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Product Support in a Maintenance Free Operating Period Strategy

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ABSTRACT

Application of a Maintenance Free Operating Period (MFOP) strategy in a fleet of vertical lift aircraft has profound implications to product support. Previous approaches to MFOP focused on estimating the operating period's probability of success with modeling techniques and improving results using design elements such as inherent reliability. These approaches were aircraft centric and neglected aspects of the sustainment system external to the airframe. Key external facets addressed are the establishment of metrics that adequately measure MFOP performance as a stochastic process, optimization of the recovery period through a systems approach, transition to risk-based maintenance using high fidelity diagnostic and prognostic systems, establishment of an architecture to facilitate quality data consumed by a digital twin, and construction of maintenance policies suited for MFOP. The study concluded that robust product support surrounding the aircraft provides the best likelihood to achieve MFOP strategy success while delivering an efficient recovery period.

INTRODUCTION

A Maintenance Free Operating Period (MFOP) is a period during which an aircraft operates without the need for services beyond routine replenishment. An MFOP maintenance program seeks to "eliminate disruptive random failures over an extended period and consolidate all scheduled maintenance into a succinct repair period called a Maintenance Recovery Period" (Ref. 1). The renewals in the Maintenance Recovery Period (MRP) restore the aircraft to a sufficient level of reliability to complete the next the MFOP (Figure 1). Mission requirements dictate the necessary length of the operating period. The actions and duration of the MRP are dependent on the accumulated damage at the end of current cycle and the expected wear in the upcoming period.

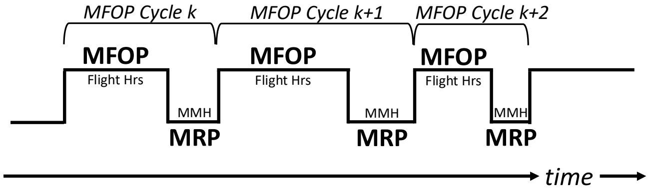

Figure 1. An MFOP cycle consists of an operating period and subsequent recovery period (Ref. 2).

An MFOP maintenance policy must provide the flexibility to both remove unnecessary preventive maintenance and to add actions as dictated by predictive measures. Preventive maintenance conducted in the MRP will change from cycle to cycle based upon the accumulated wear on aging components. The goal of an effective MFOP strategy is to synchronize preventive maintenance into the MRP to ensure an undisrupted flight operations period.

Background

The origins of MFOP began with the Ultra Reliable Aircraft Pilot study by the British Royal Air Force in the late 1990's (Ref. 3–5). Relf (Ref. 6) introduced the first design methodology and offered six options to improve the MFOP: inherent reliability; prognostics and diagnostics; understanding failure life characteristics; redundancy; reconfigurability; and lifing policy. Similar concepts have been applied as Time-Limited Dispatch (TLD) in commercial airlines (Ref. 7,8). TLD uses tiered levels distinguished by duration of dispatch: no-dispatch, short time dispatch, long time dispatch , and manufacturer/operator defined dispatch (Ref. 7). Faults are placed in one of four tiers depending on the likelihood of failure with a time limit set for repair by tier.

The U.S. Navy examined MFOP on its ships in 2005 and 2010 with recorded cost savings (Ref. 9,10). Attracted by the possibility of operating aircraft away from permanent airfields in more expeditionary operations, NATO deliberated on MFOP with the conclusions that the greatest gains may be achieved in the design of new systems (Ref. 11). The Army Science board, documented an early concept to implement MFOP into the Future Vertical Lift programs (Ref. 12). It

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recognized the need for a new generation of aircraft to achieved desired sustainment goals.

Renewal theory and reliability engineering serve as the mathematics and modeling techniques to measure MFOP in (Ref. 7,13–16). Several modeling efforts employed discrete event simulations to predict MFOP performance (Ref. 17,18). Bellocchio (Ref. 2) proposed a framework to generate a MFOP maintenance policy that ranked ordered components to be renewed at the next MRP based upon the probability of failure and the time of disruption. Most recently, Beigh et al. (Ref. 1) presented simulation results that analyzed the MFOP metrics of MFOP Success, MRP duration, availability, and cost under the context of Future Vertical Lift. They concluded the inherent reliability necessary to achieve an operating period goal of 100 hours was both impractical and "cost prohibitive." The team recommended programs pursue reliability in conjunction with the other MFOP options to realize significant gains in the next generation of rotorcraft.

The recommendations of Relf and Beigh et al. added insight on how the design of an aircraft influences MFOP performance; however, they did not address system components external to the airframe. Key external facets include acceptance of new metrics that adequately measure MFOP performance as a stochastic process, optimization of the recovery period through a whole system approach, transitioning to risk-based maintenance, establishment of the data architecture demanded by MFOP, and construction of maintenance policies to protect the MFOP.

MEASURING MFOP

At the programmatic level, evaluation of the platform's performance using traditional mean based metrics like Mean Time Between Failures (MBTF) is inadequate for forecasting MFOP (Ref. 19,20). Hockley (Ref. 4) explained the consequences of MTBF and the assumption of a constant failure rate, inherent to a "culture of the inevitability and acceptability of failures." The acceptance of MTBF as a rule neglects information vital to an MFOP user. Understanding the actual time of failure is key to the development of future systems that perform over extended operating periods and, using MTBF, this information is lost. To describe performance under an MFOP strategy, new metrics must account for the time dependency inherent to an operating period.

