A SIMULATION MODEL FOR AIRCRAFT MAINTENANCE IN AN UNCERTAIN OPERATIONAL ENVIRONMENT

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Abstract: We present a discrete-event simulation model for maintenance operations of a fleet of fighter aircraft in crisis situations, where the fleet operations are affected by a threat of an enemy's actions. The model describes the flight process and basic modes of periodic maintenance and failure repairs. Features that are specific to crisis situations include battle damages of the aircraft, decentralization of airbases, specialized maintenance personnel and spares supply. Construction and validation of the model are based on expert knowledge and statistical data on actual flight and maintenance operations in peacetime conditions. The main use of the model is the evaluation of different maintenance strategies in elevated states of readiness and in presence of hostile activities. Built with a graphical simulation software the model provides an easily manageable tool for maintenance designers. In addition, it offers a valuable educational aid in training maintenance personnel by demonstrating the implications of airbase maintenance and logistics activities to fleet performance.

Keywords: Aircraft, maintenance, discrete-event simulation, logistics

1 INTRODUCTION

F-18 Hornet fighters and Hawk Mk51 jet trainers form the basis of the aircraft fleet of the Finnish Air Force (FiAF). The aircraft are used for the different tasks involved in maintaining the nation's air defense such as pilot training and air surveillance. The flight process of the fleet and the related logistic support constitute a system with complex dynamics. Different operating policies, i.e. the use of personnel resources, materials and equipment have to be fitted together to assure that the entire system functions as desired with regard to different operational goals. In peacetime operations, the goals might be the capability to sustain certain long-term level of preparedness or the capability to restore the level in a certain limited period of time. The complexities of the problem are further amplified in states of emergency, where the fleet operates under a threat of an enemy. It is of great importance for the planners of air defense strategies to be able to predict the supportability requirements for the aircraft and the level of performance that can be expected of the fleet.

This paper presents a discrete-event simulation model for analyzing the flight and maintenance operations of a fleet of F-18 Hornet or Hawk Mk51 aircraft in an uncertain operational environment. By uncertain environment, we refer to operating conditions of crisis situations. Compared to normal operations, a greater uncertainty is involved in the flight and maintenance processes due to the limited knowledge and experience of such circumstances. The actual nature of operations is strongly affected by the actions of the enemy, which are difficult to predict.

From modeling perspective, the implications of the uncertainty of the environment are twofold. The shortage of initial data increases the uncertainty involved in determining the values of model parameters. Furthermore, the selection of an appropriate model form becomes complicated. For example, constructing a model that describes the flight process and sustaining of battle damages of the aircraft in varying operating conditions can be implemented in a number of ways.

The construction and the validation of the simulation model presented in this paper are based on expert knowledge and statistical data on actual peacetime flight and maintenance operations. Experiences on an earlier preliminary study of flight and maintenance operations are utilized in the implementation of the model, see [Raivio et al., 2001]. Thus, the validation of certain components of the model is based on formerly validated simulation results. Due to the absence of data on wartime operations, the use of expert knowledge in the construction and the validation is emphasized. In addition, the model is aimed at providing an experienced user, such as a maintenance designer, enough flexibility to consider a wide range of scenarios without further programming. Flexibility is accomplished by making alternative model forms available through change of parameters.

The simulation model describes the flight process, failures of the aircraft and different types of maintenance. The characteristics of airbases and maintenance facilities, such as material and personnel resources, are included in the model. Parts of the model that specifically describe crisis situations include the battle damages of the aircraft, the decentralization of airbases, specialized maintenance personnel, and the supply of certain spare parts.

The model is implemented using Arena, a graphical discrete-time simulation modeling environment [Kelton et al., 2001]. A graphical user-friendly environment allows the maintenance designers to use the model independently in studying the effects of different operating policies and conditions on fleet performance. Aircraft availability, defined here as the fraction of mission capable aircraft to their total amount, is used as the primary measure of performance. However, a number of other logistic indicators can be monitored. The model allows dynamically evolving operating conditions which makes it possible for the user to consider multi-phased scenarios. By demonstrating the implications of airbase maintenance and logistics activities to fleet performance, the simulation model also serves as an educational aid in training maintenance personnel.

