Best Practices in Aircraft Engine MRO:  
A Study of Commercial and Military Systems

By

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Abstract 

Maintenance, repair and overhaul (MRO) is a key activity in the lifecycle of an aircraft 
and its engines. Because of the typically long operational lifetimes expected from these 
costly assets, MRO is necessary to maintain these systems in a safe and functional 
condition, so that they can fulfill the operational role that they were designed for. 

The MRO system can be understood as a complex socio-technical system organized and 
operated to achieve aircraft availability and operation safety at minimal cost. As a 
complex socio-technical system, it consists of various layers: The environmental context, 
anorganizational structure, management, infrastructure, workers and the technical core. 
Focusing primarily on infrastructure, management, and manpower, this thesis seeks to 
identify best practices found within each layer by examining current practices in both 
commercial and military aircraft engine MRO, as well as surveying potentially useful 
concepts from related fields to propose how they can be applied to aircraft engine MRO. 
Among the issues presented are outsourcing, transportation, maintenance scheduling, 
inventory management, organization culture and human factors. 

Thesis Supervisor: Charles P. Coleman 
Title: Assistant Professor of Aeronautics and Astronautics
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<th>Description</th>
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<tbody>
<tr>
<td>AMOSS</td>
<td>Aircraft Maintenance and Operations Support</td>
</tr>
<tr>
<td>ANN</td>
<td>Artificial Neural Network</td>
</tr>
<tr>
<td>AOG</td>
<td>Aircraft-On-Ground</td>
</tr>
<tr>
<td>CONUS</td>
<td>Continental United States</td>
</tr>
<tr>
<td>CPM</td>
<td>Critical Path Method</td>
</tr>
<tr>
<td>CSC2</td>
<td>Combat Support Command and Control</td>
</tr>
<tr>
<td>CSL</td>
<td>CONUS Support Location</td>
</tr>
<tr>
<td>DoD</td>
<td>Department of Defense</td>
</tr>
<tr>
<td>DoN</td>
<td>Department of The Navy</td>
</tr>
<tr>
<td>DPCM</td>
<td>Diagnostics, Prognostics and Condition Monitoring</td>
</tr>
<tr>
<td>EAF</td>
<td>Expeditionary Aerospace Forces</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Authority</td>
</tr>
<tr>
<td>FAR</td>
<td>Federal Aviation Regulations</td>
</tr>
<tr>
<td>FOD</td>
<td>Foreign Object Damage</td>
</tr>
<tr>
<td>FOL</td>
<td>Forward Operating Location</td>
</tr>
<tr>
<td>FSL</td>
<td>Forward Support Location</td>
</tr>
<tr>
<td>GAO</td>
<td>General Accounting Office</td>
</tr>
<tr>
<td>GO/CO</td>
<td>Government-Owned/Contractor-Owned</td>
</tr>
<tr>
<td>GPA</td>
<td>Gas Path Analysis</td>
</tr>
<tr>
<td>ICAO</td>
<td>International Civil Aviation Organization</td>
</tr>
<tr>
<td>I-level</td>
<td>Intermediate-Level (Maintenance)</td>
</tr>
<tr>
<td>JIT</td>
<td>Just-In-Time</td>
</tr>
<tr>
<td>KBB</td>
<td>Knowledge-Based Behavior</td>
</tr>
<tr>
<td>LRU</td>
<td>Line-Replaceable Unit</td>
</tr>
<tr>
<td>MEL</td>
<td>Minimum Equipment List</td>
</tr>
<tr>
<td>MMEL</td>
<td>Master Minimum Equipment List</td>
</tr>
<tr>
<td>MRO</td>
<td>Maintenance Repair and Overhaul</td>
</tr>
<tr>
<td>MRP</td>
<td>Manufacturing Resource Planning</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<td>--------------</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NATO</td>
<td>North Atlantic Treaty Organization</td>
</tr>
<tr>
<td>NTSB</td>
<td>National Transportation Safety Board</td>
</tr>
<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
</tr>
<tr>
<td>OMFTS</td>
<td>Operational Maneuver From The Sea</td>
</tr>
<tr>
<td>PCA</td>
<td>Principal Component Analysis</td>
</tr>
<tr>
<td>PDA</td>
<td>Personal Digital Assistant</td>
</tr>
<tr>
<td>PERT</td>
<td>Performance Evaluation and Review Technique</td>
</tr>
<tr>
<td>RBB</td>
<td>Rule-Based Behavior</td>
</tr>
<tr>
<td>SBB</td>
<td>Skill-Based Behavior</td>
</tr>
<tr>
<td>SRK</td>
<td>Skills, Rules, Knowledge (Taxonomy)</td>
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<tr>
<td>TOC</td>
<td>Theory of Constraints</td>
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<tr>
<td>TRL</td>
<td>Technology Readiness Level</td>
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<tr>
<td>USC</td>
<td>United States Code</td>
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Chapter 1: Introduction and Context

For any complex system, maintenance actions are necessary to maintain the system in a safe and functional condition, so that it can fulfill the operational role that it was designed for. Aircraft and its engines are multi-million dollar assets that typically have very long operational lifetimes ranging from ten to over twenty years. Some aircraft, such as the B-52 bomber, has undergone many overhauls and upgrades for the past fifty years, and is expected to continue operating for another fifty. Maintenance, repair and overhaul (MRO) is a key activity that sustains operations during the lifetime of an aircraft and its engines, and it has been estimated that sustainment and operations account for about two-thirds of an aircraft system’s lifecycle cost (Goh, 2003).

On top of being a substantial portion of an aircraft’s lifecycle cost, MRO also has substantial impact on the safety of an aircraft and its engines. According to reports in The Charlotte Observer, “since 1994, maintenance problems have contributed to 42 percent of fatal airline accidents in the United States” (Alexander et al, 2003). Naturally, given its importance and impact on safety, availability and cost of an aircraft system, it follows that we should seek to discover the best methods to conduct MRO operations.

This paper seeks to do this by firstly, studying current practices in commercial and military MRO systems, and secondly, surveying potentially useful concepts from related fields to propose how they can be applied to aircraft engine MRO. The remainder of this chapter shall place MRO in the context of the US Navy, the US Air Force, and commercial airlines to understand the motivations behind pursuing improvements in MRO practices. Chapter 2 will give an overview of MRO as a complex socio-technical system, and present a framework to help understand what constitutes the MRO system. From there, Chapter 3, 4, 5, and 6 will focus on different aspects of the MRO system based on that framework. Chapter 3 discusses the outsourcing of MRO services, while Chapter 4 focuses on the infrastructure of MRO systems. Chapter 5 will present MRO management practices, including maintenance scheduling and inventory management.
Chapter 6 focuses on the human aspect, looking at best practices related to MRO manpower. Chapter 7 goes on to discuss the role of technology and research in the MRO system, while Chapter 8 summarizes the conclusions and recommendations presented throughout this paper.

1.1 The US Navy

When the Cold War ended, the United States Navy shifted its military strategy from a focus on worldwide conflict centered in Europe, to a focus on regional conflicts and instabilities. In 1992, the Navy presented a white paper titled “... From the Sea” that announced a shift from operations on the sea toward expeditionary operations conducted from the sea that target land regions adjacent to ocean and sea bodies. Following that in 1994, a second white paper titled “Forward... From the Sea” further emphasized the role of naval forces in “preventing conflicts and controlling crises” (DoN, 1994) by being “engaged in forward areas” during peacetime.

The nature of naval operations is one of sustained and prolonged deployment around the world with the aim of protecting U.S. interests. Naval forces are structured to be “self-sufficient, supplied and sustained in forward areas by a ‘steel-bridge’ of naval logistics ships.” (DoN, 2002). However, if deterrence fails and conflict erupts, “naval forces provide the means for immediate sea-based reaction.” (DoN, 1994)

In 1996, a vision for Operational Maneuver From The Sea (OMFTS), in the event of conflict, began to take shape. As opposed to the current practice of establishing a beachhead as a logistics staging point, this vision proposes using the sea as maneuver space from which to directly launch operational forces towards inland objectives. This concept has advantages in reducing the logistics footprint ashore as well as reducing the vulnerability associated with a large and immobile forward base. However, the logistical challenges posed by this strategy are great. With OMFTS, naval forces will likely be positioned well inland without first securing en route locations as is the practice. Coupled
with the lack of secure land routes as supplies and logistics lines, OMFTS will depend greatly on transportation by air. Consequently, there will also be an associated increase in the need for escort aircraft. The naval air wings already play a pivotal role in current naval operations, but their importance will continue to increase with the increasing emphasis on OMFTS.

Maintenance is one part of the total logistics system, and is crucial to the sustainment of operational readiness in peacetime as well as the sustainment of forces during conflicts. As the Navy’s dependence on air power increases, so will the maintenance burden associated with aircraft engines. Current capabilities are not sufficient to support OMFTS. When required during conflicts, logistics bases in forward locations can be seized or secured to provide important supplies and maintenance sustainment support beyond the first 30 days. However, this does not address critical issues prevalent during peacetime operations.

The forward nature of naval units far from the Continental United States (CONUS) poses significant challenges in providing responsive support in terms of maintenance. Forward-deployed naval units are self-sustaining by design, and operations within each unit like a carrier are undoubtedly efficient, responsive and highly prepared at all times. However, the integration of operations with mainland maintenance operations is relatively weak, causing many delays. This unresponsive nature of the maintenance support system in CONUS has drawn much attention and effort to studying and improving the military maintenance system, and in particular the public depot system.

Spurred in part by decreasing defense budgets since the cold war, there is a need to revamp the military logistics system to maintain a capable force at reduced costs. This has sparked much interest in learning from business practices in the commercial world, where operations are streamlined and optimized to gain maximum profit.
1.2 The US Air Force

Like the US Navy, the US Air Force has begun shifting towards a strategy focusing on smaller, regional conflicts and contingencies. While it used to maintain a forward presence with strategic positioning of air bases throughout the world, the Air Force is moving towards a concept of Expeditionary Aerospace Forces (EAF), where units will be deployed swiftly from CONUS in response to regional crises that threaten US interests. The goal is to be able to deploy units to Forward Operating Locations (FOLs) to begin operations as quickly as possible, and sustain operations for as long as necessary. Typically, preparations are targeted at sustaining operations in the order of about 90 days.

Current capabilities are not adequate to support such a strategy and much effort is being put into reorganizing resources to meet this goal. From a number of studies, it is projected that the strategy will require five components to be in place (Tripp et al, 2000):

1) Forward Operating Locations (FOL) – Bases in forward areas with pre-positioned equipment, particularly in regions with high threat levels, so that expeditionary forces deployed can begin operations with minimal delay.

2) Forward Support Locations (FSL) – Centralized logistics bases strategically positioned in forward locations to support contingency operations in the assigned region. These may serve as ammunition storage and spares inventory, and may also serve as maintenance centers. Probable locations for such bases may be within Western and Central Europe.

3) CONUS Support Locations (CSL) – These locations typically provide depot-level maintenance capabilities to forces in CONUS, and additional support to FSLs and FOLs. They include private sector contractor facilities.

4) Transportation Networks – Transportation networks form essential links between FOLs, FSLs, and CSLs.

5) Combat Support Command and Control (CSC2) – A central control system is required to orchestrate operations and support activities.
In peacetime, the bulk of operations will be contained within CONUS. In many ways, this makes the operational structure similar to that of US domestic commercial air transportation, so insights could be gained by examining the two in parallel. During conflicts, it can be expected that the EAF concept will cause the structure of operations to share similarities to that of the US Navy, where units are deployed far from CONUS, and require responsive support from CSLs to sustain prolonged operations. In this respect, potential problems might surface if the maintenance support system from CONUS remains unresponsive. Best practices learned from the study of both the civil and military aviation MRO systems could provide the direction to which improvements should be made.

1.3 US Commercial Airlines

A commercial airline is just like any other business; the most basic objective is to gain a profit, and it does so by providing transportation services to the traveling public. However, airline operations are nothing less than complex, and the industry is typically characterized by high capital outlays, high revenues, but volatile profit margins.

Before 1978, the US airline industry was highly regulated. Airline routes and frequencies were determined by the government, and prices were adjusted according to operating expenses. With deregulation, airlines were free to make these economic decisions in competition with other airlines. This spurred significant growth of the industry as US domestic air travel more than doubled in the first 10 years of deregulation. Furthermore, ticket prices continue to decline with the intense competition among carriers.

However, the industry continues to be highly operational and safety-regulated. Airline safety has always been under public scrutiny, and is the foremost concern for the industry as a whole. Airline and aircraft certification, manpower and crew training, maintenance standards and policies are some examples of regulations that remain in the interests of passenger safety.
With lower ticket prices cutting into profit margins, airlines are continually pressured to optimize revenues. This is exacerbated by the rise and increased acceptance of low-cost carriers that typically offer no-frills transportation services at steep discounts to regular airline fares. Currently, a plethora of tools exist to assist the airline manager in optimizing parameters like fleet schedules and routes, aircraft utilization and seat inventories. On top of that, there is a continual need to seek cost savings or productivity gains in their operations to beat the competition.

Four aspects usually make up the bulk of a typical US carrier’s operating expenses: labor, fuel/oil, aircraft ownership, and maintenance. In the first quarter of 2003, maintenance accounted for an average of 11% of total operating expenses for US network carriers. This was the third largest portion of expenditure behind labor (34.1%) and fuel/oil (13.7%) (Aviation Daily, 2003). Considering that maintenance expenses for a major network carrier like American Airlines was about $665 million in the first quarter of 2003, a mere 1% reduction in maintenance expenses (so that it becomes 10.9% of total expenses) can translate to an additional profit of $26.6 million annually.

Maintenance costs are also of particular interest due to their fixed-cost nature. Once an aircraft or engine is procured, it has to be maintained regularly in order to meet operational and safety standards. Furthermore, delays, cancellations and aircraft downtime due to poor maintenance translates into significant losses for airlines. Improvements in maintenance processes, practices, and efficiency will not only bring down a fixed annual cost, but it will also bring significant savings and higher passenger satisfaction with reductions in maintenance-related disruptions.
Chapter 2: Overview of the MRO system

2.1 Maintenance as part of the Total Logistics System

Logistics usually refers to the branch of activities that provides support for commercial or military operations. The range of logistical activities includes acquisition or procurement, distribution of supplies, maintenance of equipment and engineering.

Figure 1: Maintenance as part of Logistics (McLennan, 1995)

Figure 1 above illustrates the relationships between Logistics, Supply, Engineering, Maintenance, and Operations. Logistics and operations are separate entities, but they are mutually dependent. Usually, operational goals and activities will determine logistics requirements, which are delivered upon by the logistics organization. Within logistics, supply and engineering are separate divisions with maintenance being part of engineering. The distinction between engineering and maintenance is that engineering is generally more cognitive in nature and involves design and manufacture. Maintenance is usually associated with more hands-on activities, which includes tasks such as servicing, repairs, and modifications. Supply involves the provisioning, storage, distribution and transportation of material in the system. Just as logistics and operations are mutually dependent, supply and maintenance are also closely linked in that maintenance activities
determine equipment and spare parts requirements, while supply delivers upon these requirements. Also, as equipment, components or parts are serviced or repaired, they are fed back into the system via supply activities.

It is important to note that the relationships between operations and logistics and between maintenance and supply are more than just links. Just as operations cannot be sustained without the support of logistics, neither can maintenance go on without supplies. The success and efficiency of the maintenance system depends, to some extent, on the supply chain. Due to this inter-connected nature of maintenance and supply, analysis of the maintenance system also requires evaluation of supply activities, and this will be discussed in subsequent chapters.

2.2 MRO as a Complex Socio-Technical System

In order to identify best practices within the MRO system, we need to first gain a better understanding of how the system is organized. Making use of Vicente’s (1999) cognitive engineering framework, Goh (2003) has argued that the MRO system falls into the definition of a complex socio-technical system. Figure 2 shows the breakdown of such a system into its various layers.

![Figure 2: Layers of a Complex Socio-Technical System (Vicente, 1999)](image-url)
In the core of the complex socio-technical system lies the technical system, which is the aircraft or engine in this case. Above the technical system, maintenance personnel, flight crew, engineers and other workers form the next layer. The physical infrastructure, management, and the various organizations such as the airlines, MRO shop and military form the layer above, within which the workers function. Beyond that, the environment encompasses the rest of the system below. In this context, the environment represents government, policies and regulations.