Previous published work focused on the addition of MFOP duration and its probability of success (*MFOP Success*) (Ref. 1,13,14). The use of probability of success acknowledges the stochastic nature of failures in complex systems. *MFOP Success*, originally called *MFOP Survivability*, was introduced by Kumar (Ref. 14) in 1999. It is a conditional probability event that measures the mission reliability that the system will survive the upcoming operating period given it survived up to the current cycle. Survival is defined as the absence of corrective and unscheduled maintenance occurring during the operating period. *MFOP Success* is calculated as

$$MFOPS(t_{mf}, i) = \frac{R_{sys}(k \times t_{mf})}{R_{sys}([k-1] \times t_{mf})}. \qquad (1)$$

where R_{sys} is the mission reliability of the system, k is current cycle, and t_{mf} is the time or period of maintenance free operation.

Each component and subsystem may be described in reliability engineering as failure distribution, typically Weibull, lognormal, or exponential. Given a sufficiently complex system like an advanced aircraft, the Central Limit Theorem reveals the system tending towards a normal distribution. The cumulative distribution of *MFOP Success* versus duration follows a normal distribution and is plotted in Figure 2.

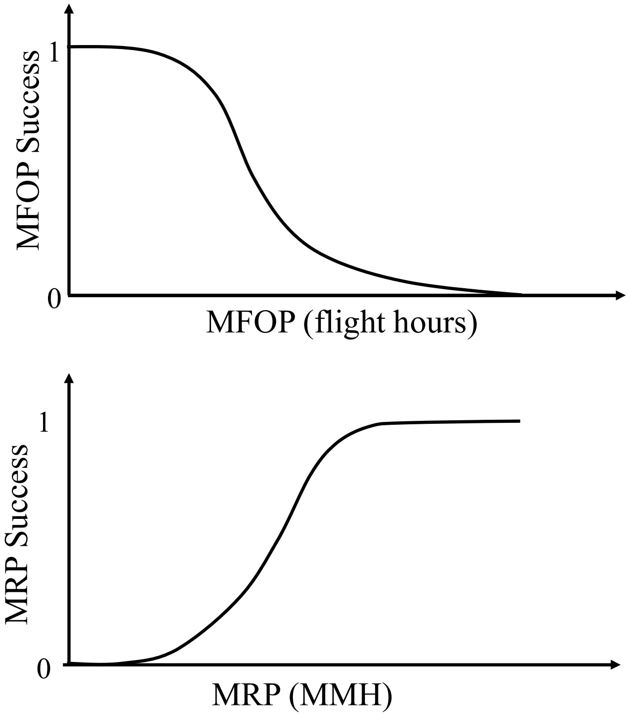

Figure 2. Single cycle cumulative distributions for the success of MFOP (top) and MRP (bottom).

The MRP is the necessary penalty for achieving a future period of sustained, flight operations. The MRP includes not only the accumulated scheduled and deferred maintenance, but it also includes predictive maintenance (any preventive maintenance forecasted as necessary to improve *MFOP Success* for the upcoming period). The necessary maintenance and subsequently maintenance man-hours (MMH) are a function of the health of the aircraft as it enters the recovery period. Thus, the MRP has a success rate much like the MFOP has a success rate. The MRP curve is a cumulative distribution function as drawn in Figure 2. *MRP Success* measures the probability that the recovery period duration will be less maintenance man hours (MMH) than a given value. The value is generally variable because necessary repairs are a function of wear and repair times.

Evaluation metrics must capture the MRP penalty. Ratio metrics such as availability (2) and maintenance ratio (3) express the balance between the operating period and the recovery period.

$$Availability = \frac{Uptime}{Uptime + Downtime} \qquad (2)$$

$$Maintenance\ Ratio = \frac{MMH}{Flight\ Hours} \qquad (3)$$

Care must be taken to not fix too many requirements with the ratio metrics. By fixing the MFOP duration, MRP goal duration, and maintenance ratio, the evaluation becomes over constrained in a pure MFOP strategy. Only two of the three metrics should be specified to avoid conflicting requirements. The utilization of MFOP duration and MRP duration with their respective success rates helps product managers measure the time dependency while taking account of the stochastic nature of component failure and repair actions.

TAKING A WHOLE SYSTEM APPROACH

The desired benefit of an MFOP concept into aviation operations is the increased availability and dependability of an airframe during periods of execution. While gains in performance can be found by increasing the reliability of the airframe, as Beigh et al. clearly articulated, improving reliability is necessary, but not sufficient to meet identified end states. Bottomley similarly cautioned that the efforts to increase reliability of systems “provided diminishing returns” (Ref. 5). To meet the goal of consistently achieving a longer operating period, future research efforts need to go beyond the examination of component reliability to identify other potential areas for investment.