Simulation approaches have formerly been used in studying availability or supportability requirements of different weapon systems by, e.g., Pohl [1991], who presents a simulation model for flight and maintenance operations of a squadron of F-15E fighter aircraft. The model is used to study the performance of the squadron in both peacetime and wartime scenarios. Kang et al. [1998] examine strategies for reducing repair cycle-times in naval aviation depots. They present a simulation model, which primarily concentrates on the repair of aircraft components that are critical to readiness due to short supply. Balaban et al. [2000] consider the effects of proposed reliability improvement schemes on availability of C-5 Galaxy cargo aircraft through a Monte Carlo simulation model. In [Sadananda and Srinivasan, 2000] and [Cook and DiNicola, 1984] the availability of fleets of aircraft and helicopters, respectively, are modeled. Both of these papers consider battlefield operations.

2 FLIGHT AND MAINTENANCE OPERATIONS

The F-18 Hornet and Hawk Mk51 aircraft of FiAF are primarily operated in three squadrons that are located in their own air bases. A majority of peacetime flight operations consists of pilot training. Along with the normal daily flying, the aircraft are used in exercises that may, e.g., involve wider scenarios or co-operation of forces. Other types of missions are patrol and identification missions. The daily flight schedules are planned in advance. In the planning process the effects of the cumulated usage and the maintenance requirements of individual aircraft on future flight and maintenance operations are taken into account.

Between flights the aircraft undergo turnaround inspections and replenishments. A pre-flight check is conducted before the first flight of the day. Maintenance of this type is referred to as everyday maintenance. Besides normal tasks, possible component failures are preliminarily analyzed during turnaround inspections. Aircraft that are defined not mission capable are directed to an appropriate repair facility. The aircraft are also subject to damages that are here defined as being caused by some unexpected event and not gradual deterioration of components.

Periodic maintenance constitutes a major part of all maintenance operations. The frequency of periodic maintenance is based on cumulated usage hours of the aircraft. Aircraft manufacturers initially specify maintenance intervals but they are generally later adjusted by the users. These intervals have certain amount of tolerance that allows variability in the actual time between maintenance operations. Thus, the workload of repair shops can be taken into account in the planning of these operations. In FiAF, six levels of periodic maintenance are performed for the Hawks.

The different types of maintenance are carried out in facilities of variable capabilities and resources. Turnaround and preflight inspections, some periodic maintenance as well as minor failure or damage repairs are conducted by each squadron at the airbase. Maintenance of this type is generally referred to as organizational level (O-level) maintenance. The squadrons also have separate aircraft repair shops that are located in the airbases. These repair shops handle more elaborate periodic maintenance and failure repairs. They are referred to as intermediate level (I-level) facilities. The most elaborate maintenance takes place at depot level (D-level) repair shops. In practice, the allocation of tasks to different levels is not strict because the planning of maintenance schedules and the availability of resources affect where the aircraft are ultimately maintained.

2.1 Crisis Situations

As there exists very limited amount of data on maintenance and flight operations in wartime conditions, the knowledge of these circumstances is based on expert judgement of FiAF personnel. In crisis situations, the fleet operates under threat of an enemy, hereafter referred to as the opponent. Some insight of the nature of these kinds of operating conditions can be gained from war-game-like exercises and contingency plans. However, this data is classified to a large degree and has not been made entirely accessible to the model constructors. The general principle of the modeling effort has therefore been to develop a simulation tool with enough flexibility to allow the end users to independently analyze any scenarios that involve the use of confidential data.

The most evident change in flight operations between normal conditions and crisis situations are the engagements with opponent's aircraft. Subsequently, the fleet may suffer losses in the form of damaged or destroyed aircraft. Also, the average flight intensity most likely increases during a crisis. The flight pattern in wartime operations may be very uneven, with periods of high and low intensity operations recurring randomly.

Changes in the flight operations add to the requirements of the maintenance system. Besides battle damages, increased flight intensity increases the need for failure repairs. Demands for aircraft maintenance are further amplified by alterations in the nature of actual maintenance tasks. Larger amount of maintenance consists of failure and damage repairs. Furthermore, there is a pressure to restore the aircraft to a mission capable condition as quickly as possible. In crisis situations, non-critical maintenance can be discarded in order to ease the workload of repair shops.

The squadrons may be required to decentralize their operations and use alternate airbases that are located as to provide better defense against the threat caused by the opponent. These alternate airbases are categorized into three levels according to existing infrastructure and operational capabilities. Class I airbases refer to such facilities that can respond to all operational needs of a squadron. Basically, they correspond to the main airbases of peacetime operations. Class II and III airbases lack some of the operational capabilities and may, e.g., not be able to conduct certain elaborate maintenance tasks. In a decentralized setting, a squadron operates from multiple airbases. Benefits of decentralization include the added flexibility in directing the use of forces. However, relying on a cut down infrastructure can affect the conduction of maintenance activities or the supply of materials.