The breakdown of a complex socio-technical system into these layers is helpful in understanding what constitutes the MRO system; however, the processes within each layer need to be uncovered before we are able to identify what contributes to the success or failure of the MRO system. At the same time, we need also to define the measure of success or failure upon which the system processes may be assessed. For this purpose, we shall look at goals of the MRO system.

2.3 Availability Goals

As described at the beginning of this chapter, maintenance is performed as part of the logistics effort to support ongoing operations. With respect to civil and military aviation, maintenance contributes to operations by ensuring the availability of aircraft. For commercial airlines, an aircraft that is unavailable to fly when it is scheduled to causes delays or cancellations, which ultimately affect revenues. For military aircraft, availability directly affects the readiness of the combat force to react and to do battle during contingencies. During peacetime, availability also affects training schedules. Availability of transport aircraft may also affect the performance of the supply system in some instances.

Availability goals strongly influence maintenance practices and processes. In order to achieve a high level of availability, airlines and the military services try to minimize
downtime through various means. Aircraft downtime is the period of time that an aircraft is not in operation due to malfunctions, and it can be broken down into three components:

\[
\text{Mean Down Time} = \text{Mean Time to Repair} + \text{Logistics Delay Time} + \text{Admin Delay Time}
\]

(McLennan, 1995)

Mean time to repair is simply the amount of time needed to bring a piece of equipment back into working condition. Logistics delay time is the delay time associated with activities like transporting the equipment to and from the depot, bringing spare parts to and from inventory, packaging and handling the equipment. Administrative delay time refers to time spent on all other support functions like documentation, administrative procedures, work allocation and so on.

As can be seen, reduction in any component contributes to reduced downtime. Some factors that help to reduce mean time to repair include highly-skilled maintenance personnel, cognitive support tools for maintenance personnel, accessibility of faulty components and modular equipment design. A low mean time to repair also contributes to keeping up the level of spares circulating in the system; reducing the need for additional inventory and the need for cannibalizations (in the military)\(^1\).

Logistics delay can be reduced by enhancing transportation or supply lines. Keeping a large inventory also ensures availability of spares for replacement, after which the faulty component can then be diagnosed and repaired at a later time. This decreases the pressure on mean time to repair (to return the broken component back into the system), but has correspondingly high costs and space requirements.

Reduction of administrative delay depends on things like streamlining of procedures and work processes, support for documentation (reducing paperwork), and decision support

\(^1\) Cannibalization is the process of removing a working piece of equipment from a next-highest assembly, sometimes from another aircraft, when additional spares are not available at the required time. Cannibalization will be discussed further in Section 5.2.4
tools for managers. Implementation of reliable information systems would generally contribute to this area.

2.4 Safety Goals

Maintenance can bring about a high level of availability, but safety is equally important. Besides allowing aircraft and engines to continue operations, maintenance also reduces the risk of failures and hazards to operational personnel. An MRO system that neglects safety of operations is simply an unsuccessful system.

As previously mentioned, US civil aviation has been deregulated economically since 1978 but the industry continues to be highly safety and operationally regulated. The Federal Aviation Administration (FAA) is the regulatory body for civil aviation in the US. Its primary objectives include the regulation and promotion of safety, operation of the air traffic control system, and research and development of the civil aviation system. With respect to maintenance, the FAA issues as well as enforces regulations and minimum standards for maintaining aircraft and engines. It also issues certification for qualified maintenance organizations and personnel.

The parts of the Federal Aviation Regulations (FAR) that pertain to engines and maintenance are Part 33, Part 43, Part 65, and Part 145. Part 33 specifies airworthiness standards of aircraft engines, including design, materials, testing and inspection. Part 43 covers regulations pertaining to maintenance, preventive maintenance, rebuilding and alteration. Certification of mechanics and repairmen are addressed under Part 65, while Part 145 covers certification and rules that govern the performance of repair stations.

The military equivalent of the FARs are military specifications. Generally, military specification documents specify performance and design criteria to meet mission objectives, but do not specify regulations that govern maintenance practices or
performance of military maintenance depots. Each service within the military runs its own maintenance training program customized according to the different aircraft used.

Due both to public pressures and stringent regulations, it has been statistically proven that aviation continues to be a safer mode of transport as compared to other forms of travel. Nevertheless, public sentiment is still relatively doubtful, partly due to the high publicity and attention given to aviation accident events, as well as the fear sparked by the terrorist attacks of Sept 11, 2001. The number of incidents reported every year remains low, but the industry still faces many challenges in improving safety.

According to reports, “since 1994, maintenance problems have contributed to 42 percent of fatal airline accidents in the United States” (Alexander et al, 2003). This is indeed a large proportion, and more attention needs to be given to such maintenance-related incidents. Besides the government, responsibility also lies with all other stakeholders, including airline management, flight crew, maintenance personnel, the public, manufacturers, suppliers and so on. Although regulations can be drafted according to the safest practices known, there is a realistic limit to how much can be controlled.

Within both civil and military aviation organizations, there are many practices that can be adopted to enhance flight safety. In subsequent chapters, current practices at the organization, management, and worker levels will be presented and future improvements and recommendations will be discussed.

**2.5 Economic Goals**

The incurring of operational costs for maintenance is inevitable, and the reduction of cost is another major driving factor for the military and commercial airlines to improve maintenance practices. As discussed, the safe transportation of passengers for profit is the main goal of any airline, and reducing maintenance costs without compromising safety will contribute to achieving this goal. For the military, mission objectives (availability)
usually take priority, but reduced defense budgets since the cold war have imposed significant pressure to maintain a capable force at reduced costs.

Maintenance costs are usually made up of airframe and engine direct maintenance, and overhead costs, including spare parts and hangars. Similar to availability, engine direct maintenance costs include the cost of manpower, spare parts, overheads, and transport. Generally, downtime costs airlines and the military services money, so reduction in downtime (increasing availability) usually has related cost savings. From another point of view, efficient operations mean that more is accomplished with less, hence saving both time and money.

Subsequent chapters will analyze and discuss a number of strategies that civil and military organizations have undertaken to cut costs, and discuss how the two could possibly learn from each other.

2.6 The Role of Best Practices

As mentioned in Section 2.2, each layer of the MRO system contains processes and practices that form the means by which the outlined goals are attained. Figure 3 shows these links between the MRO system and its goals. At the technical layer, good engineering design is the basis by which safety, availability and economic goals are attained. Fundamentally, a well-designed engine that is safe, reliable (does not breakdown often) and easy to maintain can have significant effects on the rest of the MRO system above the technical core, easing much of their “burden”. At the idealistic extreme, an aircraft or engine that does not breakdown and is never damaged has no need for the other layers to support it.

At the topmost layer, the government relies upon legislation, policies, and regulations to attain MRO system goals. In particular, public safety in civil aviation is a primary concern for the government, and the FAA oversees that aspect. The safety of military
aviation is correspondingly a concern of the Department of Defense (DoD). As the airline industry forms part of the national infrastructure, the government also has a stake in the availability and economic aspects of airline transportation. However, in terms of MRO, availability and costs are primarily a concern for individual airlines in a deregulated environment. For the military, availability affects national security, while MRO costs affects the national budget. Hence, legislation and policies do play a part in achieving availability and economic goals for the military.

![Diagram of system goals and processes](image)

**Figure 3: Attainment of System Goals via Processes at each Layer**

At the middle two layers, best practices form the vehicle by which the above system goals are attained. According to the glossary from The American Society for Quality, a best practice is “a superior method or innovative practice that contributes to the improved performance of an organization” (www.asq.org, 2004). In the context of the MRO system, achieving “improved performance” can be understood as attaining and exceeding safety, availability and economic goals. In subsequent chapters, this paper will focus on current and recommended practices within these two levels for civil and military aviation. The organizational, management and infrastructure level will be divided into MRO infrastructure and MRO management for clarity.
Public policy is not in the scope of this paper, but comparison of certain practices between the public and private sector makes it necessary to touch upon some policies and legislation at the environmental context level in the next chapter. Similarly, technical details and concepts of good engineering design is not the focus of this paper, but some aspects will also be touched upon because it affects practices at higher levels.
Chapter 3: Outsourcing MRO Services

3.1 Public vs Private Sector Maintenance

Many issues surround the allocation of maintenance work for military aircraft between public depots and private contractors. One of the most important is the issue of control and readiness. The United States Code (USC) Section 2466 of Title 10 limits the Department of Defense (DoD) from outsourcing more than 50% (in terms of funds) of depot maintenance work to the private sector (GAO, 2003). The main reason for this is for the military to retain a “core” capability to sustain mission-critical equipment. This concern is no doubt valid, since critical equipment that is required for national security ought to be under direct control of the government, and not be in the hands of the private sector. Furthermore, being under the direct control of the military services, public depots are generally able to provide the necessary flexibility and responsiveness to react to contingencies at short notice. Increasing the allocation of work to the private sector may constrain flexibility and control, lowering the readiness of the military to surge in response to crises.

However, the distinction between what is “core” and “non-core” is very subjective. In theory, “core” maintenance is maintenance that is performed on mission-critical systems or components, while “non-core” maintenance includes tasks on non-critical systems and tasks that can be deferred. Such a definition is arguably simple, and the DoD has in place a structured method by which to determine if a weapon system is “core”. Despite this, the classification of “core” and “non-core” remains largely dependent on subjective judgments by top military leaders.

Ideally, the military should retain full maintenance capability for all weapon systems in the interest of national defense, but this is unrealistic. Given the wide variety of systems currently operated by the military, full capability would require the government to run an unrealistically large industrial base. The cost of labor, facilities and overheads in maintaining such an extensive depot repair capability would be enormous. As the US
defense budget shrinks, and focus is shifted from the cold-war scenario to expeditionary operations, there is immense pressure to downsize in terms of number of aircraft, and also in terms of cuts in depot facilities and labor that support those aircraft.

A reduction in depot maintenance capability has capacity implications. The flow of engines and components through the public depot repair system form a chain of processes that resemble a queuing system. Figure 4 below presents a well-known result from queuing theory (Odoni and Larson, 1981, pp 199-205). It shows that a queuing system has high sensitivity to delays as utilization draws close to capacity. If workloads reach capacity or beyond, the expected delay increases exponentially; the system never recovers and delays become infinitely long. In practical terms, an overloaded depot repair system could result in engines and components being “stuck” in work-in-process inventory, and taking unacceptably long times to be returned to the line.

![Figure 4: High Sensitivity of Delays at High Workloads (Odoni and Larson, 1981)](image)

In Figure 4, the horizontal axis represents increasing “demand” or rate of arrivals (rate that engines and components are received at depot). \( \rho \) represents utilization, which is the ratio of the rate of arrivals to the rate of service completions (rate at which engines and
components are repaired). In order to reduce delays, utilization can be reduced either by decreasing the rate of arrivals or increasing the rate of service. A number of ideas to increase the rate at which components are repaired include providing better diagnostic tools, cell-based repair and others that will be discussed in subsequent sections in this report. On the other hand, reducing the rate of arrivals could be achieved not only by having more reliable engines that breakdown less, but also directing excess workload to other sources, such as the private sector.

The outsourcing of work to the private sector also has significant economic benefits. The ownership and upkeep of extensive maintenance facilities, equipment and labor contributes to a fixed cost that needs to be "spread" over a large fleet in order to enjoy economies of scale. As fleet size decreases, the proportion of maintenance costs correspondingly increases, justifying a cutback in these facilities in favor of outsourcing. Private sector firms have the benefit of the flexibility to source for contract work from a relatively wide market. It is thus easier to justify substantial economic investment in facilities, specialized equipment and manpower as compared to public depots that only have the military as a single "customer".

Furthermore, current and future aircraft continue to incorporate advanced technologies, such as composite materials for engine components, which require specialized equipment and manpower skills for maintenance. The acquisition of technology, development and training costs associated are very high, and there is great economic incentive to rely on existing production facilities of the OEMs or the private sector to maintain these specialized components. Overall, increasing the allocation of work to the private sector may save the government expenses in the order of $1 billion annually (Clay-Mendez, 1995).

The relationships between the military, public depots, and private sector MRO sources are summarized in Figure 5. Public depots give the military control and maintenance capacity with related costs for facilities, labor and overheads. Here, "control" refers to the ability of the military to directly manage risks associated with contingencies (surges),
security, safety and finance. If more maintenance is outsourced, then the military will not be able to directly manage these uncertainties, although they might still be able to exert some influence. Figure 5 also shows that a wider industrial base exists in the private sector, and individual firms have access to wider markets. Public depots also receive technology and training from the OEMs to develop certain specialized maintenance capabilities.

![Diagram of MRO services](image)

**Figure 5: Public and Private Sources of MRO Services**

Although outsourcing can bring about substantial savings, the effects on readiness and availability are questionable. According to studies, contractual component repairs generally took longer total repair times than public depot repair times (Chenoweth, 1994).
Private sector firms generally work on multiple contracts, so priority may not be given to public sector work, whereas public depots are dedicated to supporting military repairs. This may have the effect of increasing component turnaround times, thus decreasing availability. Other factors such as increased handling and poor coordination between the government and contractors were cited as factors that contribute to increased contractual repair times. Also, it is speculated that much of the repair delays were a result of time wasted waiting for parts to be provided by government sources, rather than slow repair processes. Inventory management in support of both public and private sector work is a key issue affecting repair times, and it will be further discussed in Section 5.2.

Inventory issues aside, repair work in the public sector is typically not as efficient as that in the private sector, requiring more time and expenses (GAO, 1996; GAO, 1998; GAO, 2003). As reflected in Figure 5, private sector MRO organizations are continually faced with competitive pressure from other similar organizations. The inherent competitive nature of the private sector drives individual firms to develop strategies to optimize operations and to lower costs. The nature of the public sector, however, is generally more complicated and restrictive. As a government entity, the public depot’s pursuit of reduced costs and efficient operations is often hindered or slowed down by such things as politics, funding considerations (funds come from taxpayer contributions), labor issues, a strict hierarchical structure, as well as legislative limitations. The lack of competition also reduces the incentive to improve operations (Clay-Mendez, 1995). The inefficiencies of public maintenance work have been the focus of much attention, and strategies are continually being developed to solve this problem (GAO, 1996; GAO, 1998; GAO, 2001; GAO, 2003).

Besides considerations of cost and availability, labor issues are also immensely important to the public sector. Resistance against outsourcing primarily stems from the concern for keeping jobs within the public sector, and providing work for government employees. In essence, it is similar to the recent resentment against outsourcing of local US jobs (especially in the software industry) to other countries that offer much cheaper labor. It
also bears resemblance to labor issues that commercial airlines frequently face with unions. Some of these issues will be discussed further in Section 6.1.

Balancing the allocation of "core" and "non-core" work between the public and private sectors with the aim of achieving cost and availability goals is no doubt a difficult problem. Neither a wholly private or public operation framework seems to be able to satisfy the goal these goals. Since this is the case, perhaps a maximum 50/50 division of work, as legislated, could give optimal results. This might indeed be the case in any given period of time, but the fact that a limit of 50% for private sector outsourcing exists means that military leaders have a lack of flexibility with regards to the allocation.

In the author’s opinion, an inherent problem with stipulating work division based on fund allocation is that it ignores the operational characteristics (efficiency, capacity, amount of work completed, cost-effectiveness etc) completely. In other words, an inefficient operation might accomplish the same amount of work as an efficient operation, but in a longer time and with more funds. A cap imposed on the amount of work that can be outsourced, or restrictions on the amount of work to be done in-house, simply does not give the system enough flexibility to adjust according to its workload. Furthermore, a cap imposed based on spending does not adequately address workload allocation between the public and private sectors. Funding is no doubt important, but other more representative metrics need to taken into account as well. These may include the rate at which engines are received, the rate at which engines are repaired, the number of man-hours required per repair and the number of man-hours available for repair.