Teams must broaden the scope of study from a single airframe to the full spectrum of aviation operations to identify and address underlying causes of lower than desired system performance. By taking a systems approach to the study of an MFOP strategy, future research teams can assess how system structure impacts objective achievement. Viewing the system holistically will provide the best vantage for identifying leverage points for change. For clarity, a system, as described by the International Council on Systems Engineering, is a “set of integrated elements that accomplishes a defined mission.” A system has three distinct part: components, relationships between those components, and a purpose for which it exists. In examining MFOP strategy, the system under study is aviation operations and the

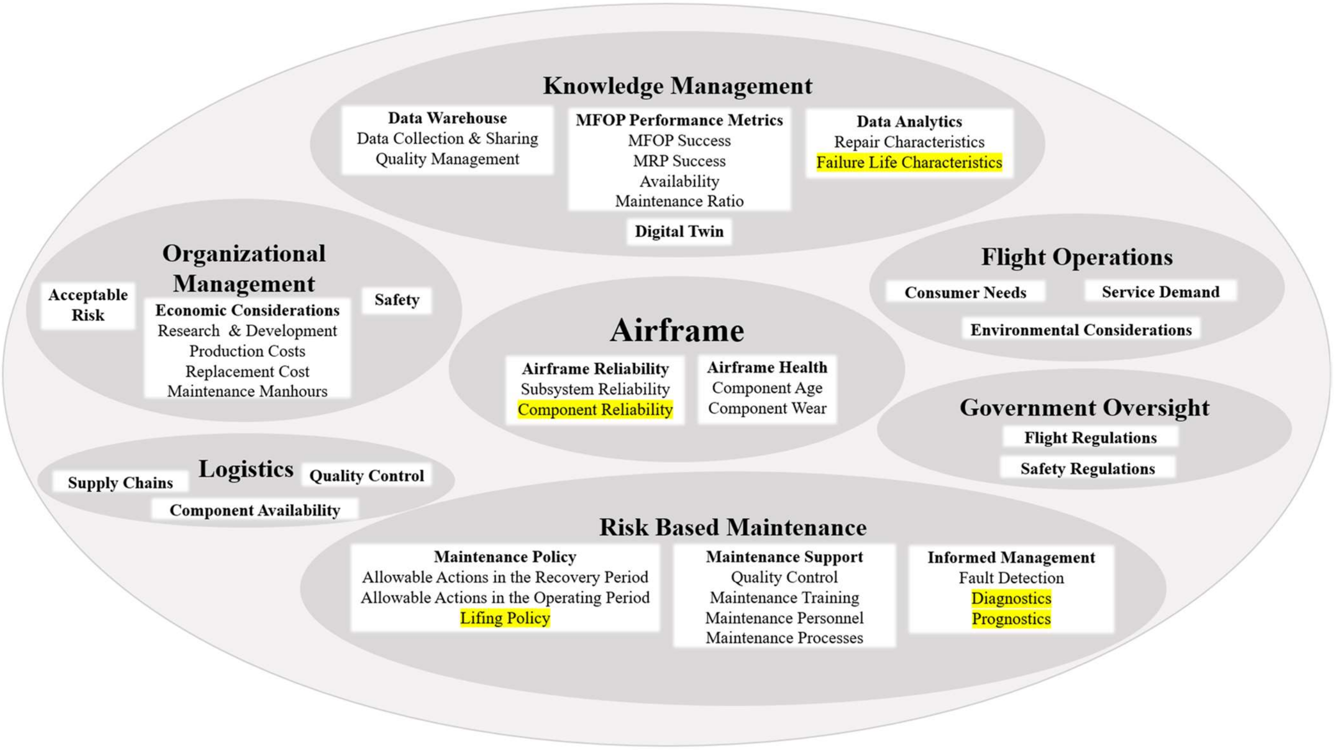

Figure 3. Product support surrounding the aircraft plays a significant role in an MFOP strategy. Options first denoted by Relf (Ref. 6) are highlighted yellow.

system objective is the completion of assigned flights. The components of aviation operations encompass the products (missions, airframes), processes (flight assignments, maintenance processes), people (pilots, maintainers, engineers), information (data, reports), techniques (predictive maintenance), facilities (flight lines, maintenance bays), and services (maintenance, replenishment, fault identification). As seen, components of a system do not have to be physical. The relationships between the components within a system Figure 3 diagrams how individual components within aviation operations are related. This breakdown of MFOP into integrated components, while not exhaustive, provides the reader with a better understanding of the scope of aviation operations when viewed as a system. Accurately defining a system's components is necessary prior to examining the relationship between the system structure and behavior.

In the case of MFOP, the behavior of the aviation operations is best described using the four performance metrics proposed earlier. Thinking about how changes in select elements within the system affect the identified metrics can illuminate potential areas for future investment. Of the four proposed metrics described earlier, three metrics utilize maintenance hours in the calculations (maintenance ratio, *MRP success*, and airframe availability). Thus, altering the maintenance processes within the aviation operations system would impact the assessed performance of the MFOP strategy. Changes to how repairs are performed to reduce time needed for repairs would lead to a decrease in the maintenance man-hours performed during the recovery period. Holding all other factors stable, the reduction in man-hours would decrease the maintenance ratio, improve airframe availability, and improve the *MRP success*. This brief example illustrates how changes to the maintenance processes alone could impact system performance. Another area of investment that could result in a lower maintenance ratio is the improved accuracy of diagnostics. A commonly cited concern within the aviation community is the high rate of No-Fault-Found removals. After the removed part was inspected, it was noted that the subcomponent could have continued to operate and that maintenance actions (and downtime) were unnecessary (Ref. 5).

