life e.g. discs)

Figure 21: Engine condition monitoring variables

Note: (xx) denotes examples of other variables that can be monitored by future DPCM systems. These variables can be grouped by modules, instead of for the whole engine. Hence different modules are monitored at the same time, and maintenance can be done on a modular, instead of whole engine, basis.

[22] VIGV: Variable inlet guide vanes, VSV: Variable stator vanes
[23] TBC: Thermal barrier coating

7.2.1.6 Troubleshooting Trajectory

Given a work domain analysis of the engine, we can then map a troubleshooting trajectory onto the engine's abstraction-decomposition space to illustrate the cognitive processes of an engine analyst or propulsion engineer when an engine fault is detected by the DPCM system. The different steps taken in the troubleshooting process would correspond to a certain level of abstraction and decomposition of the engine system.

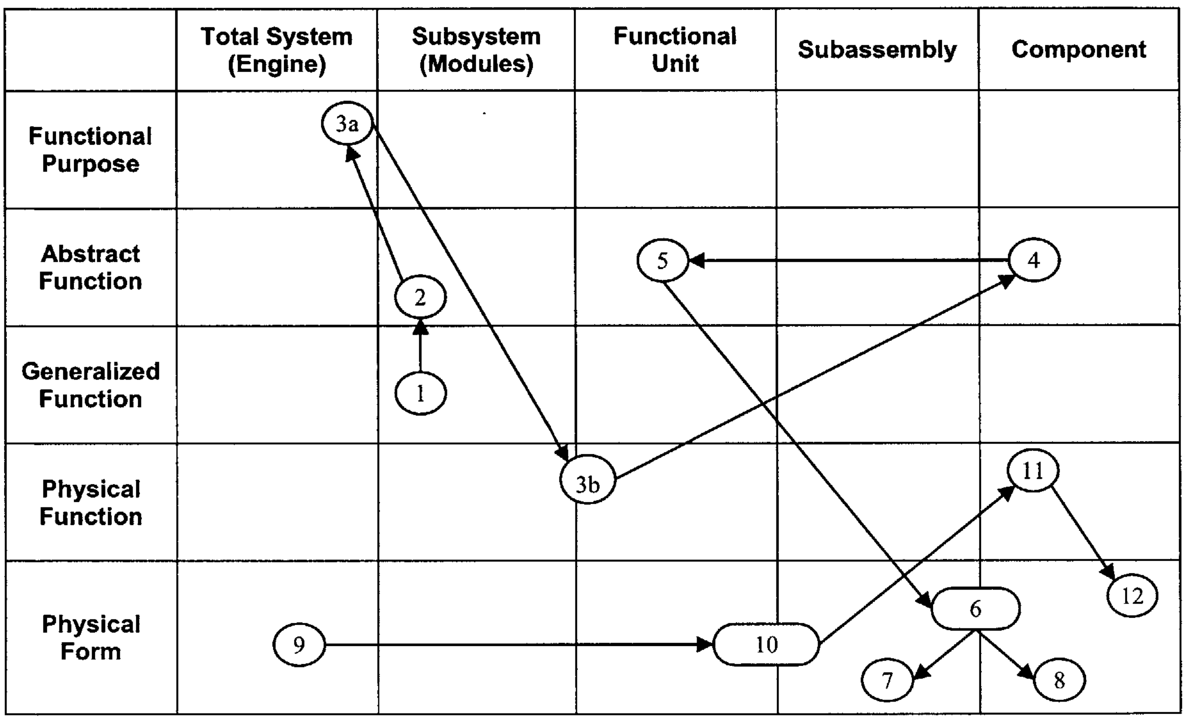


Figure 22: Mapping of a troubleshooting trajectory onto the engine abstraction-decompostion space

Figure 22 shows a troubleshooting trajectory that an engine analyst or propulsion engineer might use to diagnose an engine fault and to determine the appropriate mitigating actions.

In this example, the following steps were taken:

1) Low EGT margin, decrease in N_2

- The DPCM system alerts the analyst that the turbine gas temperature (EGT) margin[24] has decreased below the pre-determined threshold level, and that the high pressure spool speed, N2, has shown a decreasing trend.

2) Infer that HPT air flow too hot, HPT performance decreased

- The EGT thermocouple is located in the high pressure turbine (HPT) gas path. A low EGT margin means a high EGT so the airflow in the HPT is running hotter than normal. The decrease in N_2 indicates that the HPT is extracting less energy from the core airflow, thus slowing down the high pressure spool. Hence this might indicate some failure in the HPT.

3a) *Check aircraft and engine condition first*

- The engine analyst first checks on the aircraft and overall engine condition. No pilot "squawks" (reports) were reported and the aircraft is flying normally. So no immediate mitigating actions are needed. This fault is classified as non-critical and maintenance can be deferred at least till the aircraft arrives at its scheduled destination.

3b) *Check other parameters*

- The other engine parameters are checked to make sure there are no other anomalies. All other parameters are trending normally. So it seems that the engine has an isolated fault in the HPT.

[24] EGT margin: the difference between actual EGT and the maximum allowable EGT. Engines are specified to a certain safe operating range of EGT margins. An abnormally low EGT margin would indicate a potential engine fault.

4) *Guess hot section is burnt*

- From experience, the low EGT margin probably means that some HPT components have experienced thermal failure and might have either oxidized and burnt or be close to their melting temperatures.

5) *Trend Analysis by DPCM system*

- Trend analysis by the DPCM system suggests that the engine parameters correspond to a pattern resembling a HPT failure mode. From past experience and fleet trends, there are two possible failure modes:
  - (i) structural failure of the NGV[25]
  - (ii) lack of cooling air in the HPT

6) *Borescope inspection*

- Guessing that it is a HPT failure, the engine analyst issues a borescope inspection of the HPT to the line maintenance station at the next aircraft layover. The inspection specifically targets the NGV structure and the cooling passages. The line maintenance mechanic opens up the engine nacelle and inserts a borescope into the HPT inspection port.

7) *Check NGV structure – ok*

- The line maintenance mechanic reports that the NGV structure is of an acceptable condition. There is no structural damage.

8) *Check cooling holes, passages – oxidation, burnt*

- The cooling passages are inspected next. The mechanic reports that some HPT blades have oxidized near the cooling holes and show some surface cracks. This observation helps the engine analyst confirm that this engine does indeed have a failed HPT. The blades have to be replaced.

[25] NGV: Nozzle guide vane

9) Issue engine removal plan

- Once the failure has been correctly identified and confirmed, the engine analyst, in consultation with the propulsion engineer and maintenance controllers, issues an engine removal plan. The aircraft is grounded, and a spare engine is transported to replace the faulty engine.

10) Disassemble HPT module

- The engine is removed off-wing and the HPT module is disassembled at the engine shop.

11) Perform functional tests on HPT

- Further physical inspections and functional tests are performed on the HPT and its subassemblies and components.

12) Conclusion

- The cooling holes were found to be blocked by very fine sand particles, causing a lack of cooling air on the blades. Hence the blades overheated and started to oxidize. The burnt blades lowered the turbine efficiency, raising the gas temperature and lowering the spool speed. A workscope is issued to replace the blades and clean the cooling passages.

The above example describes one instance of a troubleshooting process. Depending on the type of fault alert, the engine type and fleet trend, the airline's standard maintenance procedures, experience of the analyst and many other factors, the troubleshooting trajectory could look very different from that in Figure 22.

Through this example, we have illustrated the usefulness of the abstraction-decomposition space in capturing the cognitive processes of an engine analyst and the engine mechanic. A decision support tool to support these cognitive processes has to be able to adapt to the various abstraction and decomposition levels that the cognitive processes occur. This could be in the form of a graphical interface that resembles Figure 22. Such a tool can aid the engine analyst in deciding what his/her next course of action during the troubleshooting process.

An all-integrated tool that can provide a seamless information interface between the engine analyst and the mechanics will greatly enhance and expedite the troubleshooting process. Furthermore, if such a tool can be integrated with the DPCM system, then the fault isolation and diagnostic process can be verified more quickly by the mechanic.

7.2.2 Control Task Analysis

The next step of the CWA framework is to perform control task analyses for the various operating modes of the system. For our engine MRO system, we have identified and analyzed four operating modes:

1) On-board engine monitoring and fault management
2) Ground-based engine monitoring and fault management
3) Engine MRO process (airline-side)
4) Engine MRO shop process

We have chosen to focus on the operating modes where there is a failed engine system and what are the tasks that various actors of the engine MRO system have to perform in order to meet the main goal of the system – functional and safe engines. These four operating modes entail significant decision-making processes and offer many opportunities for cognitive support tools.

For each operating mode, we analyzed the control tasks that need to be accomplished by, using the decision ladder template as described earlier in Chapter 6.2.

7.2.2.1 On-board Engine Monitoring and Fault Management

In this section, we explore the on-board engine monitoring systems (EMS), the functions that these systems perform and how the flight crews interact with these systems. Two such on-board systems are Boeing's EICAS[26] and Airbus' ECAM[27] (Pallett, 1992). Although the displays and user interfaces are somewhat different between EICAS and ECAM, they share a common function of providing flight crews with real-time information on engine parameters and are programmed to alert the flight crew of any engine malfunction through appropriate alert messages. These systems also prompt flight crews to use the appropriate checklists during any engine malfunctions.

[26] EICAS: Engine indicating and crew alerting system
[27] ECAM: Electronic centralized aircraft monitoring

Normal Mode

When the engine is operating normally, the on-board engine monitoring systems operate as shown in Figure 23. The goal state of the system is to achieve a functional and safe engine while in-flight. In this normal mode, the EMS only has to observe the engine and report to the flight crew that the engine is operating within normal limits. The intention is to assure the flight crew that there are neither engine malfunctions nor is flight safety compromised in any way by the engines. Current EMS are designed to be fully autonomous in the monitoring phase, thus relieving the flight crew of this arduous task. The reliability and accuracy of autonomous EMS have become ever more important as most current commercial aircraft operate with two-man crews without a flight engineer.

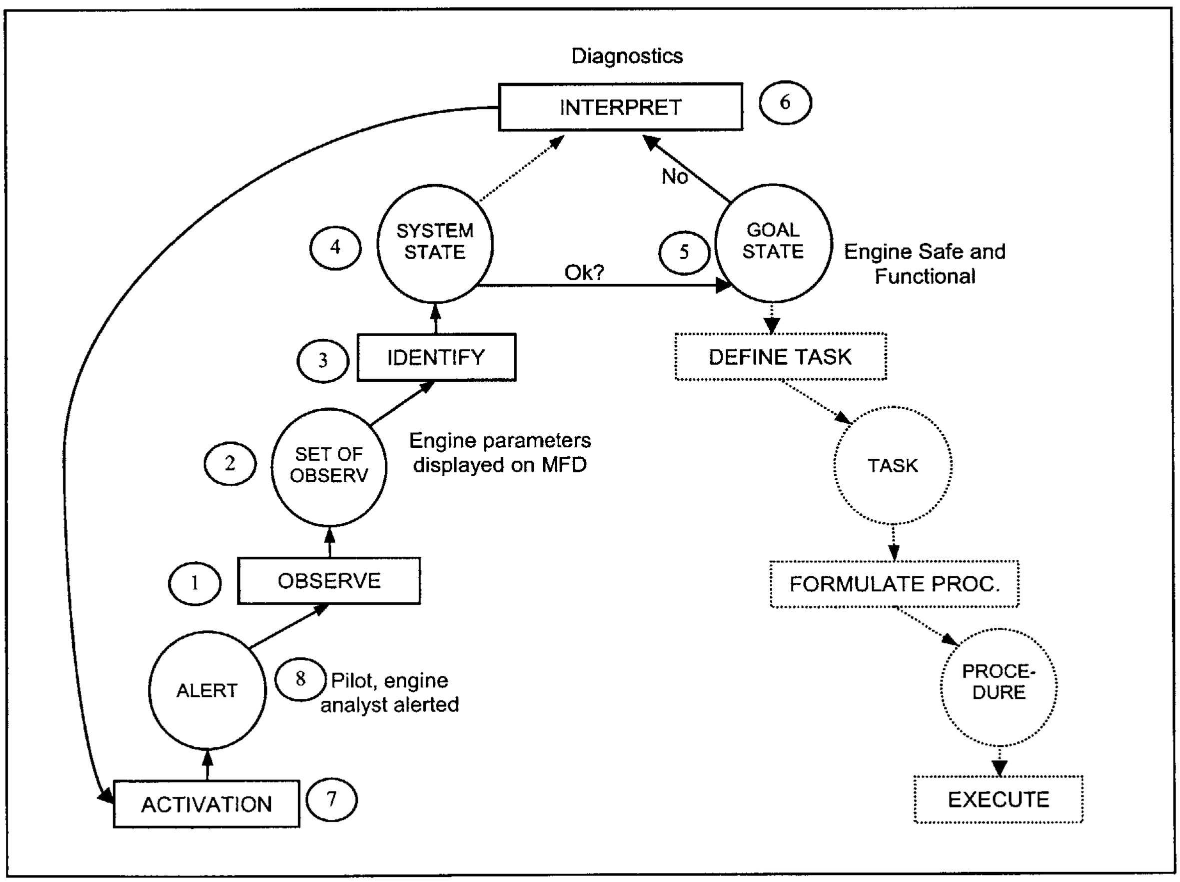


Figure 23: Normal in-flight engine monitoring

In this normal operating mode, the system operates in the following sequence:

1) *Observe:*

   On-board engine monitoring system observes engine parameters in-flight.

2) *Set of Observations:*

   Engine data is collated by engine monitoring system and displayed on multi-function displays for the flight crew.

3) *Identify:*

   The monitoring system attempts to identify the engine's system state.

4) *System State:*

   The engine's system state is identified and classified as normal or abnormal.

5) *Goal State:*

   If engine is normal, then the goal state is achieved. But if the engine is operating abnormally, the monitoring system will run a diagnostic routine.

6) *Interpret:*

   Preliminary diagnostics are used to determine the criticality of the engine malfunction, namely if this is safety-critical or a minor malfunction that can be fixed at a later time.

7) *Activation:*

   The alerting system is activated.

8) *Alert:*

   The flight crew are alerted receives a fault message on the CMC, the engine displays change color and an audio warning tone may be heard.

In-flight Engine Fault Management

In the event that an engine fault or malfunction has been detected, the engine monitoring system will switch to its fault management mode. The goal state is still to ensure that the engine continues to be safe (with respect to flight safety) and is still functional (if possible). The flight crew is advised on which mitigating actions to take according to their checklists and advisory messages from the EMS. The first objective is to keep the engine functional within safe limits like reducing the throttle for lower thrust. Pilots are reluctant to shut down the engine unless it is absolutely necessary to do so because the engine may not be able to restart while in flight. This is especially risky for twin-engine aircraft like the Boeing 777[28].

