We describe a series of projects at the US Coast Guard (USCG) Aircraft Repair and Supply Center (ARSC) that demonstrates the value of OR methodologies for efficient supply chain management. These projects provided critical decision support for planning various repair and maintenance activities at ARSC. The establishment of an OR cell within ARSC, with several new employees and interns hired for this purpose, demonstrates the sustainability of these OR initiatives. The projects have created a strong emphasis on data-driven planning at ARSC. Their quantifiable benefits include reductions in inventory by 20–70 percent for 41 critical parts; repair-cost savings of 10 percent by using maintenance information for component repair planning; a successful planning of the conversion/upgrade of the H65 aircraft, thus enhancing the safety and capability for Coast Guard missions; and a 50-percent increase in throughput of the H60 Program Depot Maintenance (PDM) line, resulting in a reduction in deferred depot maintenance from a peak of $23.6 M to $6.5 M. OR techniques have clearly been successful in transforming the culture at USCG's ARSC from a “data rich and knowledge poor” decision-support culture to an “OR ingrained” decision-making environment.

**Keywords**: government: defense; inventory: applications, maintenance policies; military; cost effectiveness; reliability, availability.

Today, the US Coast Guard (USCG) can truly claim to be “OR ingrained.” Most of its project proposals require the submission of careful data analysis, model building, and optimization as backup material to the project proposal. This was not always true. While USCG has a reputation for outstanding operational success, its aeronautical engineering program, the Aircraft Repair and Supply Center (ARSC), needed to improve its efficiency. This paper describes a unique partnership between USCG and faculty and students at Purdue University to develop an analysis-based decision-making system that made these efficiencies possible.

**US Coast Guard Missions**
USCG, one of the nation’s five armed services, is a military, multimission, maritime service within the Department of Homeland Security. Its core objectives
are to protect the public, the environment, and US economic and security interests in any maritime region in which those interests may be at risk; these include international waters and America’s coasts, ports, and inland waterways (http://www.uscg.mil). It has five fundamental responsibilities: (1) maritime safety, (2) maritime security, (3) maritime mobility, (4) national defense, and (5) protection of natural resources. USCG uses a variety of platforms to conduct its missions, including cutters and small boats on the water and fixed and rotary-wing (helicopters) aircraft in the air.

Its inventory includes approximately 200 aircraft; the number in operation fluctuates because of maintenance schedules. Major aviation missions include search and rescue, law enforcement, environmental response, ice operations, and air interdiction. Fixed-wing aircraft, such as the Lockheed Martin C-130 Hercules turboprop and the Dassault HU-25 Falcon jet, operate from large and medium air stations. Rotary-wing aircraft, which include the Eurocopter HH-65 Dolphin and the Sikorsky HH-60 Jayhawk helicopters, can operate from flight-deck equipped cutters, air stations, and air facilities. All aircraft are permanently assigned to a land-based air station, but can routinely deploy throughout the world as needed.

There are 26 air stations that are located throughout the US coast and are home to flight and maintenance crews, the aircraft, and thus services provided by USCG (Figure 1).

The nature of the missions varies based on the location of the air stations. In addition to routine missions, occasional events of national significance (e.g., Hurricanes Katrina and Andrew) create surges in demand for USCG services. These surge operations involve large-scale deployment of USCG aircraft; for example, over 18 HH-60 aircraft (about half of the...
HH-60 operational fleet) were involved in responding to Hurricane Katrina.

**Logistics Network for Aircraft**

USCG has over 200 aircraft, which it must keep airworthy, and thus available for flight crews to execute missions; this is crucial to its operational readiness, as is operating within budget constraints. ARSC operates as USCG’s aviation logistics center, providing one-stop shopping for all aviation logistics support. It provides air stations with depot-level maintenance, supply, engineering, and information services to support the missions (http://www.uscg.mil/hq/arsc).

As missions are defined and executed, they trigger a series of tasks involving the dispatching of aircraft from air stations to complete these tasks; this use results in aging of installed parts and component failures. In most cases, the air stations replace broken parts on the aircraft and send these broken parts back to ARSC to evaluate and repair locally or through outsourcing. In some cases, severe aircraft damage may require relocating the entire aircraft to ARSC for more complex repairs. Because the air stations are located in different climate regions, ranging from Miami, Florida to Sitka, Alaska, the impact of aircraft use on wear varies across air stations. ARSC, the main repair facility, thus receives broken parts, aircraft for overhaul, and requests for parts replenishment. It uses a combination of working-parts inventory, in-house repair, outsourced work, and contracts with suppliers to manage the repair process. ARSC also manages modifications of aircraft that undergo design changes, upgrades, and maintenance over time.

The ARSC repair and overhaul process follows a centralized control policy; a single facility in Elizabeth City, North Carolina serves as the focal point. ARSC owns the entire aircraft and parts inventory although it may deploy some inventory across air stations. In addition, ARSC provides information services that enable total asset visibility of parts anywhere in the system and the sharing of that inventory through parts-pooling. Thus, both components and aircraft may be moved across air stations to maintain mission coverage.

While individual air stations perform parts replacement and inspection, they depend on ARSC for individual component repair or overhaul and replacement, as well as for aircraft upgrades. Because aircraft and parts are shared across the network of air stations, a broken part received from one air station may well be sent to another—thus generating a mixing of parts and aircraft across the system.

