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Maximizing operational readiness in military aviation by optimizing flight and maintenance planning

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Abstract

The primary objective in military aviation is to optimize operational readiness: the capability to perform assigned flight missions. In terms of a flight planning process, operational readiness has three primary components: availability, serviceability and sustainability. Furthermore, it is influenced by aircraft downtime due to preventive maintenance at prescribed flight time interval. In practice, aircraft flight scheduling (including maintenance constraints) tends to be managed manually and on a day-to-day basis, leading to a reactive approach to aircraft flight hour allocation in which problems with respect to availability, serviceability and sustainability can easily develop. Optimization models have been developed to address this issue, but none of them cover the full scope of operational readiness. This work introduces a flight and maintenance planning optimization model that simultaneously addresses the aspects of availability, serviceability and sustainability, leading to a pro-active, efficient and more robust scheduling effort. The proposed model is tested, verified and validated using Royal Netherlands Air Force data and infrastructure related to the CH47D Chinook helicopter fleet.

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Keywords: Flight and Maintenance Planning; Operational Readiness; Optimization

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1. Introduction

The primary objective of a military aviation operator or air force is to optimize its readiness to respond to external threats, take part in peace supporting missions and provide humanitarian aid, wherever and whenever the home state

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or international community calls for it. This is embodied in the concept of continuous operational readiness: the capability to perform all assigned present and future flight operations. In order to maintain a minimum readiness level, air forces need to ensure that sufficient aircraft are mission capable and continue in this state for an adequate period of time. Furthermore, a sufficient amount of training flight hours need to be produced to keep aircrew in mission capable condition. These requirements must be fulfilled at all times, which requires an involved planning process. Within the context of this flight planning process, operational readiness is depicted by the following primary components:

- **Availability:** the total duration in which subject aircraft are mission capable, which influences the capacity of the military organization to meet its flight hour requirement. This requirement is derived from the necessity to meet air crew training hour requirements and perform predetermined operational assignments. Availability is an overall measure, considering the full planning horizon;
- **Serviceability:** the number of mission capable aircraft at a specific instant of time. This is therefore an instantaneous measure describing the capability to perform flight missions at any specific point in time. However, this number alone gives no information of how long the serviceable aircraft remain available for flight operations in the future. In other words, although serviceability might be sufficient, it is unknown if the subject aircraft have sufficient residual flight time left to fulfill a mission requirement;
- **Sustainability:** the total residual flight time of the entire fleet at a specific instant of time. This is also an instantaneous measure, which solves the shortcoming of serviceability. Together, serviceability and sustainability determine how long a tactical unit will remain capable of sustaining a flight mission, starting at an immediate point in time, when no maintenance resources are accessible.

Since aircraft are subject to strict safety requirements, preventive maintenance must be performed at prescribed flight time intervals, which causes downtime. This directly affects operational readiness as any downtime restricts opportunity for flight operations. As a result, all preventive maintenance efforts as well as the mission assignments must be planned and scheduled adequately for the entire aircraft fleet. The process is highly complex and time consuming due to numerous constraints (operational demand, maintenance resources, facilities, locations) and uncertainties (unpredictable operational assignments, unscheduled maintenance, changing weather conditions). As a result, the flight and maintenance plan requires to be adjusted frequently. It follows that the generation must be flexible, fast and efficient. However, in practice, aircraft utilization tends to be managed manually and on a day-to-day basis, leading to a reactive approach to aircraft flight hour allocation in which problems with respect to operational readiness can easily develop.

Several optimization models have been developed to address this specific problem, as discussed further in the next section. However, none of these models take into account the full scope of operational readiness as introduced above. It is the aim of this work to introduce a flight and maintenance planning (FMP) optimization model that can simultaneously address the three primary components, leading to a pro-active, efficient and more robust scheduling effort.

The structure of this paper reflects this aim. First, the theoretical context of the flight and maintenance planning optimization problem is discussed in more detail. Subsequently, an FMP optimization model is proposed in Section 3, followed by its application on Royal Netherlands Air Force data and infrastructure related to the CH47 Chinook helicopter fleet. The findings are given and discussed in Section 4: Results. Finally, conclusions are presented in Section 5.