A key finding from examination of the previous research efforts was that recommendations for improving MFOP performance focused primarily on inherent reliability of system components. In the seminal work by Relf (Ref. 6), the author suggested six methods to increase MFOP. Of those six, only one--the lifing policy, relied on non-materiel system adjustments to alter performance. Taking a whole system approach would lead to a greater number of alternatives for MFOP performance activities that did not rely solely on materiel research and development.

FROM SCHEDULED TO RISK-BASED MAINTENANCE

A necessary condition of MFOP is to eliminate disruption of the operating period by scheduled maintenance activities. To protect the operating period, all scheduled maintenance must be synchronized into recovery periods. Components must be designed and maintained to a life greater than MFOP (Ref. 11), ideally with scheduled intervals that are multiples of the design operating period. The synchronization requires strong maintenance policies to protect the operating period from disruption. This represents the start of implementing an MFOP strategy.

As a platform's diagnostics and prognostics mature, predictive maintenance will remove calendar and scheduled maintenance in favor of risk-based maintenance using active health-state awareness. Diagnostics convey the current state of the system. Prognostics predict a future state of the system given a current state. The progress to risk-based maintenance can be achieved in four successive levels of advancement (Figure 4). The evolution is enabled by the maturation of diagnostic and prognostic capabilities.

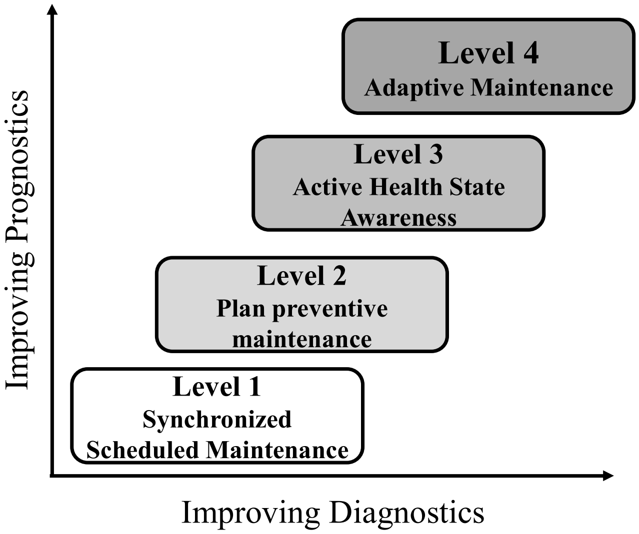

Figure 4. Risk-based maintenance requires continued advancement in diagnostic and prognostic systems.

Level 1 is the synchronization of scheduled maintenance into discrete intervals of the design MFOP duration. Both MFOP and Maintenance Steering Group 3 (MSG-3) are reliability centered approaches and share attributes. Adaptation of MSG-3's decision logic described in (Ref. 21) can help synchronize scheduled maintenance into the MRP.

Level 2 is the ability to plan preventive maintenance for the next MRP at the current MRP. This plan is built upon predicted wear and usage of components expected over the upcoming operating period as informed by fixed prognostic algorithms.

Level 3 is the achievement of active health state awareness that continuously feeds prognostics. The prognostics update the upcoming MRP's preventive maintenance plan and informs the maintenance manager of the *MFOP Success* as well as an estimated MRP duration.

Level 4 consists of adaptative maintenance policies that respond to changing operational tempo or environmental conditions. The adaptative policy recognizes that one maintenance schedule does not fit all operational demands or environments.

Diagnostics and prognostics conjoin to inform Reliability Center Maintenance (RCM). In an MFOP context, relative importance is based upon cost and the expected time of failure inside the upcoming operating period. Greater importance should be given to components most likely to fail early in the operating period. Only failure modes that require maintenance before the next flight (essential maintenance action) should be considered important. Failures that do not affect mission effectiveness and may be safely deferred to the recovery period are of minimal importance. By prioritizing essential maintenance actions and the expected time of failure, the approach becomes Risk-Based Maintenance (RBM) where risk includes disruption to the operating period and excessive recovery periods. The pursuit of RBM seeks the minimization of failure during the operating period *and* the minimization of the subsequent recovery period duration.

Accomplishment of Level 2 permits identification of upcoming maintenance activities and necessary repair parts as depicted in Figure 5. This allows logistical ordering to lead the maintenance which has the added benefit of reducing logistical downtime and increasing operational availability. Fritzsche and Lasch (Ref. 22) concluded that predictive maintenance can even avoid unscheduled component failures and further increase availability.

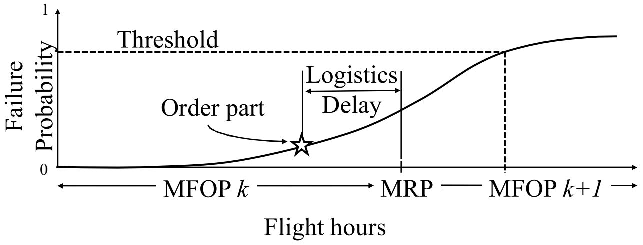

Figure 5. Accurate diagnostics and prognostics enable ordering parts such that delivery occurs as the aircraft enters the recovery period.