A possible arrangement that could offer many benefits while keeping within certain constraints is to have public depots to source for work from the private sector. This is represented in Figure 5 by the dotted arrow between airlines and public depots. Such an arrangement could offer many benefits, assuming that the public depots are not overloaded and have excess capacity. First of all, public depots will be able to retain jobs for government employees, settling the debate over labor issues, and enhancing good relationships between workers and management. Furthermore, public sector work is not
being outsourced, but rather the opposite will be true: private sector work is being brought into the public sector. As such, the level of readiness associated with control over maintenance work is not compromised, and the arrangement would not conflict with fund allocation between the public and private sectors. Instead, there might be added income that would contribute to the relief of pressures on the defense budget. Competitive pressures from the private sector could also potentially motivate the public depot system to improve upon operational efficiencies.

For the commercial airlines, access to certain specialized capabilities within public depots, such as extensive NDI equipment and skills, could prove useful in extending commercial aircraft engine life. Also, public depots could potentially offer commercial airlines stable and competitive 3\textsuperscript{rd} party MRO services. Safety could also be enhanced as regulations within the public sector tend to be more strictly adhered to, and tighter government oversight is likely.

Legislation and political implications may pose significant obstacles, and it is not the intention of this paper to study the details of public policy. However, to the author’s knowledge, mixed public/private modes of production exist, allowing the government to have varying degrees of control over operations. These mixed modes include Government-Owned/Contractor-Owned (GOCO) facilities, regulated monopolies, and government corporations (Clay-Mendez, 1995). In these mixed modes, the use of public sector facilities and manpower for private sector contractual work may be possible.
3.2 Commercial In-house vs 3rd Party Maintenance

Figure 6 shows the various sources that airlines have to obtain MRO services. Just like public depots are to the military, in-house MRO capabilities give airlines control and maintenance capacity with related costs of facilities, labor and overheads. Usually, major network carriers will have line maintenance at their own airports as well as other important locations in their service network. For ease of operations, these carriers would normally have maintenance hubs set up at major hub airport locations as well.

![Diagram showing the sources of MRO services](image)

**Figure 6: Private Sector Sources of MRO Services**

In-house MRO services typically source for additional work from other airlines, and face competition from alternative sources like 3rd party MRO shops and the OEMs. In the recent past, OEMs were not a significant source of MRO services; however, they have since realized the potential for significant, continued revenue by offering MRO services together with their products. The three major engine manufacturers (General Electric,
Pratt and Whitney, Rolls Royce) “have been very active in recent years in expanding their share of the engine MRO market” (Goh, 2003).

Just as in military aviation, the primary driver of maintenance outsourcing is cost. Most low-cost carriers in the US outsource a significant amount of maintenance work, thus being able to hold down total operating costs. The recent successes of low-cost carriers has been reflected as carriers such as Southwest Airlines and Jetblue Airways continue to make profits while major network carriers struggle to survive.

Due to the intense competition, major carriers are also increasingly moving towards outsourcing as a means to lower maintenance costs. Outsourcing maintenance services also has the benefit of allowing airline management to concentrate on operational aspects. Recently, United Airlines outsourced heavy maintenance work for its airframes to Singapore Technologies Aerospace. It was reported that such a move could reduce maintenance costs by as much as 30% (Mathews, 2004).

Similar to outsourcing of public depot work to the private sector, third-party MRO services are able to offer competitive prices for maintenance because they tend to consolidate work contracted from a wide market, enjoying economies of scale for much equipment and facilities. The OEMs also have the advantage of existing production facilities and a highly skilled workforce, such that they can offer very competitive rates for MRO services. Another very important factor is labor union agreements. Typically, major carriers face a lot of opposition from unions when attempting to cut labor costs.

Also, outsourcing may affect availability. Outsourcing requires added transportation and handling, and may pose coordination difficulties with fleet assignments and schedules. With an in-house capability, maintenance and operations can be better integrated to ensure smoother flow. Airlines also face a lot of resistance from the unions with regards to outsourcing. This is understandable since they are concerned with keeping their workers employed. As before, the cutting of jobs harms relations with workers, and is generally not advisable in this respect. Nevertheless, the survival of any company
depends on its economic “health”, and depending on the situation, outsourcing may be a very good solution to economic woes.

Finally, another primary concern with outsourcing in civil aviation is the overall reduction in safety. The concern arises from the overall loss of control of responsible authorities. As depicted in Figure 6, FAA oversight ensures safety is maintained across the respective MRO service providers. As more airlines outsource maintenance work, and as more 3rd party MRO shops enter the market, the FAA will face problems in trying to inspect a growing number of repair shops and stations. According to reports, “NTSB investigators found that poor FAA oversight contributed to more than half of all maintenance-related accidents during the past two decades” (Alexander et al, 2003). Oversight, and hence control over safety standards, becomes more and more difficult as outsourcing increases.

For many airlines, outsourcing is an effective means of lowering costs, but in order that safety is not compromised, sufficient oversight must be provided, not just from the FAA, but also from the airlines themselves; only by doing so will safety and economic goals be simultaneously met. Other airlines that are large enough to economically justify in-house maintenance have the benefit of being able to have tighter control and responsibility over its maintenance standards. When management has control, safety can be enhanced in many ways, especially at the “workers” layer in the complex socio-technical hierarchy. These will be discussed in Chapter 6. Wherever possible this ought to be the preferred alternative.
Chapter 4: MRO Infrastructure

4.1 Maintenance Levels

Figure 7 outlines the basic flow for engine maintenance in a typical airline. Here, engine maintenance is divided into two levels: Line and Base maintenance. Line maintenance basically refers to maintenance that is performed on the aircraft while it is operating on the airline flight schedule. Line maintenance consists of two subdivisions: gate maintenance and turnaround maintenance (Hessburg, 2001).

![Basic Airline Engine Maintenance Flow](image)

Gate maintenance is the maintenance performed before each departure to ensure the airworthiness of the aircraft. Usually, because gate maintenance is performed in the time between the airplane’s arrival and next departure at the airport, which is typically about
40 to 60 minutes, only the most essential tasks are performed (Hessburg, 2001). This usually involves visual checks and quick inspections for damage and leaks. Often, repair of malfunctions and faults may be deferred to a later time as long as critical equipment outlined by aircraft Minimum Equipment Lists (MELs) are functional (Hessburg, 2001). When necessary, faulty components or modules may be replaced quickly by Line Replaceable Units (LRUs). Faulty components are brought to maintenance shops for repair and testing, after which they are sent back to local inventories as spares.

Turnaround maintenance (or overnight maintenance) is usually conducted at the end location of an aircraft’s schedule. It is typically done every 3-5 days and involves some servicing, repair, and correction of MEL deferrals. Sometimes, other scheduled tasks may be worked into longer turnaround stops (Hessburg, 2001). When necessary, an engine change could be performed, so that the replaced engine can be brought to the shop for repair or overhaul.

Base Maintenance is performed when the airplane is removed from the flight schedule. Heavy structural checks (C and D checks) are performed, and the engine may be removed and brought to the shop for repair or overhaul. Depending on the severity of the condition, engine repairs may be as short as a week, or take a few months in the case of overhauls. As represented in Figure 7, the MRO shop holds necessary spare parts in its inventory, which is replenished periodically by suppliers. Local inventories in support of line maintenance also stocks spare parts and LRUs, some of which come from suppliers, and others which are returned after repairs or overhauls by MRO shops.

Figure 8 is the corresponding engine maintenance flow typical of the military. Instead of two maintenance levels, the military uses three: line, intermediate and depot-maintenance (Clay-Mendez, 1995; Amouzegar et al, 2002). The flight line is similar to that of commercial operations, where aircraft are inspected and serviced after each sortie. Similar to turnaround maintenance in commercial operations, minor scheduled maintenance tasks are also performed on the engines according to the number of flight hours accumulated by the aircraft. When an engine is scheduled for major maintenance,
or when it becomes damaged or exhibits malfunctions, the line also conducts removal and replacement of engines, and sends the removed engines to intermediate maintenance (Amouzegar et al, 2002).

![Diagram of Basic Military Engine Maintenance Flow](image)

**Figure 8: Basic Military Engine Maintenance Flow**

At intermediate-level (I-level) maintenance, the engine is disassembled, fatigued parts are replaced, and significant repairs are conducted. Spares and consumable parts for I-level maintenance are obtained from the local inventory. After reassembly, the engine goes through test-cell runs, after which it is returned to the local inventory as spares for the flight line. When I-level maintenance is incapable of more demanding repairs, or when the engine is scheduled for overhaul, the engine is sent to depot-level maintenance.
At the depot, the engine undergoes complete teardown, refurbishment and overhaul. After testing, the overhauled engine is usually sent to a centralized supply center, where spare parts and supplies are procured and distributed to deployed fleets or squadrons. The depot maintains its own inventory of spares and consumable parts, which is also supplied by the centralized supply center (Fricker et al, 2000), or other government depots and commercial suppliers (Brauner et al, 1994).

It should be noted that in military operations, fighters and bombers have different flight patterns from transport aircraft. Fighters and bombers usually take-off from their designated bases or Forward Operating Locations\(^2\) (FOLs), and return to the same base or FOL after their sorties. For transport aircraft, sortie routes are much like airline flight routes, and may take the aircraft to dispersed locations all over the world, depending on mission requirements. These locations may or may not have necessary maintenance support.

Although they are separate entities, the flight line and I-level support are usually co-located, such as in bases or aircraft carriers. In the case of FOLs, the current practice is for I-level support to be deployed together with the unit, to set up maintenance and test facilities at the FOL. The flight line and I-level support will still be co-located, but there is a significant delay of about 30 days for the setup of maintenance facilities, and 60 days for the setup of a test cell.

Upon comparison of the two systems, some observations can be made. The commercial system basically groups I-level and depot maintenance tasks together under base maintenance. Repairs and overhauls are performed by a single entity (the MRO shop) that is fully capable of all tasks. Only minor repairs and, more importantly, replacements, are performed at the flight line. In other words, the line is only focused on keeping up with daily operations and making sure that airplanes maintain their schedules.

\(^2\) A Forward Operating Location (FOL) is a location in the theater of conflict (or a “crisis”) where a unit from Continental US (CONUS) may be deployed to, to conduct necessary operations from.
In the military, however, line maintenance and I-level maintenance are usually co-located, and the boundary between them is often blurred. This is not necessarily a disadvantage, because I-level support is usually highly capable of a wide range of repair tasks. Having the two functions co-located reduces the need for transportation of the engine for major repairs. This organic maintenance capability consequently reduces the need for spares to replace faulty components or engines. In many instances, such as on a carrier, this capability is necessary for the unit to be self-sustaining over periods of extended deployment. Expeditionary Air Force units that are deployed in response to contingencies will also need to set-up or preposition I-level maintenance capability to sustain a high operational tempo in an expected period of 30 to 90 days (Amouzegar et al, 2002).

However, in the military structure, problems arise when an engine needs to undergo scheduled overhaul or more complex repairs. Because I-level support is simply not capable of the full range of maintenance tasks, the engine or faulty component is sent to the depot. An inherent problem with sending equipment to the depot is the long transportation time required. I-level support is designed to be self-sustaining to a certain extent, and this makes it rather disjoint from the depot system. Components sent to the depot may take anything from 4 to 6 weeks or more just to be transported to a depot in CONUS. Order-ship times from depot-level support also take about 2 to 5 weeks.

Looking at the flow of the engine in terms of a value-stream, the only activities in the chain that add value are the repair and testing of the engine or components. Activities like transportation do not add value but are necessary in this case, and activities like storage and warehousing where components simply wait to be processed are unnecessary and wasteful. From this perspective, the additional handling, storage, and transportation required by the flow of the engine or components through a centralized supply center are completely unnecessary. In theory, these activities should be eliminated or minimized. Nevertheless, the role of the centralized supply center is not redundant, because it

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3 Estimates taken from (GAO, 1996) and (Brauner, 1992). Estimated transport times reflected may include storage or warehousing, packaging, handling, shipping and receiving. Order-ship times typically include "requisition submission, inventory control point processing, stock point processing, transportation hold, and transportation times" (GAO, 1996). In both cases, the reports highlight that these are conservative estimates.
provides necessary transportation and distribution services, but what should be minimized is the time that engines and components sit in storage. The supply center should provide the service of transporting repaired engines and components to bases and deployed units, but it ought not to collect and store these valuable supplies in warehouses where they can be made better use of elsewhere. Further discussion on transportation and supply management may be found in subsequent chapters of this report.

Another disadvantage of the military system is the duplication of maintenance capability between the I-level and depot-level MRO shops. The depot is fully-equipped with diagnostic, repair and test equipment, and also stocks a comprehensive inventory of spares and consumable parts (such as nuts, bolts, fasteners etc). In order to have an adequate level of maintenance capability, the I-level shop also needs to have its own "partial" set of tools, equipment, and inventory. Consequently, equipment and inventory are duplicated. However, as mentioned, this might be inevitable due to the need for I-level capability to sustain military operations during conflicts or deployment.

In the commercial system, the line does have an inventory from which it draws its spares and consumable parts, but because it is designed to only have a limited maintenance capability, only the minimum amount necessary for daily operations is required. Other heavy equipment and necessary inventory are effectively pooled into a single source in support of the MRO shop.
4.2 Transportation

As discussed in the previous section, transportation time is a key factor that can contribute to delay in total engine downtime. From Section 2.3, downtime is divided into three components:

\[
\text{Mean Down Time} = \text{Mean Time to Repair} + \text{Logistics Delay Time} + \text{Admin Delay Time} \\
(\text{McLennan, 1995})
\]

Transportation largely contributes to logistics delay time, but in many instances, a lack of proper planning can lead to substantial delays in repair time as well. Transportation time is not limited to the time it takes to ship an item from point A to point B; it also includes associated tasks such as packaging, handling and receiving. It is hence possible for an item to have a large transportation time due to delays in packaging and receiving, even though the actual shipping time may be short. Besides transportation of faulty equipment to be repaired, delays associated with transportation of spares need to be considered as well. If a broken component arrives at a maintenance shop, but is unable to be repaired due to the lack of certain spares or consumable parts, then quick transportation times from a supplier to the shop may alleviate such a delay, as opposed to long delays due to long order lead times. Supply management is discussed in Section 5.2.

4.2.1 Bringing the Engine to the Shop

In US commercial aviation, airlines benefit from having a network of maintenance stations located all over the country. Aircraft can be routed such that they end their schedule at a location equipped with adequate maintenance capability to perform scheduled maintenance. Whether the maintenance performed is on-aircraft, or off-aircraft, transportation is minimized since the aircraft and the shop is effectively co-located. Figure 9 depicts how a commercial aircraft always receives line or base maintenance
after each flight leg\textsuperscript{4}. These routings are scheduled and involve the movement of the whole aircraft for each transition.

![Diagram](image)

**Figure 9: Airline Maintenance Transportation Flow**

If an engine needs to undergo unscheduled maintenance due to unforeseen damage or malfunctions, Aircraft-On-Ground (AOG) support services offered by a number of commercial organizations may be activated to transport a spare engine for replacement to the AOG location. This is depicted in Figure 9 by the unscheduled transportation of engines or components between the line and base maintenance facilities. Within CONUS, the distance transported is at most the length of CONUS (about 2600 miles). However, if an unscheduled maintenance event happens to occur while an aircraft is at a base facility, perhaps when it arrives into a maintenance hub, then the additional transportation of engines and components between the line and base facilities will be unnecessary, saving both time and money. It should be noted that unscheduled maintenance involving engine movement is relatively infrequent.

For the military, aircraft typically do not have to run schedules as complicated as that of commercial aviation. Fighters and bombers generally take-off from and return to the

\textsuperscript{4} Usually, airport locations that an aircraft lands at have varying levels of maintenance capability, but they can be generally divided into either line or base maintenance. Scheduling is usually done to ensure that aircraft arrive at these locations at appropriate times during its lifecycle. Maintenance routing will be further discussed in Section 5.1.1.
same base, FOL, or carrier, where I-level support is co-located. Hence, for a range of scheduled and unscheduled maintenance repairs, there is almost no delay in terms of transportation. This is shown in Figure 10 as transitions between sorties and line/intermediate maintenance.