2. Theoretical context

Existing work in the FMP field primarily focuses on civil aviation within the context of complex airline networks (Feo & Bard, 1989) and fleet assignment for flight schedules incorporating maintenance constraints at different levels of complexity and planning horizons (Hane et al., 1995; Clarke et al., 1996; Sriram & Haghani, 2003). These efforts however concern commercial aviation maintenance, which is different from the scope of this contribution, being military aviation. A major difference is that commercial airlines have to deal with routes in a (often complex) network, where the military flight scheme is generally concentrated around a central base. In terms of optimization, this difference acts as a relaxation of several (spatial) constraints. Constraints regarding (preventive) maintenance intervals can however be similar when considering commercial and military aviation. An even more important difference is that military operations revolve around mission readiness instead of profitability – military FMP tends to focus on availability optimization for a given budget, whereas commercial FMP literature tends to focus on profitability and/or availability. Concluding, military aviation FMP results in a different set of objectives and constraints, the latter of which include safety regulations, maintenance requirements, flight program requirements, personnel and facility capacity and logistics support.

Literature on FMP in military aviation focuses primarily on phase maintenance, a periodical extensive inspection on the aircraft which is the most elaborate of all preventive maintenance processes in military aviation. Phase maintenance typically requires the aircraft to be grounded for a number of weeks. The main tool used to (manually) execute FMP in many air forces is the phase flow chart, which depicts the operational aircraft in a unit's fleet as well as their residual flight time. Residual flight time is defined as the instantaneous total amount of flight hours that may be flown by a specific aircraft before phase maintenance is due to be performed. If the utilization of aircraft in the unit is ideally spaced, the phase flow will be shaped as a straight line. This ideal situation is presented in Figure 1(a). However, in practice this situation is very unlikely to occur and a realistic chart rather looks like the example in Figure 1(b).

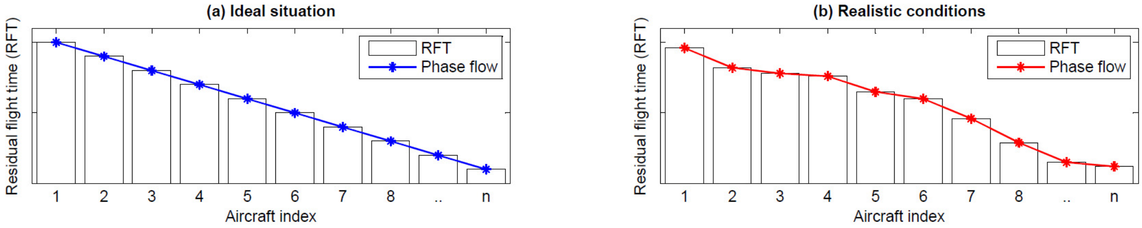

Fig. 1. (a). Phase flow chart with ideal flow; (b) Phase flow in realistic conditions

Evidently, the phase flow chart varies over time as aircraft in the unit produce flight hours. Furthermore, maintenance is being performed on continuous basis. As a result, indices shift position to the right as residual flight times decrease and aircraft that complete phase maintenance (and therefore regain full residual hours) move to the first position. The phase flow chart and/or the underlying concept of residual flight time are used as a main element to optimize fleet readiness in existing FMP models for military aviation. An overview of existing work in this area is given in Table 1. It can be observed that these models differ on their capability to take into account maintenance capacity limitations, distribution of residual flight hours over the fleet, resilience to short notice changes to the flight program and consolidation of maintenance tasks. Furthermore, one *general* limitation of these models is that they do not take into account the full scope of operational readiness. None of these models explicitly covers *all* aspects of operational readiness, namely availability, serviceability and sustainability (as introduced before). Consequently, the model developed in this paper seeks to address these issues and introduces the following novel elements:

- The model covers the full scope of operational readiness, including availability, serviceability and sustainability;
- The model simultaneously takes into account residual flight time distribution over the fleet and phase maintenance capacity limitations;
- The model is resilient to short term changes as it requires relatively little time to re-run and evaluate after any changes in conditions have been identified.