Certain life-limited parts, such as mechanical gearboxes and engines, require overhaul at predefined intervals. In addition, to preserve the useful life of the aircraft, it also needs an overhaul periodically, principally to address any latent structural damage from fleet use and repair, and prevent corrosion damage from the salt water-laden operating environment. When ARSC receives parts, it may route them through different paths depending on decisions that the item manager (the person responsible for managing the item-level inventory) makes. If the entire aircraft comes to ARSC for an overhaul or an upgrade, it undergoes a program depot maintenance (PDM) process, which we describe in the Program Depot Maintenance (PDM) Process section, or a modification process. If a subassembly is returned, it may sit in inventory before being allocated for repair, or it may be sent immediately for repair. ARSC may perform some portion of the repair, send some (e.g., anodine metal treatment) to a supplier, and perform the final steps itself. ARSC selects the optimal combination of repair resources by evaluating performance and budget availability factors and executes contracts for repair services. ARSC tracked many of the parts using serial numbers; this stems from the need to manage life-limited or flight-safety critical parts. During its life cycle, a part may undergo design upgrades to improve its performance, provided that the aircraft manufacturer and USCG’s configuration control board approve the upgrade. There may also be decisions regarding the extent of repair versus scrapping a part, such as a component or subassembly (e.g., bearing or gear), that is beyond economical repair or its service life. After some predetermined life limit, ARSC retires parts from its system and destroys them to prevent their reentry into the parts system. Tracking of individual parts and their life history enables verification that the aircraft manufacturer has approved the airworthiness of all parts on the aircraft. Information pertaining to a part, such as accumulated flight hours, enables compliance with scheduled maintenance requirements.
Focusing the repair at ARSC permits centralization of the skilled labor required to diagnose and repair complex parts. Because USCG competes with private industry for manufacturer attention (e.g., in terms of time to procure components and time to complete repairs), there is a need to balance tasks that ARSC performs and those that suppliers perform. Finally, when significant aircraft use occurs, there is a need to reduce the aircraft overhaul interval to ensure the aircraft stays functional. Selected use of suppliers, such as General Electric, Raytheon, Sikorksy, Honeywell, etc., permits balancing of USCG capacity for task performance with supplier capability, lead time, and associated repair costs.

The Need for OR-Based Tools

As of 2001, ARSC was organized into groups; each group had a specific task to manage a part of the supply chain. For example, the engineering group, which was located in a building separate from the building that housed the item managers, focused on parts performance and its effects on safety and recommended maintenance intervals; the item managers interfaced with air stations and vendors and executed budgets to make repair or purchase decisions. These two groups affected each other and had complicated areas of responsibility—there was no systematic consideration of how they could use the data from each other’s systems. There were no planning tools to facilitate systematic information collaboration across the various groups in ARSC, and hence make optimal decisions from a supply chain perspective.

In addition, item managers relied on their years of on-the-job experience in managing the repair and inventory process. Over 75 percent of these managers were eligible to retire from USCG over the 5 to 10-year period, thus creating a potential “brain drain” crisis. In addition, while the tracking of parts follows Defense Logistics Agency (DLA) standards, there was virtually no explicit modeling and analysis capability at ARSC. Starting with the work of Churchman et al. (1957), research grounded in problem contexts derived from practice developed a long history in OR. This paper describes a partnership between USCG and the Krannert School of Management at Purdue University to develop an analysis-based decision-making system. The partnership transformed ARSC and institutionalized its use of OR.

There is a long history of literature on service-parts logistics. Sherbrooke (1968) developed the well-known METRIC (Multi-Echelon Technique for Recoverable Item Control) model for management of repairable items. This seminal work generated a new research area in multiechelon inventory control as the work of Graves (1985) illustrates. The literature linking part condition, maintenance, and inventory policies is very sparse. Eppen and Iyer (1997) extensively studied the use of Bayesian models to model inventory problems. Falkner (1968) focused on jointly determining optimal inventory and maintenance policies. Deshpande et al. (2003a) analyzed priority inventory systems, while Deshpande et al. (2003b) explored service differentiation.

A Five-Year Journey—Four OR Projects

Over a period of five years, the implementation of four separate OR projects improved USCG’s aircraft supply chain substantially. The first project, Managing Inventory and Data Across the Supply Chain (MIDAS), began in August 2001 and lasted for eight months. MIDAS focused on understanding the links between the individual parts-level tracking systems and their use in improving inventory management. The associated modeling objective was to estimate the impact on overall performance of connecting two disparate transactions systems in terms of service levels for parts and repair costs. These disparate systems used an engineering database, Aviation Computerized Maintenance System (ACMS), and a finance/inventory system, Aviation Maintenance Management Information System (AMMIS). Each was designed to perform a unique and complementary role and neither had significant decision support capability. Additionally, they were developed independently, at different times, and with no systematic thought given to leveraging information between systems for logistical planning. MIDAS provided a linear-programming-based approach for linking the two databases and also generated a prototype system that used the age of parts to drive inventory management (Iyer and Deshpande 2003). MIDAS modeled the repair process as a lead-time black box. The next project tackled this issue.
This second project, *Repair Evaluation, Analysis, and Planning* (REAP), focused on the repair process, resource usage for repair, and repair bill of materials—and thus on repair lead time. REAP’s objective was to link the age of a part, which was a predictor of repair complexity and content, and thus its repair content, to the choice of when to repair the component to best deploy scarce labor resources. The linear-programming model included a choice of in-house versus outside-supplier repair to minimize overall repair costs. The appendix shows a sample of one of the REAP models. The model also considered all the important parts that would potentially require repair and the associated resource usage (Deshpande and Iyer 2004).