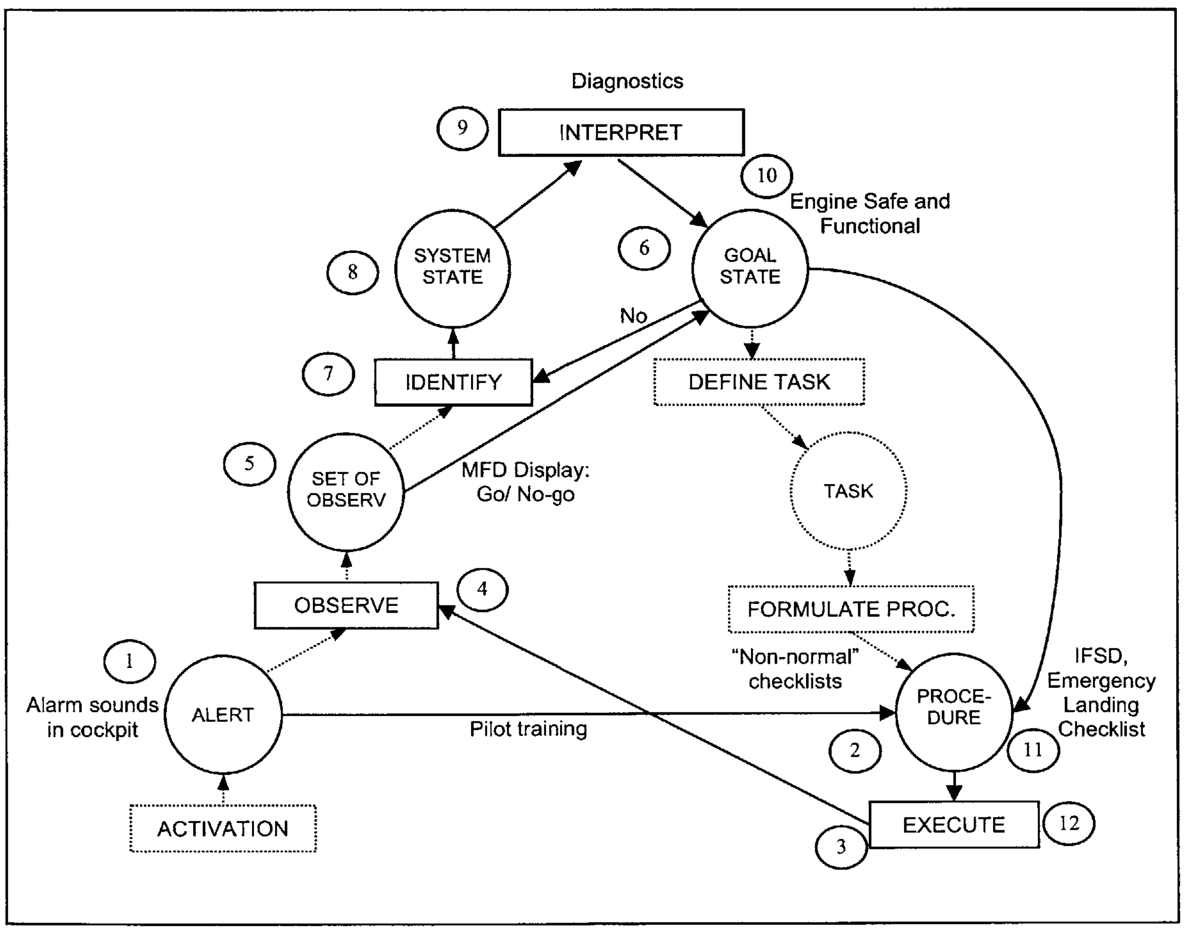


Figure 24: Decision Ladder for In-flight Engine Fault Management

[28] Even for ETOPS-capable aircraft, pilots are understandably reluctant to fly with a single engine and test the ETOPS specification of single-engine flight for 3 hours.

Figure 24 shows the control tasks that have to be accomplished in this operating mode:

1) *Alert*:

   Pilots are alerted to the engine malfunction through visual messages and/or an audio warning.

2) *Procedure:*

   Because of their training, the pilots immediately refer to their "non-normal events" checklist and correlate the checklist to the fault message that they see.

3) *Execute:*

   The pilots execute the checklist. The first step is usually to reduce the throttle and put out any fires (if any).

4) *Observe:*

   Once the checklist is executed, the pilots observe the EMS displays for any effects on the engines.

5) *Set of Observations:*

   The EMS will display on the MFD[29] the new engine conditions. Based on color codes and visual cues, the pilots can determine whether the engine is safe and still functional.

6) *Goal State:*

   If the engine returns to a safe mode, then the flight continues. Line maintenance is notified by the pilots upon landing. If the engine continues to show a malfunction, the pilots would then have to identify the engine state.

7) *Identify:*

   The EMS will attempt to identify the state of the engine.

8) *System State:*

   EMS displays the state of the engine.

9) *Interpret:*

   Engine data is transmitted or relayed via radio to ground maintenance control. Ground engineers will work with the pilots to diagnose the engine malfunction. Mitigating actions will be determined by the ground engineers.

[29] MFD: Multi-function Display

10) *Goal State:*

If the malfunction is safety-critical, the pilots would shutdown the engine and land immediately at the nearest airport. Otherwise, the engine is either throttled back or shut down and the pilots continue on to their scheduled destination.

11) *Procedures:*

Once the mitigating actions are decided, the pilots again refer to the appropriate checklists (e.g. IFSD[30], emergency landing)

12) *Execute:*

The engine is throttled back or shut down. The aircraft makes an emergency landing or continues on to original destination.

Design of on-board engine monitoring and fault management systems

Safety is the paramount factor to in-flight engine monitoring. The flight crew only needs to know what the safest option is during any emergency. For an engine problem, this translates to whether they should throttle back, shut down or immediately descend and divert to the nearest airport. The pilots do not need to know the root causes, but just the seriousness of the faults and what checklists they have to use. The actual diagnostics can be done behind the scenes by on-ground maintenance engineers.

The feedback from pilots we interviewed showed that there are two schools of thought for the level of cognitive support provided by engine monitoring systems. The first was that more information was better for the flight crew. This was exemplified in early Airbus aircraft where pilots were given very detailed checklists. The second was the "need-to-know" approach, which Boeing used, where pilots were provided with bare minimum checklists that told them just what they had to do to fly the plane safely. For both approaches, the main criterion is whether the information provided can be of use to the flight crew or that the pilots cannot do anything about piece of information. Information overload should be avoided, so that pilots can focus on flying the aircraft and

[30] IFSD: In-flight Shut Down

not waste precious time deciphering the information. The checklists can be integrated with EICAS or ECAM such that based on current engine conditions, the "non-normal events" checklist can be shortened to only display the relevant tasks.

There are two common in-flight engine problems: high EGT[31] and abnormal vibration levels. For high EGT, throttling back usually solves the problem temporarily. However, there is no fixed checklist for vibration problems. Engine vibrations can be due to rotor imbalance. As airplane vibrations can be due to a myriad of factors and not just the engines, it is a challenging task to have a checklist that covers all types of vibrations. As one airframe manufacturer aptly points out, "the response of flight crews to vibrations is fundamentally an exercise in airmanship" (Boeing, 1998). Perhaps, the on-board EMS can be enhanced with a vibration diagnostic capability, and not just be monitoring overall vibration levels.

Some pilots have suggested that researchers can pick a symptom (e.g. high EGT), narrow down the possible causes then let pilots feedback on what information will be most helpful to them in those scenarios. Not all possibilities have to be explored. Since time is limited in such situations, only the most probable procedures are needed. This can be one method for improving on-board engine monitoring systems.

[31] EGT: Exhaust gas temperature

7.2.2.2 Ground-based Condition Monitoring and Fault Diagnostics

Most of the DPCM tools that have been previously discussed fall under this operating mode. Ground-based DPCM tools have been widely used by airlines for over twenty years and their operating mode can be described below. This set of control task analyses corresponds to the engine analyst's work domain There are engine analysts who interface daily with these tools to determine the health of the engine fleet.

Normal Mode

Figure 25 shows how a ground-based condition monitoring system operates when the engines being monitored are in their normal state. In the normal state, the DPCM system is fully automated.

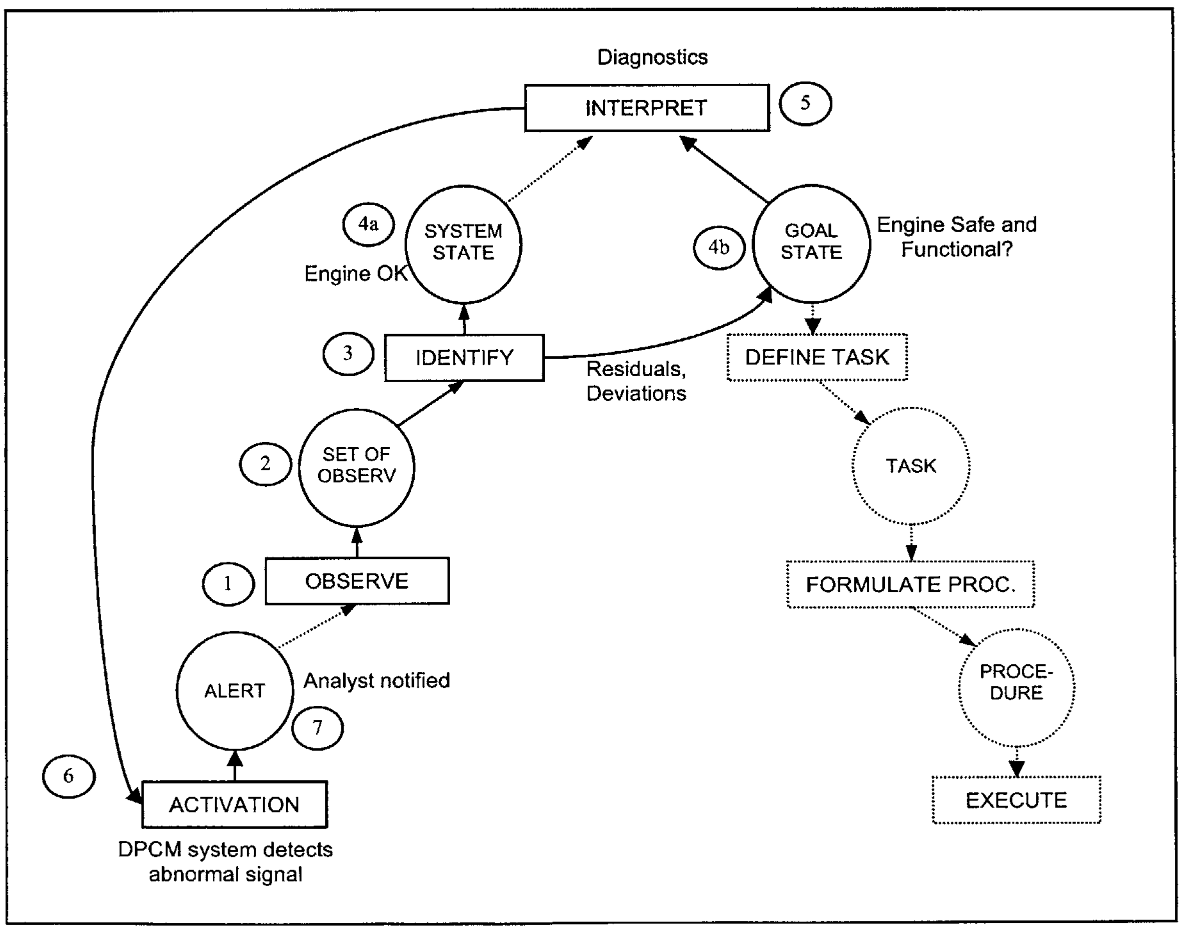


Figure 25: Normal Ground-based Condition Monitoring

In the normal operating mode, the system operates in the following sequence:

1) *Observe:*

Engine data is obtained via ACARS[32] or flight data recorders. The DPCM system monitors the recorded engine parameters.

2) *Set of Observations:*

The engine parameters are recorded, trended and displayed in tables and charts.

3) *Identify:*

DPCM system identifies the state of the engine by looking at the engine trends.

4a) *System State:*

If the engine is trending normally, then no alerts are activated.

4b) *Goal State:*

If the engine shows abnormal trends through unusual deviations or residuals from the expected trends, the DPCM will first determine if the engine fault is safety-critical or non-critical.

5) *Interpret:*

Diagnostic routines are used to determine what faults have occurred based on the trend analysis.

6) *Activation:*

The DPCM system confirms the engine fault and activates its alert routine.

7) *Alert:*

The engine analyst is alerted to the engine fault. Diagnostic and trend analysis information is shown to the analyst.

[32] ACARS: Aircraft communications, addressing and reporting system

Ground-based Engine Fault Management

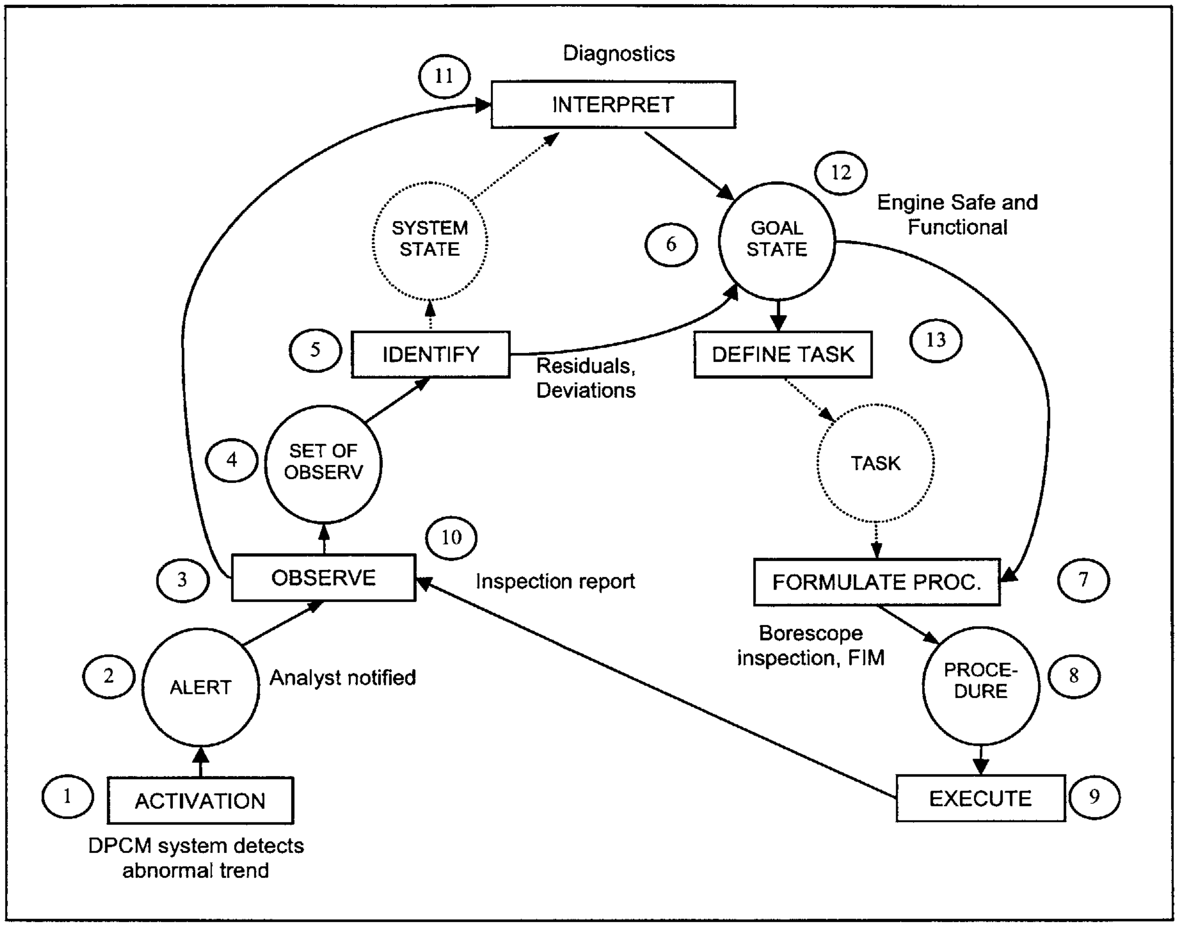


Figure 26: Ground-based Engine Fault Management

Figure 26 shows how a ground-based DPCM system interacts with the engine analyst during the engine fault management operating mode. The control tasks in this mode are:

1) *Activation:*

   The DPCM system detects an abnormal trend.