3 THE SIMULATION MODEL

The simulation model of the flight and maintenance processes describes the operations of three squadrons and a central depot-level maintenance facility. The structure of the model is presented in Figure 1. The arrows with solid lines represent the movement of the aircraft between different processes. The dashed lines describe material and information flows.

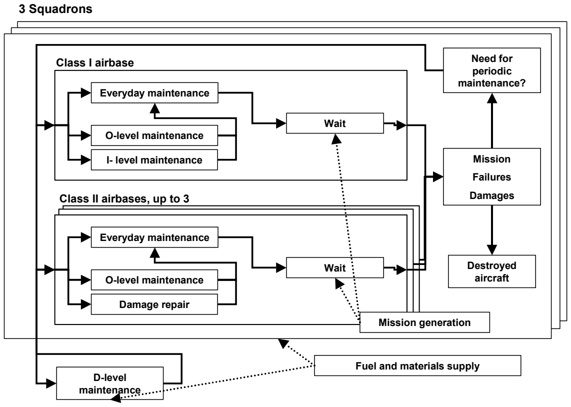

Figure 1: Structure of the simulation model

In general, all the essential characteristics of the flight and maintenance operations are included as input parameters in the model. Moreover, these parameters can be arbitrarily changed during simulation runs enabling the user to study dynamically evolving operating conditions or effects of changes in operating policies. This means that also the model structure is flexible to a certain extent. The aim has been to reduce the uncertainty that relates to the selection of the model form. A user that is knowledgeable of the underlying system and its operating environment is allowed as much freedom as possible in determining the characteristics of the model. For instance, the airbases of the squadrons can be removed out of use or introduced at all times making it possible to describe, e.g., the transfer of airbases to varying geographical locations.

In the model, the squadrons operate independently of each other. By default, the aircraft are always directed to their own airbases unless this airbase cannot conduct a required maintenance task. For simplicity, all operational aircraft are involved in the flight activities. Times between flight missions follow an exponential distribution. If a sufficient amount of operational aircraft do not exist, the mission is either carried out with fewer aircraft or discarded. The main interest in the flights is focused on the accumulation of flight hours and the occurrence of failures and battle damages. The missions do not involve specific objectives and discarding a mission does not have effect on other activities in the model. All missions that were conducted with fewer aircraft than required or that were discarded are simply registered in the simulation results.

Aircraft maintenance in the airbases is organized into different level facilities as described in the previous section. All airbases conduct everyday maintenance as well as O-level tasks. Class I airbases include a separate I-level aircraft repair shop which is in class II airbases replaced by a certain amount of additional maintenance personnel that is specialized in damage repairs. Depot-level level maintenance takes place at a single central facility that serves all squadrons.

Aircraft requiring maintenance are directly transferred to appropriate maintenance facilities. The need for periodic maintenance is determined based on accumulated flying hours and pre-specified maintenance intervals. Failures of the aircraft also occur depending on accumulated flight hours. Times between failures are assumed exponentially distributed. For each occurrence the type of malfunction is defined randomly according to type specific probabilities. Six types of failures can be defined in the simulation model. Similarly, the model contains six types of battle damages. Aircraft that carry out a flight mission face hostile aircraft with a certain probability. If an encounter occurs, the aircraft are damaged or destroyed with assigned probabilities.

In the simulation model, all maintenance facilities have their own personnel. A resource requirement and a distribution of the task time is associated with each maintenance type. The actual time required to complete the maintenance task is calculated by dividing the initial duration with allocated number of mechanics. The aircraft are maintained in order of arrival, i.e., no prioritization of jobs is considered in the model. Variation in maintenance manpower due to holidays, sicknesses or other absences is not taken into account. Thus, the number of maintenance personnel describes the effective available manpower.

During flight missions the aircraft spend fuel and certain munitions and countermeasures. In addition, spare part requirements can be associated to all types of periodic maintenance as well as failure and damage repairs. Material inventories of the airbases are replenished according to a specified order point. Alternatively, new materials may be separately acquired each time a need arises.

3.1 Estimation of Input Parameters

Base values for maintenance times, failure and flight intensities as well as parameters related to the characteristics of the airbases are defined using data on normal operations of Hawk Mk51 aircraft and expert knowledge of FiAF personnel. In crisis situations, operating conditions for the fleet are largely dependent on the threat scenario under consideration. Input parameters are therefore chosen individually for each scenario. As initial data is scarce the parameters are necessarily based on expert judgement and existing contingency plans for war-time operations. The base values provide a starting point for definition of these parameters.

