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Military aircraft flight and maintenance planning model considering heterogeneous maintenance tasks

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ABSTRACT

This paper focuses on the military aircraft flight and maintenance planning (MAFMP) problem, aiming to maximize aircraft availability. We consider heterogeneous maintenance tasks: usage-based maintenance tasks (UBMTs) to be performed before the cumulative flight time of an aircraft reaches a predetermined threshold, and calendar-based maintenance tasks (CBMTs) to be performed before the cumulative calendar time of an aircraft reaches a predetermined threshold. The MAFMP problem is a complicated problem that often needs to be solved by military operators, and the optimization of this is essential for military readiness. We formulated a mixed integer linear programming (MILP) model to solve the problem and obtained managerial insights that we recommend for military operators in experiments with varying parameter values. We also proposed two heuristic algorithms that can solve large problems in a reasonable time. The results of the computational experiment show the efficiency and effectiveness of these algorithms in several problem instances.

1. Introduction

In this paper, we consider a military aircraft flight and maintenance planning (MAFMP) problem arising in the air force bases of various countries operating military aircraft (typically, a fighter wing), including the Republic of Korea [1]. Considering that the MAFMP problem is extensively studied in diverse countries (e.g., Australia [2], France [3], Germany [4], Greece [5], Netherlands [6], Switzerland [7], and U.S. [8]), it can be inferred that such a problem is also common in other air bases besides the Republic of Korea Air Force (ROKAF). The objective of the air force is to maximize military readiness against external threats. To this end, a series of flight missions must be performed during each period, and aircraft availability must be maximized for immediate response to emergencies. Military aircraft leave the air base to perform missions and return to the base after completing missions. Maintenance activities are essential to the aircraft's mission readiness, and the number of well-maintained aircraft is directly related to military readiness. The goal of the MAFMP problem is to find a plan that maximizes the availability of aircraft while satisfying both flight and maintenance requirements. In other words, this problem is essential for the air force to maximize its military readiness (the number of available aircraft) while utilizing limited resources to meet flight and maintenance requirements.

Aircraft maintenance is the inspection and repair of an aircraft or its components, and structures, to ensure the airworthiness of the aircraft. This paper focuses on the tasks corresponding to preventive maintenance, among the various maintenance tasks [9,10]. Preventive maintenance means routine tasks specified in a technical manual provided by the aircraft manufacturer or regulated by the air force [11]. Niu et al. [12] specify preventive maintenance into two smaller categories: condition-based maintenance (CBM) and predetermined maintenance (PM). CBM is held based on the present condition of components without predetermined intervals or schedules. On the contrary, PM is some scheduled tasks based on the quantitative usage of components or prescribed dates. Military aircraft consists of numerous components, each of which is aged by flight time and calendar time. PM must be performed before each component's cumulative flight time or cumulative calendar time reaches a specific interval. If the aircraft is not inspected within the interval, the aircraft will become unavailable. Therefore, the military operator systematically manages the residual flight time (RFT) and the residual calendar time (RCT). The RFT and the RCT mean the remaining time until the cumulative flight time and the

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cumulative calendar time reach the maintenance interval, respectively. In addition, technicians perform PM to keep the airframe and parts in reliable operating condition by inspecting and correcting the early symptoms of a failure or malfunction before it develops into a severe defect. This paper considers heterogeneous maintenance tasks: usage-based maintenance tasks (UBMTs) and calendar-based maintenance tasks (CBMTs). Because the maintenance interval of a UBMT is related to the flight time of the aircraft, RFT is deducted only when the aircraft is in flight. UBMTs must be conducted in the maintenance station (hangar) before the RFT reaches zero. In contrast, that of a CBMT is independent of the aircraft's flight status, so RCT is deducted over time. CBMTs are tasks that must be performed before the RCT reaches zero.