2) *Alert:*

   The engine analyst is alerted and presented with the engine data.

3) *Observe:*

   Engine trends are displayed as charts or plots for the analyst to observe.

4) *Set of Observations:*

Information about the engine including its past maintenance records are collated with the engine trend data.

5) *Identify:*

Engine analyst will use the DPCM system and his own judgment to identify the engine state.

6) *Goal State:*

Engine's safety level is determined. If this is a safety-critical fault, immediate action is taken to recover the engine and the aircraft. Usually, such a condition monitoring would detect a gradual fault.

7) *Formulate Procedure:*

An inspection is issued to the line mechanics, either according to the fault isolation manual or a customized instruction list. Pilots are also asked to confirm any engine abnormalities experienced in-flight.

8) *Procedure:*

Line mechanics are given the allowable limits and settings to check against during the inspection.

9) *Execute:*

Inspections of suspected modules and components are carried out.

10) *Observe:*

Inspection reports are passed on to the engine analyst and propulsion engineer. The physical damage (if any) is confirmed through these reports.

11) *Interpret:*

The failure modes are determined, based on both the DPCM analyses and the inspections.

12) *Goal State:*

With the failure mode known, the engine's safety and functional levels can be ascertained.

13) *Define Task:*

If the engine is still airworthy, then maintenance is deferred to the next available opportunity. If the engine is unserviceable, then the aircraft has to be grounded and the engine removed off-wing.

Current and Future Engine DPCM systems

Referring to Figure 27, the currently available DPCM systems provide decision support for the left-hand side of the decision ladder. These systems have proven to be successful in early detection of engine faults before failures set in. As our literature review had shown, much effort has been spent on improving the accuracy and reliability of engine fault diagnostics. However, we have found that there is a dire need for work support tools for the other half of the engine fault management process. Issuing inspections and generating workscopes have been largely manual processes. It is time-consuming and tedious to plan a unique inspection and workscope since engines rarely show the same fault symptoms and exact same failure modes. Fault isolation manuals (FIM) were found to be often times too procedural and not flexible. Only veteran mechanics and engineers were able to work around these constraints to successfully isolate and diagnose complex engine malfunctions.

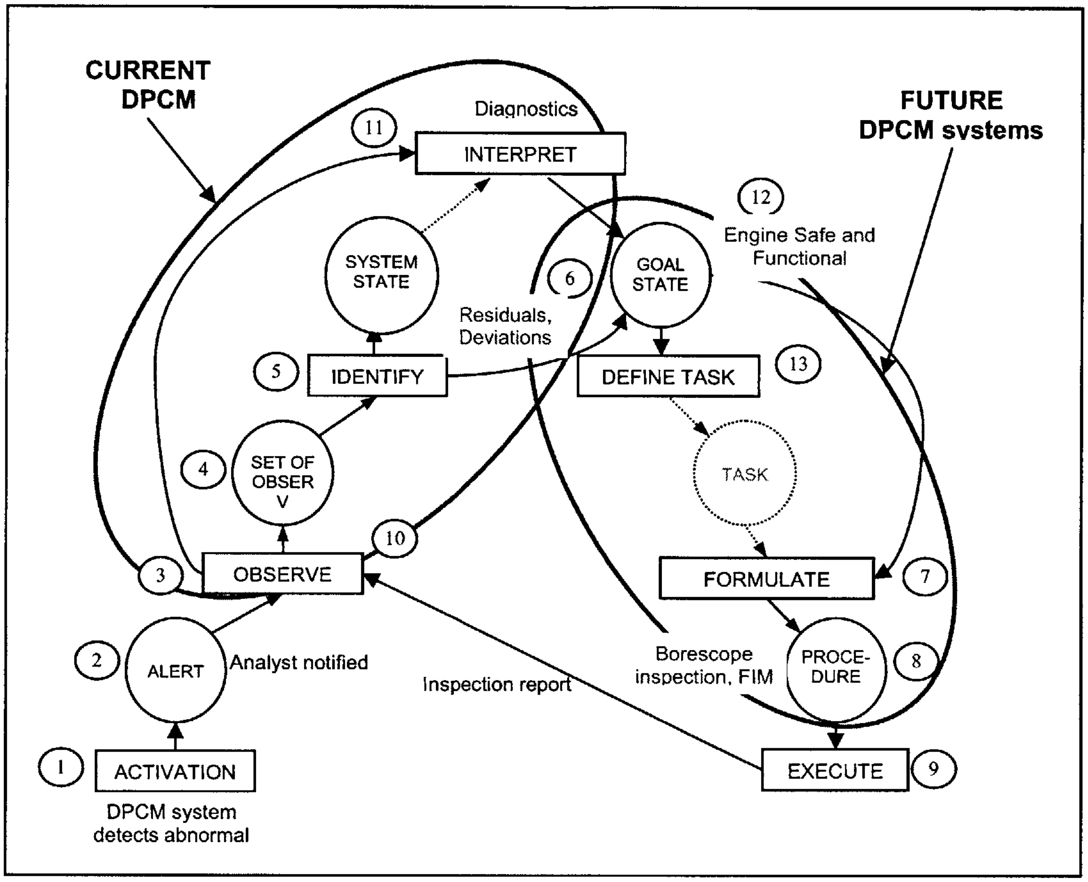


Figure 27: Current vs. Future DPCM systems

Therefore, we propose that future DPCM tools can be expanded to a wider range of functionality. Perhaps case-based reasoning tools, currently being developed for diagnostic systems (Price, 1999), can be extended to prompt more specific inspection and fault isolation procedures for the line mechanic.

7.2.2.3 Engine MRO Process (Airline-side)

Once an engine fault has been detected and diagnosed, a series of management steps has to be undertaken by the engine MRO group to determine when to maintain the engine and what resources are needed for this task. This operating mode is exemplified typically by propulsion engineers and MRO planners within the airline. If engine MRO is out-sourced, then these tasks are performed by the contracted MRO provider. However, the airline still has to be involved in some of the planning tasks, so that it will know when their engines are going to be removed from service and when they are restored to service.

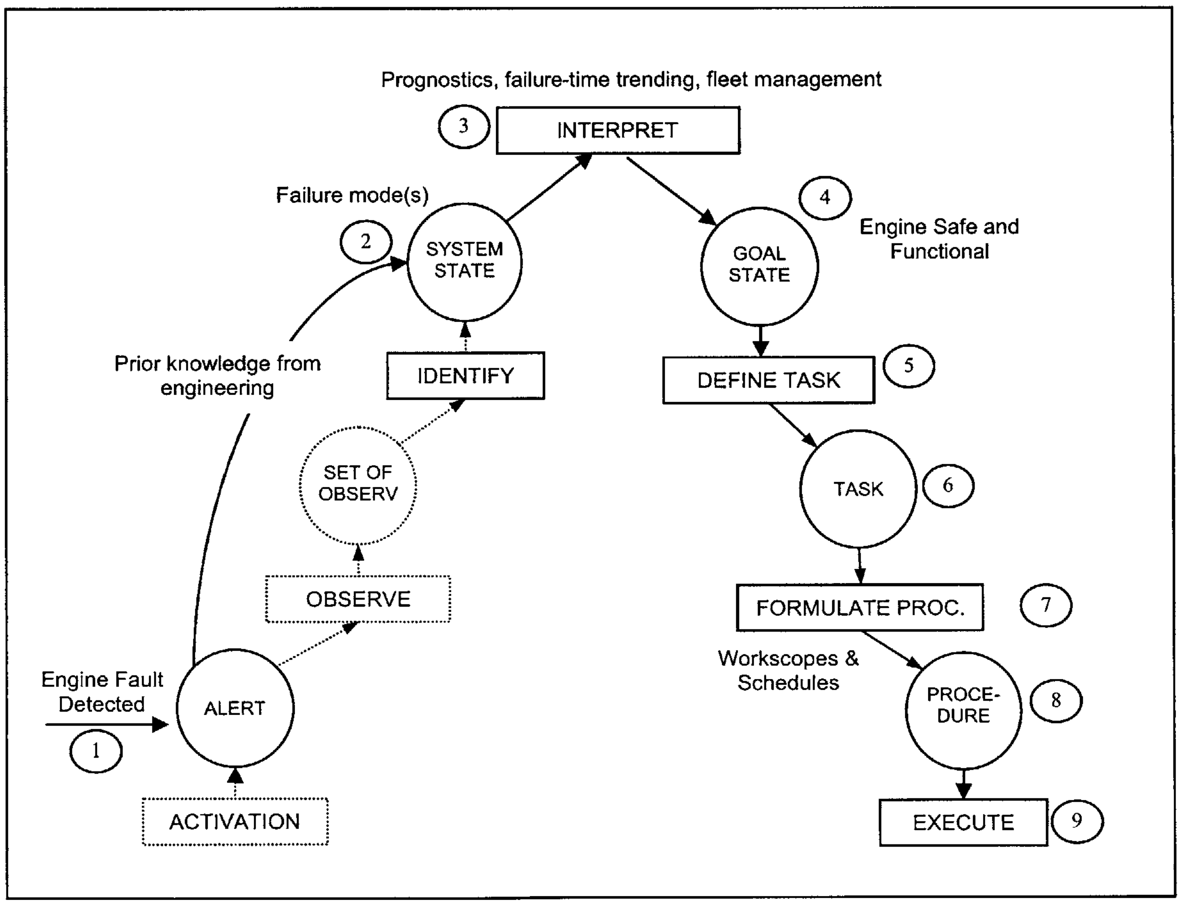


Figure 28: Engine MRO Management

Figure 28 shows the various decision tasks that are made at the management level:

1) *Alert*:

   The MRO planner is informed once it is determined that an engine requires maintenance.

2) *System State:*

   The engine's failure modes and malfunctions are known from prior analysis by the engineering group. Knowing the engine's state would help determine when maintenance is due and what spares and manpower are needed for the maintenance job.

3) *Interpret:*

   Prognostics and failure-time trending is done to determine the optimal maintenance time. The impact on the rest of the engine fleet and overall aircraft operations is also investigated. This becomes very important if this engine fault detected turns out to be a fleet-wide problem, whereby many more engines have to be grounded.

4) *Goal State:*

   The optimal maintenance time is predicted. At the same time, the engine must continue to be safe and functional before that time.

5) *Define Task*:

   The maintenance tasks have to be defined such that the engine is restored to the desired performance levels after maintenance

6) *Task*:

   Several sets of maintenance tasks are identified, either from the maintenance manuals or from engineering analysis.

7) *Formulate Procedure:*

   Workscope is generated and he work schedule is planned.

8) *Procedure:*

   The workscope and schedule is handed over to line maintenance (engine removal) and the engine shop.

9) *Execute:*

The engine is removed off-wing and sent to the engine shop for repair and overhaul.

New decision support tools can be developed to support several resource-intensive tasks in this operating mode. These tasks include failure prognostics and failure trending, fleet management and workscope generation. Most of the airlines that we studied were performing all these tasks manually, while some airlines had developed some semi-computerized tools to aid their engineers in these tasks. However, there remains a large potential for computer-based decision support tools in these steps of the engine MRO process. Strategies for developing some of the tools are discussed in Chapter 7.2.3.

7.2.2.4 Engine MRO Shop Process

When the failed engine is sent to the engine MRO shop, an engine repair and overhaul process has to be put in place to restore the engine back to a serviceable status. Figure 29 shows what such a process looks like[33].

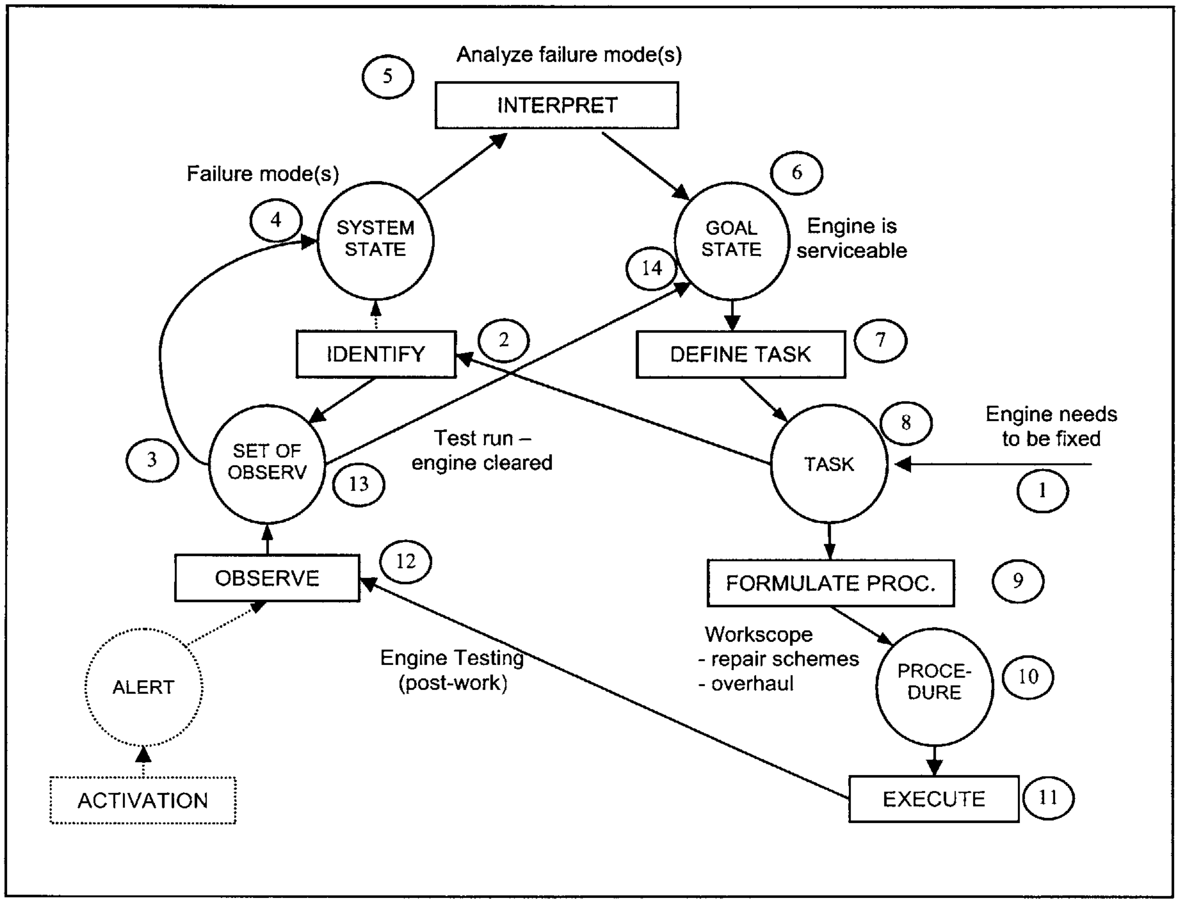


Figure 29: Engine MRO Shop Decision Ladder

The steps in this process are:

1) *Task:*

The shop receives a failed engine that needs to be fixed.