![Diagram](image)

Figure 10: Military Maintenance Transportation Flow

Transport aircraft, on the other hand, may need to fly to and from a variety of locations all over the world where maintenance support may or may not be present. In this case, "en route maintenance is conducted opportunistically by the onboard crew chief, by local personnel (when qualified), or by mobile repair teams" (Ramey, 1999). Supply of replacement parts are typically provided by Forward Supply Locations (FSLs) dispersed around the world, but general repair and overhauls are still conducted at bases in CONUS.

Depot-level maintenance for all aircraft is generally performed in CONUS. While this means that the military basically shares the same benefits of a vast network of maintenance stations all over the country, an important limiting factor is legislation. As previously discussed in Section 3.1, the USC Section 2466 of Title 10 limits the DoD from outsourcing more than 50% of depot maintenance to the private sector. The rationale behind this ruling is that the military needs to maintain "core work" in public, government-controlled depots to handle mission-critical tasks.

In terms of transportation, this basically means that engines and components need to be transported to centralized depot locations for repair and overhaul. While it was advantageous for fighters and bombers to always return to the same base after a sortie for I-level maintenance, depot maintenance would always require transportation of engines
or components, irregardless of whether it is scheduled or unscheduled. This link between line/ intermediate maintenance and the depot is depicted in Figure 10 as well. For forward-deployed units and sometimes transport aircraft, this need to transport items back to depots in CONUS exacerbates delays due to the distance between their locations and CONUS.

Either system has its advantages and disadvantages. Because the military system has I-level support at the base, aircraft have access to repair capability after each and every sortie, whereas this is generally not the case for commercial aircraft. The military system is structured in this way so that I-level support, which is small enough, can be deployed along with units on expeditionary operations. Currently, I-level support can be set-up in forward locations within 30 days (Amouzegar et al, 2002). The commercial system may not be as good in this respect, but due to the nature of commercial aviation, there is no need for such a capability in the first place. In commercial aviation, a large part of MRO is optimizing scheduled maintenance, and the military can make use of some practices for peacetime operations.

To emulate the commercial system, the military could explore the possibility of scheduling sorties that land at the depot for scheduled engine repair and overhaul. Such a structure would resemble that shown in Figure 11. This arrangement could minimize transportation delays associated with scheduled depot maintenance. An engine change could be performed at the depot so that the aircraft can be returned into service with minimum downtime, and also allow the depot to keep hangar facilities to a minimum. Naturally, depots would then need to be equipped with landing and take-off support facilities. This then lends itself to the possibility of having a combined depot-base facility, where it can function as a sort of maintenance hub for the military. The dotted transition from the depot to sorties represents the possibility that an aircraft is returned to its home base before being deployed again, as opposed to being assigned directly from a depot-base facility.
The unscheduled movement of engines and components remain as before, and corresponding delays can still be expected. To reduce these delays, either the occurrence of unscheduled maintenance, or the transportation time between the line and depot, need to be reduced. Greater engine reliability or better prediction of malfunctions via DPCM tools can help reduce the frequency of unscheduled maintenance. DPCM and monitoring engine life consumption are discussed in Section 5.1. Reducing transportation times can be achieved by making use of airlift or increasing the speeds of sealift vehicles (in the case of deployed carriers). Strategic deployment of support facilities or ships in forward areas, instead of in CONUS, can also help by reducing the distance between deployed units and depot-level capabilities.

**4.2.2 Bringing the Engine around the Shop**

It has been mentioned that the only process that adds value in a repair pipeline is the actual repair of the engine. All other activities do not add value, and should be minimized or eliminated. Most of the time, transportation of components to a shop or depot is inevitable, but it should be minimized as much as possible.
Within the shop or depot, transportation should be minimized as well. According to data from the US Navy, the average time taken to receive and repair an item at a repair facility was 73 days. The study reported that because “functions such as testing, cleaning, machining, and final assembly are sometimes done at different locations at the repair facility… parts could be handled, packaged, and transported several times throughout the repair process” (GAO, 1996). One item examined in an investigation took 232 hours to go through the system even though only 20 hours was needed for actual repair. Looking at this, it would be logical to find a way to reduce the need for transportation.

One method that has been used by some commercial airlines is cell-based repair. Cell-based repair brings all the resources necessary, such as repair and testing equipment, manpower, and spare parts (inventory), to a single location, so that the engine or component need not be moved from place to place for all repairs to be done. The same GAO study (GAO, 1996) found that one airline reduced average repair times by about 50% to 60% after adopting the cell-based approach.

The cell-based approach also brings the equipment to be repaired to the same location. This reduces delays and manpower, because the broken engines or components need not be separately stored in a warehouse to await repairs. It also gives a sense of visibility of work-in-process, thus increasing the sense of urgency for maintenance personnel.

The cell-based approach shares underlying concepts with a Lean production system where transportation and movement (people) times are minimized to eliminate time wastage. Lean or Just-In-Time systems are discussed further in Section 5.2.1.
Chapter 5: MRO Management

5.1 Maintenance Scheduling

5.1.1 Maintenance Routing

For a commercial airline, fleet assignment is typically a complex problem that involves detailed origin-destination market analysis, spill and demand modeling, network optimization, hub network scheduling and more. A tremendous amount of effort is usually put into optimizing the type and size of airplane, and frequency of flights between two airports. Operational and marketing considerations aside, the maintenance of an aircraft needs to be taken into account as well.

Although a certain type and size of aircraft may be assigned to fly between two airports, it is usually not the case that the same airplane flies back and forth. Normally, maintenance scheduling would require an airplane to fly certain routes so that it will be able to land at airports equipped with necessary maintenance capability at scheduled times in its operational lifecycle.

<table>
<thead>
<tr>
<th>Checks</th>
<th>Approximate Frequency</th>
<th>Estimated Duration</th>
<th>Possible Engine Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-flight/Gate</td>
<td>Every departure</td>
<td>40-60 min</td>
<td>Visual checks, LRUs</td>
</tr>
<tr>
<td>Turnaround</td>
<td>3-5 days</td>
<td>Overnight</td>
<td>Visual checks, LRUs</td>
</tr>
<tr>
<td>A check</td>
<td>2000 flight hours, 4 months</td>
<td>Overnight</td>
<td>LRUs, engine change if necessary</td>
</tr>
<tr>
<td>C check</td>
<td>6,200 flight hours, 12 months</td>
<td>3-5 days</td>
<td>System checks, minor component repair, engine change if necessary</td>
</tr>
<tr>
<td>D check</td>
<td>30,000 flight hours, 72 months</td>
<td>1 month</td>
<td>Off-wing maintenance, repair and overhaul</td>
</tr>
</tbody>
</table>

Table 1: Typical Scheduled Check Cycles (adapted from Goh, 2003)

Table 1 summarizes typical maintenance checks that a commercial aircraft may undergo throughout its lifecycle, and some corresponding engine maintenance activities that might
be performed. These schedules could vary substantially between different airlines, airplane and engine models, and are also influenced by routing limitations.

According to such a schedule, an airline manager will need to route the aircraft through different locations where maintenance stations have the appropriate capabilities to support maintenance of the appropriate aircraft. Table 2 shows a typical classification of maintenance stations, and the corresponding capabilities of each station. If a hypothetical airline only flies to these destinations, then it would want to plan for its aircraft to land at SFO every 6 years, at either ORD or SFO every year, at SEA, ORD or SFO every 4 months and so on. Normally, to allow equal wear and tear across the fleet, airlines will route their aircraft through cycles, where the plane repeats its route every few days. Then another aircraft of similar class size will “follow behind”. For example, an aircraft that (hypothetically) flies through the five stations in turn, SFO – ORD – SEA – AKL – BKK – SFO, will have a similar plane starting from BKK, then going through SFO – ORD – SEA – AKL and ending in BKK. Behind that plane, there will be another starting and ending at AKL and so on.

<table>
<thead>
<tr>
<th>Station</th>
<th>Category</th>
<th>Preflight</th>
<th>Overnight</th>
<th>A check</th>
<th>C check</th>
<th>D check</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFO</td>
<td>1</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>ORD</td>
<td>2</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEA</td>
<td>3</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AKL</td>
<td>4</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BKK</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Maintenance Station Classification (adapted from Hessburg, 2001)

The military uses a similar concept for periodic maintenance, except that it is not complicated by fleet assignments and scheduled routes. The equivalent of up to the commercial C check can normally be done with I-level support at the base, and D check equivalent maintenance is sent to the depot. As discussed previously, commercial

\[5\] The airport codes presented correspond to: SFO – San Francisco, ORD – Chicago O'Hare, SEA – Seattle/Tacoma, AKL – Auckland, New Zealand, BKK – Bangkok, Thailand
aviation gains some transportation time savings by landing at appropriate stations for scheduled maintenance, and the military could look into scheduling flights to land at depots (perhaps as part of peacetime training) to reduce transportation time and cost.

5.1.2 Diagnosis, Prognosis, Condition Monitoring

Diagnostic, Prognostic and Condition Monitoring (DPCM) systems are fundamentally tools used by an airline’s maintenance organization to identify existing faults (diagnosis) and to predict impending failures of aircraft engines (prognosis). Based on accurate modeling and reliable algorithms, DPCM systems are highly useful in supporting efficient diagnosis of failures. Furthermore, safety is enhanced since the condition of an engine is monitored continually for potential hazards. Due to the possible benefits that DPCM systems can offer, it is actively developed and widely used by airlines and military services alike.

In order to diagnose or predict failure, the condition of an engine needs to be monitored as time goes by and flight hours accumulate. Much like monitoring the health of patients, DPCM systems look for symptoms in an engine’s performance in order to identify or predict malfunctions or failures.

![Figure 12: Gas Path Analysis Principle (Volpini, 2003)](image)

There are a variety of DPCM methods currently employed and researched. One technique that is widely used is Gas Path Analysis (GPA) (Volpini, 2003). The underlying concept of GPA is shown in Figure 12. As an engine experiences wear and tear, or if it becomes
damaged, characteristics such as mass flows and efficiencies will change. This degradation in performance will in turn affect observable engine parameters taken along the engine’s gas path, such as temperature, pressure, speeds and fuel flows. Faults are deduced when measured parameters deviate from regular values. By comparing the parameters to previously established trends, possible causes can be isolated, helping maintenance personnel isolate the cause of faults and malfunctions.

GPA is an example of a model-based approach to DPCM. Fundamentally, the approach makes use of the difference between measured quantities and predicted quantities derived from a mathematical model of a healthy engine. A significant difference implies a faulty engine, and subsequent methods are then employed to isolate the fault, using information given by the quantities measured. Other model-based approaches usually involve different methods of comparing observed characteristics with the idealized model. These methods include the parity space approach, dedicated observer approach, principal component analysis, parametric statistical approach, and parameter identification approach (Grodent and Navez, 2003). A brief description of these methods may be found in the appendix.

Another novel approach to DPCM makes use of Artificial Neural Networks (ANN) (Mathioudakis, 2003). ANNs are information processing structures modeled after the human nervous system. ANNs “learn by example”, and may be trained for tasks such as pattern-recognition for fault diagnostics, and modeling engine performance. The training of ANNs requires a large database of inputs and associated outputs. These can be obtained from mathematical models, experimental data from the engine, or from data obtained throughout the lifecycle of the engine. With adequate training, ANNs allow DPCM systems to efficiently diagnose engine faults.

The various DPCM tools are generally used in three different settings: in-flight, on ground-based stations, and in the MRO shop (Goh, 2003). In-flight systems function in real-time, and alert the flight crew of anomalies detected during flight, allowing the flight
crew to take adequate corrective action. This greatly enhances safety, and also helps to extend engine life. Information obtained in-flight may also be transmitted to ground-based stations before landing, so that line maintenance personnel will have lead-time to get ready any equipment necessary (such as LRUs) for quick turnaround of aircraft. For example, Honeywell provides an aircraft maintenance and operations support system (AMOSS), which uses information transmitted from the aircraft’s in-flight diagnostic systems to uncover maintenance problems so that ground stations can be prepared before the aircraft arrives (Careless, 2002).

Ground-based systems are normally operated by line maintenance personnel to monitor engine condition, helping to ensure continued airworthiness, as well as detecting any impending failures that need corrective action. Knowledge of impending failures is also helpful in giving maintenance management lead-time to order appropriate spares, and also helps the scheduling of future maintenance activities. Furthermore, by being able to predict failure, there will be less occurrence of unscheduled maintenance. This makes the regulation of a scheduled maintenance program easier, and facilitates smoother operations.

In the MRO shop, DPCM tools are mostly focused on fault diagnostics. Here, DPCM tools greatly assist in lightening the cognitive workload of maintenance personnel, permitting higher efficiency and shorter overall repair times.

5.1.3 Monitoring Engine Life Consumption

Monitoring engine life consumption is different from DPCM activities. While DPCM systems aim to identify malfunctions or engine failures by symptomatic analyses, monitoring life consumption deals with monitoring structural fatigue of engine life-limited components, such as compressor and turbine disks, primarily by detection of cracks and their propagation.
Tracking the lifetime usage of parts can be done in a number of ways. The simplest method is just to record the number of hours flown. An improvement upon that is to record the number of cycles that the engine goes through based on hours flown and the mission profile. Here, it is important to note that commercial and military aircraft exhibit significant differences. The flight profile for a commercial aircraft is almost always a take-off, cruise and landing cycle. However, military aircraft experience increased cycles due to maneuvers such as touch and go, airdrops, loaded turns and so on. According to the different missions, a cycle per hour rate is normally derived, which can then be used to estimate the number of cycles the engine has gone through.

Since the early 80s, electronic controls have been developed and introduced into aircraft engines, and this had direct benefits for efforts in monitoring engine life, since the data required could be provided by the necessary instrumentation for electronically-controlled engines. This facilitates on-board collection of data, such as the number of cycles or amount of time that the engine exceeded a certain temperature. This data can then be downloaded into ground-based systems for record-keeping and analysis after each flight. More advanced systems can collect and store the data in on-board computers, keeping track of all engine configurations and parts lives.

Given usage data, there are basically two approaches to managing the life of an engine. The first is a “safe life” or “hard time” approach. In this approach, engine components are considered to have failed as soon as an initial crack appears, so the policy aims to retire or replace them before that happens. Parts are replaced and maintained solely according to the number of flight hours or cycles accumulated. The second approach is “damage tolerance”. Here, engine components are inspected after a number of flight hours or cycles, and allowed continued usage as long as the size of a crack is within safe limits. Once the size of the crack propagates to a pre-determined level, the component will be replaced. In both cases, the life or crack-size limits of the components are usually determined through a combination of analytical studies and testing.
Commercial aircraft engines adhere to safe-life procedures, as regulated under FAR Part 33. The military services' procedures are regulated by corresponding Milspecs. The US Navy follows the safe-life approach as well, but damage tolerance standards have been introduced since 1995. The Air Force practices damage tolerance.

Each approach has its pros and cons. In the "safe life" approach, minimal maintenance is required, since parts are replaced as soon as they reach their life limits. With a reduced need for inspection, the engine remains on-aircraft longer, and additional infrastructure and equipment for inspections are not necessary. However, components are almost always retired prematurely, wasting functional life. Also, a large inventory is generally needed to support more frequent replacements.

The damage tolerance approach reduces wastage, and maximizes the life of components. This minimizes inventory needs. As inspections for crack propagation proceeds, maintenance personnel will have a good idea of the remaining life of parts, allowing sufficient lead-time to restock inventories. In the process of certifying the engines and components in accordance to damage tolerance standards, designs are more comprehensively developed, tested and understood, which greatly improve safety, and also provide more data in support of future designs or upgrades.

However, components designed to these standards would normally be heavier in order to achieve the level of durability required. Additional costs are also required for additional design, development and testing work, as well as for the infrastructure and equipment to support the inspection program. As inspections increase in frequency, so does off-wing time.

5.1.3.1 Optimizing Work-scope at the Shop

A recent NATO study (NATO, 2000) investigated the relationship between material cost per shop visit and cost per engine flight hour for the commercial CF6-80A engine used
on the Airbus A310. The result is presented in Figure 13: as the net material cost per shop visit increases, the overall cost per engine flight hour decreases dramatically.