The flight and maintenance plans of the air force fighter wing are greatly affected by PM. Each PM includes removing access plates, panels, and screens for inspection and replacement of parts. As a result, PM cannot be completed the same day the aircraft enters the maintenance hangar, which has a significant effect on the fleet availability. In the real world, PM requires a period of 3 to 14 working days, depending on the type of task. Also, although UBMTs and CBMTs have different interval parameters, they are dependent on each other for two reasons, which significantly affect flight and maintenance plans. First, the aircraft will become unavailable if either maintenance task is not completed. When grounded to perform a CBMT, even an aircraft with sufficient RFT cannot fly. The second reason is that it is more beneficial to improve aircraft availability by performing tasks in parallel than by doing them separately. This reduces the grounding period of the aircraft while performing both tasks.

Fig. 1 shows the overall flow of the MAFMP problem. The air force fighter wing typically has about 60–80 aircraft. Flight demands, such as pilot training and combat patrol, must be met. Moreover, maintenance requirements, such as intervals and durations, must also be satisfied. Multiple checks can be serviced in parallel and share the maintenance resources, such as technician teams and facilities. After all checks are completed, the aircraft can be available again.

Planning flight and maintenance schedules is generally a demanding and complicated task. The flight and maintenance plans in the field are usually determined by the operator's experience. This planning approach is time-consuming and leads to poor solutions. Operators often spend several days or weeks creating flight and maintenance plans, considering flight requirements, arranging maintenance requirements, and allocating resources. If a plan exceeds a given resource or fails to meet requirements, the operator must continuously adjust flight missions or maintenance tasks until a feasible plan is found. Due to the limitations of the manual planning approach, the operator's goal is generally to find a feasible plan rather than an optimal one [13]. Thus, this planning approach necessarily requires many operators' time and effort, and results in reduced fleet availability [14]. Therefore, the optimization model for the MAFMP problem increases fleet availability and saves operators' time efficiently.

We formulated a mixed integer linear programming (MILP) model that reflects practical factors. We also verified the model and obtained managerial insights that could be recommended to military operators in various experiments. In large problems, the complexity of the MAFMP problem increases the computation times required to find an optimal solution. In this regard, we developed two heuristic algorithms to solve large problems. In the real world, the status of aircraft and missions can be modified for various reasons, and unplanned events, such as weather conditions and aircraft defects, can occur frequently. When quick decisions must be made to cope with these changing situations, it is necessary to find an alternative that is close to the optimal for solving the problem in a short time, rather than finding the optimal solution over a relatively long time [15]. Heuristics are useful in that they provide a good solution to react quickly to these changes in a reasonable time.

In summary, the main contributions of this paper are as follows. First, we proposed a MILP model for the MAFMP problem, including practical considerations such as heterogeneous maintenance tasks, advancing the check schedule, and merging between tasks, considerations that are lacking in existing studies. The proposed MILP model aims to achieve a balance between academic material and practical applications. Second, our model can be used to test or analyze current maintenance policies and support military operators' decisions, based on the managerial insights we derived. Third, we developed two useful heuristics to solve large problems in a reasonable time for practical purposes. In the early stage of planning, multiple alternatives should be considered, and plans may have to be revised urgently. In this case, endeavoring to find optimal solutions may not be suitable, considering that heuristics can suggest reasonable solutions in acceptable times.

The remainder of this paper is organized as follows. Section 2 summarizes the related literature. Section 3 provides the problem description and a MILP model has been developed. The two heuristic algorithms for solving large problems are described in Section 4. Section 5 presents a sensitivity analysis of the model and the performance of two heuristics. Finally, Section 6 summarizes this paper, along with offering recommendations for future research.

2. Literature review

2.1. Military aircraft flight and maintenance planning (MAFMP)

Flight and maintenance planning problems have been raised in both civilian [16] and military applications [17]. Civilian and military applications have many similarities but also present significant differences. First, maximization of profit is the typical objective in the civilian domain represented by the commercial airline industry, but maximization of readiness is the main objective in the military domain [18]. Thus, the objective in the military domain is fleet availability rather than financial profit [3]. Second, civilian aircraft travel through several cities along predefined flight routes, while military aircraft flights typically fly around their home air base. Some studies [19,20] deal with the airlift routing problem. However, most military aircraft typically return to their home air base for resupply and maintenance after completing missions. We deal with the MAFMP problem. Flight missions and maintenance tasks at a single air base are considered, and thus, routing between bases is not covered. It aims to maximize fleet availability in a military context and adds practical considerations that were not dealt with in previous studies. As mentioned above, the objectives and problem description are different between the civilian and military applications. Thus, this section focuses primarily on research work carried out in a military context.