[33] It is interesting to note here that the engine MRO shop is quite similar to a manufacturing plant with a similar process control set-up. However, the engine MRO shop does not produce new products per se and most shops do not have an assembly-line type of shop floor operations.

2) *Identify:*

   Current engine state is identified through a induction process, to confirm the customer's work order.

3) *Set of Observations:*

   Engine records are gathered from the shop's archive or from the customer. These records would include past workscopes performed on the engine and in-service observations by the airline customer.

4) *System State*

   The engine faults and failure modes are known from earlier steps.

5) *Interpret:*

   The failure modes are analyzed and the level of damage is reviewed. Analysis is also needed to ascertain which repair schemes or overhaul processes will be best suited for each engine failure. Workscopes are suggested to the customer.

6) *Goal State:*

   Engine is unserviceable at this point of the process.

7) *Define Task:*

   Based on earlier analysis, the repair and overhaul tasks are defined. The spare parts, manpower and tooling are also defined.

8) *Task:*

   The customer's initial work order is matched against the shop's analysis of the damage. If there is more work to be done than the customer initially thought, then negotiations are conducted to determine how much work has to be done[34].

9) *Formulate Procedure:*

   Once the work order is confirmed, then the actual workscope has to be generated. This workscope will include the various repair schemes, overhaul processes and task allocation among the shop personnel.

[34] Very often, when an engine is disassembled at the shop for a closer inspection, there are more problems than were initially reported. Hence, the airline customer has to decide if it wants to pay for more repair work or if possible, defer the extra work to the next shop visit for that engine.

10) *Procedure:*

Each shop section receives their relevant part of the engine's workscope, including the materials section which procures the required spare parts.

11) *Execute:*

The engine is repaired and overhauled according to the workscope.

12) *Observe:*

After the workscope has been completed, the engine is tested in the test cell.

13) *Set of Observations:*

The engine is certified to be serviceable again based on the test results. If test results were unsatisfactory, then the engine is sent back for new analysis and more re-work.

14) *Goal State:*

The engine has been restored to serviceable status and delivered to the customer.

7.2.3 Strategies Analysis

In this section, we present strategies corresponding to five sets of tasks that were found to be the most resource-intensive among all the operating modes that were discussed in the previous section. We believe that if applied appropriately, computer-based decision support tools can effectively complement the human users in accomplishing these resource-intensive tasks. These tasks are:

1) Engine condition monitoring
2) Engine fault diagnostics
3) Engine fault prognostics
4) Workscope generation
5) Engine MRO planning

Information flow maps are used to represent how these tasks can be accomplished. We also discuss role allocations between automation and human users for each strategy.

7.2.3.1 Engine Condition Monitoring

As described earlier in chapter five, engine condition monitoring (ECM) systems is the predominant method for maintaining engines nowadays. Though the transmission and data processing methods may differ, most currently fielded ECM systems employ a similar information flow path which can be represented by Figure 30 below (Brochu, 2002, & Barwell, 1988).

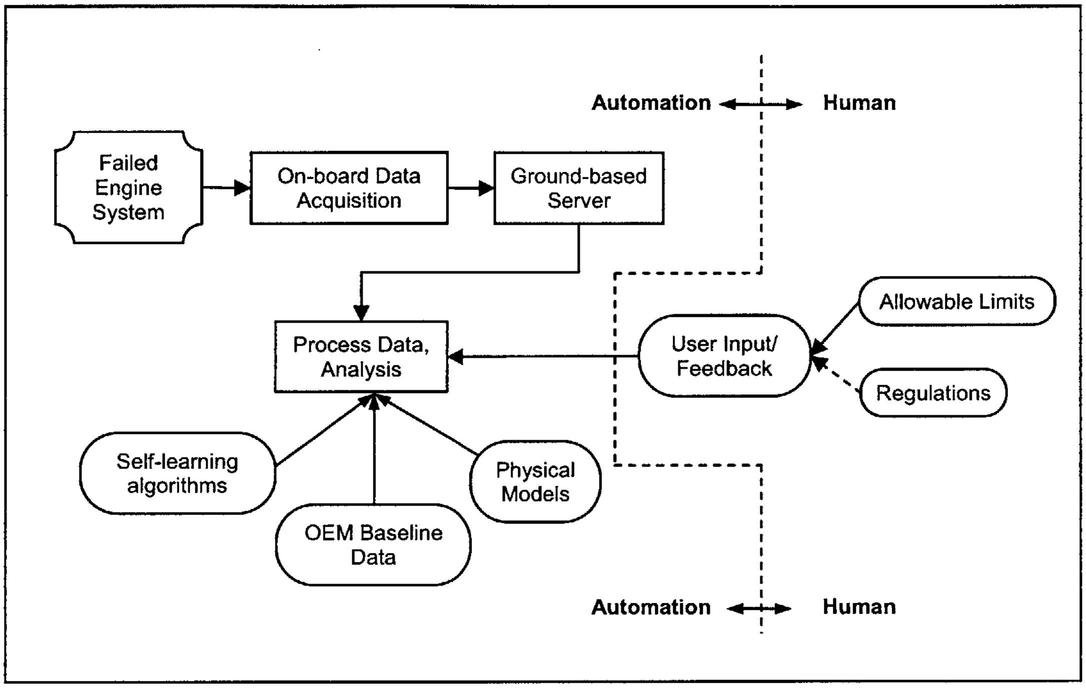


Figure 30: Condition Monitoring

There is an on-board data acquisition system (e.g. ACMS[35]) that records the engine parameters. The engine data is transmitted to a ground-based server either through ACARS, flight data recorders or handwritten log books by the flight engineer. The ground-based server processes and analyzes the engine data, using information from OEM baseline data and techniques like physics-based models and self-learning algorithms. These analysis methods have proven to be quite reliable.

The weak link in this strategy lies in the user input/feedback to the ECM system. Current ECM systems require a human user to set the allowable limits and threshold settings for each engine parameter that is being monitored. These limits or thresholds directly determine the level of alerting as the ECM system only alerts the operator when the limits or thresholds are exceeded. It was found that most users set these limits and settings in an arbitrary manner, with little engineering basis other than their experience of supporting a particular engine type. Very often, these inputs are determined according to the airline's maintenance philosophy. For example, a conservative operator would set

[35] ACMS: Aircraft condition monitoring system

lower thresholds to catch more potential faults, but this implies that more engines have to be scrutinized. On the other hand, a less conservative operator would want to maximize the engine's on-wing time so their threshold range is larger. With the lack of guidance on what actual settings to use, a wide range of fault alerts are possible. This complicates engine maintenance since theoretically, engine faults would be addressed at varying alert levels. Standardized maintenance plans recommended by the OEM would thus be ineffective, and more effort has to be spent on customized workscopes for each engine operator.

To address this problem of arbitrary alerting levels, it is proposed that results from the fault prognostics software can suggest what limits and threshold settings to use. Based on fleet trends and operator experience, accurate prognostics can adjust the alert levels such that engine faults can be picked up at a more optimal time.

Regulations indirectly affect these user inputs. As some engine types experience certain perennial problems (e.g. high vibrations), regulatory authorities may issue advisory circulars (AC) or airworthiness directives (AD) which call for closer monitoring of certain engine components and parameters. For example, if a particular engine type faced perennial high vibrations, the vibration level thresholds would be set to a tighter band to catch more impending vibration-related failures. Flight safety also plays a major role through regulations. When there are any aircraft incidents related to engine failure, the public's demand for the highest levels of flight safety implies that airline operators be more conservative after such incidents. Regulatory authorities typically issue ADs to this effect. Because of regulatory factors, future ECM systems should still have the facility for a human user to change these limits and threshold settings.

7.2.3.2 Diagnostics

Current engine DPCM systems are moving towards automating the principle of pattern-recognition or "fingerprinting" in diagnosing engine faults and failure modes (Tumer & Bajwa, 1999b). This method relies on a pre-determined library of patterns which the DPCM software recognizes. When the engine parameters match a certain known pattern, the software would infer a set of symptoms and present a diagnosis to the human user.

In the pattern-recognition category of strategies, the diagnostic or monitoring system first has to be given an input of what the patterns of known failure modes (see Figure 31). This is usually done during the software development phase, where data from the engine's testing phase can be used to simulate known faults and the corresponding failure signals. Ideally, each pattern is then labeled in terms of the event, system state, cause and what the follow-up tasks should be as shown in Figure 31.

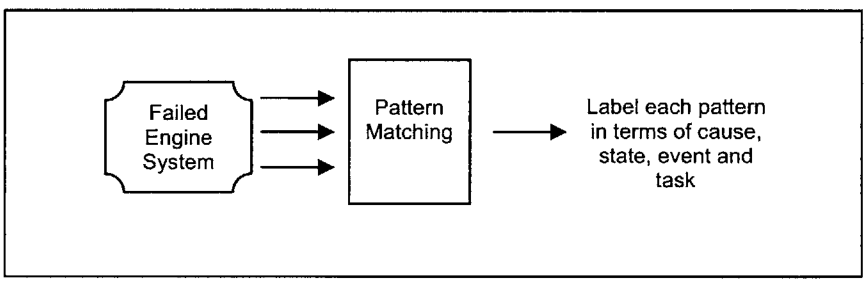


Figure 31: Pattern Recognition

DPCM systems currently in the market have been quite successful at capturing and identifying these patterns which are based on trend analysis of engine parameters. The built-in algorithms are programmed to compare ideal trends against actual trends and determine the residuals or deviations (see chapter 5.2.1). Some of these systems develop the pattern library through a self-learning algorithm (e.g. neural networks), while others use physics-based models of the engine (Tumer & Bajwa, 1999b). However, current DPCM systems have not been as adept in capturing the follow-up tasks associated with each failure pattern. These tasks are the end objectives for the engineers and analysts in their diagnostic process as they need to tell the mechanics how to physically verify the fault (through inspections or tests) and later how to fix the engine. Having a database that matches both the fault patterns and the appropriate follow-up tasks will be an invaluable asset in reducing the time spent on diagnostics and subsequently workscope generation.

Decision Table

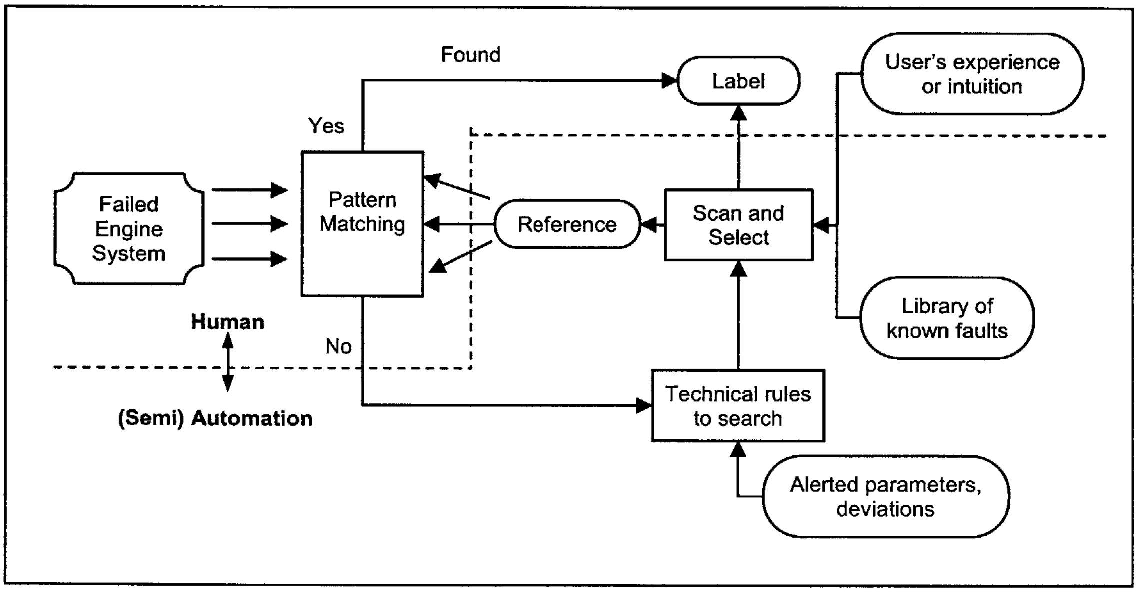


Figure 32: Pattern-matching using a decision table

Older generation condition monitoring systems use a decision table strategy to detect and identify engine faults. These systems have a semi-automated component, due to the older computing technology. As such, these systems have a much larger human operator involvement than newer DPCM systems.

If the failed engine pattern was not immediately recognized, the system would search a table of known faults using a set of technical rules. These rules are pre-determined by the human operator in the form of signal deviation (residual) thresholds or the alerting of certain key engine parameters which can narrow down the troubleshooting scope. For instance, a decrease in oil pressure would very likely be caused by an oil system malfunction. Some decision table search processes are automated through an electronic fault library. However, it was found that most engine analysts, especially the veteran experts, still relied heavily on their own experience or intuition to pinpoint the right fault patterns. This is because different operating environments for each engine results in unique deterioration rates and engine problems. For instance, engines that fly transoceanic are more suspect to salt water corrosion while engines that fly across deserts often experience abrasion and clogging by sand grains. Moreover, the technical complexity and tight manufacturing tolerances for aircraft engines gives rise to the notion that "no two engines are built the same". So in reality, the "textbook" patterns in the fault library are indicative of potential fault patterns but they are not definitive for in-service engines. Veteran analysts who have worked many years with the same engine fleet would know the "chronic" problems of each engine.

The actual pattern-matching is done manually. In the case of trend analysis, past experience for each engine type has evolved several patterns of trends and diagnosis (Treager, 1996). Novice analysts are trained to match the trends with "textbook answers", while veteran analysts use their vast experience to complement the "textbook" and they often can diagnose the fault much faster than the novices.

The disadvantage of such a strategy was that if the engine trends were unusual and never been encountered before, then the analyst would not be able to identify the fault based on this strategy alone. He/she would have to resort to physical inspections to offer more clues on the engine failure.

It is worth mentioning here that though the pattern-matching task is becoming more automated, it is our opinion that the human user should be able to confirm the pattern-matching once the DPCM system has concluded its analysis. In other words, a fault diagnostic system based on such an approach should not eliminate the human user from the decision process. As engine fault diagnostics is directly related to engine airworthiness and aircraft safety, it would be imperative that the human user has the final authority on the engine fault diagnosis.