The third project, *Coordinating Repair, Inventory, and Supplier Planning* (CRISP), focused on the upgrade process for the HH-65 aircraft. A USCG commitment in 2004 to complete a major upgrade of all 95 HH-65 aircraft by December 2006 drove this project. The upgrade included replacing the existing engine and engine control system to provide for increased power and reliability, upgrading the gearbox for durability, and rewiring the aircraft. While some parts were available, others had long lead times. We developed a linear-programming model to provide decision support for the upgrade process. In addition to maintaining aircraft uptime, the models had to consider the impact of aircraft upgrades on future spare-parts needs. And, because the manufacturer had recommended different repair and overhaul intervals for the upgraded aircraft, we used the model to examine the impact of this recommendation on the upgrade process and the associated resources required (Iyer and Deshpande 2005).

The fourth project, *Optimizing Production Throughput of HH-60 Aircraft* (OPT), focused on the HH-60 aircraft overhaul process and planned conversion to a new version that was codenamed Tango. The HH-60 helicopter-depot overhaul facility was experiencing diminishing production rates; in 2005, the annual rate was five—decreasing from an historic rate of approximately nine per year. If this continued, the HH-60 program would have to start grounding operational aircraft beginning in March 2007. We developed an extensive simulation model of the PDM process to identify the bottlenecks in the PDM process. The simulation model confirmed bottleneck processes and recommended aggressive efficiencies to address the problems. Figure 2 shows a sample set of outputs.

We next describe each of the four projects in detail.

### MIDAS—Turning Data to Gold

#### MIDAS Background

The USCG and Purdue University team embarked on MIDAS in June 2001. Lieutenant Commander (LCDR) Shirk had expressed his frustration that there were two independent and unconnected information systems that tracked parts. Anecdotal evidence had suggested linking data from these systems could provide quantum improvements in inventory-replenishment planning. His challenge was to estimate the benefit of linking these databases before awarding any contracts to implement this linkage.

ACMS tracked the serial numbers of individual parts and organized them by family groups, which were defined by a *component end item* (CEI) number. Within the system, parts were tracked for significant component history including installation, removal, repair, overhaul, upgrades, etc., as well as for their position in the system (e.g., installed on the right engine of CGNR 2102). Mechanical parts typically had
a life limit at which they were required to be examined for potential repair. In addition, combinations of parts in a subassembly may also have life limits, as would aircraft, which had calendar-based maintenance schedules. The ARSC engineering group was responsible for the management of ACMS.

In contrast, AMMIS, the inventory system, was designed to provide total asset visibility, comply with the Chief Financial Officer (CFO) Act, which mandated 100 percent visibility of all parts through tracking mechanisms, and provide for the order movement and replenishment of parts inventory through the system. Among other things, the CFO act mandated 100 percent visibility of all parts through tracking mechanisms. Because broken parts are shipped from air stations and good parts are shipped to air stations, the system recorded parts requested from air stations and the parts shipped. This system seldom included data on part serial numbers. It did carry data on the originating aircraft, its air station location, the Julian date of the order request, and the priority type of the order. AMMIS uses a national item identification number (NIIN) to track parts. There is a unique NIIN for each combination of manufacturer and manufacturer part number; this is nearly equivalent to the ACMS CEI number. The team selected a set of 41 items on which to focus (Deshpande et al. 2006).

Linking the Databases—A Linear Programming Model
The data within ACMS provided a time stamp for part removals that included aircraft tail numbers at each air station, reasons for failure, and time of reinstallation of the part on the aircraft. The corresponding data within the inventory systems show a series of demand arrivals from air stations, priority codes for the demands, and the ship date. Because ACMS did not link these transactions using database business logic, there was a need for a model that would link these codes.

If the air station did not have the required parts in inventory and it had not anticipated the event, then removal of the part in ACMS was followed by a demand request in AMMIS, then a shipment to the air station, and finally by an installation on the aircraft. However, if the air station had inventory, then removal could be followed by an installation with the arrival of demand requests and shipment taking place before or after the installation. The sequence could change if the demand was a Priority 5 (scheduled-maintenance demand) that anticipated the removal of the part. In such a case, demands could be observed in anticipation of a part removal and the install and ship dates could cross.

The various possible constraints generated an assignment model to match AMMIS demand requisitions to ACMS remove-install pair transactions, which we optimized to minimize the distance between the transactions observed for each air station. Complete details of the LP model are available in Deshpande et al. (2006). While the result was an approximation, it is important to emphasize that the process did succeed in matching many of the transactions in a manner that the Coast Guard found acceptable.