Accomplishment of Level 3 fully utilizes predictive maintenance to provide decision space for maintenance managers. The progressive phase maintenance of the U.S. Army's OH-58D Kiowa Warrior offered a limited set of options to conduct maintenance inside a defined window (Ref. 23). The approach was appealing because it provided modest options to fit maintenance around operational demands. An MFOP strategy at Level 3 multiplies this effect. With active health state awareness, high fidelity diagnostics and prognostics empower the manager to make informed decisions that balance operational demands and cost against the risk of disruptive unscheduled maintenance and lengthy recovery periods. Organizations become less reactive to unscheduled maintenance and begin to control the *MFOP Success* and MRP to best meet mission demands. Level 4 applies the same freedom but tailors the information to a specific aircraft operating in a particular environment at a desired tempo.

MEETING THE DATA DEMANDS OF AN MFOP STRATEGY

The progression towards prognostics and probability-based decision-making demands increased information and robust knowledge management. These demands represent a third consequence.

Digital Twin

Future diagnostics and prognostics will generate and utilize large amounts of data. The data must be timely, relevant, and accessible by a myriad of systems on and off the aircraft. The data architecture is the backbone of an MFOP strategy. The digital thread documents the design, employment, and management of the cyber-physical product throughout its life cycle. The thread houses the fleetwide data that informs individual aircraft's digital twin. Glaessgen and Stargel (Ref. 24) offer a clear definition for digital twin in an MFOP context, "an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin." Informed by the 2010 NASA Materials, Structures, Mechanical Systems, and Manufacturing Roadmap (Ref. 25), this paper recognizes four significant capabilities of a digital twin in MFOP (Figure 6).

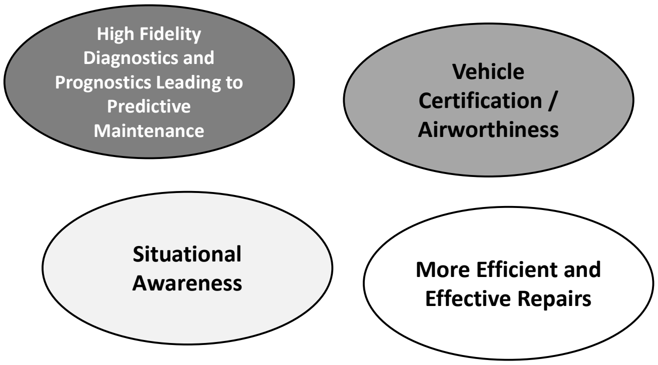

Figure 6. Capabilities of a digital twin in an MFOP strategy.

The digital twin houses the diagnostic data and prognostic models that facilitate predictive maintenance. The digital twin also provides both the aircrew and maintainer with situational awareness on the loads, wear, and health of the aircraft. With a comprehensive twin, aircraft certification processes can be streamlined and replace costly physical testing. Finally, the digital twin is expected to reduce repair time and error by aiding maintainers in fault detection and visually guiding repairs.

Of key importance in building the physical models and prognostics is a better understanding of failure characteristics and, where physical models have shortcomings, the generation of time to failure distributions based upon experimental and historical data. Designers must identify the correct set of components to monitor. This set of components should consider the frequency of failure, level of disruption caused by the failure, time of failure in the operating period (earlier is worse), and the variability of time to failure (more variability introduces uncertainty into prognostics). In an MFOP strategy, the time a part fails is just as important as how often a part fails. Parts with a high variance in failure time or wear are prime candidates for monitoring.

Collecting, storing, retrieving, and managing data are significant efforts. Sharing of data while maintaining proprietary rights is an especially important requirement in a digital thread. Accomplishing these tasks requires policies, architecture, and training to generate the digital twin that informs operators of an aircraft's current state and feeds the prognostics to predict the future state.

Quality Data

A successful MFOP strategy is reliant on quality data to inform decision making. The term quality data refers to data that accurately reflects the performance of the system. Aviation leaders must assess all available information to make decisions on what maintenance to perform at a point in time based on the operational environment, available resources, airframe status, and acceptable risk to future flight operations. Without accurate data, decisions makers will direct action that potentially incurs unnecessary risk to life, increases system cost due to inefficient resource utilization, or may lead to early termination of a flight period. Building a data repository that will support an MFOP strategy entails choosing what relevant data metrics should be tracked, building a culture of accurate data reporting, and sustaining the commitment reviewing material performance assumptions given recent data point.

There are two key areas for which data must be collected. First, relevant knowledge for aircraft components must be tracked to include the failure distribution of the component and the current age of each individual component. To retain leadership trust in the numbers, the failure distribution must be evaluated using current component fault reports. Failure distributions are used to assess the probability that the component will fail during the next operating period given the current age of the component. If the failure distribution inflates the component age before failure, the decision maker may not replace the component during the recovery period. The component may then fail during an operating period resulting in loss of life, loss of equipment, or the inability to perform desired flight operations. The second area for which data must be collected and retained is maintenance repair data. Success of the MFOP strategy is dependent on maintenance being performed within a predefined recovery period. If the analysis underestimates the repair time, the decision maker will authorize a repair that may potentially delay the start of the next operating period. On the other hand, if a repair time distribution overestimates the time to repair a component, the decision maker may elect not to complete deferred maintenance. The airframe will leave the recovery period capable of finishing the next operating period, but with a backlog of deferred maintenance that could have future repercussions.