Table 1. Existing FMP models for military aviation

Reference	Objective(s)	Approach	Limitations
Sgaslik, 1994	Optimize aircraft distribution over flight events and maintenance tasks, using equitable (smooth) operation of fleet assets.	Two-step approach connecting a long-term (yearly) and a short-term (mission assignment) model, penalizing failure to meet flight hour requirements or going beyond	Does not consider residual flight hour distribution over fleet; does not consolidate maintenance tasks.

		maintenance capacity.	
Pippin, 1998	Maximize number of available aircraft by optimizing for steady-state phase flow	Penalizing for deviation from the ideal phase flow line; minimize this penalty, while respecting flight hour requirements and constraints	Does not take into account phase maintenance capacity limitations; reactive; not resilient to short term changes; does not consolidate maintenance tasks.
Kozanidis & Skipis, 2006	Achieve maximum availability over the planning horizon for an air force unit which exists of multiple squadrons (subunits), by (1) maximizing the number of available aircraft and (2) maximizing the number of available flight hours	Incorporate residual flight and maintenance time to express (un)availability; maximize available aircraft and flight hours while respecting maintenance capacity constraints	Does not consider residual flight hour distribution over fleet, although later work (Kozanidis, 2008) adds a heuristic to deal with phase flow chart. Reactive; not resilient to short term changes; does not consolidate maintenance tasks.
Steiner, 2006	Minimize overall number of maintenance actions and evenly distribute capacity and flight hours over time	Incorporate flight hour requirements and constraints and maintenance capacity constraints; allow consolidation of maintenance tasks by shifting usage-based and calendar-based maintenance actions in order to realize mergers	Does not consider residual flight hour distribution over fleet; reactive; not resilient to short term changes.
Cho, 2011	Minimizing the maximum number of aircraft in phase maintenance at any given time to balance the variability in phase maintenance demand	Minimizing aircraft in phase maintenance, while assuring aircraft utilization is evenly distributed over the fleet by introducing end-of-horizon targets in terms of residual flight times per aircraft	Reactive; not resilient to short term changes.

3. FMP optimization model for maximum operational readiness

Operational readiness is depicted by the primary components availability, serviceability and sustainability, as described in the introduction. In Section 3.1, operational performance indicators are introduced relative to these primary components. In the subsequent section, a model framework is introduced and the performance indicators are used in formulation of the FMP model. The objective function, constraints and model dynamics are briefly discussed.

3.1. Performance indicators related to operational readiness

In order to be able to properly introduce the three aspects of operational readiness into an optimization model, it is first necessary to define applicable performance indicators. These are discussed below.

3.1.1. Availability

Availability is the total amount of time in which the aircraft or fleet is mission capable over the full planning horizon. In other words, availability is the absolute total duration of the state of functioning of the aircraft (or fleet). This can be translated into various performance indicators such as total availability, net total availability (Knezevic, 1993) or net scheduled total availability (Kumar et al., 2000) . However, the first two do not distinguish between preventive and corrective maintenance and the third only considers mean time values for (intervals between) maintenance events, whereas the FMP problem considers preventive maintenance only and incorporates actual values related to events. Given these shortcomings, the following availability metric is defined:

$$\text{scheduled total fleet availability} = \sum_{i=1}^{n}\sum_{m_i}^{M_i} TBM_{m_i}, n = 1 \ldots AC \tag{1}$$

,where a fleet of size *AC* is considered (indexed by *n*), *M* is the number of scheduled maintenance actions over the planning horizon of a single aircraft, and TBM_m is the time between the maintenance actions *m* and *m-1* (or between maintenance action *m* and *t = 0*, when maintenance action *m* is the first scheduled maintenance on the planning horizon).

3.1.2. Serviceability

Serviceability is the number of aircraft in mission capable condition at a specific instant of time. In other words, serviceability is the absolute number of aircraft in state of functioning. This can be translated into a performance indicator by expressing the ratio of the number of serviceable aircraft and the total number of aircraft in the fleet (Raju et al., 2012). However, this expression does not distinguish between downtime due to preventive and corrective maintenance. The following serviceability metric is defined to only take into account preventive maintenance:

$$\text{scheduled serviceability } (t) = SoFu_{sched}(t) = SoFu(t) + SoFa(t) - SoFa_{sched}(t) \tag{2}$$

,where $SoFu(t)$ represents the total number of aircraft in a state of functioning at instant of time *t*, $SoFa(t)$ the total number of aircraft in a state of failure at *t*, and $SoFa_{sched}(t)$ represents the number of aircraft undergoing scheduled maintenance at *t*.