Using Part-Age Information for Inventory Management
After linking the databases, we needed to develop an approach to use part-age data to make inventory-level decisions. While some part-age monitoring was reasonable, it was unlikely that detailed part-age monitoring would be possible because monitoring thousands of parts at a detailed level was deemed impractical in the system. Therefore, we agreed that the most practical approach would be to use the number of parts whose ages have crossed a critical threshold age level; we would obtain these threshold values using a model.

How can part age be used to make decisions? Consider the difference between a proactive inventory-management system and a pull-replenishment system. If we can forecast impending demand, then we can synchronize the inventory of good parts with demand, such that we can replenish or repair the parts inventory just as anticipated demands arrive. Because there is a correlation between part aging and failures, low current part demand might suggest impending high demands, and thus the need to build up inventory. This is counter to the strategy that replenishment systems use—i.e., high demand triggers replenishment and low demand scales back replenishment.

Imagine a signal light (e.g., a computer program) that switches on when a particular part’s age or time
since overhaul (TSO) on an operating aircraft reaches its age threshold. This threshold could consider the time-to-repair and make a good part available based on a part’s age. The concept is to use statistical data to develop a demand over the repair lead time, and thus a trigger threshold for each part.

Deshpande et al. (2006) give a detailed description of the algorithm and its associated impact on repair budgets. In this paper, we provide a summary of its effects on repair budgets. We provided thresholds for both for mechanical and avionics parts. Avionics parts did not have planned repair intervals; similar to home computers, they were repaired as necessary. However, we found that even avionics parts had predicatable failure distributions that we could use to manage parts repair, and thus improve inventory management. The next observation was that, depending on the part, a synchronized system could decrease the inventory costs significantly—as high as 70 percent for some parts. This cost reduction resulted because the system held a lower level of repaired-parts inventory; this provided the flexibility to offer a significantly higher service level for the same repair budget.

"REAPing" the Benefits of Maintenance Information

MIDAS treated the repair lead times as a black box, with its impact on inventory modeled as a demand during the lead-time process. REAP focused on expanding the description of the repair process. Its goal was to understand the transactional data linking part demand, age, maintenance data, and extended work-order repair data for ARSC repair shops to improve scheduling of parts repair in these shops. This understanding could then be used to optimize the release of parts to the shop or to suppliers to improve the overall system performance, measured in terms of costs and repair lead times.

Lieutenant Commander Gary Polaski had responsibility for the ARSC repair shops. He was a fervent believer in data-driven decision making and wanted to infuse that approach throughout his organization. The long lead times to repair parts were a problem and a growing number of parts were being shipped to outside vendors for more rapid repair. Additionally, because item managers were not charged for in-house repairs, they had an incentive to use ARSC’s in-house capability even if the opportunity cost for other repairs significantly exceeded their immediate decisions. Further, the repair shops only had limited control over parts inventories and were committed to providing a certain number of repairs to item managers each year. Gary Polaski felt that the repair shops faced a demand from item managers for parts repair that was difficult to anticipate, and that item managers and repair shops had not coordinated their repair-parts requirements.

The Repair Process and an LP Model

The REAP project began by examining the broken parts in inventory; it looked at their age data based on their serial numbers, and focused on the path of the part’s repair work order as it was routed through the repair shop, and the resources that would be required to complete the repairs. The associated repair bill of materials showed the parts to be changed for each component, the labor hours, and the costs associated with each repair. The data collected for each component also included the cost of outside repair. In one example, the number of components required for repair and associated labor increases significantly beyond a certain threshold of part age for the part requiring repair (i.e., 2,700 flight hours for the main gearbox). The data also showed how parts were released for repair. Frequently, the part chosen for repair was not the newest in terms of age, as we might have expected. Resource capacity constraints affected the overall repair costs significantly. The outside vendor was seldom used strategically to ease resource bottlenecks at the repair shops.

USCG personnel repeatedly mentioned the need to repair a mix of part ages to keep the system stable. They argued that the tendency to repair the newest part would result in a synchronization of part ages; therefore, when parts did fail, they would all fail at nearly the same time, creating a crisis similar to many Baby Boomers needing Medicare resources at the same time. This avalanche of demands for parts would result in aircraft being grounded as the swell of demand created a run on the inventory. In other words, demands would move to a more nonhomogenous pattern and exacerbate the problem. This feedback provided an intriguing conceptual model context that continues to fascinate the academics to this day.
Developing an elegant model to capture the intuition of the line managers suggested that great insights based on practical experience could lead to elegant theoretical models—suggesting that it is possible to intertwine developments in theory and practice.

The Purdue faculty team decided to build a model that would select the parts released for repair from inventory to the repair shops, select parts sent to the vendor, and track repair lead times and required parts inventory (from the repair bill of materials) based on part age. The objective of the model was to minimize the total repair costs for in-house and outside vendor repair of parts while maintaining all resource constraints, such as labor resources, budget and budget-smoothing constraints, commitments to inventory managers, and vendor contracts. A key finding from this analysis was that TSO or effective part age, measured in flight hours and accumulated on a part at failure, could be a significant predictor of labor and material repair requirements at repair shops. REAP analysis showed that base capacity was tight and that overtime played an important role in enabling current constraints to be satisfied, with the shadow prices for resources providing an estimate of the marginal value by resource type.