The quality of the data impacts key leader confidence in subsequent analysis and recommendations. If the quality of the data is poor, a leader will be less likely to accept risk in operational accomplishment to potentially preserve resources.

CONSTRUCTING AN MFOP FRIENDLY POLICY

Actions During the Recovery Period

Relf (Ref. 6) offered "lifing policy" as an option to improve a system's MFOP. The lifing policy focused on determining the timing to renew a component. Obtaining accurate models of this time to failure is a central aspect in constructing a maintenance policy for aircraft that are comprised of many components and subsystems. While the majority of previous MFOP studies centered on estimating the MFOP and *MFOP Success*, the MRP and its interaction with the aircraft and surrounding whole system has not been fully explored. Reliability engineering has used renewal theory and branch and bound methods to optimize preventive maintenance, logistics, and cost (Ref. 14,15,22). Bellocchio (Ref. 2) presented a framework to construct a maintenance policy using renewal theory, although optimization at the MFOP's discrete intervals remained unsolved. Application of a policy for a new aircraft designed specifically to operate in an MFOP has not been done and requires developers' attention.

Figure 7 illustrates actions inside the recovery period that are the building blocks of a policy. As the aircraft concludes its current operating period (k), its *MFOP Success* for the upcoming cycle ($k+1$) achieves its minimum. Maintainers

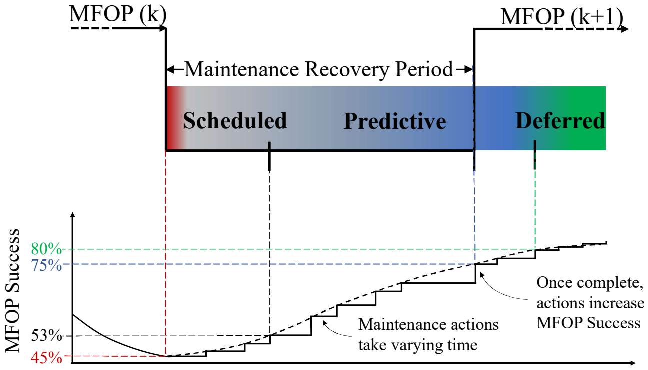

Figure 7. Maintenance in the recovery period will incrementally raise the *MFOP Success* for the upcoming cycle. Predictive maintenance should continue until the desired Success is achieved.

begin the recovery period with scheduled maintenance (Level 1 and Level 2) or predictive maintenance (Level 3 and Level 4). After completion of scheduled maintenance, predictive maintenance actions incrementally increase the *MFOP Success*. Predictive maintenance continues until either the maintenance man-hours grow the goal recovery duration or *MFOP Success* is achieved. Should predictive maintenance achieve the *MFOP Success* goal before the MRP goal, then the manager may direct to repair deferred, non-mission critical faults or begin the operating period of *k+1* early. Should predictive maintenance exceed the recovery period goal, the manager must either exceed the goal recovery period duration or accept a less than desired *MFOP Success* in cycle *k+1*. The latter is shown in Figure 7 with a *MFOP Success* goal of 80%.

The objective of an MFOP policy is to maximize *MFOP Success*, minimize the recovery period duration, and remain affordable while retaining an operating period undisrupted from maintenance. The requirements, policy, and aircraft must be compatible to achieve *MFOP Success* with an efficient recovery period. Finding the right trade-offs between operating period duration, recovery period duration, and affordability is the challenge in constructing a well-suited policy.

Allowable Actions During the Operating Period

The introduction of an MFOP strategy raises several questions regarding the correct way to manage maintenance. England (Ref. 26) posed a series of questions regarding achieving an MFOP strategy. This paper introduces additional, considerations for the management of an MFOP system.

Defining a Broken MFOP

An MFOP policy must define the level of failure that breaks the MFOP. In the strictest sense, any repair necessary before the next flight breaks the operating period and counts as a cycle failure. Toleration of limited repairs (e.g., less than a few maintenance man-hours) may or may not be considered disruptive. Management should state if limited repairs break the operating period. The decision informs how close repair packages (maintainers, tools, and parts) must be located to the aircraft's forward operating site. This drives forward footprints and logistical trains.

Actions Following a Broken MFOP

When an aircraft experiences a failure during the operating period, a policy must direct how to proceed with the necessary repair. Figure 8 shows three possible approaches: (1) full MRP; (2) fix and fly; and (3) short MRP.

The full MRP approach counts the MFOP as broken at the time of first failure. With the operating period broken, the aircraft goes to maintenance for execution of a full recovery period in preparation for the next full cycle. This is the strictest and most traditional interpretation of an MFOP strategy. Under a fix and fly policy, the single failure is repaired, and the aircraft returns to flight operations for completion of its remaining operating period. The policy may count the MFOP as broken or resume the MFOP if the repair is limited. In a Level 1 or Level 2 system, , the fix and fly approach is the only viable option because preventive maintenance is pre-programmed to follow a rigid plan. The third approach is a short MRP. This approach counts the MFOP as broken upon failure and sends the aircraft to maintenance for repair of the identified failure. Based upon prognostics, additional repairs may be conducted to restore the desired level of probability of success to complete the remaining MFOP duration. A Level 3 or Level 4 system supports the full MRP and short MRP approaches. They also enable a manager to flex between the three approaches based upon mission requirements. This is the most preferred of all.