Raw statistical data for estimating I- and D-level periodic maintenance times is available from one I-level facility. Additionally, estimated values for mean and variance of maintenance times in one of the depot-level repair shops are at disposal. Based on graphs of the raw data, alternative models for maintenance times include several probability distributions. Statistical tests show that distributions with right-sided tail are a more suitable choice compared to symmetric distributions. As the number of observations is somewhat limited for certain maintenance types, stronger conclusions cannot be made. Ultimately, the gamma distribution has been chosen as the model for the duration of all periodic maintenance types. It shows a reasonably good fit for all data sets and in particular, provides a good fit for those types of which most observations exist. Gamma distribution is commonly used to model different task times [Law and Kelton, 2000].

Normal distribution is chosen as the model for the turnaround and pre-flight inspections. Justification for the choice is that the contents of these maintenance types generally remains fairly unchanged. Elaborate periodic maintenance may involve considerable amount of additional tasks such as delayed repair of non-critical failures causing the distribution of the maintenance duration to be skewed. Maintenance types with fewer tasks have less variability in contents and are less likely to be severely delayed even in individual cases. Values for the mean and standard deviation of the duration are provided as subjective estimates of maintenance personnel.

The mean and standard deviation of failure repair times as well as the mean time between failures are directly available from reference data provided by FiAF. Times between failures are assumed exponentially distributed. Failure repair times, on the other hand, are assumed to follow the gamma distribution. Failure repair times are commonly modeled with non-symmetric distributions such as gamma or exponential distributions. For simplicity, the gamma distribution was chosen in this case, since it provides as good a model as other right-tailed distributions with regard to the available data.

Average flight intensity and average flight duration are defined on the basis of statistical data on all missions of the Hawks during a time period of one year. The amounts of accumulated flight hours for each aircraft are also available from these statistics.

3.2 Validation of the Model

Since reference data does not currently exist on some aspects of the system under consideration, the process of verification and validation of the model relies, to a certain degree, on subjective measures. Close collaboration between the model constructors and the representatives of FiAF has been maintained during the entire modeling effort. Additionally, the model structure, its underlying assumptions, principles of implementation, input parameter values and ultimately simulation results have been presented to a variety logistics and maintenance personnel of different organizational levels. These reviews have taken place throughout the modeling process and feedback from these occasions has been actively utilized to further develop the model. Preceding the final accreditation, the simulation model will undergo independent tests of the end user.

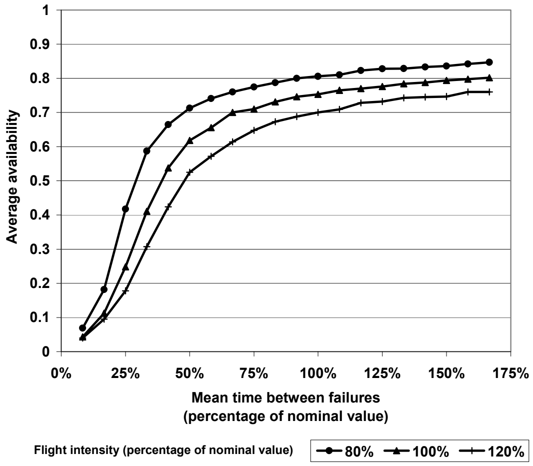

Figure 2: Sensitivity of the average availability to flight and failure intensities

As the characteristics of the model are adjustable to a large extent, it can describe normal operations with suitably chosen values of input parameters. The simulation results can therefore be partially validated with reference data from actual flight and maintenance operations in normal conditions. Available data includes values of aircraft availability from a period of four years. This data exists in the form of 3- and 12-month moving averages. The simulation model predicts an average availability of approximately 75% for normal operations, which differs slightly from the actual value. The difference is most likely due to the simplifying assumptions such as the exclusion of certain types of maintenance and administrative delays from the model.

The validity of the current model may also be assessed by comparing its outputs with other simulation results. The preliminary study of the flight and maintenance operations provides a validated model for this purpose, see [Raivio et al., 2001]. Sensitivity analyses were conducted to find out how responses of the current model are affected by variations in important input parameters and to evaluate the extent to which these results differ from those of the other model. Figure 2 shows an example analysis of the current model. In the example, the sensitivity of average availability to flight and failure intensities in normal operating conditions is considered. The responds show similar behavior with those of the earlier model and are therefore regarded as valid.

4 EXAMPLE SIMULATION

As an example of possible applications of the model, a scenario with dynamically evolving operating conditions is presented. We study how the timing of a change in maintenance policy affects fleet performance and specifically aircraft availability.