![Work Scope - Value Relationship](image)

**Figure 13: Optimizing Engine Flying Hours Cost (NATO, 2000)**

Simply put, the results show that it is more economical to repair and replace more life-limited parts per shop visit. Rationally, the underlying reason for this is that because more parts are replaced or repaired each time, the engine does not need to be taken off-wing and sent to the shop as often, saving both time and transportation costs. Furthermore, the engine does not need to undergo the time-consuming and labor-intensive disassembly and assembly as frequently, contributing to more efficient operations.

The idea behind this is synchronization of replacement schedules. Synchronization does not only apply to replacements, it can also be applied to major maintenance work. Commercial airlines often delay upgrades and modifications of airframes or engines to coincide with the heavy D check every 6-7 years, saving substantial effort by not repeating the teardown and disassembly work.
In order to be able to follow such a schedule, the various components and parts of the engine, such as turbine and compressor disks, need to have synchronized lifetimes. This undoubtedly depends on the design of the engine and life-limited parts, and is an important consideration that should be incorporated during the design of future engines or for upgrades of existing models.

With existing infrastructure and equipment, the military can make use of a combination of safe-life and damage tolerance policies to adjust component lifetimes such that they are synchronized. In other words, part replacement schedules could be brought forward or deferred (subject to damage tolerance limits), so that as many parts as possible are replaced in a single shop visit. Nevertheless, the potential savings here must be weighed against the cost of any potential waste of component lifetime.

Commercial airlines could explore this possibility as well; however, significant investment in additional equipment and skilled labor, along with regulatory restrictions pose considerable obstacles. If regulations do change, possibilities exist for airlines to make use of inspection infrastructure that exists in public depots. Although the military regularly outsources work to the private sector, the reverse has never been done. Discussion of public and private sector work has been presented in Section 3.1.

5.1.4 Deferred Maintenance

In accordance with established regulations outlined in the FARs, commercial airlines are allowed to defer repairs on a range of non-critical items to a later time. The primary reason for this is to allow airlines to continue flight operations with minimal disruptions until the part can be replaced or repaired at a better-equipped base or when there is more time at hand. Such a list outlining minimum required functional equipment is called a Minimum Equipment List (MEL).
The FAA publishes Master Minimum Equipment Lists (MMEL) for each large aircraft type. The MMELs are based on the aircraft OEM's initial recommendations and refined with inputs from operators and public stakeholder groups (such as unions or foreign regulatory bodies). However, the MMELs are not designed for operational use, and individual operators are required to draft and seek approval for customized MELs based on the MMEL for each aircraft type. Further information regarding the regulatory framework governing MELs may be found in Hessburg (2001).

For both commercial and military operations, deferring maintenance has the benefit of improving aircraft availability during time-sensitive periods, allowing repairs to be completed during other “non-peak” periods. In the absence of appropriate spare parts, ordering and waiting for parts increase logistical delays. However, when repairs are deferred, aircraft can continue to fly while maintenance management plans ahead by rerouting planes to where spares might be, or moving spares to where the planes will be in the scheduled operational plan. Also, as described previously, consolidating repairs for different parts increases efficiency, and deferring repairs to synchronize repair times can afford potential cost savings. By allowing airplanes to get to better-equipped repair facilities, and also to better-skilled personnel, the chance of maintenance error is also decreased. On top of that, if repairs are deferred to a less time-sensitive period, the absence of time pressure also helps to reduce maintenance error. This not only enhances safety, it also enhances longevity of the engine, and reduces maintenance actions in the long-term.

Nevertheless, deferring maintenance has a flipside. Generally, maintenance deferrals increase the chances of something going wrong. In order to ensure that safety is not compromised, it must be emphasized that only non-critical equipment should have maintenance deferred. Even so, non-critical items must not have maintenance deferred indefinitely – They must be repaired eventually, and within specified time limits. Wartime considerations (and the willingness to take greater risks) aside, regulations and approved procedures need to be enforced by respective authorities to make sure that
deferred maintenance is practiced within specified boundaries, and that safety remains the top priority.

5.2 Inventory and Supply Management

Inventory management is a crucial aspect of all production operations. For engine maintenance, inventory management is mainly directed at off-aircraft maintenance, which is very similar to production and manufacturing operations. In these operations, a key problem has always been providing the right parts at the right place and at the right time. In the case of factory production chains, a machine may need parts from a supplier or parts output from a previous machine in order to complete its work. In the case of a mechanic working on engine repair, he or she needs the appropriate spare and consumable parts to complete his or her work. Without the right parts, repairs or production cannot proceed, and time is hence wasted waiting for parts to arrive.

To illustrate the extent of the problem, it is reported that “despite reporting $10.5 billion dollars in appropriations spent on spare parts since fiscal year 2000, the Air Force continues to report shortages of spare parts” (GAO, 2003). In the same report, it was presented that the Air Force has a total budget request of $5.3 billion for spare parts in fiscal year 2004 alone.

Inventory management has been the focus of much study both in academia and business, and three dominant approaches have generally been adopted: Manufacturing Resource Planning (MRP II), Lean or Just-In-Time (JIT), and Theory of Constraints (TOC).

5.2.1 Manufacturing Resource Planning

MRP II, as the name suggests, is built up from more traditional Material Requirements Planning (MRP) systems. Typically, MRP relies on “a master production schedule, a bill of materials listing every item needed for each product to be made, and information on
current inventories of these items in order to schedule the production and delivery of the necessary items” (Womack and Jones, 1996). On top of that, MRP II incorporates capacity and financial planning tools, and simulation tools to assist judgment of alternative production plans.

Fundamentally, MRP and MRP II rely on forecasts and predictions of future demand and production in order to assess inventory requirements. These forecasts are usually made on the basis of past experience and extensive statistical analyses. In the context of maintenance planning, orders for spare and consumable parts are made according to component lead-times, breakdown and repair rates, predicted demand and so on. Because MRP and MRP II rely heavily on forecasts, they are very useful for schedules that are stable and exhibit little variation with changing environments. On the other hand, MRP and MRP II are generally ill-suited to handle fluctuating demands, changing usage patterns and rates.

5.2.1.1 Forecasting Demand and Stocking Parts

In general, attempting to predict the future has been a significant human pre-occupation. In business, organizations attempt to predict market demand and financial costs, and analysts attempt to predict stock market performance. In government, forecasts need to be made for purposes of budget allocation. In technical applications such as MRO, we try to predict fatigue lifetimes, engine condition, production times and even workloads to estimate manpower requirements. In the case of inventory management, attention has primarily been given to predicting demand for spare and consumable parts.

Ideally, accurately predicting the demand for spare and consumable parts will allow inventories to be stocked with appropriate amounts of parts so that repairs will not be delayed. The more accurate the prediction, the less money spent on purchasing excess inventory just-in-case, and the less time an engine or aircraft is spent waiting for spare parts to arrive. However, the world is not deterministic, and forecasts generally rely upon stochastic analyses based on mathematical models, algorithms and simulations that
approximate real-world behavior. The more accurate and reliable these estimations are, the more accurate predictions will be.

A recent study by the National Defense Research Institute (Fricker et al, 2000) that investigated inventory management strategies for the Marine Corps highlights some important problems. It was found that parts were available for repair from local (flight line or I-level) inventory about 60%-70% of the time, which was a fairly high percentage. However, because repairs almost always require more than one part, the probability of having all the required parts in the local inventory is about \((0.6)^n\), where ‘n’ is the number of parts required. The likelihood of having all the required parts available to conduct repairs reduces dramatically as the number of parts required increases. When a part is unavailable from the local inventory, it would be ordered from the wholesale system, which is the inventory kept by a central logistics organization that acts as a supplier. When this happens, delays result due to the processing and shipping time required. Because repair depots also receive supplies from the wholesale system, they face similar inventory issues as the bases.

Hence, a major objective of better forecasting is to raise this probability of availability at the local inventory. One major problem pointed out in the Marine Corps study is the use of mean or average demand in the methodology to determine the amount of spare and consumable parts that should be kept in the local inventory. Traditionally, a classic probability distribution such as a Poisson, binomial, or negative binomial distribution is commonly used to characterize the demand of parts (Fricker et al, 2000). However, empirical data rarely follows these distributions, and an alternative “bootstrap” method is proposed. This empirically-based method was first developed by Brad Efron (1979), and essentially, what it does is to form a demand distribution based on empirical data during the lead time after the order of a part. Focusing on the lead time is sensible because the minimal amount of inventory needed is the amount required to sustain repair activity before new stock arrives. It then ties this distribution to the risk of stock-out (unavailability of a part), so that the amount of inventory kept is increased (according to the distribution) as the acceptable risk of stock-out decreases.
Fricker et al (2000) further advocates the use of unit cost as a variable to determine the amount of inventory. This proposition is motivated by the discovery that delays were sometimes caused by the unavailability of very inexpensive parts (i.e. less than $10), even though other very expensive parts (i.e. more than $10,000) were available. In general, cheaper parts can be stocked more liberally, while expensive parts should be stocked more carefully. In other words, the more expensive a part is, the greater the demand required for the part to be stocked, and vice-versa. A combination of this methodology with “boot-strapping”, where the acceptable risk of stock-out rises as the price of the part increases, was found via simulation to be very effective in increasing the availability of parts, while decreasing inventory levels.

However, this method does not suitably quantify the relative impact of delays should a part be unavailable. In other words, the acceptable risk is tagged to the unit cost and not to the time delays that the unavailable part would cause. A useful idea proposed by Brauner et al (1994) suggests the use of “value” of a part as a metric to determine the importance of a part. The definition of “value” is “how much the part contributes to shortening the repair time of the end-item that uses it” (Brauner et al, 1994), and it attempts to quantify the value of a part in terms of both time and money. A part with a long lead time will delay repairs longer than a part that has a short lead time, so its time-value will be higher. Also taking into account the expected demand of the part, the time-value is converted into a monetary equivalent, and comparing it to the unit cost of the part will give a measure of the value or return on investment associated with the part. Instead of unit cost, this measure of “value” more adequately characterizes the importance of each part, and it can be used with the “boot-strapping” method, such that acceptable risk goes down as the value of the part goes up.

As outlined earlier, the objective of inventory and supply management is to provide the right parts, at the right place and at the right time. At this point, it should be apparent that MRP, MRP II and methods for forecasting demand concentrate primarily on determining the right number of parts to be stocked at the right place (the local inventory). Timing is
important, but not emphasized. In the following section, however, the importance of timing will be highlighted.

5.2.2 Lean and Just-In-Time Systems

In relatively recent years, the idea of Lean production has transformed the manufacturing process. As opposed to mass production, Lean focuses on small-batch production and eliminating waste in order to minimize the time it takes each product to be manufactured from raw materials to final product. According to the “founder” of Lean concepts, Taiichi Ohno⁶, there are seven types of waste in production: defects, overproduction, inventories, unnecessary processing, unnecessary movement of people, unnecessary transport of goods, and waiting (Womack and Jones, 1996). Inventory is wasteful, hence the idea of Just-In-Time (JIT) systems.

In essence, JIT systems aim to deliver or produce the right parts in the right amount at just the right time, such that there will not be a need for inventory. This is normally accomplished via a “pull” system, where the signal to begin a production process is initiated by the customer (Womack et al, 1990; Womack and Jones, 1996). By producing only in response to customer orders, inventory is minimized, and there is no overproduction. Production rates can therefore also change rapidly according to fluctuating demands. In order to achieve rapid production and delivery times, a Lean system generally cuts movement and transportation time by locating machines, people, parts, equipment, and suppliers in close proximity for optimal flow. Also, each product is moved from machine to machine and process to process, with as little interim storage and waiting time as possible.

The minimizing of inventory in JIT systems make them relatively fragile, since any problems associated with manpower, operations, supplies and the organization tend to

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⁶ Taiichi Ohno (1912-1990) was a “production genius” that contributed to the Toyota Motor Company’s (Japan) soaring success. In the 1950s, he experimented with and developed new production methods in response to the success of mass production in western nations. The term “Lean production” was coined in the 1980s by researchers in MIT’s International Motor Vehicle Program. Refer to (Womack et al, 1990).
have significant effects on the flow of the whole system. On the other hand, this is good because it exposes inherent systemic problems (Sale and Inman, 2003), and motivates the need for a healthy, open organization culture, as well as the need for high quality work standards. A well-tuned Lean production system can dramatically cut costs and increase efficiencies, and many examples of successes abound.\(^7\)

Since off-aircraft maintenance operations are very similar to production operations, many concepts from JIT production systems can also be applied. Reduced inventories and costs can be achieved by delivering the right spares and consumable parts in the right amount at just the right time. To do this, parts should only be ordered and stocked in response to repair orders. This is in direct contrast with Just-In-Case inventories, where parts are kept in anticipation of predicted demand, which may or may not materialize. To achieve rapid repair times, a cell-based approach that locates machines, equipment, people and parts in the same facility can be implemented. A high-velocity infrastructure will also contribute significantly to reducing inventory and cost.

5.2.2.1 High-Velocity Infrastructure

The two main components of inventory management are “the parts requirement and the time to get the parts” (Brauner et al., 1994). As mentioned in Section 5.2.1, MRP focuses on the determining the right number of parts. It tries to maintain the minimal amount of inventory necessary to sustain repair operations until new stock arrives. Theoretically, if this lead time can be reduced to zero, then there will be no need for any inventory. In practice, inventory cannot be reduced to zero, because supplies are not delivered instantly. Suppliers need some amount of lead-time to deliver components and parts, so the best possible scenario is to minimize this lead time so that only a minimal inventory is necessary to support daily operations.

Developing a high-velocity infrastructure, where suppliers are able to deliver parts quickly, contributes greatly to reducing lead-time. An Air Force study (Ramey, 1999)
evaluated the effect of having a high-velocity logistics infrastructure, and results were consistent with documented performances of Lean production systems: Inventory requirement is reduced, and the system was less affected by variations in demand. Orders to replenish supplies also need to be made as soon as parts are used; otherwise, the advantage gained from quick transportation would be lost through delayed ordering. Automated information systems, such as Point-of-Sale barcode scanning systems, already exist to help in this area. Depending on the application, Lean systems have been known to receive supply shipments daily or even a few times a day. Depot maintenance re-supply intervals will likely be longer due to the longer time for each engine or component overhaul and repair.

Instead of ensuring that parts are transported quickly from the supplier to the MRO shop, suppliers could be established in close proximity to the MRO shop, so the distance that parts need to be transported is reduced in the first place. Dell Computer Corporation does this by ensuring that all its suppliers are within two hours of its assembly factory. Coupled with strong integration of operations with its suppliers, Dell is able to maintain minimal inventory, while shipping customer orders within hours.

Besides reducing the time it takes to obtain spare parts, a high-velocity infrastructure should also be implemented to encompass the transportation of components and engines to the repair depot or MRO shop. Studies conducted for the Air Force and Navy pointed to the enhanced responsiveness and decreased turnaround times that are possible by having shortened transportation pipelines between deployed units and repair facilities (Brauner et al, 1992; Abell, 1993). This can be brought about by faster transportation vehicles, setting up maintenance facilities closer to deployed units, and sending unserviceable items for repair immediately after it has been removed from the aircraft.
5.2.3 Theory of Constraints

Somewhere in between the concepts of MRP, MRP II and JIT systems lies the Theory of Constraints (TOC). While TOC also champions the reduction of inventory levels, it argues that inventory is not wasted if it provides buffers for constraint activities (Sale and Inman, 2003; Blackstone, 2001; Gupta, 2003). For example, in a system with a number of concurrent processes, some activities could take longer than others, such that the final processing time depends on the rate of these activities. Such activities can be identified as “bottlenecks” or constraints. In other fields such as chemistry, this is a similar idea to a “rate-determining” step in a chemical reaction. It should also be pointed out that TOC concepts bears resemblance to Critical Path Methods (CPM) and Performance Evaluation and Review Techniques (PERT) often used in program management, where bottleneck activities are activities that lie on the “critical path”.

Since final processing time ultimately depends on these constraint activities, TOC advocates that buffers (inventory) should be maintained in front of these activities, so as to minimize delays. Other than that, inventory should be eliminated for other non-constraint activities (activities not on the critical path), since they effectively have capacity or schedule buffers. Besides providing inventory, TOC also advocates the focusing of resources on constraints.