To the best of our knowledge, the first optimization model for the MAFMP problem was created by Sgaslik [4]. This model describes a decision support system designed to assist with yearly maintenance planning and short-term mission assignment. The author decomposed the problem into two subproblems and developed two MILP models for these subproblems. The U.S. Department of the Army has presented the aircraft flowchart technique, a graphical tool for planning periodic inspections of aircraft and assigning aircraft to missions [21]. This tool is also used by many air force units around the world [22], and is a tool upon which one of the heuristics in this paper is based.

Pippin [23] addressed the MAFMP problem with a MILP and a quadratic programming model to minimize the deviations of each aircraft RFTs from their ideal values. Several recent papers have extended the model based on this work. Kozanidis et al. [22] proposed a MILP model to maximize the minimum number of available aircraft. The model includes constraints to impose a lower bound on the number of available aircraft of each squadron and the average RFT for aircraft overall. They used both a MILP and two heuristic methods. One is a heuristic based on an aircraft flowchart technique concerned with minimizing deviations from the target line, and the other is a heuristic that solves subproblems for each by splitting the planning horizon. Kozanidis et al. [24] extended the problem to a multi-objective model that maximizes the minimum number of available

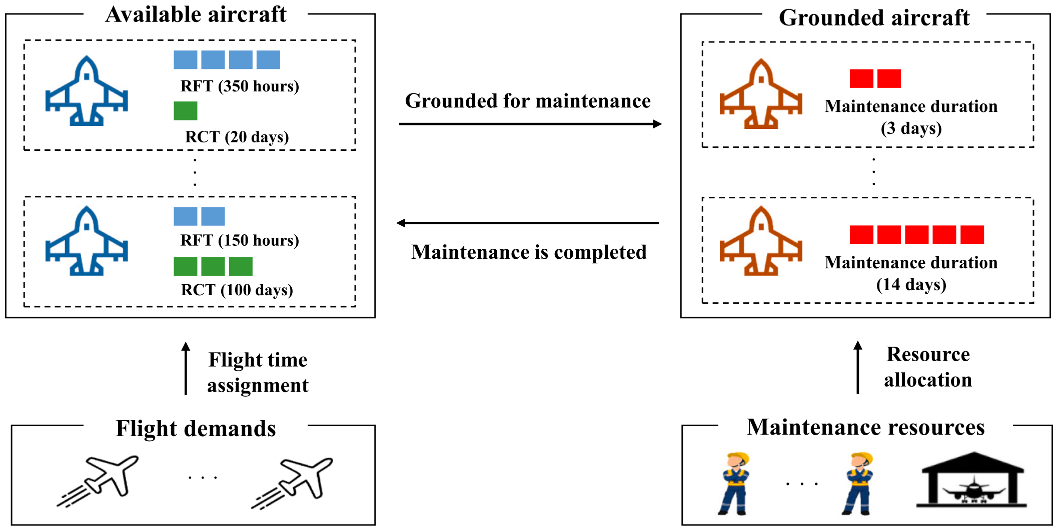

Fig. 1. Overall flow of the MAFMP problem.

aircraft and the minimum RFT. More recently, Gavranis and Kozanidis [25] developed an efficient solution algorithm for a model that aims to maximize the total RFT. In [5], this method is extended to deal with the multi-objective model in which total RFT is maximized at the same time as its variability is minimized. Verhoeff et al. [6] proposed a MILP model to consider three components of operational readiness (availability, serviceability, and sustainability). The objective is to maximize the minimum RFT. Peschiera [17] thoroughly studied the MAFMP problem. Starting with a complexity analysis, NP-hardness of the MAFMP problem has been shown. Exact methods and machine learning methods were developed to address the proposed model, as heuristic methods were also provided to deal with large-scale problems.