**REAP Results**

The REAP results showed the importance of using a vendor for product repair even if the vendor was more expensive. The mathematical model runs showed the use of a vendor as a function of the vendor costs for products to be repaired. The purpose of the vendor capacity was to relieve resource bottlenecks, and concentrate on repair of expensive-to-repair parts, particularly in times of repair-request surges. In addition, if repair requests could be coordinated, then large repairs could be done when resource capacity was available, thus permitting smoothing of resource use. In addition, it did appear that a mix of parts of varying ages was thus repaired, in line with the recommendations of USCG personnel.

A few key model-generated numbers played a role in decision making. The first concerned the impact of increasing available resources by type at the repair facility. The analysis showed the objective function impact of changing different resource types; one analysis showed that a particular resource had a shadow price of $6,500 per hour—certainly enough to convince ARSC not to decrease that resource. The next analysis showed the benefit of coordinating item manager requests with repair shops—for some parts the impact was estimated to be significant. The final analysis showed the impact of changing the committed repair of particular parts.

**Developing CRISP Insights**

After the team had completed two projects, ARSC personnel and the faculty team were enthusiastic about continuing the quest to understand the overall aircraft-repair supply chain. Estimates of the benefit of incorporating part-age information in synchronizing both parts repair and selection of parts to repair were being used to influence decision making throughout the organization. At this time, USCG was planning a major upgrade of the HH-65 Helicopter.

**The Aircraft Conversion Process**

The driving force behind the upgrade was the need to improve the HH-65’s reliability. The new engine would also provide increased power to facilitate the added responsibilities being requested of USCG. Thus, CRISP, a new project to analyze the optimization of component repair capacity needed during the conversion of the HH-65 from a “B” to “C” configuration, began in 2004. The “B” version is an older version of the aircraft; the “C” version is newer and includes a more powerful engine and gearbox. In the conversion process, the aircraft would receive a new engine and engine control system, an upgraded gearbox, a new wire harness system, and several avionics components. These upgrades and the regular aircraft overall process would have to be performed using the existing resource capacity.

Congressional approval for upgrade funding was based on flight safety improvements and the restoration of the unrestricted operations that had been handicapped by power limitations and unacceptable engine and control-system reliability. Approval required a commitment to complete all of the upgrades by December 2006; this would require a two-fold increase in normal aircraft PDM/modification throughput. However, delays in contracting affected the timing of order releases to component
suppliers. This significantly reduced inventory availability, particularly of gearbox conversion kits being shipped from Europe. ARSC thus faced the challenge to complete aircraft upgrades within the deadline, given delays of some parts. In addition, it was clear that the timing of upgrades would influence future parts requirements when aircrafts faced operational difficulties in the field.

Data Analysis and the LP Model

The team collected all the transactional data regarding parts conversion, obtained development plans for product upgrades, and mapped the conversion tasks that could be performed in parallel. It also mapped the components required for each subassembly upgrade, the worker skill levels associated with each task, the repair shops that would play a role in these subassembly conversions, and the testing lead times for parts that had to be sent to manufacturer locations for approval. The data set included a combination of digital and physical data that were necessary to get a complete picture of the system.

We developed an optimization tool to capture the impact of repair capacity on the HH-65 conversion. The model provided support for decisions such as the gearbox conversion schedule (i.e., G2 to G4), capacity needed for the conversion, capacity needed for gearbox overhauls during and after aircraft conversion, and other resources needed for aircraft and gearbox conversions (e.g., gearbox housings). It also allowed us to capture constraints, such as the availability of conversion kits, overhaul kits, housing, and labor hours (i.e., repair capacity). The model directly captured the impact of decisions (e.g., repair capacity) on critical performance metrics, such as aircraft downtime, number of aircraft grounded, and number of aircraft converted from a “B” to a “C” configuration. Figure 3 shows a description of the state transitions in the model. There are two gearbox types: G2 (old) and G4 (new). Each can be in one of four possible states: (1) broken and in a warehouse, (2) in repair in a repair shop, (3) good, in inventory, and ready for issue to fly, or (4) flying on an aircraft. Similarly, there are two aircraft types: “B” (old) and “C” (new). Each aircraft can be in one of three possible states: (1) flying, (2) grounded and waiting for repair or overhaul, or (3) undergoing overhaul and conversion, either on a PDM (depot maintenance) line or a MOD (modification) line. The network model was used to develop a corresponding mixed-integer program (Iyer and Deshpande 2005). The models quantify the impact of flexibility of aircraft configurations in determining the rate of conversion of aircraft, and thus the impact on aircraft uptime and performance.

The CRISP project provided a critical decision-support tool for the successful upgrade of the HH-65 (i.e., from “B” to “C” configuration), a critical effort in enabling the safe, unrestricted operation of the HH-65 to conduct USCG missions. Figure 4 shows a summary of the results.

CRISP Results

We used the results of the CRISP model to adjust parts availability, select the number of modification lines (i.e., assembly lines that convert an aircraft from a “B” configuration to a “C” configuration) to operate in parallel, consider the impact of changes in manufacturer repair-interval recommendations, and adjust available resources at ARSC. The results showed that an accelerated program to upgrade all aircraft would result in rapid grounding of upgraded aircraft unless funds were made available for spare-parts inventory.