For depot maintenance, among interdependent activities such as inspection of engine condition, transport of supplies, transport of broken components, diagnostic and repair work, and delivery of repaired items, constraints could be identified at various points in the flow, depending on the context. For example, in commercial engine repair and overhaul, engine repair intervals are sufficiently long, and transportation of parts and broken components may be sufficiently quick, such that diagnostics and troubleshooting may be a constraint that contributes more significantly to total downtime. For naval carriers deployed in the Pacific, transportation of broken items back to depots in CONUS may be the constraint, such that other tasks such as the transportation of spare parts and allocation of manpower may be done within the time the items take to arrive at the depot.
For I-level maintenance within bases in CONUS, repair times may be sufficiently low, and no transportation may be needed for broken items. In this case, the total repair time may be dependent on the availability of spare parts, and keeping adequate levels of inventory may be justified.

### 5.2.4 Cannibalization and Lateral Supply

Cannibalization and lateral supply are management adaptations in supply management, to achieve availability goals in the event of supply chain deficiencies and shortfalls. Cannibalization is the process of removing a working piece of equipment from a next-highest assembly, to use as a spare part in the repair of another piece of equipment. It is predominantly a practice in the military, and is performed to meet the demand of operational goals. Lateral supply is similarly a military practice and is the process of obtaining spare parts from other organizations at a similar hierarchical level (hence the term "lateral").

Cannibalization has been shown to be relatively effective in increasing the availability rate of aircraft (Abell, 1993; McLennan, 1995), and is a useful practice to make up for supply shortages; however, there are many negative effects that arise. These negative effects include increased workloads of maintenance personnel, adverse effects on personnel morale, un-usability of expensive assets, and the potential for mechanical side effects (GAO, 2001). Cannibalizations increase workloads because the number of maintenance actions required is twice as much as using a new part from the inventory. Instead of obtaining spare parts off the inventory, cannibalizations require maintenance personnel to disassemble the next-highest assembly, remove the required part and reassemble the next-highest assembly before a part is available. As a result of these actions, personnel also lose morale because of the increased hours needed to accomplish maintenance tasks. The increased number of maintenance actions also increases the chance that errors will be made, resulting in safety and functional issues. Typically, an aircraft that has been designated as the “target” for all cannibalization actions is called a
“hangar queen” or “Christmas tree” (McLennan, 1995). These “hangar queens” that have a large number of parts missing are expensive assets that remain unusable for extended periods of time. According to a GAO study (2001), one Navy wing had 6 out of 28 aircraft grounded for 37 days or more because of missing parts. “One of these aircraft had not flown for more than 300 days and... was missing 111 parts... [It was] estimated that it would take more than 1,000 maintenance hours to return the aircraft to flying status” (GAO, 2001).

Similarly, lateral supply has been shown to effectively increase aircraft availability rate (Abell, 1993). Compared to waiting for parts to arrive from CONUS or similar supply bases positioned in central locations, forward-deployed units can obtain spare parts available from other units that are closer, reducing delays associated with transportation. Fundamentally, lateral supply pools the resources of similar units together, allowing parts to be moved from lower priority locations to where they are most needed. Units supplying the resource will need to obtain replacement parts from the supply base, but it is assumed that they can afford some delay, because the part in question is not needed immediately. In a similar fashion, commercial airlines reap benefits by setting up a common inventory to reduce duplication across airlines. However, a difference between airlines and military units is that separate military units still function under a common objective, while separate commercial airlines may face obstacles in such collaboration due to competitive pressures.
Chapter 6: MRO Manpower

This chapter aims to present best practices that can be applied at the “workers” layer in the hierarchy of the complex socio-technical MRO system. While not exhaustive, the objective is to outline efforts in various fields to gain a broad understanding of what contributes to the success of the system.

6.1 Organization Culture: High Performance Relationships

Southwest Airlines is an outstanding airline, posting profits for the past 32 years, when all other airlines struggle to stay afloat in a fluctuating and difficult market. Many theories and studies have sought to uncover the reasons behind their success, analyzing their business model, operational as well as organizational factors. In particular, one study conducted over eight years has revealed that a major factor in Southwest’s success has been the effect of “High Performance Relationships”.

This study by Gittell (2003) points to a strong correlation between high performance and the degree of “Relational Coordination” within an organization. As defined by Gittell, Relational Coordination is characterized by six dimensions:

1) Shared Goals – Employees work towards a common goal.
2) Shared Knowledge - Employees have a clear idea of their role in the overall system, as well as how they are linked to others
3) Mutual Respect – Functional divisions or departments understand how each division contributes to the success of the system; no one is taken for granted.
4) Frequent Communication – Information is constantly shared and dispersed to everyone involved.
5) Timely Communication – Information is given and shared in a timely manner.
6) Problem-solving Communication – When problems occur, employees communicate and work together to uncover the cause and to learn from it, instead of assigning blame.
The first three are measures of underlying relationships, which affects communication patterns outlined by the last three, and vice-versa. The study further outlines ten organizational practices that can be learned from Southwest:

1) **Lead with Credibility and Caring** – Organization leaders need to establish credibility and trust, so that workers feel their well-being is taken care of.

2) **Invest in Front-Line Leaders** – Higher staffing levels of supervisors at the front-line fosters better, meaningful relationships, and better information flow to higher organization levels.

3) **Hire and Train for Relational Competence** – Employees with higher relational competence can work better and integrate their work with others, enhancing coordination in the organization.

4) **Use Conflicts to Build Relationships** – Conflicts are inevitable, so formally resolving and learning from conflicts will prevent them from getting worse, and enhance relationships.

5) **Bridge the Work/Family Divide** – Good family and community relations can bring energy to the workplace and vice-versa.

6) **Create Boundary Spanners** – Boundary spanners are people who coordinate work across functional divisions, enhancing performance and relationships.

7) **Measure Performance Broadly** – Dividing measurement of performance into functional departments creates a culture of finger-pointing. Cross-functional performance measurements are more effective in encouraging communication across groups.

8) **Keep Jobs Flexible at Boundaries** – Keeping jobs flexible allow focus on broader characteristics of success instead of just specific tasks. It allows better distribution of workload and manpower utilization, as well as enhancing relationships between functional groups.

9) **Make Unions Your Partners** – The quality of the union relationship, not the level of unionization, determines organizational performance. A partnership with unions can build on shared goals and develop strong ties between employees.
10) Build Relationships with Key Suppliers – Building relationships and sharing information with key suppliers fosters shared goals between organizations, and greatly improves coordination and effectiveness.

![Diagram]

Figure 14: Ten Southwest Practices for Building High Performance Relationships (Gittell, 2003)

Figure 14 outlines the framework encompassing the six dimensions of relational coordination, and the ten organizational practices that help to develop these six dimensions. This framework has been developed based on studies in the airline industry,
but it is largely relevant to any other organization and to the MRO system as well. We shall make use of this framework to analyze possible practices that can be adopted to improve performance of the civil and military aircraft engine MRO system.

As outlined previously, the main goals of the MRO system are availability and safety at minimal cost. This is consistent with the high quality and efficient performance brought about by relational coordination; high repair work quality enhances safety, while efficiency improves engine availability and reduces costs.

*Leading with credibility and caring.* Leadership in any organization is integral to the culture that exists within the organization. In the 1920s, George Elton Mayo conducted experiments on human behavior in a factory production setting, revealing what is now known as the Hawthorne effect: Workers show increased performance when they know they are being cared for. The Hawthorne effect remains relevant in today’s work environment, and has been adapted in many guises in management theory.

Depending on whether the MRO organization is an in-house commercial MRO shop, 3rd party MRO shop, or public depot, the leaders might be an airline’s top and front-line management, the MRO firm’s CEO and shop managers, or the DoD and military’s leaders. Leaders should establish credibility and seek to gain trust from workers below them in the hierarchy by adequate sharing of information, an open attitude to feedback, as well as genuine concern for working conditions.

“Sticking together” and preventing layoffs during difficult times and restructuring retains jobs and instills trust and confidence in organization leadership. In return, workers have a psychological investment in the organization and will cooperate and work hard to pull the organization through. This is one key factor against outsourcing as a means to lower costs. Wherever possible, organizations should think twice about the decision to outsource, and look for alternatives. Nevertheless, as presented previously, outsourcing offers substantial economic benefits, and tradeoffs have to be made depending on the organization and its situation.
Investing in front-line leaders. As known in social psychology, proximity is a key factor in establishing meaningful relationships in any context. In the workplace, front-line leaders come into direct contact with workers on a daily basis, and thus have the greatest impact with regards to work relations. In an MRO context, shop managers and supervisors play this role, and are also especially important in ensuring that repair and maintenance work is completed properly, and safety is not compromised. Higher staffing levels not only build better relationships, it also spreads supervisory work out, contributing to lower chances of maintenance errors.

Hiring and training for relational competence. In the MRO environment, teamwork is as important as technical competence. Social competence is thus an important factor contributing to better communication, coordination and relationships among workers, supervisors and managers. It would be desirable to hire only socially adept individuals, but this is idealistic and not necessarily possible all the time. Where relational competence is less than satisfactory, training and teambuilding programs can offer a way to foster better relationships between workers.

Using conflicts to build relationships. Conflicts are bound to occur in any social setting. Being a complex socio-technical system, the MRO system is no different. Conflicts, if left unresolved, will remain hidden and grow serious enough to undermine relationships within or across working groups. Conflict resolution is more an art than a science, and management expertise goes a long way in handling such situations. However, organization policies can help by formalizing conflict resolution, encouraging workers to bring problems out into the open.

Bridging the work/family divide. Work and family are the two most important social groups for the average adult. Tension between commitments to work and commitments to family are potentially stressful for any worker, and negatively affects his or her well-being as well as work performance. Bringing the two groups together fosters supportive relationships between them, and gives intangible energy to workers. Bridging the divide is generally beneficial to any organization, and it not specific to airlines or MRO.
Creating boundary spanners. Cross-functional communication facilitates coordination across functional boundaries. In the MRO context, cross-functional coordination is necessary between the aircraft and pilots, flight operations and planning (schedules, routing), gate and line maintenance, intermediate maintenance, and base maintenance services. For most commercial airlines, the maintenance control center plays this role. It coordinates maintenance activities and events, obtaining and distributing information so that scheduled maintenance activities are conducted, and unscheduled maintenance tasks are taken care of. For example, pilots might inform maintenance control of a fault detected on board, and maintenance control would advise the appropriate course of action. Line maintenance may be informed of the fault in order to ready LRU s for replacement, or be prepared for repair work. More severe faults may require immediate landing, in which case maintenance control will arrange for base maintenance activities, as well as inform flight operations to make appropriate adjustments to the schedule.

Measuring performance broadly. When functional divisions are separately assessed on their performance, it creates an unhealthy competitive environment between working groups, and a tendency to assign blame to others when problems occur. By measuring performance broadly, a number of groups may be simultaneously “accountable” for success or failure, encouraging cross-functional communication and coordination. It also shifts the focus of problem causation away from individuals and towards the process, so workers will be more open in providing feedback and information.

In the MRO context, performance may be measured broadly by focusing on goals of safety, availability and cost, at the high, system level or at lower team levels. For example, at the system level, unsatisfactory availability levels as well as increased costs may be the result of delayed shipment of broken or repaired parts, inefficient repair processes at the base or depot, inadequate scheduling and planning, or inadequate sharing of fault information between the pilots and line maintenance or between line and base maintenance. In these instances, no individual is particularly responsible for delays, but processes within and between functional groups can be improved at various stages in the maintenance pipeline to reduce maintenance time and cost. At lower levels in the
hierarchy, team performance can be emphasized. An MRO shop could be assessed as a whole on repair turnaround times, so responsibility lies with all functional groups like the shop manager, supervisors and mechanics. If delays occur, it may be that the shop manager allocated work late or inappropriately, the supervisors did not provide enough guidance, the mechanics did not have enough training, or insufficient diagnostic tools were provided. By measuring performance broadly, processes rather than people come under scrutiny, and the different groups would be encouraged to coordinate better with each other to tighten up the complete act, rather than assigning blame to individuals.

Safety is also better assessed at a system level. Maintenance errors are frequently and conveniently attributed to mechanic error, but there are many factors beyond the mechanic’s actions that contribute to the error. Leveson (2004) argues that accidents need to be analyzed from a systems perspective in order to understand all the factors involved and to uncover the reasons why they occur. Doing so will avoid the practice of assigning blame, and facilitate the future design of safer systems. For example, mechanic error may be the “cause” of an accident, but unsatisfactory working conditions like insufficient lighting may have contributed to it. The mechanic might not have followed approved maintenance procedures; the supervisor may have failed in his or her role, and poor organization culture may have also contributed in condoning such practice. Performance in terms of safety is thus better reflected and measured broadly.

*Keeping jobs flexible at boundaries.* By keeping jobs flexible at the boundaries, focus is shifted from specific goals of individual jobs to higher level organization goals. Workers are given responsibility not only for their own specific tasks, but also general responsibility to help others in order to achieve collective goals. The cross-functional communication encouraged by this practice also helps to build relationships between functional groups. In the MRO system, this can be conceived as a blurring of boundaries between maintenance levels. Line mechanics could help the gate mechanics with certain tasks with the objective of dispatching the plane quicker, shop personnel could lend diagnostic expertise to line maintenance where necessary and so on.
In the military, the line and I-level functions are usually co-located and cross-functional assistance is already common. In other instances, I-level maintenance takes on depot-level work in order to cope with increased workloads. This is partly due to the fact that I-level capability is specifically equipped to handle some forms of major repair, and unfortunately also because the depot system is generally inefficient, spurring some units to take on the repairs themselves.

Cross-functioning is arguably good practice, but each function must also understand that its main role takes priority for the system to be successful. Cross-functionality that is spurred by negative push factors suggests existent system or process deficiencies that need to be addressed.

At the team level, supervisors could chip in to help mechanics with some technical work, and it is also beneficial that management helps as well during crunch time. However, if respective functions are neglected in the process, system goals may still be compromised. For example, a supervisor who helps a technical team conduct some repairs may inadvertently neglect his or her supervisory role, and thus allow some maintenance error to slip by, which might cause an accident later on.

*Making unions your partners.* The benefits of having unions in an organization are debatable. Proponents and opponents of unions exist, and both have many valid reasons. Nevertheless, organizations that are unionized need to understand that an adversarial relationship between the organization and unions breeds distrust, and a negative organization culture. The relationship between the organization (management) and its employees is symbiotic; the organization needs workers, and workers need the organization that provides them with jobs. This is general to all organizations, and is not specific to the MRO system.

A culture of partnership with unions seeks cooperation between the two parties and an understanding that there is mutual dependence. When employees have a stake in and feel ownership of the organization, there are psychological and material incentives to work
hard, to progress and to protect the interests of the organization. Southwest is not the only example where this has been demonstrated. In the late 1940s, after struggles with the unions, Toyota guaranteed lifetime employment for its employees along with other rights and benefits, in return for company loyalty, flexible work assignments, and a proactive attitude towards improving the company (Womack et al,1990). Employees became part of the whole Toyota community, where their lives and well-being were inextricably linked to the success of the company.

*Building relationships with key suppliers.* When there are close relationships, shared goals and knowledge between an organization and its key suppliers, their successes are linked, encouraging better communication and coordination. In a lean production system, suppliers need to be part of the total coordination scheme so that the right parts can be delivered at the right time and at the right place, ensuring smooth and efficient operations. This is the case with Toyota Motor Company, as well as Dell Computer Corporation. Dell established strong links with its suppliers, such that it could update its manufacturing schedule, and direct its suppliers to deliver parts to particular buildings and docks every two hours. This allowed Dell to maintain minimal inventory, while shipping customer orders within hours.

For both the civil and military aviation MRO system, suppliers also play a vital role in efficient operations. Building relationships with suppliers allows successful cooperation and a willingness to contribute to the MRO organization’s success. Successful coordination of schedules with key suppliers can lead to high performance by potentially minimizing inventory levels and minimizing the shortage of spare parts at the same time.