Hahn and Newman [26] presented a MILP model that includes deployments and maintenance requirements of aircraft. The objective is to minimize the penalty for failure to meet flight requirements and for the movement of aircraft between areas. Safaei et al. [27] proposed a MILP model with the goal of maximizing fleet availability over a 24-hour period. They considered three types of maintenance (line activities, minor faults, and major faults) and three types of technician trades. Cho [8] proposed a MILP model to evenly distribute the maintenance workload over the planning horizon. The model includes constraints to prevent aircraft from being inducted into periodic maintenance too early. These constraints are included in this paper for the same purpose. However, the model does not consider maintenance capacity. Marlow and Dell [2] used a MILP formulation that aim to minimize the sum of various penalties, such as penalties for failure to achieve the target flight times and failure to maintain the RCT stagger.

2.2. Other considerations on maintenance

The above literature has mainly dealt with homogeneous maintenance tasks based on flight time. Despite the increasing interest over the last several years in addressing practical considerations, there are still few studies dealing with heterogeneous maintenance tasks [28]. The concept of heterogeneous maintenance tasks is broad because they can be heterogeneous with respect to the type of technicians, demand for manpower, and the interval and duration of each task. In this paper, we define heterogeneous maintenance tasks as flight time-based tasks and calendar time-based tasks, and the differences in the intervals and durations of each task are also taken into account. At the airbase maintenance site, each task is performed in a team unit under the supervision of skilled technicians in accordance with regulations, and only qualified technicians perform each task in compliance with the step-by-step work time specified in the technical manual. Additionally, because all maintenance tasks are conducted by teams, one comprises various types of technicians required for the PM. Hence, we do not consider the difference in working times by technicians' types and skill levels.

Consideration for multiple components has been covered until recently, regardless of the field [29–31]. In practice, military operators also handle numerous components and thus, consider merging between tasks and advancing the inspection schedule to increase fleet availability. "Advancing the schedule" means performing a task earlier than the interval of the check. Advancing the maintenance schedule can be an effective way to perform tasks in parallel and shorten the maintenance duration. While an aircraft is grounded for a task, other tasks can be performed in parallel within the maintenance capacity. This provides an opportunity to effectively utilize maintenance capacity and increase aircraft availability. Opportunistic maintenance represents this situation and offers benefits such as lower costs or shorter maintenance durations [32,33]. Some CBMTs involve preparatory processes similar to UBMT, such as opening access plates and removing panels. Therefore, if these tasks are performed together, the maintenance duration of a CBMT can be shortened because similar processes can be omitted. We define "merging" as conducting CBMTs with a UBMT when an aircraft is grounded for UBMT. However, few studies have addressed these factors. Steiner [7] proposed a heuristic method for aircraft maintenance planning with the goal of minimizing the overall number of maintenance actions. Both heterogeneous tasks and advancing the check schedule were considered. The proposed heuristic can get a good solution quickly under various settings and constraints, but no comparison is made on how close the solution is to the optimum. Also, it does not cover the case where the maintenance duration is partially shortened by merging tasks. Lee et al. [1] developed a MILP model to maximize the weighted sum of completed missions. They considered two types of maintenance activities: short-term maintenance activity to be performed when the cumulative flight time for an aircraft reaches a predetermined range; and long-term maintenance activity to be performed after a predetermined number of short-term maintenance activities. However, both activities are based on only flight time. Seif and Andrew [34] extended the work of Gavranis and Kozanidis [25] to a model applicable to multiple preventive maintenance types and maintenance stations. The proposed model considered various tasks, but all of them were based on flight time. Also, although advancing the check schedule and merging tasks were included in the model, but the tolerance concept for advancing the schedule was not taken into account, and only one case in which tasks were merged into a task with the shortest interval was considered.