Physics-based DPCM systems

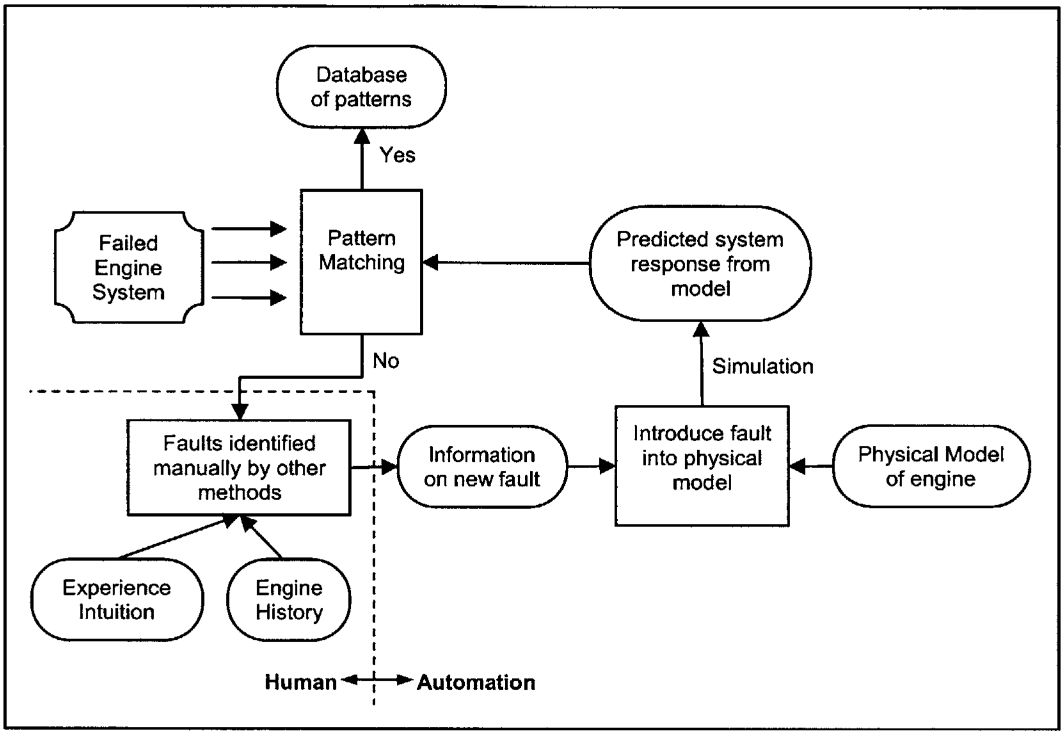


Figure 33: Pattern-matching using physics-based engine models

Some DPCM systems use a physics-based approach to model the engine's response. This approach is represented by Figure 33 above.

Signals of engine parameters are fed to the DPCM system. If the signals are different from the expected value, the engine is classified as failed. The DPCM system tries to match the signal pattern. If the pattern can be matched (Yes), then the DPCM system will look at the database of patterns to identify the fault/failure mode and alert the analyst appropriately (this could be an automated search or similar to a decision table approach).

If the pattern cannot find an immediate match (No), the system will classify the set of signals as a new fault pattern. Information on a new fault can be obtained through at least two sources. The fault could be identified through manual diagnostic methods and the system can be updated given the known fault. The human user can also guess a failure mode based his/her experience or perhaps from a chronic engine history. The fault or failure mode is then simulated in a physical model of the engine and the engine's response is predicted. This predicted response is matched with the original fault pattern. If the patterns match, then the initial guess was correct. As these simulation models become more robust, an iterative search could be performed. Each predicted response and the associated diagnostic characteristics are stored in the database for future pattern recognition. Such an information flow map depicts how physics-based DPCM systems can learn from the experience and data of in-service engines.

7.2.3.3 Prognostics

There are two forms of fault prognostics which can be aided by computer-based support tools. These prognostic methods are used by predictive maintenance tools that are beginning to emerge in the engine MRO industry today.

Short-term Prognostics

The first type of fault prognostics is where the engine system had already failed and the failure mode has been correctly diagnosed. The objective here is to predict the "resistance to failure-time" distribution of this failure mode, also known as a P-F curve (Moubray, 1997). This curve indicates how the engine would deteriorate over time under a particular failure mode between the initial detection point (P) and when the engine has completely failed (F) and is not airworthy or unserviceable. Knowing this temporal distribution will give the maintenance engineer a good indication of how much time the engine can still be operated before it has to be removed. In the meantime, manpower and spares can be arranged and the engine can be removed off-wing at a more optimal time.

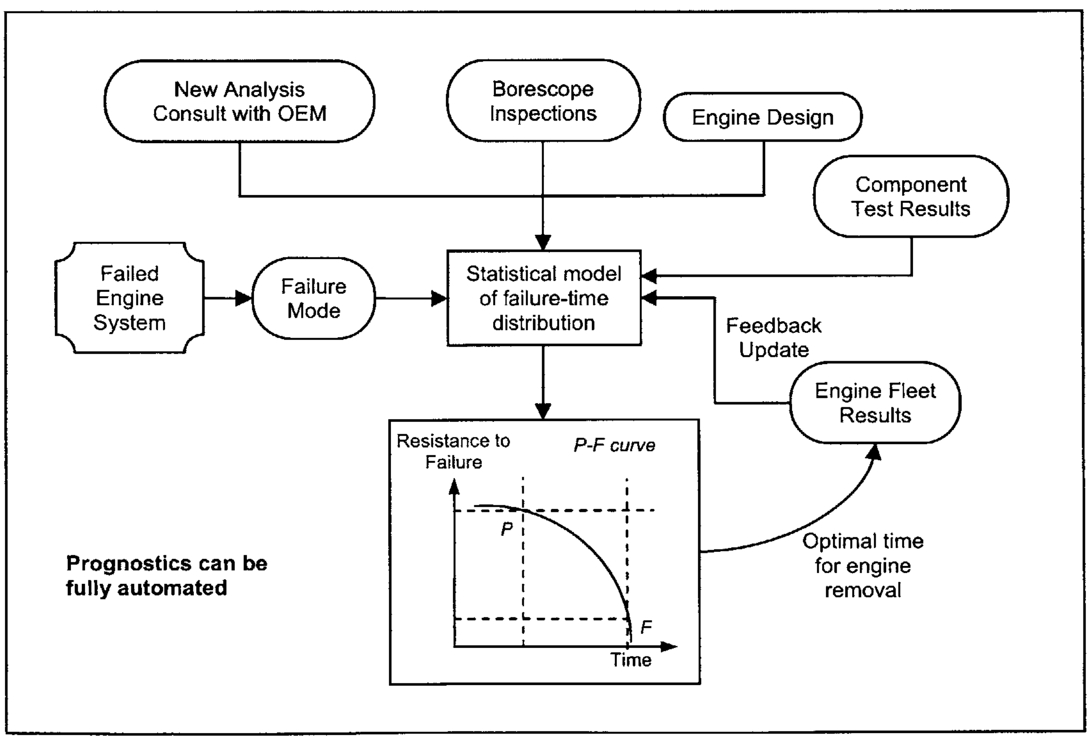


Figure 34: Prognostics for a Failed Engine System

Figure 34 above shows how such a prognostic system can be developed. This approach first assumes that the failure mode has already been diagnosed by the diagnostic system. The engine's structural and aerothermal design and models of the engine's operating envelope are built into the standard prognostic algorithm. Results from component failure tests are also needed (e.g. bearing and pump failures). Physical status of the failed components can be determined from borescope inspections. Finally, as over the course of service, each engine has been repaired and overhauled different, individual engine configurations and maintenance history also has to be taken into account. A prognostic algorithm consolidates all this information to produce a statistical model of the P-F curve for the particular failure mode. Hence the maintenance engineer can use this P-F curve to determine the optimal engine removal time. Actual results after maintenance has been carried can later be used to update the statistical model and improve the accuracy of future prognosis.

It is envisioned that such a fault prognostic system can be fully automated, given the appropriate data transfer interfaces between the diagnostics, engine configuration and other information sources.

Long-term Prognostics

The second type of fault prognostics is a long-term strategy, where the engine MRO organization wants to predict the occurrence of future engine faults. An accurate fault prognosis can help maintenance planners plan their resources more effectively by pre-positioning manpower and equipment and having the appropriate spare parts in the inventory at the right time.

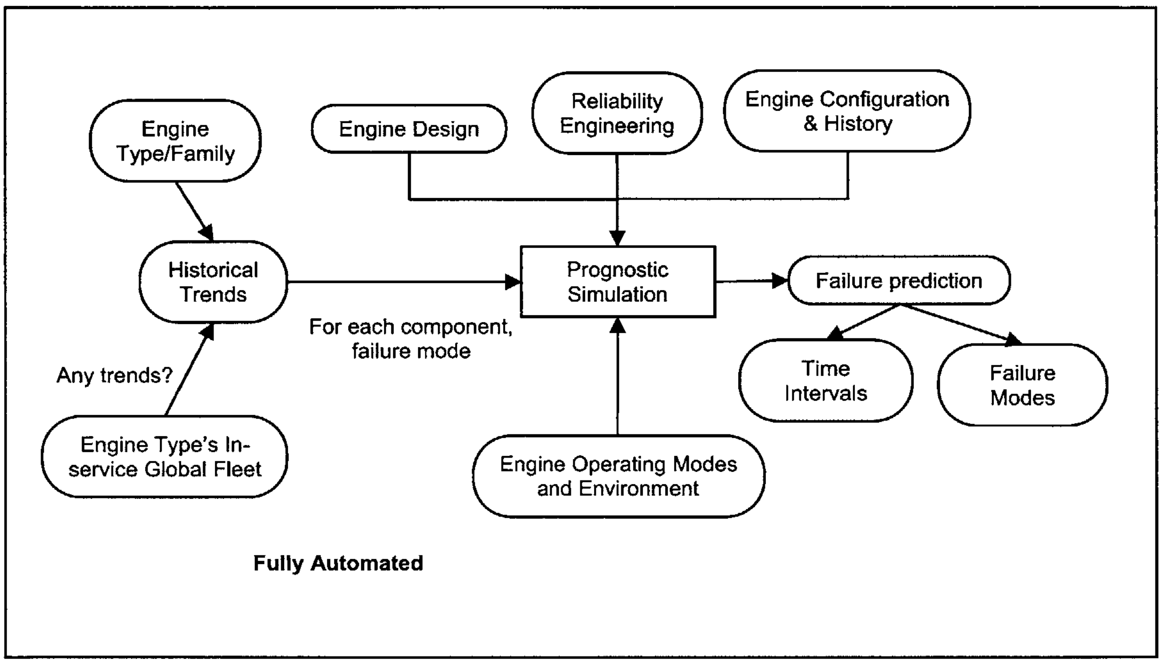


Figure 35: Engine Fault Prognostics

In the approach shown in Figure 35, the objective is to predict future engine faults with an estimated time interval (e.g. MTBF[36]) and the possible failure modes. Several information sources are available for this prognostic simulation. Historical trends have been known to be a reliable indicator of failure occurrence, especially for engines that have extensive in-service records (e.g. JT8D). Such historical data can be derived from both the particular engine's global fleet experience or the engine's parent family or

[36] MTBF: Mean time between failures

derived baseline engine[37]. The actual engine design, together with the engine's operating modes, is used to obtain the structural and thermal loads that could cause mechanical or thermal failure. Data from reliability engineering methods can also be used. A prognostic algorithm can then simulate the engine's deterioration over time and predict at what time the engine will fail and according to which failure mode.

Given the complexity and magnitude of data inputs, this fault prognostics task can be fully automated. The human user can manually input the operating modes, based on the flight routes and extreme environmental conditions (e.g. flying over deserts or trans-oceanic routes). The engine's configuration and the engine type's historical trends can be obtained from an electronic database of engine condition monitoring records. Eventually, such a prognostic algorithm will be able to provide time intervals and failure modes for each individual engine. This type of fault prognostics has not been used yet in the engine MRO industry.

[37] Very few new engines are being developed from scratch these days as the latest engines are typically derived from older designs (e.g. Trent series from RB-211, PW4000 series from JT9D). Engines of the same family tend to show similar operating trends.

7.2.3.4 Workscope Generation

Workscope generation is another task that has to be accomplished each time maintenance has to be performed. Because of the multitude and complexity of maintenance tasks, and that in reality no two engines behave the same way, the workscope engineer often faces a tough challenge to devise the appropriate workscope for each engine.

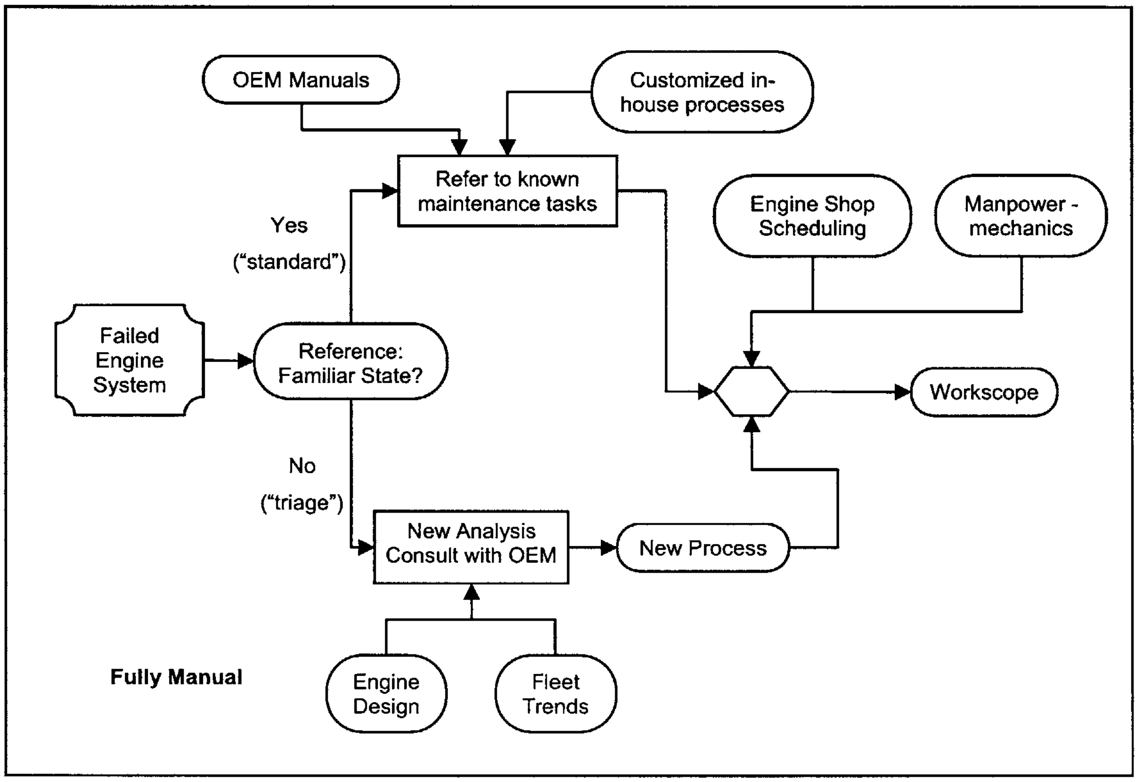


Figure 36: Workscope Generation

Figure 36 shows how workscope generation is currently done manually. If the engine failure is a familiar (known) state, then the workscope engineer will use a standard workscope that he/she can reference from OEM manuals and customized in-house processes.

If the engine failure is unfamiliar, then it could be due to a new fault or a new combination of several symptoms that had not been seen before. "Triage" has to be performed on this engine to determine which workscopes are appropriate. For a new fault, the maintenance engineers would first consult with the OEM to determine if this is a new problem to the engine type. The OEM, by overseeing the global engine fleet, is able to provide feedback from other operators who may have encountered a similar engine failure. Engineering analysis is carried out to isolate the faulty components and to devise a new repair or overhaul process. In the latter case, the workscope engineer would have to combine several smaller workscopes, while ensuring that there are no conflicts among all the tasks.

Once the maintenance tasks are identified, the workscope engineer would then need to check what manpower is available (who to assign the work to) and what slots are available in the engine shop (when the engine can be worked on). The manpower refers to either line maintenance mechanics that have to perform an engine change or engine shop mechanics that have to do the repair and overhaul work. These two factors affect the estimated downtime of the engine and the overall duration of the workscope.

Our study showed that workscope engineers were actually veteran engineers or shop floor mechanics that have the experience to determine what workscopes are suitable. However, workscope generation continues to be a time-consuming task even for these experts. Moreover, the workscope often changes and grows as more faulty components are discovered after the engine has been disassembled. These workscope changes take up even more time – time which is somewhat non-productive and costly as no work can be done on the engine until the workscope has been approved and issued to the mechanics.