*In summary,* the ten practices described above are best practices that can be applied at the workers-level in the complex socio-technical MRO system, in order to achieve the system goals of availability and safety at minimal cost. They are targeted at building high-performance relationships, and are synergistic in nature. As pointed out by Gittell, each practice can reinforce others, but a deficiency in one can also undermine efforts in
another. Careful effort has to be taken to apply the practices as a whole to achieve the best results.

6.2 Human Factors

Human Factors, as the name suggests, aims to uncover how humans, our capabilities and limitations, contribute to performance at work tasks. It is targeted at understanding the human and his or her relationship with the environment, so that efforts can be made to improve safety, prevent accidents, and improve efficiency. Although increased efficiency is one of the goals of human factors research, the main focus has by and large been to improve safety and to prevent errors and accidents.

Early efforts in this field have concentrated on physiological aspects such as how noise and environmental conditions like heat and lighting affect performance. It has since developed to include the cognitive aspects such as human decision making, displays and controls, documentation and so on. Much of the focus of Human Factors research in the past decade has been in reducing pilot error, and significant progress has been made in that area. However, maintenance-related causes are rising in proportion. As pointed out previously, 42 percent of fatal airline accidents in the United States since 1994 have been attributed to maintenance problems (Alexander et al, 2003).

A basic model that helps in the understanding of Human Factors is the SHEL model, first developed by Professor Elwyn Edwards in 1972, and modified by Capt. Frank Hawkins in 1975. Figure 15 is an illustration of this model. In the model, the letters “SHEL” represents software, hardware, environment, and liveware respectively. Software refers to things like documentation and procedures, hardware refers to machines, environment refers to the surrounding conditions, and liveware refers to the human. Each aspect of the model has characteristics that need to be well understood.
In the diagram, liveware (the human) is at the center of the model and is regarded as the most important. Some significant characteristics of humans that have been suggested by ICAO (1995) are:

1) Physical size and shape – Physiological characteristics like height, weight and body movement characteristics.
2) Physical needs – Vital, basic needs required by people, such as food, water and air.
3) Input characteristics – The various means by which humans collect information from the surroundings, such as sight, sound, reading, touch and so on.
4) Information processing – The ability of the human to recall and process information, which may be affected by complexity of task involved, environmental conditions, social well-being and so on.
5) Output characteristics – Action, body movement, or communication initiated when decisions are made following sensing and processing of information.
6) Environmental tolerances – How humans are affected or constrained by environmental conditions such as temperature, noise, lighting, time of day, work conditions, nature of work and so on.

Besides the characteristics of individual components, the model suggests that the interactions between liveware in the center and components around it are equally important. For safe, efficient operations, there needs to be an adequate match between the various components.

Liveware-Hardware. This interface is concerned with how machines or tools can be designed to fit the human. Ergonomics primarily deals with this aspect. Some examples of efforts in this area include the ergonomic keyboard and mouse, specially-designed seats, and cockpit layouts to suit pilots’ needs. For aircraft engine MRO, maintainability features such as access panels, consolidation of test points, and modular design facilitates inspection and repair work. Better equipment and tools such as compact, lightweight diagnostic kits to be easily carried around by line mechanics can also help in this area.

Liveware-Software. This interface involves the interaction of humans with less tangible aspects of the system, such as documentation, procedures and interfaces with computer software. It is generally a more difficult area to address, because much of it is cognitive in nature, such as ensuring that procedures are not misinterpreted. For engine MRO, some effort has been made in this aspect by a move to adopt plain, clear language in maintenance procedure documentation to avoid inaccurate semantic interpretations.

Maintenance personnel can also benefit from improvements aimed at reducing administrative time. It is estimated that 25% of a technician’s time is spent on paperwork and documentation (ICAO, 1995). Adequate computerization programs may help in this area. Computerization can also help in providing maintenance personnel with procedures and documentation in compact form, such as in Personal Digital Assistants (PDAs) or tablet PCs. With adequate information technology infrastructure in place, updating of procedures and issue of job cards can also be automated and done very quickly. Recently,
United Airlines moved from a manual system of updating, printing and issuing job cards and maintenance requirements to a standardized, automated solution with reported success (4D Inc, 2004).

Liveware-Environment. Examples in consideration of the human-environment interface are plenty, since early efforts in Human Factors began in this area. These include equipment such as flying suits and oxygen masks, and environmental control such as pressurization, air circulation and so on. In the MRO environment, concerns include weather conditions, lighting, noise, perceptual errors, time of day and sleep rhythms.

Worker performance, especially at the gate, is affected by adverse weather conditions and the chance of error may increase. Wherever possible, proper planning should avoid the assignment of complex maintenance tasks under such harsh conditions. Workers also need to be provided with sufficient lighting equipment such as flashlights, floor lamps, hangar lighting and so on. Often, on-aircraft engine maintenance occurs under the wing, which blocks ceiling lighting, so proper consideration needs to be given in providing other sources of light. Proper lighting can also decrease the chance of perceptual errors during inspection and repair work.

An airport or air base is typically a noisy environment to work in. Besides worker well-being, noise can also affect communication, so workers need to be able to communicate via alternative sources such as electronics or hand signals. Often, inspections and line maintenance work occurs overnight to make use of time when aircraft are not in revenue service or flying missions. As widely researched and shown, people are generally at their lowest alert levels in the early morning hours, so this is the time when workers will be most prone to making errors. Hence, extra caution and oversight needs to be given to ensure that overnight maintenance is conducted safely and properly.

Liveware-liveware. Interaction between people is the final category to consider. As discussed previously, the MRO system is a complex socio-technical system, involving not only technical aspects at its core, but also social interactions, structures and
organizations. Teamwork, communication, cooperation, leadership and relationships are all important aspects that need to be taken care of to ensure safe and efficient worker performance. These factors have been extensively discussed in the previous section.

Human Factors is largely concerned with the prevention of accidents, and it is useful to have a big picture of how humans contribute to the prevention or causation of accidents. For this purpose, Reason (1990) developed a model of accident causation as shown in Figure 16.

![Figure 16: Model of Accident Causation, modified version (Reason, 1990)](image-url)
The model is broken down into five components: Decision-makers, line management, preconditions, productive activities, and defenses. “Decision-makers” represent upper management in an organization who set goals and regulates organization activities. “Line management” refers to personnel who execute upon decisions made by upper management. “Preconditions”, such as available facilities, workers, equipment and resources, are conditions that are necessary before “productive activities” can be carried out. “Defenses” is the last component, and it represents measures taken to prevent accidents, injuries, damages and so on.

The model shows that accidents are not the result of single actions. Instead, a sequence of deficiencies needs to be present in the system before accidents occur. Defects in the decision-maker, line management and preconditions levels are deemed as “latent failures”. They interact to form a “window of opportunity” for front-line workers to create an “active failure”. These “active” acts can be prevented by defenses that are in place, thus preventing accidents. Otherwise, failure at this final level will allow the accident to occur. Although failures at each level are laid out in sequence, the Reason model does not state that they necessarily occur one after another, bottom-up or top-down. Instead, it simply argues that accidents are caused by a combination and interaction of various factors throughout the system. This is also consistent with Leveson’s (2004) system view of accidents, where she argues that accidents can be better understood from a systems perspective. In her analysis (Leveson, 2004), a system that has been designed with the appropriate safety checks and constraints in place may degenerate over time to an unsafe state, where opportunities for accidents arise and an accident will inevitably happen, regardless of who (which worker or actor) finally triggers it.

Put in the context of MRO, the Reason model suggests that best practices are those that address defects at these various levels. Leaders at the top of the organization can contribute to preventing accidents by assessing how their decisions can result in unsafe acts at the front-line. This can be in terms of intangibles like taking an active interest in safety and building a culture of safety, or directly disallowing unapproved maintenance procedures with a system of rewards or punishments. Middle management that executes
upon decisions can similarly prevent accidents by ensuring that decisions and procedures in place to enhance safety are indeed followed through. They can also contribute by taking a proactive attitude towards identifying unsafe decisions, and providing feedback to upper management.

To reduce the possibility of unsafe preconditions and activities, maintenance operations can be analyzed under a Human Factors framework to ensure that the L-H, L-S, L-E and L-L interfaces are taken care of. For example, Drury (1999) suggests that Human Factors audit programs can be developed and implemented to identify and improve upon mismatches. Some other notable suggestions include a hangar-floor Human Factors program, improved error analysis and reporting systems (better feedback), workcard redesign to match cognitive needs with type of maintenance task, and improved diagnostics training. Finally, adequate defenses need to be in place. There needs to be sufficient oversight and supervisory work by authorities and front-line leaders. Smooth and efficient documentation and checklist procedures will also help.

6.3 **Cognitive Systems Engineering: Worker Competencies**

Human Factors has highlighted the importance of matching human capabilities with the surrounding environment and task-at-hand in order to achieve efficient and safe work performance. However, the cognitive aspect of human work performance is one important component that has not been fully addressed thus far. In that light, this chapter shall present knowledge drawn from Cognitive Systems Engineering to illustrate the importance of matching the cognitive requirements of a task to the competencies that a worker has.

Cognitive Systems Engineering is a field that combines knowledge of human cognition, psychology and human factors with the holistic approach of Systems Engineering with the aim of designing systems that are flexible and adaptable. To do so, it makes use of the
central idea of a constraint-based approach. Instead of specifying and designing exactly what each worker needs to do, the worker “finishes the design”, having the freedom to accomplish tasks using “local information, knowledge, and expertise” within specified boundaries (Vicente, 1999). This is consistent with the idea of “keeping jobs flexible at the boundaries” presented in Section 6.1, where workers in different functional groups are given the flexibility to adapt to changing local conditions, and help in other groups’ work when necessary while keeping within constraints (i.e. workers must not neglect their main role).

Another example of letting workers “finish the design” is the case of battle damage repair in the military during wartime. In battle damage repair, formal maintenance procedures are foregone in the interest of achieving rapid repair rates and high aircraft availability. Many constraints that are in place during peacetime disappear, significantly enlarging the space within which workers can function. Mechanics work with whatever material is available, and rely heavily on creative adaptations to repair damaged aircraft, and return them into service as quickly as possible. The success of letting workers “finish the design” can be seen from reports that battle damage repair was a significant factor contributing to high US aircraft availability rates in many conflicts, including the Vietnam War and the Gulf War in 1990.

Extending from this context, the analysis of worker competencies identifies human cognitive capabilities as a constraint. In order to achieve safe and efficient operations, we should understand the cognitive processes that workers go through to accomplish their respective tasks, so as to shape MRO practices to suit human limitations.

One useful tool in understanding human cognitive processes is the Skills, Rules, Knowledge (SRK) Taxonomy developed by Rasmussen (1983). The SRK taxonomy classifies human behavior into three different categories: skill-based behavior (SBB), rule-based behavior (RBB) and knowledge-based behavior (KBB). In SBB, human actions are guided by real-time conditions in the environment, and it involves little depth in terms of cognitive processing. An example of SBB might be walking or running,
where a person’s perceptions of the environment guide his or her steps without much thought. RBB, as the name suggests, guides human action through rules that may be formulated from work procedures, orders and instructions, past experience and so on. Actions guided by RBB have an “if-then” relationship between some phenomenon and a related action. For example, while walking, if there is a puddle of water ahead, then walk around it. Such an internalized rule may have been the result of past experience that walking into a puddle of water gets your shoes wet, which is uncomfortable. Unlike SBB, RBB involves some conscious attention, but no deeper cognitive reasoning has been invoked. Lastly, KBB guides actions through deeper cognitive processes and analytical reasoning. It requires conscious effort, and is often, but not always, used when encountering unfamiliar situations, as well as in knowledge-based problem-solving. For example, a jogger might be thinking of how far she should jog today. Feeling energetic, she decides to run at a quicker pace. Then, judging by how much time she has, the pace she is running, and the number of calories she wants to burn, she estimates a certain distance to run. Figure 17 below summarizes the three categories of the SRK taxonomy.

Figure 17: The SRK taxonomy of human performance categories (Vicente, 1999)
From the example of a person walking or running, it should be apparent that activities generally do not fall into one specific category within the SRK taxonomy. Every task or activity usually requires a worker to exercise a mixture of the three types of cognitive processes. With respect to MRO, a technician repairing a faulty LRU might rely on KBB to diagnose the fault and RBB to perform disassembly, repair and assembly. While performing the repair, the technician might still exercise KBB when he or she comes across an unfamiliar situation during the process. Throughout the whole repair procedure, SBB might continually be used as the technician screws nuts and bolts in and out without conscious attention.

It is also important to note that for the same task, different people might rely on different competencies to accomplish it, depending on the level of skill. For example, a novice mechanic may need to fall back on KBB to tackle a simple scheduled maintenance task. As familiarity with similar, repetitive tasks grows, the mechanic begins to become more efficient, and exercises RBB instead. If the task is not very complex, the mechanic might gain a certain level of proficiency such that he performs the required actions as SBB. This learning process of moving from KBB to RBB to SBB characterizes typical growth towards “expertise”, but Vicente (1999) points out that “some tasks require learning completely within a level”.

From the nature of these three competencies, it can be easily seen that KBB is the most effortful, followed by RBB, and the least effortful being SBB. Because of greater cognitive demands at the KBB level, it also tends to be more error-prone. It is then not surprising that “people have a definite preference for carrying out tasks relying on lower levels of cognitive control” (Vicente, 1999).

Knowledge of the SRK cognitive levels and how workers rely on them is insightful and has a number of implications. It shows that, as much as possible, tasks should be designed to allow workers to use SBB and RBB. Wherever KBB is unavoidable due to the nature of the task, such as in fault diagnosis, the worker should be supported by cognitive aids. Recommended maintenance procedures related to typical faults and
scheduled maintenance tasks contribute greatly to achieving this, so they must be clear, unambiguous and accurate. DPCM tools, as presented in Section 5.1.2, also contribute significantly in reducing the cognitive workload of workers. By internalizing models of an engine, DPCM systems take on KBB aspects of the workers' tasks, so that they need only rely on SBB and RBB. In this way, it is possible for novices, who are not as familiar with the knowledge base, to perform some tasks that would otherwise require an expert.

Also, in MRO, testing, inspection and fault diagnosis are tasks that are generally knowledge-based, and require greater cognitive effort, even if cognitive aids are provided. Knowing that engaging in KBB is also more error-prone, managers should be aware and not allocate personnel to KBB-level tasks over extended periods of time. Where possible, there should be suitable breaks or rotation of personnel between KBB and RBB or SBB-level tasks.

Even though engaging in KBB is generally an effortful process, workers need to have knowledge of underlying principles governing their work tasks. Cognitive aids can be designed to support workers at the KBB level so that work is more efficient and safe (because KBB is more error-prone), but they cannot replace the knowledge that a worker needs. With knowledge of the underlying principles and mechanisms behind the components and parts that are being repaired, a worker would be able to question the automated system and countercheck his or her knowledge with results from the system. He or she can also constantly reflect upon his or her maintenance actions to ensure that they are consistent with his or her knowledge. In this way, safety is enhanced by this internalized self-checking system.

The fact that knowledge remains invaluable, especially in ensuring a high standard of safety, shows the importance of training. With training and experience in the field, novice workers can strengthen their knowledge base, while progressing towards RBB and SBB competencies. This is especially so with regards to maintenance activities, where work is generally hands-on in nature.
However, the attainment of “expertise” is not a definitive process, where “experts” remain experts forever. With the continual introduction of new technology, machinery and maintenance processes in an aircraft’s lifecycle, maintenance personnel will undoubtedly fall back to a novice level of competency with regards to new conditions and situations. When this happens, it is hypothesized that without adequate knowledge to support analytical thinking and KBB, workers in the field will rely primarily on RBB to accomplish tasks without understanding why things are done a certain way. Tasks can continue to be accomplished properly and on time, but since the “internalized self-assessment” based on KBB is not present, the risk of unsafe actions increases. According to reports, “…there is no specific requirement [in the FARs] for training after a mechanic receives a federal license”, and the airline industry as a whole is not concentrating enough on training for its mechanics (Levein, 2004). Whether in civil or military aviation, continual training should be a priority, and it ought to be targeted at improving each worker’s knowledge base.
Chapter 7: Technology and Research

This chapter aims to outline the importance of technology and research by discussing how they contribute to achieving availability, safety and economic goals in an MRO organization. No specific technologies or research methods will be advocated as a “best practice”; instead, it will be argued that adequate attention to technology and research is in itself a best practice.