One aspect that we modeled was the potential 1,800-hour overhaul recommendation for the G4 gearbox by the manufacturer. This would have decreased the overhaul hours from the 3,000 hours for the G2 gearbox. The model captured the impact of this reduced overhaul interval on the projected repairs. It suggested a significant impact on the resources, thus indicating a mix of C-G2 and C-G4 aircraft; a C-G2 aircraft uses G2 gearboxes, while a C-G4 aircraft uses G4 gearboxes. Discussions with the manufacturer indicated that all the 1,800-hour life-limited parts were exterior to the aircraft, thus avoiding this constraint. Thus, the model explicitly captured the impact of engineering specifications on the repair shops and the aircraft overhaul.

Based on the analysis that the model provided, it was clear that there was a shortage of resources for timely completion of the conversion. The model suggested the need for flexible deployment of a mix of C-G2 and C-G4 aircraft. Because USCG was reluctant to implement this recommendation, there was
an urgent need for changes. Gary Polaski explains, “We implemented lean events in the gearbox shop and reduced the average time to repair a gearbox from 405 hours to 250 hours. The process change saved 8,060 labor hours, which equates to $741,000 in savings. We project that the savings will continue to the end of the project, thus saving another 5,210 labor hours and $479,000. As a result, we are ahead of schedule on production and have avoided the need for a mix of C-G2 and C-G4 aircraft. We also avoided the need to restrict operational limits at the air-stations.”

“OPTimizing” Production Throughput of the HH-60 Aircraft
The success of CRISP provided the impetus for OPT—a project focused on the PDM overhaul of the HH-60 aircraft. USCG had played an extensive role in assisting the affected population during Hurricane Katrina. However, this intense activity also highlighted the need for aircraft that would be ready to respond to such intense demands. It was critical that the aircraft be overhauled quickly to prevent future groundings due to aircraft life limits. Hurricane Katrina brought great visibility to the flexible response roles of USCG, and the HH-60 was integral to the humanitarian response that saved or assisted in saving more than 33,520 lives.

Background—Aircraft Aging and Decreased Production Throughput
Commander Carl Riedlin was responsible for the HH-60 product line at Elizabeth City. This product line performs extensive corrosion repairs to USCG’s
medium range and recovery helicopter designated the HH-60J. The PDM is a four-year maintenance cycle with a 12 to 24-month extension available depending on the location of the incoming aircraft. Currently, all aircraft in the field are expected to be in the extension period when they reach PDM.

The HH-60 helicopter-depot overhaul facility had been experiencing diminishing production rates since it reached its peak of nine overhauled aircraft in 1999. Each year, because fewer aircraft were being produced, aircraft awaiting overhaul were staying in the field for extended times. By 2005, production dropped to an all-time low of five aircraft. The effects of aging on an all-metal aircraft and the increase in mission scope following the September 11, 2001 attacks caused increased amounts of work during the PDM process. As the rebuild process increased in scope, product-line throughput decreased. This directly impacted the PDM scheduling causing aircraft to remain in the field longer and resulted in the classic maintenance dilemma, “the longer the aircraft stay in the field, the more work is required during the PDM process, which leads to an increase in cycle time and ultimately, a decrease in throughput.”

With 10 aircraft in the field beyond their planned PDM date, the deferred depot maintenance burden on USCG reached a high of $23.6 M. At this rate, the HH-60 program would need to start grounding operational aircraft beginning in March 2007; this would put 24 percent of USCG’s operational fleet at risk. To address the situation, USCG needed to increase its HH-60 product line to a production rate of nine aircraft per year and sustain that level for several years.

The Program Depot Maintenance (PDM) Process

The HH-60 PDM process involves multiple steps (Figure 5).

Several factors inhibit the production capacity of the PDM process. These include bottleneck resources, a limit to the number of aircraft allowed in the production flow, and process design. Each of these limiting forces must be thoroughly evaluated to design and develop a process to minimize total ownership cost of the HH-60 fleet. Because aircraft production is an extremely complex and labor-intensive process, optimizing the use of human resources to improve the flow of aircraft through the production process is also imperative.
In November 2005, we embarked on a study to model the production process of the HH-60 product line and to use the model to explore the most effective changes to the process. Because of the time constraints caused by the looming aircraft groundings, the HH-60 product-line staff presented several options for immediate implementation. For example, these included efficiencies to address the bottlenecks and the addition of buffer inventory in the form of additional completed aircraft hulls. In 2006, we embarked on streamlining its process through the use of lean manufacturing techniques; we completed several training sessions and kaizen (i.e., continuous quality improvement) events. Attending these events has empowered workers to make needed changes to processes.

**A Simulation Model**

The primary model was an ARENA, a simulation modeling language that was used to build a prototype simulation model that tracked both overhaul-related repairs for components and demands for components based on field failures. The model also tracked the specific subcomponents of each component throughout their lives. In addition, it captured the details of the ARSC repair process at each of the supplier locations, and the repair-related logic. The models captured three sets of flows within the system—the aircraft overhaul flow, the components flow, and the modules (within components) flow. Each follows different criteria. For example, the aircraft overhaul uses a calendar date; many components use accumulated TSO flight hours; some components use heat cycles or number of takeoffs and landings as the maintenance criteria. Many different entities are involved in the repair process; these include air-station personnel, ARSC PDM line and engineering staff, and subcontractors. Rules are associated with the flows; these include prioritizing repair, setting inventory levels, and triggering repairs. Based on USCG empirical data, we developed a comprehensive model that captured all of the detailed rules.