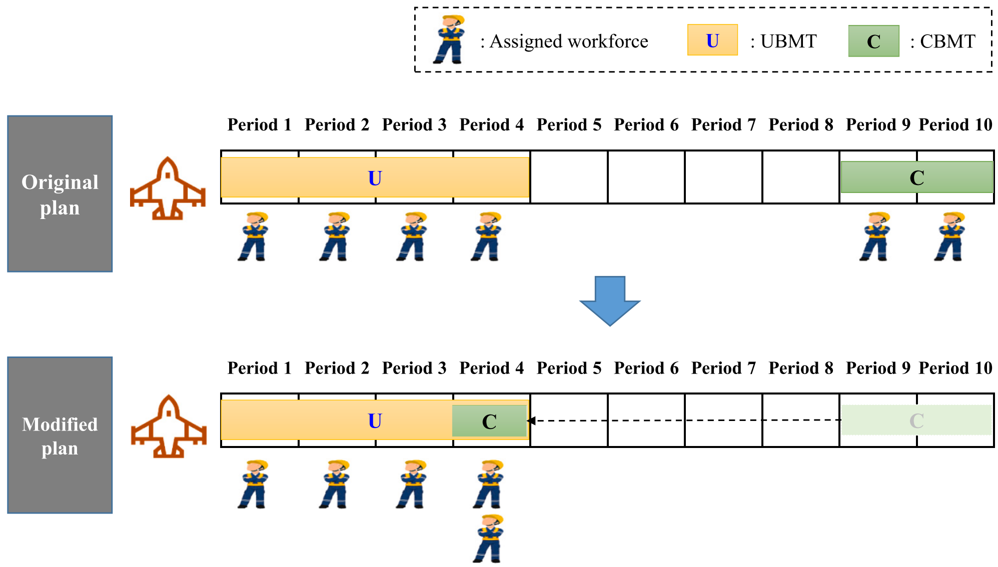

Fig. 2. An example of advancing the check schedule and merging tasks.

Table 1
Comparisons of this research and previous studies.

Paper	Objective	Maintenance type		Capacity		Advancing the check schedule	Merging checks
		UBMT	CBMT	Workforce	Hangar		
Steiner [7]	Min. total number of maintenance actions	O	O	O	O	O	△
Kozanidis et al. [22]	Max. minimum number of available aircraft	O	X	O	O	X	X
Cho [8]	Min. maximum number of grounded aircraft	O	X	X	O	O	X
Kozanidis et al. [24]	Max. minimum number of available aircraft Max. minimum total residual flight time	O	X	O	O	X	X
Verhoeff et al. [6]	Max. total residual flight time	O	X	O	O	X	X
Gavranis and Kozanidis [25]	Max. total residual flight time	O	X	O	O	X	X
Lee et al. [1]	Max. weighted sum of completed missions	O	X	O	O	△	X
Seif and Andrew [34]	Max. total residual operating time	O	X	O	O	△	△
This study	Max. total number of available aircraft	O	O	O	O	O	O

"O" represents covered, "△" represents partially covered and "X" represents none.

We summarize the relevant studies in Table 1 to emphasize the characteristics of this study. This shows the lack of an MAFMP model that reflects all aspects of the problem under consideration. We propose a MILP model that considers practical considerations: heterogeneous maintenance tasks, advancing the check schedules, and merging between tasks in response to this lack. In addition, we developed heuristics to find a solution to large problems within a reasonable time, and evaluated the performance of the heuristics.