7.1 The Role of Technology and Research

Looking back at the framework presented in Figure 3 (reproduced here as Figure 18), where best practices form the means by which the complex socio-technical MRO system attains its goals, one begins to wonder how technology and research fall into this picture. Certainly, we can readily identify many examples of technology that exist at each layer, which contribute to the attainment of safety, availability and economic goals. At the technical layer, more fuel-efficient and reliable engines help to achieve these system goals. In the workers layer, DPCM tools and electronic documentation are examples of technology serving this purpose. At the organizational layer, information systems help to synchronize and integrate work processes, while communication technologies assist the overarching regulatory framework in the dissemination and retrieval of information.

![Diagram](image)

Figure 18: Attainment of System Goals via Processes at each Layer
Since technology exists throughout, we could imagine it as some component that spans the whole system. It is a vital aspect of the technical core, but it is not vital for the rest of the system to function; instead, it is an augmentation that the system makes use of to function *better*. In that light, we could see technology as a performance enhancer, helping the system to 1) achieve its set goals more easily, and 2) allow goals to be set to a higher standard. With continual improvements in technology, MRO practices can continually improve as well.

However, introduction of technology is not guaranteed to be beneficial, and substantial risks are involved. In a study investigating how the introduction of information technology has affected productivity, Landauer (1995) argued that the introduction of information technology actually caused a decrease in productivity. Related studies reveal that this may be caused by computer-related problems and unproductive time spent by employees "futzing" with their computers (Vicente, 1999).

There have been efforts to assess the risk involved with the introduction of new technologies. NASA uses a framework of Technology Readiness Levels (TRL) to judge the maturity of a developing technology. The TRL scale ranges from level 1 to 9, with higher levels representing greater maturity and lower risk in the use of a certain technology. The TRL scale and level descriptions are provided in Table 3 below.

<table>
<thead>
<tr>
<th>Technology Readiness Level</th>
<th>Description</th>
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<tbody>
<tr>
<td>1. Basic principles observed and reported</td>
<td>Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.</td>
</tr>
<tr>
<td>2. Technology concept and/or application formulated</td>
<td>Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.</td>
</tr>
<tr>
<td>3. Analytical and experimental critical function and/or characteristic proof of concept</td>
<td>Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.</td>
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<tr>
<td>4. Component and/or breadboard validation in laboratory environment</td>
<td>Basic technological components are integrated to establish that they will work together. This is relatively &quot;low fidelity&quot; compared to the eventual system. Examples include integration of &quot;ad hoc&quot; hardware in the laboratory.</td>
</tr>
<tr>
<td>5. Component and/or breadboard validation in relevant environment</td>
<td>Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include &quot;high-fidelity&quot; laboratory integration of components.</td>
</tr>
<tr>
<td>6. System/subsystem model or prototype demonstration in a relevant environment</td>
<td>Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in the technology’s demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.</td>
</tr>
<tr>
<td>7. System prototype demonstration in an operational environment</td>
<td>Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space. Examples include testing the prototype in a test bed aircraft.</td>
</tr>
<tr>
<td>8. Actual system completed and qualified through test and demonstration</td>
<td>Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.</td>
</tr>
<tr>
<td>9. Actual system proven through successful mission operations</td>
<td>Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.</td>
</tr>
</tbody>
</table>

Table 3: NASA Technology Readiness Levels (Graettinger et al, 2002)
Although the TRL scale is a useful tool, Valerdi and Kohl (2004) suggests that it is incomplete and should also take into account other factors like obsolescence, and “leapfrogging”. Obsolescence occurs when a mature technology is “retired” because it loses functionality, or when it becomes infeasible to support it. “Leapfrogging” occurs when newer, less mature technologies overtake other more mature technologies because of better capabilities.

Given the rapid rate of technological change and the need for continual improvement, MRO organizations need to continually reassess their technological capability as well as the risks involved in introducing new technologies. Here is where research plays a role in contributing to the success of the system.

Through research, organizations can benchmark their current state to chart future goals and to act to implement new technologies in a constant process of renewal. In organizational psychology, it has been shown that certain individuals, known as “gatekeepers”, contribute significantly to updating the technological knowledge within technical organizations. These “gatekeepers”, who play the role of an “internal consultant” (informally), are typically highly technically competent and, more importantly, keep up-to-date with “external technology” through the scientific literature (Allen, 2004). Conceptually, this is very similar to the role that research and education plays at the organization level.

Figure 19 depicts a symbiotic relationship between research, education and industry practice. This successful relationship emerged out of the Lean Aerospace Initiative, where Massachusetts Institute of Technology linked up with the U.S. Air Force, defense aerospace businesses and labor unions to apply Lean principles from the auto industry to the aerospace industry. What is important to note in this relationship is that research provides the technology, tools and frameworks to education and industry, which in turn provide feedback in a process of continual improvement. Besides that, industry obtains its manpower from educational and training institutions, so it is only logical that industry
provides input to education to avoid what is usually a disconnect between the two groups, ensuring the relevance of its future manpower.

Figure 19: Symbiotic Relationship between Research, Education & Industry Practice (Murman, 2004)

According to reports, out of “more than $150 million a year [that the FAA spends] on research, engineering and development, about $1 million of that typically goes toward research aimed at preventing maintenance mistakes” (Alexander et al, 2003). Considering the impact that maintenance activities, as well as maintenance errors, have on the successful functioning of the aviation system as a whole, MRO research does not seem to have the kind of attention it deserves. In what might in itself be considered a best practice, sufficient attention and resources need to be allocated towards “peripheral activities” such as technology, research and education to indirectly improve industry practice.
7.2 Information Systems

A key component of any complex system, such as the MRO system, is the management and flow of information. Throughout this paper, the importance of adequate information exchange has been stressed many times. In Section 5.1, it was mentioned that transmission of engine information from the cockpit to ground-based stations contributes to quicker turnaround times at the gate. The on-time dissemination of aircraft information also facilitates the coordination of maintenance routing and unscheduled maintenance activities. In Section 5.2, the smooth flow of inventory information between suppliers and operators was further stressed as an important factor in achieving an integrated workflow. Section 6.1 then presented how relationships and good communication within the MRO organization can bring about high performance. In the previous section, collaborative exchanges between industry, research and education were also shown to produce encouraging successes.

Extrapolating from this, it can be seen that a common theme in achieving high performance is the adequate sharing of information between functionally separate entities or organizations. This is an integrated approach. In Section 2.1, we placed MRO in the context of the total logistics system, and showed how traditionally separate divisions are mutually dependent. If successful operations are expected, then the divisions need to come together as a coherent whole and progress in unison. This is not to say that boundaries are irrelevant. Analogous to how individual workers should give priority to their primary role while seeking to assist others, separate divisions, organizations, or entities need to pay attention to their own functions, while keeping collective goals in mind.

Traditionally, information systems have also been developed separately within divisions or organizations. Figure 20 depicts the inefficiencies that can exist when distinct information systems are used among functional groups within an organization. Information flow among internal divisions is difficult and hinders cooperation. At the
same time, information exchange between internal and external groups is not organized, creating confusion.

![Diagram of information islands and interchange tangle](image)

**Figure 20: Current Information Islands and Interchange Tangle (Seamster and St. Peter, 2002)**

Within the domain of MRO, many private organizations are already moving towards an integrated information system approach. Pratt & Whitney has been progressing towards a common information management system for all its MRO businesses to “achieve common business processes..., common business performance tracking, global inventory management, and worldwide supply chain optimization... [The system] manages all aspects of the order-to-cash cycle for engine overhaul and component repair, including sales, receipt, tear-down, part inspection, assembly, material procurement, warehousing, shipping, and invoicing” (Careless, 2002).

A large part of the issue is the format in which the information exists. If information is to be shared in a meaningful and efficient way between groups, there has to be a common language or standard. As a simplified example, one group that uses electronic
documentation could easily share information with another that relies on a manual system and vice-versa. However, mismatches arise when these two groups attempt to integrate each other’s data. The electronic system will require manual conversion of paper-based data, essentially duplicating efforts, and the manual system will similarly require adaptations to update its system.

Documentation is a major issue in aviation because of the sheer amount of information. This includes maintenance manuals, operating and safety procedures, parts specifications and classifications, engineering data, financial information and more. As an illustration, an aircraft maintenance manual that is printed double-sided can be as much as six-feet thick. As the second generation of the evolution of standards takes aviation documentation from paper to electronic forms, there has been a need to standardize text and graphics formats so that information could be efficiently shared between suppliers, operators, and regulatory bodies (Sorenson, 2002). Significant progress has been made, and the industry is moving towards the third generation, where “intelligent documentation” will allow users to retrieve relevant information specific to their needs (Sorenson, 2002).

In maintenance operations, a third generation system would materialize as a database where maintenance personnel can quickly retrieve maintenance procedures specific to the repair task on-hand. Using a common documentation standard, OEMs can provide updated maintenance information to the military and the airlines, which can then pass this information to maintenance personnel on the ground quickly and seamlessly, making operations both safer and more efficient. One important point highlighted by Seamster and Norman (2002) is that an industry standard need not be a regulatory standard where everyone uses the same documents and format. Organizations can continue to make use of internal formats as long as it is possible to convert to and from a common standard. Standardization can also apply to documentation of parts specifications and classifications. This will greatly facilitate common understanding between manufacturers, suppliers and operators.
Besides documentation, MRO organizations need to be able to share operational data and make use of emerging technologies to manage such data. Data like engine conditions and inventory levels should be shared among functional groups of the organization as well as external organizations like suppliers. Information sharing between groups like maintenance planning, flight operations and marketing can help to create smooth work processes. Inventory and engine maintenance data shared with key suppliers could also help suppliers to better anticipate and fill the demand for parts. Emerging technologies that can potentially help to manage and automate such data flow between organizations include agent architecture and multi-agent systems, and enterprise resource planning systems.
Chapter 8: Conclusions and Recommendations

Throughout this paper, we have attempted to uncover MRO best practices by analyzing the commercial and military MRO systems at different levels – environment context (policy), infrastructure, management and manpower. In many cases, however, we find that the best practice or best course of action depends largely on the context and individual organizations’ situations, so we have tried to address important issues that should be considered. Through the analyses, we can also observe that many issues are not isolated to each particular level, but instead are affected by and have implications for practices in other levels. A summary of the various issues presented is given below.

Outsourcing. A main consideration is the distinction between what is essential and non-essential. As much as possible, essential services should be kept within the organization so that there is better control over availability and safety. The size of the organization and magnitude of MRO services required are also important considerations. Smaller organizations tend to have smaller capacity and a smaller fleet, so outsourcing is usually a good idea to handle excess workload. Larger organizations tend to have larger capacity and a larger fleet, so it is easier to justify retaining facilities, equipment and manpower due to economies of scale. The decision of what needs to be outsourced should be based not just on cost, but also on operational characteristics like capacity, rate of work received and rate of work completion. Labor is an issue when organizations need to downsize. For reasons associated with maintaining good relationships, organizations should retain labor as much as possible. Finally, public depots could look into sourcing for work from the private sector as a viable alternative to outsourcing.

Infrastructure. Reducing transportation time is a key factor in improving performance of the MRO system. This can be done by reducing the number of intermediaries that parts need to go through. Also, storage should be minimized, so faulty and repaired parts should be shipped as soon as possible. To minimize shipping in the first place, aircraft should land at maintenance bases whenever scheduled maintenance is needed. Within the
repair facility, movement of components, parts, labor, and equipment should be minimized by a cell-based or similar arrangement.

*Maintenance Scheduling.* As mentioned, aircraft should land at maintenance bases whenever scheduled maintenance is needed. If planned adequately, scheduled maintenance can be a smooth and efficient process. So, as much as possible, unscheduled maintenance should be reduced. Unscheduled maintenance is also undesirable because safety may be compromised. The use of DPCM tools and the monitoring of engine life consumption are recommended to anticipate failures and avoid unscheduled maintenance. Synchronization of parts replacement schedules can also reduce repeated teardown, transportation and assembly work. Finally, the design of an engine and its components according to these considerations can have a major impact on lifecycle costs.

*Inventory Management.* The goal is to provide the right parts, at the right place, and at the right time. Three approaches have generally been adopted: MRP, JIT and TOC. Depending on the context, either approach may be best, but important concepts from each can be extracted. From MRP, demand should be forecasted as accurately as possible to provide good estimates of what is needed. Organizations may need to periodically update their approach based on the latest stochastic techniques available. From JIT, in order to handle variable demand and to reduce excess inventory, a high-velocity infrastructure should be established, so that supplies can be delivered as quickly as possible. Strong links with suppliers are also important for this. From TOC, given limited resources, priority should be given to “bottleneck” or “critical” activities. When all else fails, and supplies are urgently needed, management adaptations like cannibalization and lateral supply can be made use of to relieve supply shortages temporarily.

*Manpower.* High performance is strongly correlated with the degree of “relational coordination” in an organization. In turn, the degree of “relational coordination” is characterized by shared goals, shared knowledge, and mutual respect, which affect the quality and frequency of communication within an organization. To develop “relational coordination”, organizations can follow the ten recommended practices described in
Section 6.1. Human Factors is another important consideration that requires adequate attention. It primarily focuses on matching human capabilities with the surrounding environment and task-at-hand in order to achieve efficient and safe work performance. From cognitive engineering theory, the SRK taxonomy helps us to understand the cognitive needs of workers, and points to the importance of providing adequate cognitive tools and continual training.

*Technology and Research.* Technology and research are important “peripheral” activities for any organization. Technology is a performance enhancer and it is important that organizations keep up to date with the latest developments. However, there needs to be adequate assessment of the risks involved. Information systems are a key technology that should be made use of to manage data flow internally and externally to streamline operations. In a world of rapid change, feedback is important in allowing organizations to react appropriately to change. As such, sufficient attention and resources should be allocated to research and link-ups with educational institutions.

*In conclusion,* the above issues and practices are by no means exhaustive, but it gives a good idea of the scope of best practices in aircraft engine MRO. Each of the sections covered in this paper are already an area of continuing research, or can potentially be a subject for future studies. Finally, I would argue that the research and study of best practices is in itself a best practice, because it gives people and organizations the knowledge and direction to continually progress and improve.
Appendix

Brief Description of Various Model-based Approaches to Gas Turbine Fault Diagnostics and Isolation (FDI). Extracted from (Grodent and Navez, 2003).

1. Parity Space Approach – The key idea is to check the parity (i.e. consistency) of the mathematical equations of the system by using the actual measurements. A fault is declared to have occurred once pre-assigned error bounds are exceeded.

2. Dedicated Observer Approach (or state estimator approach) – The basic idea of the observer approach is to reconstruct the outputs of the system from the measurements with the aid of observers (in the deterministic case) or Kalman filters (in the stochastic case) using the estimation error or innovation, respectively, as a residual for the detection and isolation of the faults. This method is essentially dedicated to FDI in dynamic systems.

3. Principal Component Analysis (PCA) – The principle of the method is to capture measurement correlations by searching for linear relationships between the measurements. Although initially dedicated to the detection of instrumentation faults, PCA methods have been recently applied with success to the isolation of process faults.

4. Parametric Statistical Approach – The key element of this approach is the possibility to reduce the original problem to a simpler one, for which changes in the mean value of a residual\(^8\) (with Gaussian probability distribution) are monitored. For model-based physical diagnosis, the mean value of this residual depends directly on the monitored physical parameters and, therefore, faults affecting these parameters can be detected.

5. Parameter Identification Approach – The idea of the parameter identification approach is to detect a fault via an estimation of the parameters of the mathematical model. If the identified parameters differ significantly from the \emph{a priori} healthy values, then a fault is likely to have occurred. If a complete physical model of the monitored system is available, physically meaningful parameters can generally be

\(^8\) The residual is the difference between the measured value and predicted value (by the model) for observed engine parameters.
chosen for identification purpose. Therefore, it becomes possible to relate any change in a given parameter to a particular component fault (for instance, the performance degradation of a turbine stage can be detected through a change of its isentropic efficiency).
Bibliography