**OPT Results—Identifying Optimal Ways to Increase Production**

A preliminary study by the Purdue staff confirmed bottlenecks and recommended pursuing efficiencies aggressively while building a more detailed model. The study determined that the addition of buffer inventory would only produce a short-term gain but no long-term increase in productivity. During the course of this study, we used the models to explore the following approaches to optimizing HH-60 maintenance throughput:

1. Analysis of different ways to increase throughput production of the HH-60J from six per year to nine or more per year;
2. Identification of the impact of reduced variability in the process, e.g., evaluation of the increase in throughput derived from reducing the standard deviation of assembly time;
3. Exploration of different production-management options (e.g., cellular manufacturing, assembly line, or cycle-time-driven pull system);
(4) Understanding of the impact of optimizing the aircraft release process for the current PDM process;
(5) Modeling of the impact of the additional processes required for the HH-60T conversion process, and evaluation of the impact of alternate timing and capacity levels.

As a result, we reduced the overall cycle time to build an HH-60 aircraft from 200+ working days to an impressive 145. In only eight months, this dramatic reduction resulted in a production increase to nine aircraft per year. Thus, USCG avoided the requirement to outsource some of its HH-60 product line production processes at a cost saving of $5 M annually. In addition, the preliminary study eliminated buffer inventory as a viable option, thus avoiding an $8 M cost to build two new hulls. Impressively, we reduced the deferred depot maintenance burden on USCG from a peak of $23.6 M to $6.5 M with only three aircraft waiting for overhaul. Most importantly, the rapid response avoided the loss of operational aircraft, thus maintaining USCG’s mission readiness.

An increase in the production of aircraft on the HH-60 PDM line is essential for the future viability of the HH-60J as a safe and reliable aircraft. This study has accelerated the throughput of the HH-60 product line to nine aircraft per year. In the past few years, USCG has embarked on a major recapitalization of most of its surface fleet and some of its aviation assets; however, its budgetary climate has been very constrained. This study has helped USCG to increase its HH-60 production and will have a significant impact on future aircraft availability to complete its missions.

**Organizational Impact**

**Establishment of an OR Cell**

Today, we see a thriving Logistics Support Branch (LSB) headed by Lieutenant Commander Kent Everingham. The LSB supports all activities related to keeping aircraft airworthy at air stations. OR has become ingrained within the LSB and the evolution of the LSB into an OR cell is ongoing. There are three employees in the cell and the LSB workload has grown to such a level that the size of the cell must expand to meet this increased workload. The requirement for OR modeling and analysis to accompany budgetary requests is now commonplace.

When a funding shortfall threatened to prevent the proper sparing of the HH-65 main gearbox, the LSB utilized the findings of the CRISP study to help design a new simulation model that it used to determine the required asset level for the operational fleet. The results, which were supported with hard data, quickly earned the support of senior management who redirected more than $9.9 M to ensure the attainment of a proper sparing level. Similarly, all statements of work released against a vendor contract now require that they implement the prototype developed using MIDAS OR. In addition, ARSC has integrated the LSB, Component Repair division, and planned Capacity Planning Cell into a new Industrial Operations division to leverage information sharing and OR applications across the enterprise. These four projects were basically stepping stones that have allowed the LSB to make the next step—a supply chain management system solution, which will provide tools to allow ARSC to better optimize the supply chain. This will let ARSC achieve a nominal 10-percent reduction in annual inventory purchase and repair costs and a nominal 10-percent reduction in depot maintenance costs (i.e., repair and operating costs) over a total budget of over $200 M.

**Quantifiable Benefits of the Four Projects**

The four projects have led to the following quantifiable benefits:

(1) MIDAS provided inventory reductions of 20–70 percent for 41 critical parts that the model projected; this represents 50 percent of the dollar volume at ARSC;

(2) REAP provided 10-percent model-projected savings in repair costs by using maintenance information for component-repair planning. The savings are significant considering that the total repair budget of ARSC is over $200 M;

(3) CRISP provided a successful planning for the conversion of the HH-65 aircraft from a “B” to “C” version, thus enhancing the safety and capability of USCG equipment. The limited resource capacity that the model identified justified “Lean” events at the gearbox shop that reduced labor hours by 13,270 from the original estimate and saved $1.2 M in repair and labor costs;
(4) The improved productivity of the gearbox repair shop permitted all repairs and overhauls to be done at ARSC, thus saving an average of $650,000 annually ($50,000 per gearbox for 10–15 gearboxes per year);

(5) CRISP analysis was used to justify and redirect $9.9 M to ensure proper sparing levels for fleet support;

(6) The OPT project resulted in a decrease in the PDM lead time for the HH-60 aircraft from 200+ days to 145 days. This resulted in a 50-percent increase in throughput of the H60 PDM line and decreased the deferred depot maintenance burden on USCG from $23.6 M to $6.5 M. The increased productivity prevented nine HH-60 aircraft from being grounded.