3.1.3. Sustainability

Sustainability is the total residual flight time of the entire fleet at a specific instant of time. This can also be explained as the total remaining duration of the state of functioning of the entire fleet. For the FMP problem, residual flight time is defined as the remaining flight time before an aircraft is due for preventive maintenance. Hence, the sum of the residual flight times of all serviceable aircraft, serves as a proper metric for sustainability:

$$\text{scheduled sustainability } (t) = \sum_{i=1}^{n} RFT_i(t), n = 1 \ldots AC \tag{3}$$

3.2. Model framework and formulation

In this section, a novel mixed integer linear programming model is proposed that generates optimized flight and maintenance schedules. The model is defined to optimize the operational readiness, while taking into account all relevant operational requirements and maintenance capacity limitations. Operational readiness is considered optimal when (1) the *scheduled total fleet availability (3.1.1)* allows the operator to meet the flight hour requirement for the planning horizon, (2) the *scheduled serviceability (3.1.2)* satisfies the aircraft requirement for each planning period and (3) the minimum *scheduled sustainability (3.1.3)* over the planning horizon is maximized.

In order to keep the model uniform, adaptable and tractable, the scope is limited to phase maintenance, which is considered most relevant and challenging with respect to scheduling. Moreover, phase maintenance follows a clearly defined process with known dependencies and resources, which significantly reduces the amount of variables.

The elements of operational readiness, influencing variables and outputs of the proposed FMP optimization model are given in the framework represented in Figure 2. On the input side, the fleet arrangement (composition) and initial status are required, as well as requirements and constraints pertaining to operations and maintenance. These inputs feed into the FMP optimization model, which generates two main outputs: flying and maintenance assignments.

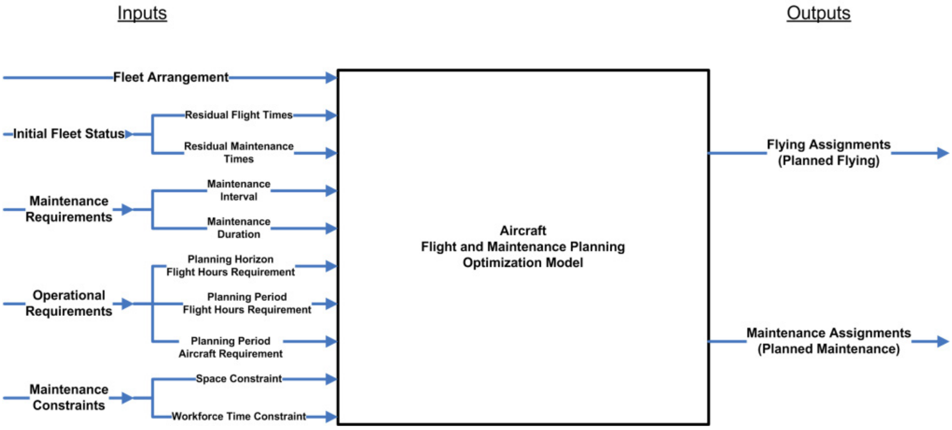

Fig. 2. Schematic representation of the proposed aircraft flight and maintenance planning optimization framework

In the framework given in Figure 2, the FMP optimization model is considered as a ‘black box’. The model itself is mathematically formulated as follows. First of all, input parameters and decision variables are given in Table 2.