Many workscope engineers agreed that a computer-based tool to support workscope generation would greatly aid their work by saving time and improving efficiency. This tool can be in the form of an electronic library of job tasks found in the engine maintenance manual (EMM) or customized in-house processes, whereby the engineer can mix and match the various tasks through a graphical user interface. A more advanced version of such a tool may be able to read the failure mode and automatically narrow down the applicable tasks, which would vastly reduce the time required. We believe a workscope generation tool can be rapidly developed using commercial-off-the-shelf technology, since this requires not very much more than database algorithms.

7.2.3.5 Engine MRO Management

Two modes of engine MRO planning were identified in our study: short-term and long-term. Short-term planning refers to the situation where an engine has already failed and a maintenance plan has to be put into action immediately. Long-term planning is for developing engine maintenance plans with the goal of optimizing maintenance intervals and having the appropriate resources (both manpower and material) in the right amounts at the right time and place.

Short-term Planning

The next strategy in Figure 37 describes how the engine MRO organization manages an engine failure at the system level. Suppose an engine has failed. Through earlier routines, the optimal time for maintenance, failure analysis and the workscope have all been determined. If this is a safety-critical or single-mission failure, the aircraft has to either make an emergency landing or be grounded at its next destination. Maintenance and operations controllers have to activate a contingency plan for this AOG situation, which would include sending the appropriate spare parts, tools, manpower and possibly a spare engine to the aircraft's location.

The difficulty lies in determining what these appropriate resources are, which depends heavily on the extent to which the engine failure is known. Hence, if the maintenance planners can have the three sets of information (time, failure analysis and workscope) readily available through an integrated decision support tool, they can more effectively put in place the contingency plan and minimize the aircraft and engine downtime.

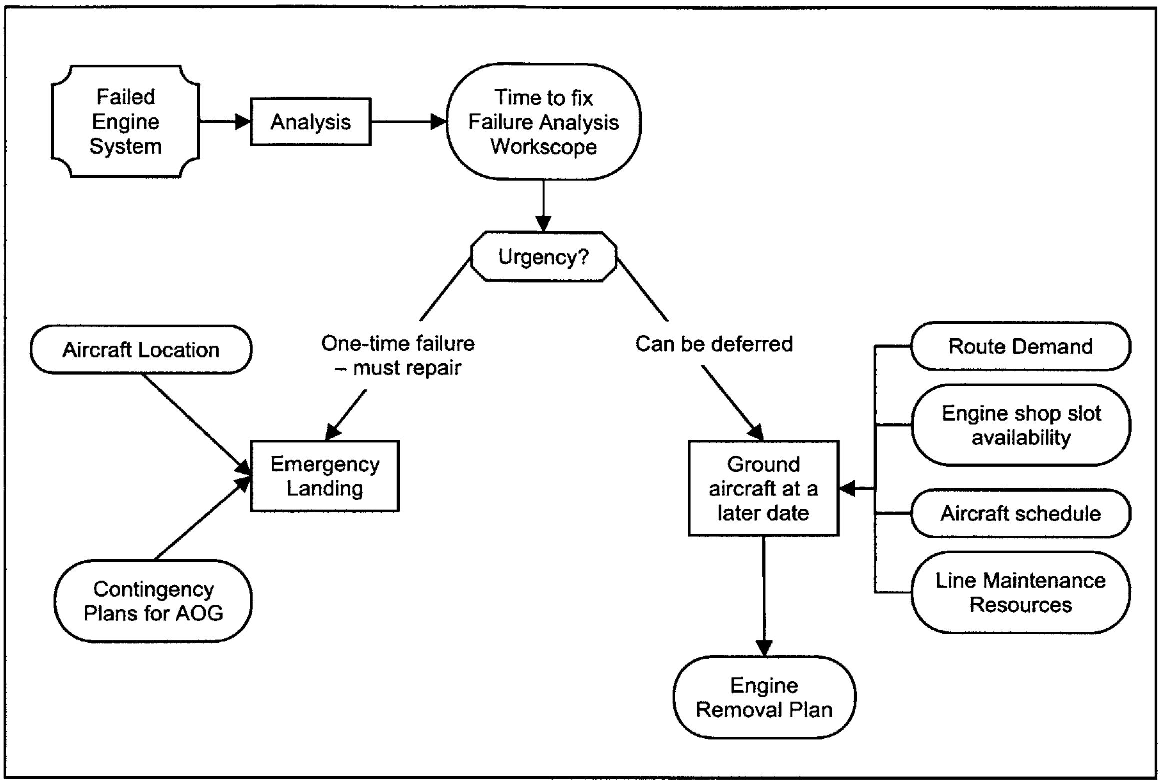


Figure 37: Short-term Engine Maintenance Management

If the engine maintenance can be deferred, the maintenance planner then has to coordinate an engine removal plan. The maintenance planner's goal is to maximize the on-wing time and only remove the engine at the latest possible moment. Since the engine contributes revenue when it is flying, engine downtime causes a revenue loss for the airline. Besides the "optimal time" predicted by fault prognostics (if available), four other factors affect the engine removal time. If the routes flown by the affected aircraft are facing high demand, then from a commercial standpoint, it is obviously not economical to ground the aircraft for an engine change. The aircraft's schedule also has to be considered as the same aircraft may be flying several routes each day and not return to a maintenance base for quite some time. The engine also should be removed only at a line station or maintenance base that has the appropriate mechanics and ground equipment. Finally, the maintenance planner has to check whether there is an open slot at the engine shop. If the engine is removed, but the engine shop cannot work on it, then unnecessary downtime is incurred.

Therefore, coordinating an engine removal plan involves balancing these various constraints. A decision support tool for the maintenance planner in such situations would be most effective if it can present to the planner what all these constraints through an informative user interface. Other airline departments like Scheduling and Line Maintenance can link their systems to that of the planner's, providing real-time access of the planner to aircraft schedules and line maintenance resources. In the case of deferred maintenance, this decision support tool can be used to optimize these various constraints, to aid the creation of an engine removal plan.

This tool can be extended to support overall aircraft maintenance, not just for the engines. Such a short-term maintenance planning tool can be integrated with an airline's main operational control system that was proposed by Mathaisel (1996), which will allow smooth coordination each time an aircraft experiences a maintenance problem.

Long-term Planning

For long-term planning, the goal of this strategy is to develop individual engine maintenance plans (EMP), instead of relying on a standard EMP as recommended in the OEM's Maintenance Planning Guide (MPG). Because of the varying operational environments and internal configuration of engines, each engine would have a different deterioration rate over time. Thus, if EMPs can be customized for each engine, then these engines can be maintained at the right time with the right MRO process. This will also yield financial benefits since unnecessary maintenance work and engine downtime can be avoided.

Figure 38 shows how long-term maintenance planning can be achieved.

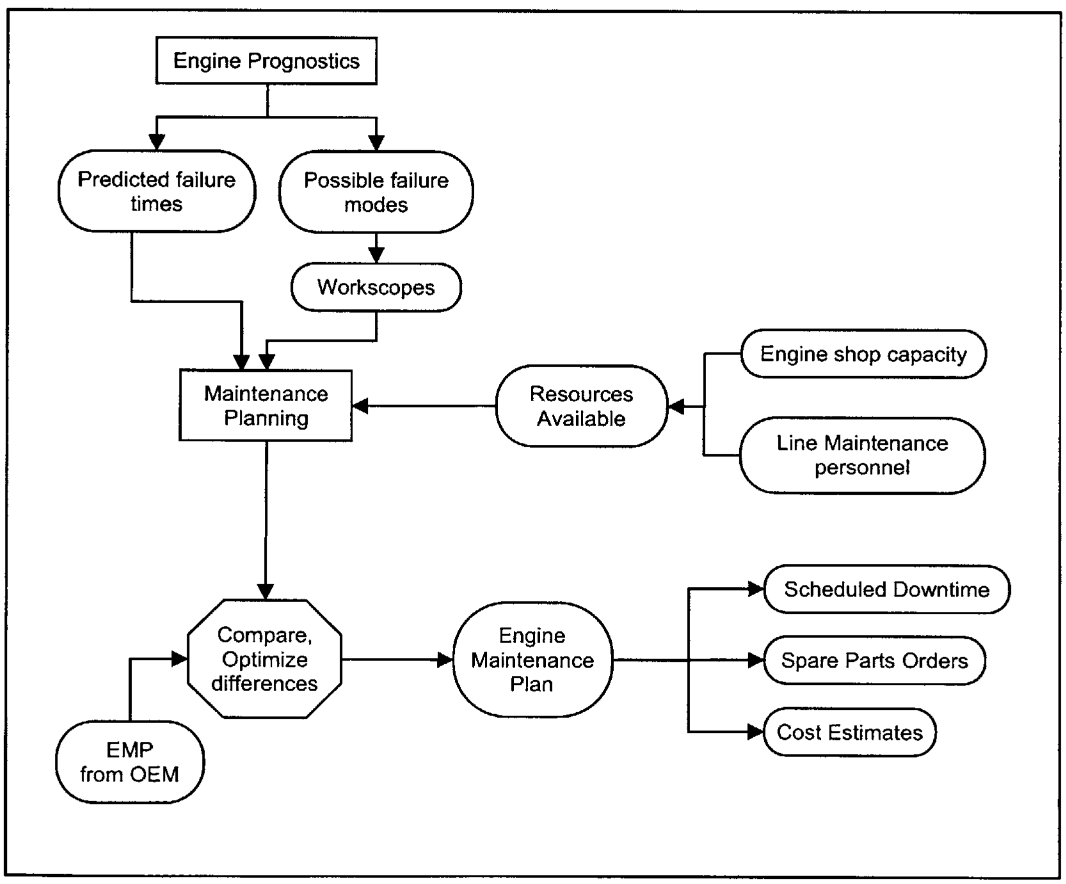


Figure 38: Long-term Engine Maintenance Management

For each individual engine, the long-term prognostics system would provide predicted failure times and the possible failure modes. Workscopes can be generated once the failure modes are known. Manpower and shop resources also have to be considered in the planning process. The properly-skilled line maintenance personnel and their ground equipment have to be available at the correct locations to perform any engine maintenance at the flight line or at a maintenance base. Capacity of the engine shop would limit when an engine can actually be repaired or overhauled. An initial engine maintenance plan (EMP) is created based on these inputs.

The OEMs, through their own analyses, develop standardized engine maintenance plans for each engine type, with the recommended maintenance intervals and workscopes. These general guidelines cover a broad spectrum of possible engine failures. The initial EMP is compared against this standard EMP, and the differences are optimized to determine the most suitable combination of maintenance intervals and workscopes.

The final engine maintenance plan provides maintenance planners with useful estimates on MRO costs, spare parts required and the predicted downtime for each engine. Cost estimates are important for the MRO budget and overall business model, and these estimates can be relayed to the MRO manager and to the airline's finance department for their budget planning. The predicted spare parts orders are vital to effective inventory planning, which can be aided by supply chain management tools. Airlines and engine shops do not want to keep unnecessary inventory, yet would prefer to overstock sometimes to avoid a long wait on a missing part. So if the material planners have a good idea of what spares they would need, then the inventory can be stocked with the correct spares in the required quantities. Lastly, the predicted engine downtime helps the flight operations schedulers re-route their aircraft so that there is minimal disruptions to the flight schedules due to engine maintenance.

A long-term maintenance planning tool can be developed from the information flow map shown in Figure 38. This tool can be an integrator of other tools that support individual functions like prognostics and manpower planning. The various inputs and outputs for this tool can be derived from Figure 38. Engine MRO managers and planners can use this tool to better plan and organize their MRO operations in the long-term. This maintenance planning tool can act as the central decision support tool for the whole engine MRO system, with the various supporting actors of the system like the MRO shop, materials planning and operational elements (line maintenance, flight operations etc.) all being connected to the airline's maintenance planning system.

This strategy attempts to advance engine MRO from on-condition maintenance to a state of predictive maintenance, relying heavily on the long-term prognostics system described earlier. Though some airlines are shifting towards a total on-condition maintenance philosophy, we believe that predictive maintenance, such as in the form described, will be more cost-effective for the airline in the long run. If the prognostics and maintenance plans can be shown to be accurate enough, then the certainty of predicted engine maintenance will lead to a more certain airline business model. After all, if maintenance costs can be predicted, then the airline has a good picture of what its financial standing is like.

Chapter 8: Conclusions and Recommendations

8.1 Summary of Research Findings

The commercial aviation MRO system is indeed a very complex one, with multi-tiered interactions and a vast network of inter-related customers and suppliers. The burgeoning of MRO alliances further complicates the system. Because of the many actors involved, it is a challenging task to accurately map the various interactions that take place. Furthermore, these interactions take the form of actual products, information exchange, value exchange and even exchanges of manpower (in the case of alliances). Fully tracing the impacts that a change in a maintenance practice (e.g. predictive maintenance) would have on the overall system can be quite complicated. However, this thesis has attempted to break down the complexity of the MRO system by focusing on one of the most crucial aspects of the system, which is aircraft engine MRO. By understanding the engine MRO system, the same sustainment principles and decision support concepts can be extended to the sustainment of other aircraft systems and to the overall aviation MRO system as a whole. The methodology and framework presented in this thesis for the design of decision support tools are applicable to other aircraft systems.

This thesis has illustrated how a novel cognitive engineering approach can be used to create a framework that more fully captures the decision support needs of the engine MRO organizations. A three-tier hierarchy of the MRO system has been identified and the different cognitive needs of actors in each tier have been discussed. The appropriate decision support tools for each set of cognitive needs were also outlined using the Cognitive Work Analysis framework in the form of abstraction-decomposition spaces, decision ladders and information flow maps. These recommendations can be used as a framework for the design of future decision support tools for engine MRO. There are however several challenges that have to be overcome in order for decision support tools to realize their full potential. These challenges include issues over certification and regulations of decision support tools, as all systems and processes in the commercial aviation industry are highly regulated. More advanced algorithms for diagnostics, prognostics and asset management also have to be developed, and the right implementation of information technology is needed for the right user.

Appropriately implemented decision support tools aid their users in the decision-making process of MRO and this is where their benefits can be most greatly realized. Key maintenance decisions like when to remove an engine off-wing, what repairs to initiate and what inventory of spare parts to stock are very costly propositions for the MRO organization. By properly integrating appropriate decision support tools into their maintenance process, maintenance personnel are able to make more accurate and informed decisions like the ones above. The key factor is in how the information from the decision support tools is brought forth to the user and how useful this information is presented. Furthermore, if the experience of veteran maintenance staff can be incorporated into the decision support tools, then younger less experienced staff will be able to learn from this knowledge base and raise their own effectiveness to the organization. Hence, the level of cognitive support that such decision support tools provide defines their effectiveness and value to the MRO industry and sustainment of the commercial aviation system.

8.2 Recommendations for Future Research

As the MRO system involves numerous actors and a multitude of decision-making processes, this thesis alone is not able to capture the many other interactions and processes that have not been mentioned. Future researchers can expand this model of the engine MRO system to the larger overall commercial aviation MRO system. This can be done by performing field studies and using a similar cognitive engineering approach (as presented in this thesis) to other aircraft systems like airframes and avionics.