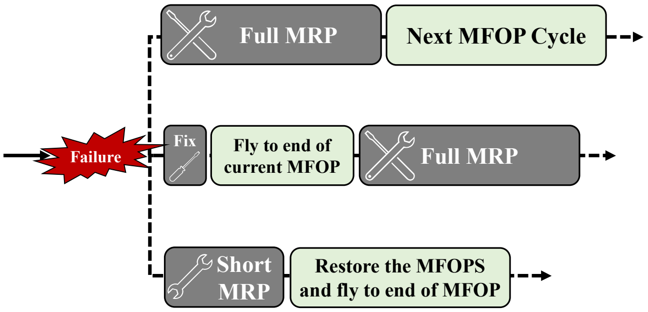

Figure 8. Three approaches are available to a manager after a failure in the operating period: conduct a full MRP (top); fix the fault and resume flying (middle); or enter a short MRP (bottom) to restore MFOP Success then resume the operating period.

Ending the MFOP

It is unlikely that a particular flight will land at end of the operating period's flight hours. This presents an option that should be spelled by a policy. Figure 9 provides an example.

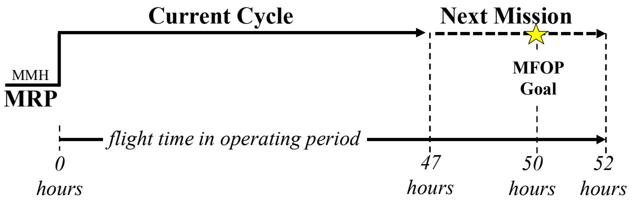

Figure 9. A policy should define mission sequencing at the end of the MFOP duration.

Suppose a fleet has a 50-flight-hour MFOP where flight missions typically take five hours. If an aircraft is 47 hours into the MFOP, the dispatcher may decide to attempt the final mission and end the MFOP at 52 hours or halt the MFOP three hours short of the duration goal and enter the MRP early. A maintenance policy must clarify if an MFOP is successful or broken should the aircraft successfully fly 50-hours maintenance free but then experience a failure before the end of the mission on the 52nd hour.

CONCLUSIONS

Product support to MFOP is essential to achieving operating periods that are a magnitude greater than today's enduring aircraft. A complete MFOP strategy must look beyond the airframe's reliability to achieve significant improvement. The requirements, architecture, policy, and aircraft must be compatible to achieve *MFOP Success* with an efficient recovery period.

- Previous works have shown that the inherent reliability necessary to achieve MFOP goals will become cost prohibitive. To make significant gains and remain affordable, product support must be part of a whole system approach.

- An MFOP strategy represents a significant departure in maintenance philosophy from traditional approaches and requires new evaluation metrics. The MFOP duration, by definition, is a time dependent metric and should be evaluated probabilistically with a success rate.

- MFOP provides the incentive to progress maintenance approaches from calendar-based scheduling that frequently disrupt flight operations to consolidated, efficient recovery periods that minimize disruption. This full benefit of an MFOP strategy is achieved by robust diagnostics and prognostics that bring about risk-based maintenance.

- Product support must adjust to the subsequent information needs by requiring highly developed component failure characteristics, comprehensive maintenance records, and greater fleet data management.

- Maintenance managers must build policies that prioritize predictive maintenance over scheduled maintenance. This eliminates unnecessary preventive maintenance while maximizing the *MFOP Success*. Finally, a complete policy accounts for a new set of planning factors for the recovery period and resumption of operations following unscheduled maintenance.

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REFERENCES

1. Beigh, M., Bellocchio, A., Burgess, J., and Schrage, D., "Modeling a Maintenance Free Operating Period Strategy for Future Vertical Lift," Vertical Flight Society 76th Annual Forum Proceedings, Virtual, October 2020.
2. Bellocchio, A., "A Framework to Enable Rotorcraft Maintenance Free Operating Periods," Ph.D. Disseration, Georgia Institute of Technology, 2018.
3. Hockley, C. J., "Design for success," *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, Vol. 212, (6), Jun. 1998, pp. 371–378. DOI: 10.1243/0954410981532342.
4. Hockley, C. J. and Appleton, D. P., "Setting the requirements for the Royal Air Force's next generation aircraft," Annual Reliability and Maintainability Symposium, Philadelphia, PA, pp. 44–49, DOI: 10.1109/RAMS.1997.571662.
5. Bottomley, T., "The Ultra Reliable Aircraft," DTIC ADP010430, 2000.
6. Relf, M. N., "Maintenance-free operating periods—the designer's challenge," *Quality and Reliability Engineering International*, Vol. 15, (2), Mar. 1999, pp. 111–116. DOI: 10.1002/(SICI)1099-1638(199903/04) 15:2<111::AID-QRE237>3.0.CO;2-2.
7. Prescott, D. and Andrews, J., "Modelling the use of maintenance to minimise aircraft service disruption," *IFAC Proceedings Volumes (IFAC-PapersOnline)*, Vol. 1, (PART 1), 2010, pp. 44–49. DOI: 10.3182/20100701-2-pt-4012.00009.
8. Cini, P. F. and Griffith, P., "Designing for MFOP: towards the autonomous aircraft," *Journal of Quality in Maintenance Engineering*, Vol. 5, (4), Dec. 1999, pp. 296–308. DOI: 10.1108/13552519910298055.
9. Housel, T., Hom, S., and Guertin, N. H., "The Impact of Maintenance Free Operating Period Approach to Acquisition Approaches, System Sustainment, and Cost," Naval Postgraduate School NPS-LM-13-005, 2013. DOI: https://dair.nps.edu/handle/123456789/2563.
10. Guertin, N. H. and Bruhns, P., "Comparing Acquisition Strategies: Maintenance-Free Operating Period vs. Traditional Logistics Support NPS-AM-11-C8P25R03-081," Eight Annual Acquisition Research Symposium Naval Post Graduate School, Monterey, CA, April 2011.
11. Eastaugh, G. F., "Enhanced Aircraft Platform Availability Through Advanced Maintenance Concepts and Technologies," Research and Technology Organisation of NATO TR-AVT-144, 2011.
12. Sega, R., "Army Science and Technology for Army Aviation," Army Science Board Technical Report AD1058359, 2016. DOI: DTIC AD1058359.
13. Ren, Z. and Wu, Y., "Modeling the Performance of Aircraft Utilizing Maintenance Free Operating Periods,"