Table 2. Aircraft FMP optimization model input parameters and decision variables

Parameter		Variable	
AC	Set of aircraft in the fleet, indexed by n	$RFT_{n,t}$	Residual flight time of aircraft n at the start of period t
T	Length of the planning horizon, indexed by t	$RMT_{n,t}$	Residual maintenance time of aircraft n at the start of period t
RFT_{max}	Maximum residual flight time of an aircraft	$SVC_{n,t}$	Binary variable (1 if aircraft n is serviceable at the start of period t, 0 if it is grounded for maintenance)
RFT_{min}	Minimum residual flight time of an aircraft	$OPR_{n,t}$	Binary variable (1 if aircraft n is operational at the start of planning period t , and 0 otherwise)
RMT_{max}	Maximum residual maintenance time of an aircraft	$FT_{n,t}$	Assigned flight time of aircraft n in planning period t
FHR_{tot}	Flight hour requirement for the fleet over full planning horizon	$MT_{n,t}$	Assigned maintenance time of aircraft n in period t
FHR_t	Flight hour requirement for the fleet in planning period t	$MS_{n,t}$	Binary variable (1 if aircraft n starts to receive maintenance in planning period t, 0 otherwise)
tol_{FHR}	Tolerance on flight hour requirement	$MR_{n,t}$	Binary variable (1 if aircraft n finishes maintenance by the start of planning period t, 0 otherwise)
ACR_t	Operational aircraft requirement for the fleet in planning period t	$Sust_{min}$	Minimum sustainability over the planning horizon
M_{max}	Maximum number of aircraft that can be maintained simultaneously	$P_{n,t}$	Auxiliary binary variable for aircraft n in period t
MT_{max}	Maximum maintenance time per aircraft per planning period	$R_{n,t}$	Auxiliary binary variable for aircraft n in period t
$SVC_{n,1}$	Binary parameter (1 if aircraft n is serviceable at the start of period 1, 0 if it is grounded for maintenance)		
$RFT_{n,1}$	Residual flight time of aircraft n at the start of period 1		
$RMT_{n,1}$	Residual maintenance time of aircraft n at the start of period 1		
K	Arbitrarily large number		

The model formulation, which is based on the programming logic by Kozanidis and Skipis (2006), is listed in equations 4-28. First of all, the objective function (4) maximizes the minimum scheduled sustainability over the planning horizon, which is denoted by the constraint in eq. 5. Hereby the model seeks to smooth the variability in fleet residual flight time while pushing it to the highest feasible value.

The first set of constraints, eq. 6-9, force the serviceability at the start of the next period to the proper value. When the residual flight time is larger than zero, constraint 6 forces the variable $P_{n,t}$ to zero. Subsequently, constraint 7 makes sure that the serviceability at the beginning of the next period is forced to zero whenever $P_{n,t} = 0$

and the residual flight time is equal to the assigned flight time in the current period. In a similar way, constraints 8 and 9 force the serviceability at the beginning of the next period to one when the residual maintenance time is larger than zero and the assigned maintenance time is equal to the residual maintenance time in the current period. As a result, the serviceability at the beginning of period *t* is set to zero when aircraft *n* is grounded to receive maintenance and set to one when the aircraft is available.

$$\textbf{Maximize:} \quad sust_{min} \tag{4}$$

$$\textbf{Subject to:} \quad sust_{min} \leq \sum_{n} RFT_{n,t} \qquad ,\forall t \in [1,T] \tag{5}$$

$$RFT_{n,t} + K \cdot P_{n,t} \leq K \qquad ,\forall n \in AC, t \in [1,T] \tag{6}$$

$$SVC_{n,t+1} \leq (RFT_{n,t} - FT_{n,t}) \cdot K + K \cdot P_{n,t} \qquad ,\forall n \in AC, t \in [1,T] \tag{7}$$

$$RMT_{n,t} + K \cdot R_{n,t} \leq K \qquad ,\forall n \in AC, t \in [1,T] \tag{8}$$

$$1 - SVC_{n,t+1} \leq (RMT_{n,t} - MT_{n,t}) \cdot K + K \cdot R_{n,t} \qquad ,\forall n \in AC, t \in [1,T] \tag{9}$$

$$RFT_{n,t+1} = RFT_{n,t} - FT_{n,t} + MR_{n,t+1} \cdot RFT_{max} \qquad ,\forall n \in AC, t \in [1,T] \tag{10}$$

$$MR_{n,t+1} \geq SVC_{n,t+1} - SVC_{n,t} \qquad ,\forall n \in AC, t \in [1,T] \tag{11}$$

$$0.1 \leq SVC_{n,t+1} - SVC_{n,t} + 1.1 \cdot (1 - MR_{n,t+1}) \qquad ,\forall n \in AC, t \in [1,T] \tag{12}$$