Future work is also suggested in analyzing the socio-organizational aspects of the engine MRO system, and in exploring the worker competencies required to operate future decision support tools. An ecological interface design (EID) for this new decision support tools can also be used to develop informative and useful interfaces between the tools and their users. These two research topics would complete the cognitive work analysis begun by this thesis. Once this is completed, the potential decision support tools will be fully outlined with their inputs and outputs identified through information flow maps and their interfaces prescribed through EID. Software developers can then look into the rapid and accurate prototyping and maintenance of these tools.

As potential decision support tools have already been identified and their benefits have been qualitatively discussed, it would be a natural extension for the engine MRO industry to quantify how decision support tools can improve engine MRO efficiency and reduce engine MRO costs. Industry partners consisting of airlines, MRO shops and OEMs can work together with researchers to validate the effectiveness of new decision support tools and to also offer feedback on the implementation and usage of these tools.

The work presented in this thesis aims to help researchers generate a knowledge base to improve the design of sustainment tools in general. A similar methodology can be applied to the development of sustainment tools for other complex sociotechnical systems like rail transportation and hospitals.

8.3 Conclusions

Sustainment of commercial aircraft gas turbine engines in the form of MRO is a primary activity in the life-cycle of a modern commercial aircraft system. Reducing the life-cycle cost through more cost-effective sustainment has always been a prime objective for airlines. This thesis has illustrated the importance of decision support tools in improving the cost-effectiveness of engine MRO. Understanding the MRO landscape and the actors involved is the most critical factor for effective decision support tools. It can be concluded with strong evidence in recent years that the shift towards predictive maintenance using more effective and appropriately developed decision support tools has brought about improved efficiencies and lower costs for all parties involved.

In conclusion, our findings have shown that there is a significant level of sustainment engineering awareness in the aviation MRO industry. No longer do OEMs "just throw the product over the wall", as many veteran mechanics often lament. OEMs now place a lot of emphasis on maintainability and sustaining performance during the design phase of their products. Furthermore, the OEMs are dedicated to providing a high level of service support during product's lifecycle. Though the invasion of the OEMs into the MRO market would pose stiff challenges to the independent and airline MRO shops, the author believes that this increase in importance of sustainment bodes well for the aviation industry on the whole. If sustainment concepts are put in place right from the drawing boards of the next generation of commercial aircraft, engines and other sub-systems, then all the actors in the aviation MRO system will benefit in the long term.

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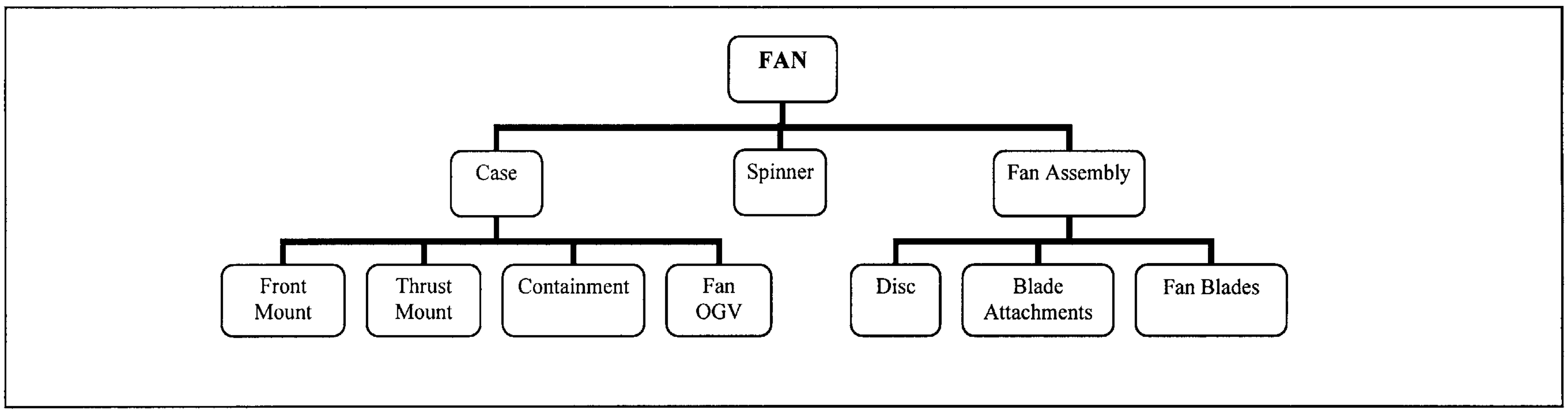
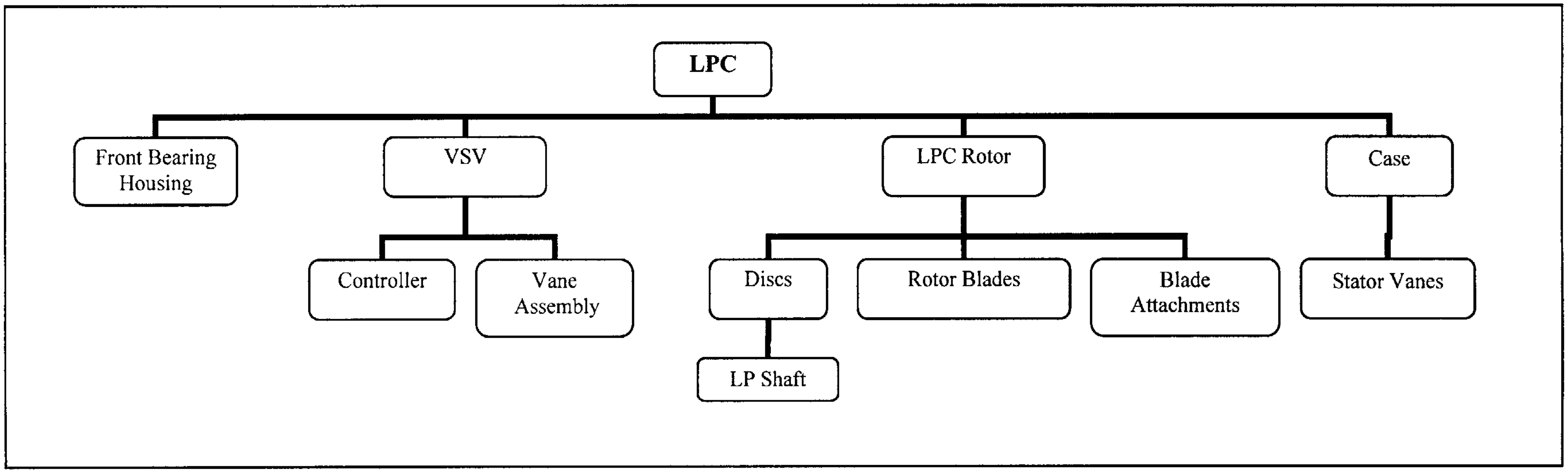
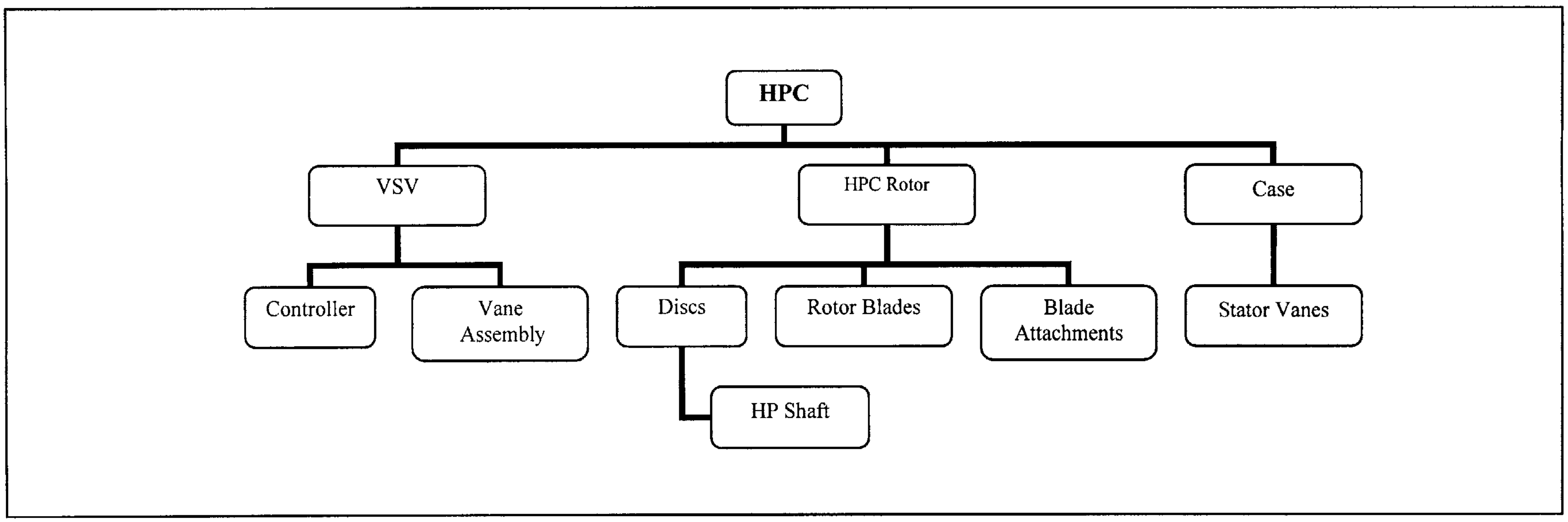
Appendix A: Decomposition Levels for Engine Modules

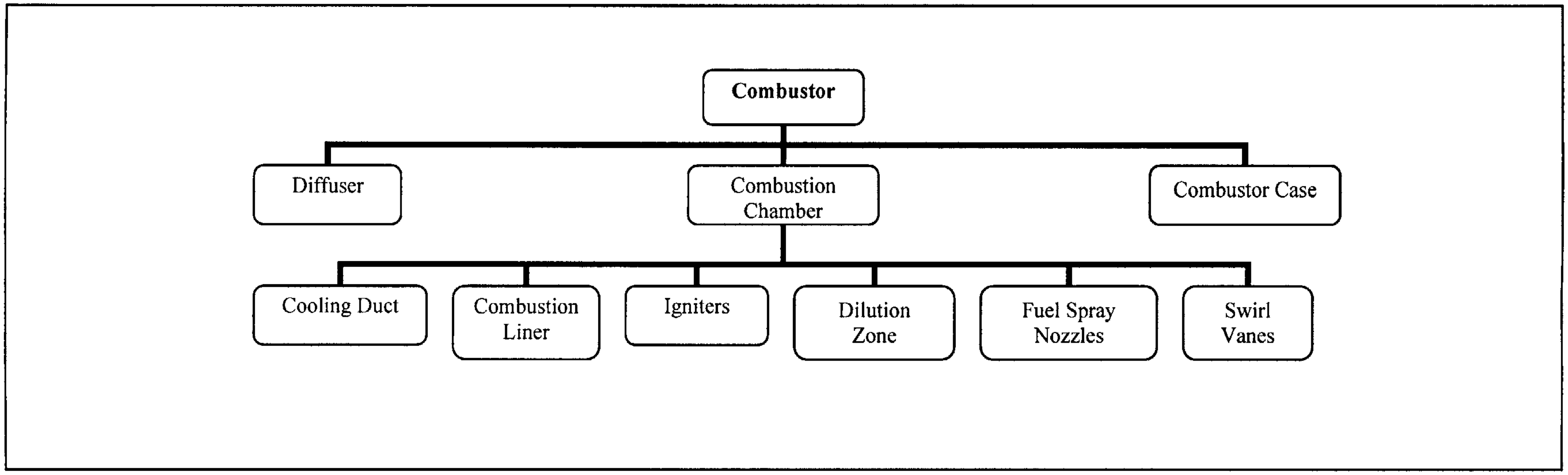
This appendix shows examples of the decomposition levels for each engine sub-system (or module). For an aircraft engine, the part-whole links across each decomposition level run parallel with the means-ends links associated with the functions of each component, sub-assembly and module. Each part of the engine has a specific function, which helps the engine to function properly, efficiently and most importantly safely. These decomposition levels are used in the work domain analysis described in Section 7.2.1.4 (Aircraft Gas Turbine Engines). These figures also help the reader to identify the various parts of the modern turbofan fan as used in commercial jet aircraft.

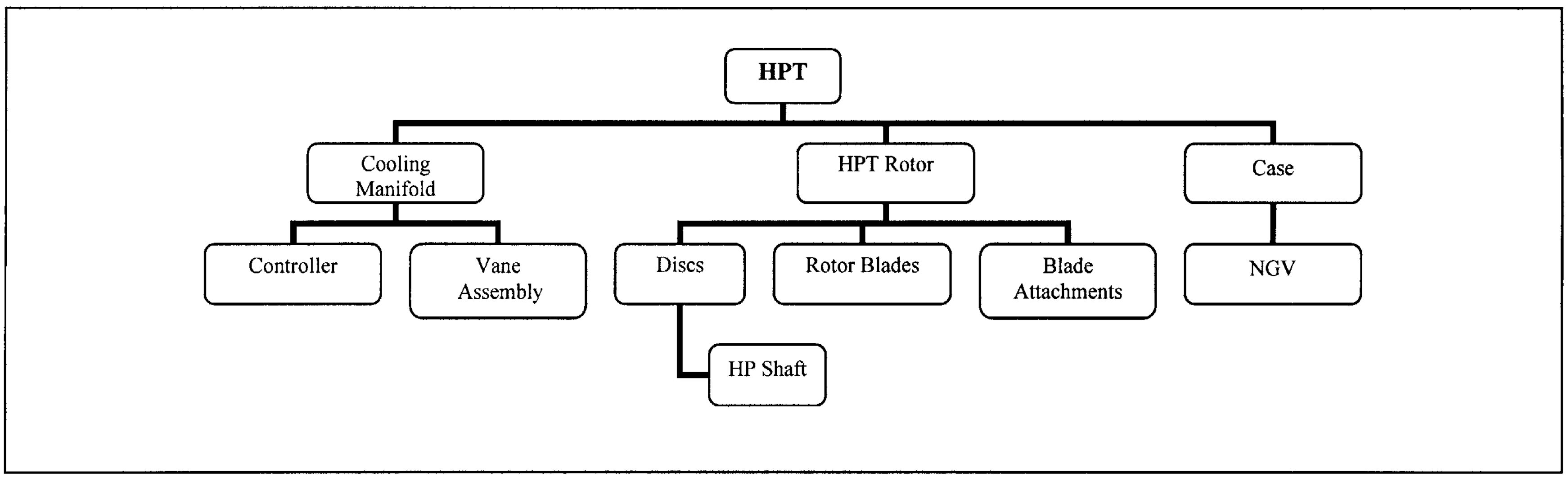
Note: These figures are not meant to be comprehensive as actual engine design consists of many more parts. They are instead meant to illustrate how an abstraction-decomposition space can be developed for the gas turbine engine.