REAP identified the impact of material delays on the repair lead times and repair capacity requirements. The new organizational structure releases money for kits so that material delays are reduced. This need to release complete kits has also affected the budgeting process for parts with money earmarked specifically for item managers to purchase complete kits. To manage parts release for repair, repair shop job-release planners work with shop supervisors and item managers to project impending demand, contracted work, and plans for releasing jobs. This is an initial step toward vendor-managed inventory and use of the upcoming supply chain management tools. With a total inventory value of over $780 M and a repair budget of over $200 M at ARSC, the long-term savings generated from these projects are expected to be significant.

While these dollar savings are significant and important, the most important quantitative metric for USCG is mission readiness and mission execution, particularly during events such as Hurricane Katrina, which require a surge in the use of assets as aircraft are redeployed from air stations around the country. During this hurricane, 18 HH-60 aircraft were deployed continuously for one month. Hence, having aircraft that are mission ready and capable to redeploy on short notice is a key metric for USCG.

Mission readiness is also a key measure of performance at the air stations. The minimum readiness requirement (for an asset) is launch readiness within 30 minutes. Mission execution is defined as having flyable assets against all mission types. If a decrease in PDM had resulted in the grounding of nine HH-60s, 6,300 flight hours would have be lost—a reduction of 24 percent of the capability. Replacing those aircraft would have cost approximately $270 M; however, that would have been infeasible given aircraft procurement lead times and budgetary realities. Therefore, the actual result would have been a decrease in mission readiness and mission execution. The models estimate that mission readiness would have dropped from 100 percent to 96 percent, while mission execution would have fallen from 84 percent to 4 percent because of the grounding of the nine HH-60 aircraft. This would have implied that a large fraction of critical USCG missions, such as responding to Hurricane Katrina, would have gone unsupported. By ramping up the HH-60 PDM throughput, the mission readiness was maintained. ARSC believes that this is one of the most important quantifiable benefits of the OR projects.

**Summary**

The series of projects at ARSC demonstrate the value of OR methodologies for efficient supply chain management at USCG’s Aircraft Repair and Supply Center. These projects have provided critical decision-support tools for planning various ARSC repair and maintenance activities. The establishment of the OR cell within ARSC, with several new employees and interns hired for this purpose, demonstrates the sustainability of these OR initiatives. The projects have created a strong emphasis on data-driven planning within ARSC. A suite of software tools were used to develop prototypes to automatically extract, transform, and load critical lead-time, demand, and component history data from AMMIS and ACMS. The quantifiable benefits of these projects include reductions in inventory by 20–70 percent for 41 critical parts (MIDAS), 10 percent savings in repair costs by using maintenance information for component repair planning (REAP), a successful planning of the conversion of the H65 aircraft from a “B” to “C” version, thus enhancing the safety and capability of USCG missions (CRISP), and a 50 percent increase in the throughput of the H60 PDM line and a resulting decrease in the USCG deferred depot maintenance burden from a peak of $23.6 M to $6.5 M. The increased PDM productivity also prevented the grounding of nine HH-60
aircraft, thus enhancing USCG’s mission readiness. OR techniques applied by the team have clearly been successful in both transforming the culture at ARSC as well as enhancing the understanding of real-world systems for the academic team. Today, USCG’s ARSC can truly be considered to be “OR ingrained.”

Appendix

REAP—Repair Optimization Model

\[
\begin{align*}
\text{Min} & \quad \sum_i CG_i X_{i1} + \sum_i c_i X_{i2} + \sum_j CO_j OR_j \\
(\text{minimize the sum of in-house repair, vendor repair, and resource availability constraint})
\end{align*}
\]

s.t. \( \sum_i a_{ij} X_{i1} \leq R_j + OR_j \),

\( X_{i1} + X_{i2} = IM D_i \),

(IM total demand constraint),

\( X_{i1} \geq \text{Commit}_i \) (in-house repair at least equal to commitments made to IM’s),

\( OR_j \leq \text{OT scale} \ast R_j \),

(overtime availability constraint),

\( X_{i1} \)—in-house repair quantity,

\( X_{i2} \)—vendor repair quantity,

where \( i \) is for NIIN and \( j \) for shop or resource.

What Is a Resource \( j \)?

- Shop capacity
- Skilled labor
- Component inventory
- Carcasses available

Variable Definitions

\( X_{i1} \)—in-house repair quantity for each NIIN \( i \);

\( X_{i2} \)—vendor repair quantity for each NIIN \( i \);

\( R_j \)—annual average resource capacity for each shop \( j \);

\( OR_j \)—overtime capacity for each shop \( j \);

\( a_{ij} \)—amount of capacity used by each NIIN \( i \) in each shop \( j \);

\( CG_i \)—per unit total cost in-house for each NIIN;

\( c_i \)—per unit repair cost charged by vendor for each NIIN;

\( CO_j \)—overtime capacity costs for each shop;

\( \text{Commit}_i \)—parameter for Commit made to IM;

\( \text{OT try} \)—overtime yes/no;

\( \text{IScale} \)—in-house cost scaling;

\( \text{VScale} \)—vendor cost scaling;

\( \text{OTScale} \)—overtime scaling;

\( \text{CScale} \)—regular capacity scaling.

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