$$RMT_{n,t+1} = RMT_{n,t} - MT_{n,t} + MS_{n,t+1} \cdot RMT_{max} \qquad ,\forall n \in AC, t \in [1,T] \tag{13}$$

$$MS_{n,t+1} \geq SVC_{n,t} - SVC_{n,t+1} \qquad ,\forall n \in AC, t \in [1,T] \tag{14}$$

$$0.1 \leq SVC_{n,t} - SVC_{n,t+1} + 1.1 \cdot (1 - MS_{n,t+1}) \qquad ,\forall n \in AC, t \in [1,T] \tag{15}$$

$$RFT_{n,t} \leq SVC_{n,t} \cdot RFT_{max} \qquad ,\forall n \in AC, t \in [1,T] \tag{16}$$

$$FT_{n,t} \leq RFT_{n,t} \qquad ,\forall n \in AC, t \in [1,T] \tag{17}$$

$$RMT_{n,t} \leq (1 - SVC_{n,t}) \cdot RMT_{max} \qquad ,\forall n \in AC, t \in [1,T] \tag{18}$$

$$MT_{n,t} \leq RMT_{n,t} \qquad ,\forall n \in AC, t \in [1,T] \tag{19}$$

$$1 - SVC_{n,t} \leq MT_{n,t} \qquad ,\forall n \in AC, t \in [1,T] \tag{20}$$

$$\textstyle\sum_{t=1}^{T} \sum_{n} FT_{n,t} \geq FHR_{tot} \tag{21}$$

$$(1 - tol_{FHR}) \cdot FHR_t \leq \textstyle\sum_{n} FT_{n,t} \leq (1 + tol_{FHR}) \cdot FHR_t \qquad ,\forall t \in [1,T] \tag{22}$$

$$0.1 \leq FT_{n,t} + K \cdot (1 - OPR_{n,t}) \leq K \qquad ,\forall n \in AC, t \in [1,T] \tag{23}$$

$$\textstyle\sum_{n} OPR_{n,t} \geq ACR_t \qquad ,\forall t \in [1,T] \tag{24}$$

$$FT_{n,t} \leq OPR_{n,t} \cdot FHR_t / ACR_t \qquad ,\forall n \in AC, t \in [1,T] \tag{25}$$

$$\textstyle\sum_{n} (1 - SVC_{n,t}) \leq M_{max} \qquad ,\forall t \in [1,T] \tag{26}$$

$$MT_{n,t} \leq MT_{max} \qquad ,\forall n \in AC, t \in [1,T] \tag{27}$$

$$RFT_{n,t} \geq SVC_{n,t} \cdot RFT_{min} \qquad ,\forall n \in AC, t \in [1,T] \tag{28}$$

The second set of constraints, eq. 10-12, ensure that the residual flight time at the start of the next period is updated based on the residual flight time and the assigned flight time in the current period. Following the same procedure, constraint set 13-15 update the residual maintenance time at the start of the next period based on the residual maintenance time and the assigned maintenance time in the current period. Constraint set 16-20 impose limitations to the main model variables, in order to keep them within the boundaries of the model dynamics.

The final constraint set, 21-28, impose additional user defined constraints that are not of necessity for the model dynamics. Those introduce the remaining model output requirements as defined in the model framework, such as the flight hour requirement for the full planning horizon and specific periods, operational aircraft requirements, active maintenance capacity limitations and minimum residual flight time.

Constraint 21 forces the total scheduled flight time to meet the flight hour requirement. Since the total scheduled flight time is bounded by the scheduled amount of availability, constraint 21 pushes the scheduled total fleet availability to an appropriate value. Similarly, constraint 24 ensures that the number of operational aircraft meets the aircraft requirement in each period, which sets appropriate lower boundaries to the scheduled serviceability.

3.3. Dataset characteristics

For this paper, the FMP model was implemented for real problem instances drawn from the Royal Netherlands Air Force (RNLAF) in three consecutive years in the past: 2011-2013. In order to demonstrate the performance of the model, the model outputs were compared with the actual RNLAF results in terms of operational readiness. For this reason, actual input data must be available for all parameters in Table 2.