Procedia Engineering, Vol. 99, (99), Jan. 2015, pp. 214–218. DOI: 10.1016/j.proeng.2014.12.528.

14. Kumar, U. D., Knezevic, J., and Crocker, J., "Maintenance free operating period – an alternative measure to MTBF and failure rate for specifying reliability?," *Reliability Engineering & System Safety*, Vol. 64, (1), Apr. 1999, pp. 127–131. DOI: 10.1016/S0951-8320(98)00048-9.

15. Lesobre, R., Bouvard, K., Bérenguer, C., Barros, A., and Cocquempot, V., "A maintenance free operating period policy for a multi-component system with different information levels on the components state," *Chemical Engineering Transactions*, Vol. 33, Sep. 2013, pp. 1051–1056. DOI: 10.3303/CET1333176.

16. Kumar, U. D., "Tutorials on Life Cycle Costing and Reliability Engineering." Indian Institute of Mangement Bangalore, [Online]. Available: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiBoc2I4_bvAhXkF1kFHWzpCHMQFjAAegQIAhAD&url=https%3A%2F%2Fshahroodut.ac.ir%2Ffa%2Fdownload.php%3Fid%3D1111117617&usg=AOvVaw2aevA4BaUndd93Xt8xd19c.

17. Chew, S. P., Dunnett, S. J., and Andrews, J., "Phased mission modelling of systems with maintenance-free operating periods using simulated Petri nets," *Reliability Engineering and System Safety*, Vol. 93, (7), Jul. 2008, pp. 980–994. DOI: 10.1016/j.ress.2007.06.001.

18. Price, J. K., Ashok, S., Armstrong, R., Collins, K. B., Mavris, D. N., and Schrage, D., "Integrated Discrete-Event Simulation Environment for Analysis of Rotorcraft Reliability, Availability, and Maintainability," American Helicopter Society 73rd Annual Forum Proceedings, Fort Worth, TX, May 2017.

19. Trindade, D. and Nathan, S., "Field Data Analysis for Repairable Systems: Status and Industry Trends," in *Handbook of Performability Engineering*, K. B. Misra, Ed., Springer London, London, 2008, pp. 397–412.

20. Shaalane, A. Al and Vlok, P. J., "Application of the aviation derived maintenance free operating period concept in the South African mining industry," *South African Journal of Industrial Engineering*, Vol. 24, (3), Jun. 2013, pp. 150–165. DOI: 10.7166/24-3-598.

21. Ahmadi, A., Soderholm, P., and Kumar, U. D., "An overview of trends in aircraft maintenance program development: past, present, and future," Proceedings of the European Safety and Reliability Conference 2007 (ESREL 2007), Stavanger, Norway, 2007, pp. 2067–2076.

22. Fritzsche, R. and Lasch, R., "An Integrated Logistics Model of Spare Parts Maintenance Planning within the Aviation Industry," *International Journal of Social, Behavior, Educational, Economic, Business and Industrial Engineering*, Vol. 6, (8), Aug. 2012, pp. 1958–1967. DOI: 10.5281/ZENODO.1071890.

23. Bell, Z. M. and Teague, E., "Comparison of army aviation maintenance methods via discrete event simulation," 2014 IEEE Systems and Information Engineering Design Symposium (SIEDS 2014), Charlottesville, VA, 2014, pp. 277–282. DOI: 10.1109/SIEDS.2014.6829920.

24. Glaessgen, E. H. and Stargel, D. S., "The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles AIAA Paper 2012-1818," 53rd Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, 2012. DOI: 10.2514/6.2012-1818.

25. Piascik, B., Vickers, J., Lowry, D., Scotti, S., Stewart, J., and Calomino, A., "Materials, Structures, Mechanical Systems, and Manufacturing Roadmap Technology Area 12," NASA, 2010. [Online]. Available: https://www.nasa.gov/pdf/501625main_TA12-MSMSM-DRAFT-Nov2010-A.pdf.

26. England, R., "Maintenance Free Operating Periods (MFOPs) - A Systems Perspective," Health & Usage Monitoring & Condition-based Maintenance Symposium 2007 at Defence College of Management & Technology, Shrivenham, United Kingdom, May 2007.