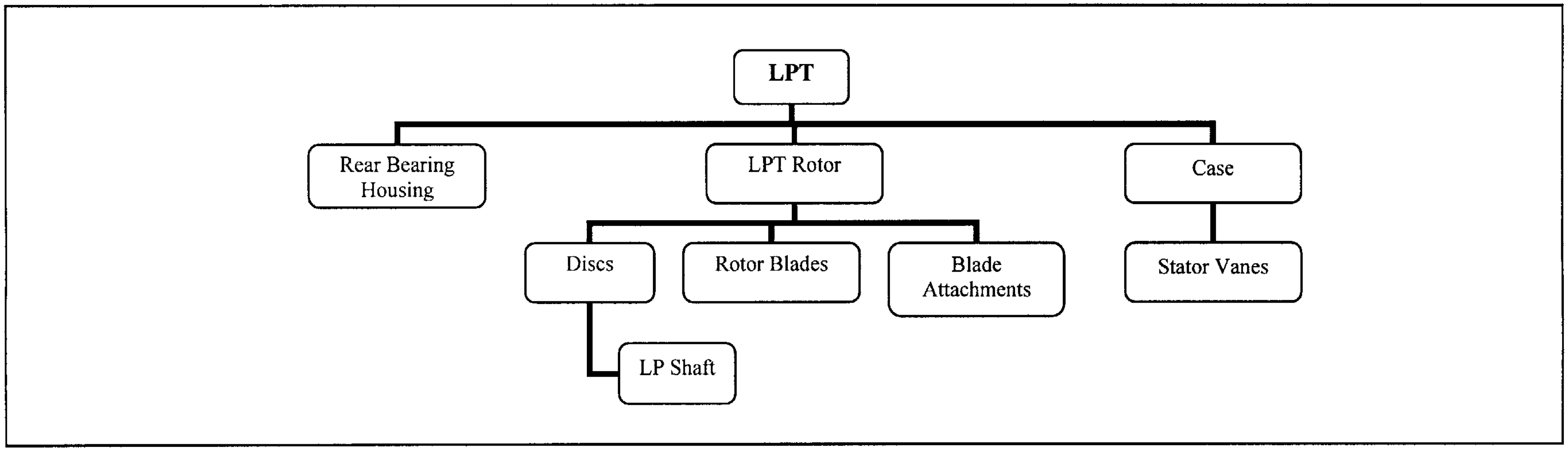


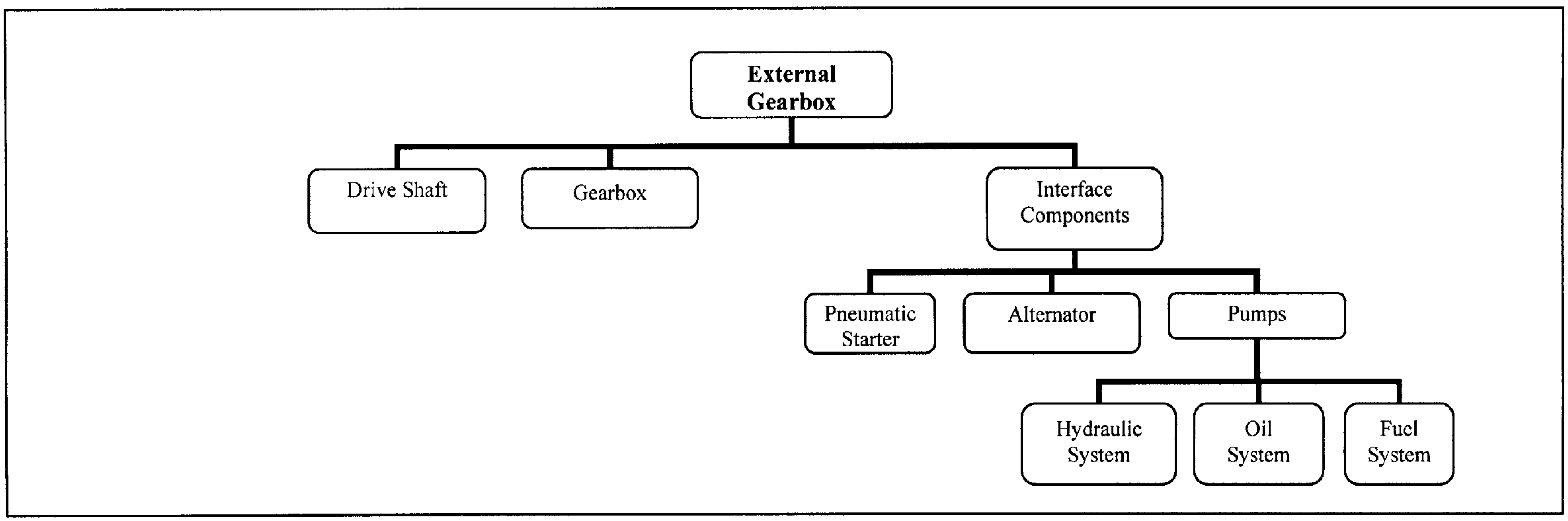

LPC
Front Bearing Housing
VSV
LPC Rotor
Case
Controller
Vane Assembly
Discs
Rotor Blades
Blade Attachments
Stator Vanes
LP Shaft

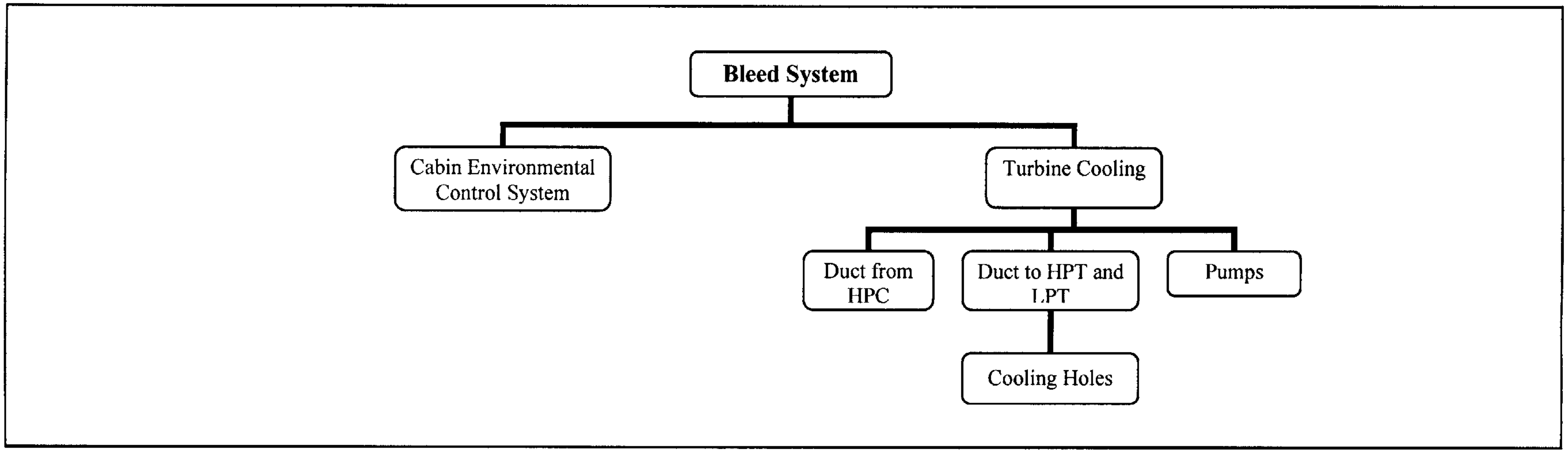

HPC
VSV
HPC Rotor
Case
Controller
Vane Assembly
Discs
Rotor Blades
Blade Attachments
Stator Vanes
HP Shaft

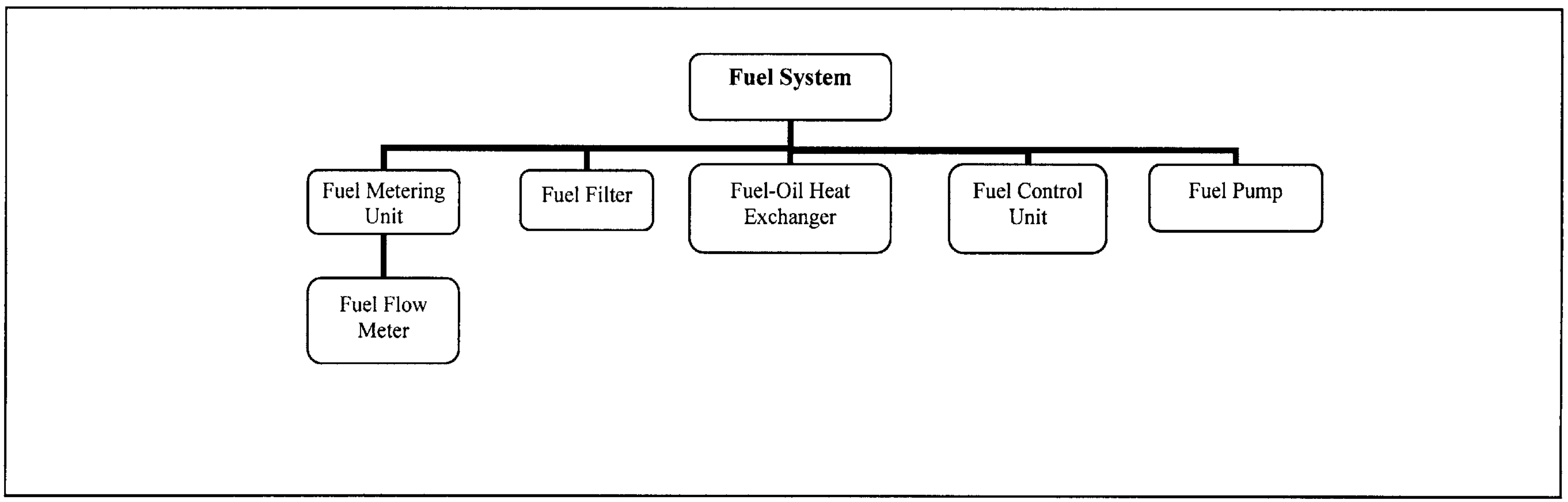

Combustor
Diffuser
Combustion Chamber
Combustor Case
Cooling Duct
Combustion Liner
Igniters
Dilution Zone
Fuel Spray Nozzles
Swirl Vanes

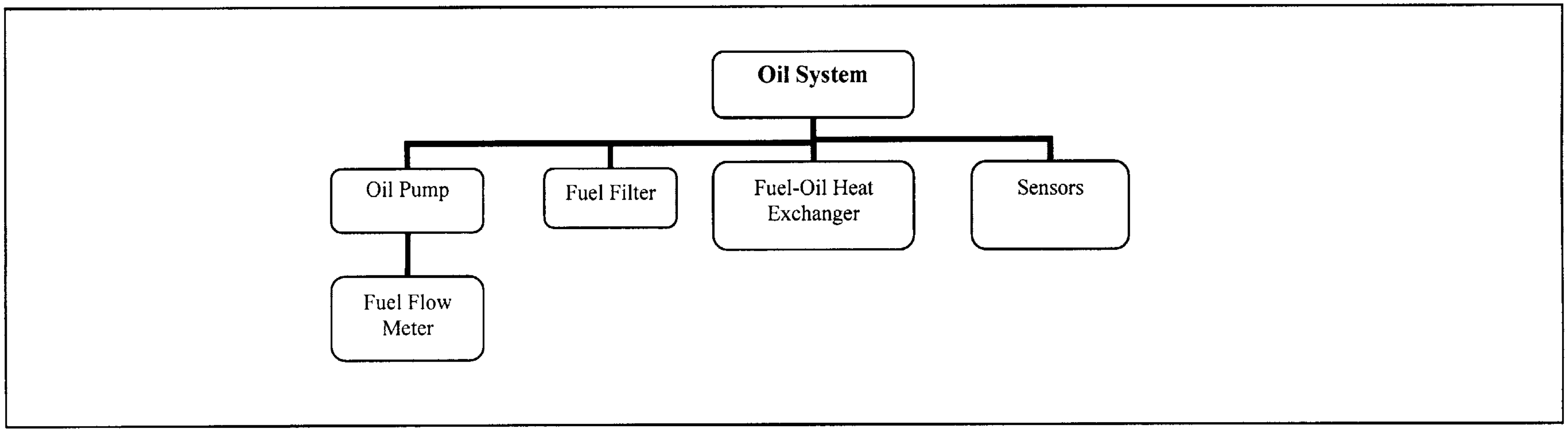

HPT
Cooling Manifold
HPT Rotor
Case
Controller
Vane Assembly
Discs
Rotor Blades
Blade Attachments
NGV
HP Shaft

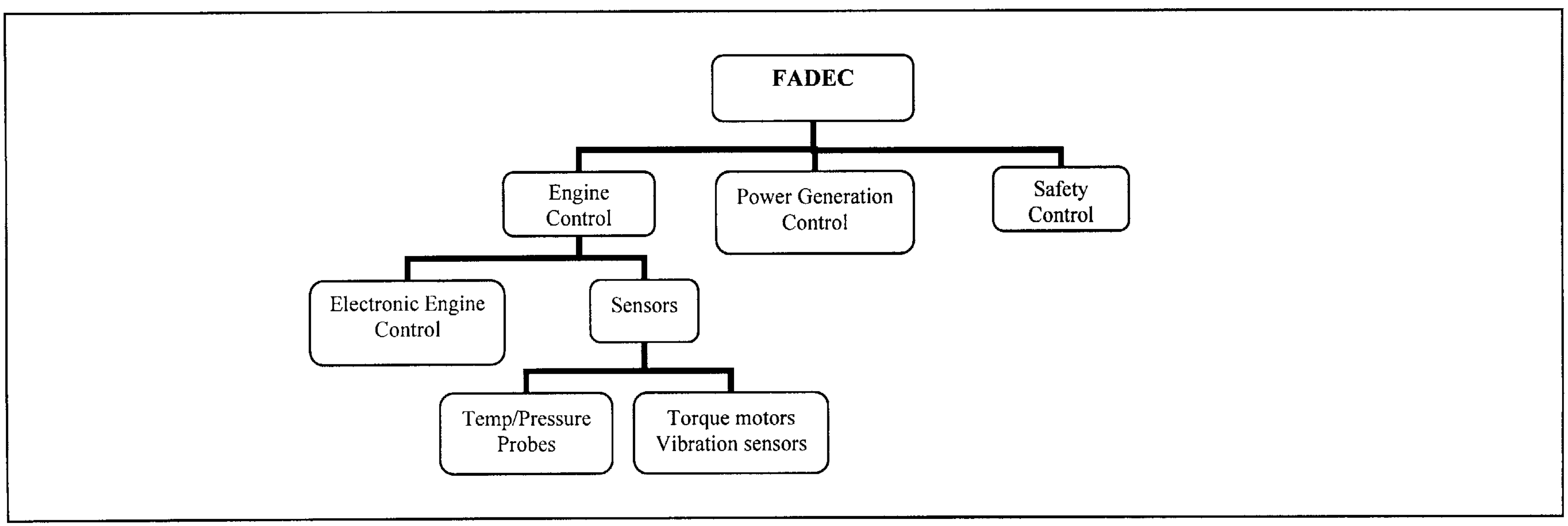

LPT
Rear Bearing Housing
LPT Rotor
Case
Discs
Rotor Blades
Blade Attachments
Stator Vanes
LP Shaft


External Gearbox
Drive Shaft
Gearbox
Interface Components
Pneumatic Starter
Alternator
Pumps
Hydraulic System
Oil System
Fuel System


Bleed System
Cabin Environmental Control System
Turbine Cooling
Duct from HPC
Duct to HPT and LPT
Pumps
Cooling Holes


Fuel System
Fuel Metering Unit
Fuel Filter
Fuel-Oil Heat Exchanger
Fuel Control Unit
Fuel Pump
Fuel Flow Meter


Oil System
Oil Pump
Fuel Filter
Fuel-Oil Heat Exchanger
Sensors
Fuel Flow Meter


FADEC
Engine Control
Power Generation Control
Safety Control
Electronic Engine Control
Sensors
Temp/Pressure Probes
Torque motors Vibration sensors