The planning horizon, T, comprises a one year period which is divided in 52 one-week periods. The RFT_{max} for a Chinook phase inspection is 400 flight hours. In order to eliminate the situation in which serviceable aircraft hold negligible residual flight time, RFT_{min}, is set at 10 flight hours. The RFT_{max} was determined to be 20 weeks, which is based on the actual average phase maintenance duration in the years 2011-2013. During the subject years, the space capacity for Chinook phase maintenance was bounded at a maximum of four docks which could be simultaneously manned with a single-shift workforce, so $M_{max} = 4$ and $MT_{max} = 1$. The fleet arrangement, initial fleet status (SVC, RFT, RMT) and operational requirements are kept out of this paper for confidentiality reasons.

3.4. Results and validation

In order to fully demonstrate the model's capabilities, two separate model runs were performed for the RNLAF Chinook problem. Run 1 has utilized the real starting points for the years 2011-2013 to validate model performance through comparison with actual RNLAF figures. However, the starting points for each year are presumed to be suboptimal, which is a downside as they 'anchor' the model on an annual basis. In order to demonstrate the full potential of the model, the second run avoids this by neglecting the first quarter of each year in the optimization calculations. This way, the first quarter is used to ramp up the scheduled sustainability in order to produce a maximized and smooth scheduled sustainability over quarters 2-4. Furthermore, for the years 2012 and 2013 the model output of the previous year is provided as the starting point. This way, a continuous FMP effort is simulated.

The model formulation and input parameters were programmed in the AMPL mathematical programming language (Fourer et al., 2002). The problem instances of run 1 have been optimized by the CPLEX solver (IBM, 2014) on a local PC. For the problem instances of run 2, which were found to be more elaborate, the Gurobi solver (Gurobi Optimization Inc., 2015) was found more appropriate since it identified the optimal solution significantly faster than the CPLEX solver. The required computational times were found to be approximately 2 hours for run 1 and 8 hours for run 2.

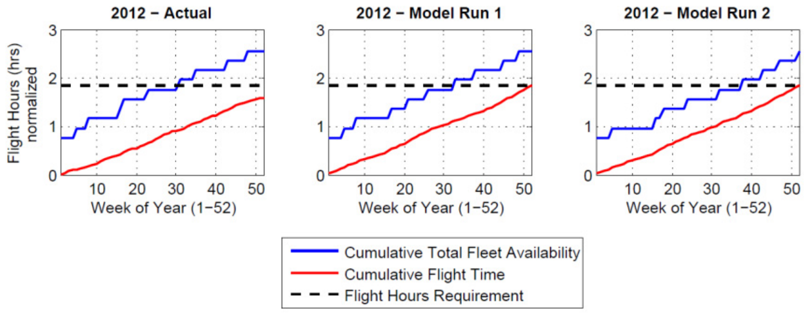

Fig. 3. FMP results with respect to total fleet availability (values along vertical axis normalized for confidentiality reasons)

The model outputs regarding scheduled total fleet availability show to be adequate and comparable to the actual RNLAF performance for the years 2011-2013. Figure 3 shows the model output regarding scheduled total fleet availability and cumulative flight time for 2012. The FMP model assigns phase maintenance and flight hours as such that sufficient availability and cumulative flight time is scheduled to meet the flight hour requirement by the end of the planning horizon.

The model shows similar behavior regarding scheduled serviceability, which is scheduled in such way that the concerning requirements are fully satisfied for the three years under consideration. Furthermore, the model managed to distribute the demand for phase maintenance more equitable over the planning horizon, which leads to logistical benefits.

Overall results with respect to scheduled sustainability are given in Table 3, compared with the RNLAF FMP performance in the years 2011-2013 (not represented directly due to confidentiality). Run 1 results in an 3-11% increase of scheduled sustainability, while the bandwidth is decreased by 5-44%. The large variation of output performance for the different years is a result of fluctuating starting point conditions. Run 2 manages to increase the scheduled sustainability by 18-22%, while the bandwidth is decreased by 23-32%. The results for 2011 are not taken into account for run 2 since this year is mainly utilized to create a better basis for the following years.