In the scenario, the operating conditions are assumed to change in four phases. In the first phase, the state of readiness is elevated and the flight intensity increases compared to normal operations. The second phase involves further increase in the amount of flight missions. Additionally, the operations of the squadrons are decentralized into four airbases. The third phase represents the transition to the actual combat phase as the squadrons respond to activities of the opponent. During the missions, the aircraft may be damaged or destroyed. In the fourth phase, the intensity of the combat decreases as the opponent is assumed to suffer losses that limit its operational capabilities.

The change in the maintenance policy involves discarding most of the periodic maintenance in order to release more aircraft to flight operations. Thus, the example examines one alternative periodic maintenance strategy compared to the maintenance program of normal operations. The alternative policy is applied to all aircraft with no exceptions. It might seem desirable to consider each maintenance decision separately, i.e., whether individual aircraft could be maintained during periods of lower flight intensity. In a highly uncertain environment, this would, however, entail a certain amount of risk by reserving the resources for non-critical operations. The assumption of no exceptions can here be regarded as reasonable.

The new policy is employed at the start of one of the first three phases of the scenario. These transition times can be thought of representing time instants where new strategic information on the opponent is received. At each time instant, the commander of operations is to decide on the course of action in the changed circumstances. Figure 3 presents the simulation results for the three cases where the new maintenance policy is employed and for the case where the policy is not employed. The plotted availability figures represent values that are averaged across 20 independent replications.

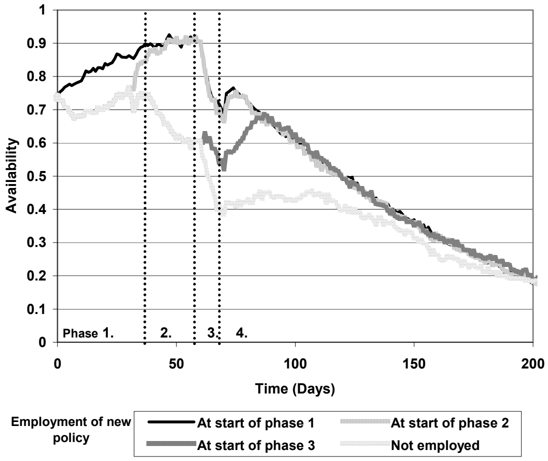

Figure 3: Effect of the timing of maintenance policy change on aircraft availability

Figure 3 clearly shows that some types of periodic maintenance have to be given up to maintain the capability of fulfilling the operational requirements of a high intensity crisis. Depending on how quickly the situation evolves, certain amount of periodic maintenance may be conducted at the early stages of the crisis. If all maintenance is completed without pre-emptions, the availability will, however, rise rather slowly.

For further conclusions sensitivity analyses are required to assess the effect of the underlying assumptions of the example. These assumptions are mainly concerned with the usage of resources in the airbases and the strategy of the opponent. Furthermore, the short-term effect of discarding periodic maintenance on failure intensity of the aircraft has to be considered.

5 DISCUSSION

The primary objective of the modeling effort is to gain new insight into the effect of maintenance policies and operating conditions on the overall performance of the aircraft fleet of the Finnish Air Force. The presented simulation model describes the essential features of the flight and maintenance operations in both normal conditions and crisis situations, where the fleet is faced with added operational uncertainty. The model provides a way to quantitatively assess the effects of proposed improvements to the maintenance system. The model is constructed and validated in close co-operation with representatives of FiAF. In addition, it is implemented with graphical simulation software and thus allows easily manageable simulation analyses.

The introduction of the model to FiAF has been started by initiating a user-training process for potential end users. The training aims at familiarizing these users to the general objectives of the modeling effort, principles of the simulation methodology and the features of the model. Simultaneously, the training process serves as a way to collect feedback on the functionality of the model to support its further development and updating. Training is also necessary to assure that the simulation methodology will be correctly applied and its limitations are understood by the user-organization. Overall, early experiences of the use of the model suggest, that the model provides the Air Force a valuable aid in the design of aircraft maintenance policies and education of maintenance personnel.

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BIOGRAPHY

Ville Mattila received his M.Sc. degree in industrial engineering and management in Helsinki University of Technology in 2002. He currently works as a researcher and conducts his Ph.D. studies at Systems Analysis Laboratory in the Department of Engineering Physics and Mathematics. His research interests include simulation and optimization of discrete-event systems, specifically aircraft maintenance and airbase logistics systems.