Table 3. FMP results with respect to scheduled sustainability

Parameter	2011			2012			2013		
	actual	run 1	run 2	Actual	run 1	run 2	actual	run 1	run 2
$Sust_{min}$	-	+10.9%	+10.9%	-	+3.0%	+21.5%	-	+6.8%	+18.0%
$\Delta Sust$	-	-5.2%	+28.9%	-	-44.0%	-32.2%	-	-17.2%	-22.6%

The outputs of the model runs for 2012 with respect to sustainability are graphically displayed in Fig 4. The phase flow curves that result from the RNLAF and model scheduling efforts show to be adequate (close to diagonal). FMP model run 1 produces strong performance in smoothening the sustainability over the planning horizon, while slightly increasing the minimum value. Due to its better starting position resulting from the model's scheduling effort for 2011, run 2 achieves a significantly higher minimum sustainability while maintaining low variability.

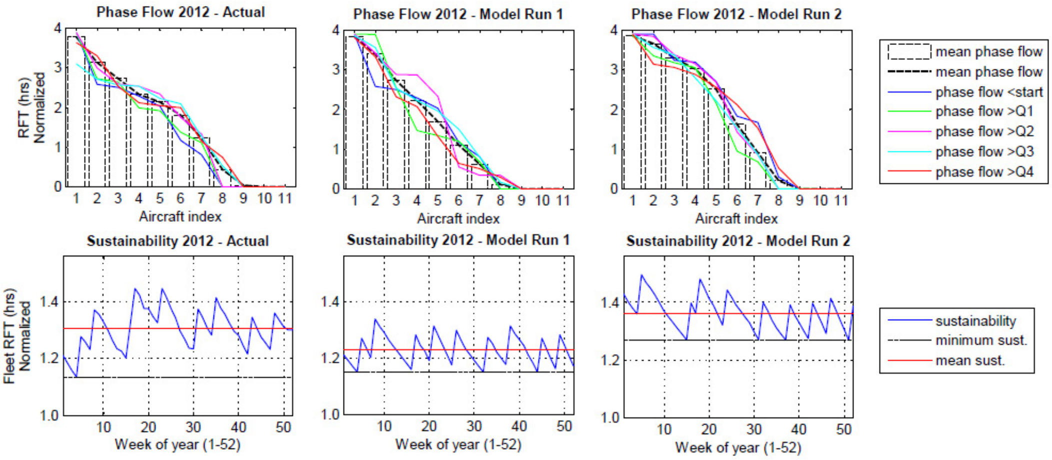

Fig. 4. FMP results with respect to scheduled sustainability (values along vertical axis normalized for confidentiality reasons)

3.5. Assumptions and limitations

The mathematical formulation provides a strong foundation for further development of more complex or wider adaptable FMP models. In its current state, the model is subject to a number of assumptions and limitations:

- The model can take into account one maintenance station, since only one set of maintenance constraints regarding space and workforce capacity can be input. This implies that the maintenance capacity is assumed to remain constant over the planning horizon;

- The model can handle one set of maintenance requirements, which means that the *time between maintenance* and the *scheduled maintenance time* are assumed to be constants. As a result, the model can handle one type of standardized maintenance work;
- The model does not distinguish between separate aircraft in the fleet when assigning flight time. As a result, all serviceable aircraft are assumed to have the same operational capabilities;
- The fleet is assumed to be homogeneous;
- The developed model does not explicitly consider stochastic phenomena that occur in the military aviation environment (e.g., corrective maintenance, flight cancellations due to bad weather, etc.).

5. Conclusion

It was demonstrated that the described aircraft FMP optimization model is an effective means to define long term flight and maintenance schedules that are feasible in practice. The model provides the RNLAF or any other comparable military of response-driven aircraft operator with a number of benefits, including automatic identification of mathematically optimal schedules with respect to operational readiness, while taking into account all requirements and constraints; single generation runs for flight and maintenance schedules for the duration of a complete user defined planning horizon, enhancing supervision and controllability; coherent flight and maintenance schedules, since they are output of a single optimization process; user-defined inputs enabling trade-offs for different stakeholders; substantial reduction in schedule production time compared to current continuous manual processes, which also allows for the operator to cope with unforeseen circumstances, unpredictability and active experimentation with different organizational scenarios.

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