3. Mathematical model

3.1. Problem description

The primary objective of air forces is to maintain military readiness against external threats, which requires a series of flight missions to be carried out and aircraft availability to be maximized for immediate response to emergencies. The method of measuring aircraft availability can vary depending on each country's security environment and operating conditions. In previous studies, availability is measured in two ways: (1) in terms of the serviceability, the total number of available aircraft [23]; and (2) in terms of the sustainability, the total RFT of available aircraft [6,25,34]. In this paper, we focus on the case of the ROKAF, which must maintain a constant state of readiness against existing external threats. Therefore, we conclude that the total number of available aircraft is a more appropriate objective in the Republic of Korea's security environment, which focuses on its ability to respond immediately to external threats. This is because total RFT cannot guarantee a sufficient number of available aircraft in a crisis. It is also consistent with the ROKAF's application of the average number of available aircraft when evaluating a wing's readiness. Flight planning is the assignment of flight times to available aircraft to meet flight requirements. There are minimum and maximum flight time constraints for aircraft in a single period for technical and practical reasons. Maintenance planning determines the start dates for maintenance tasks and allocates technician teams and space for grounded aircraft. The ROKAF typically creates and manages three-month (quarterly) and six-month (half years) flight and maintenance plans. Therefore, this paper sets the planning horizon to three months and six months. Additionally, we set half a week as a single period, considering that the maintenance duration of each PM is more than three workdays.

In the context of military aircraft maintenance, most aircraft types typically have one type of UBMT [22,24,25]. Therefore, in this paper, we focused on one type of UBMT, as known as phase inspection. Phase inspection is checking the overall system of an aircraft, including its components, before cumulative flight time of the aircraft reaches a specific interval. In particular, F-15/F-16 fighter aircraft, the most operated models by the ROKAF, enter the maintenance hangar to receive phase inspection every 400 flight hours. Therefore, the application of one UBMT to our model can be considered plausible. On the other hand, there are dozens of tasks that correspond to CBMT, but this paper focused on ten tasks. There are only a few studies dealing with both UBMT and CBMT together [7]. Moreover, regarding that previous studies [1,34] dealt with only up to three tasks, considering one type of UBMT and ten types of CBMT together is a new attempt. Each CBMT has a different maintenance interval and duration. In practice, the maintenance capacity (space, workforce) is finite. A hangar with a variety of equipment and tools is an essential space for performing phase inspection [35,36]. The tasks corresponding to CBMT are relatively simple and are not constrained by hangar space. We define "workforce" as a team of technicians, and each team can only be assigned to one task in a single period. This reflects the real world, in which technicians work in teams under the supervision of a skilled workforce, and in which their work does not often change so that they can focus on their work. For grounded aircraft, the residual maintenance time (RMT) is deducted as the task is performed by the workforce.

In this paper, the term "tolerance" means the proportion of a maintenance interval that is allowed to advance the check schedule. This ensures that maintenance intervals are not wasted excessively by advancing the check schedule. There are a small number of tasks with tolerance specified in the technical manual or regulations (e.g., phase inspection, 10 percent). Additionally, the tolerance levels for other tasks are arbitrarily determined and applied on a case-by-case basis, according to the operator's experience. In this study, without loss of generality, we set the tolerance to a value within 10 percent.

Fig. 2 shows the benefits of advancing the check schedule and merging tasks. In the original plan, the aircraft would be unavailable for at least six periods. If a CBMT planned for the ninth period can be advanced to the fourth period, it can be performed together with a UBMT. As a result, a CBMT, which previously required two periods, can be completed in one period, reducing the amount of work. In addition, the number of periods when the aircraft is unavailable is reduced to four periods.

3.2. Problem formulation

The following assumptions are made in the model:

1. All aircraft are homogeneous in terms of flight missions and maintenance requirement types.
2. Flight requirements and maintenance capacity of the planning horizon are given in advance.
3. The initial RFT and RMT for each aircraft is provided in advance.
4. There is no shortage of parts or components required for maintenances.
5. Unplanned factors such as faults in flight are not considered.
6. Technician teams are homogeneous with no differences in skill levels and skill types.

The first five assumptions are common to many MAFMP studies. The final assumption is based on the fact that the MAFMP problem is a type of strategic problem aimed at macro planning rather than at detailed scheduling.

The following notation is used in the formulation:

Sets

N	Set of unit aircraft, indexed by n
P	Set of UBMTs, indexed by p
Q	Set of CBMTs, indexed by q, $P \cap Q = \emptyset$.

Parameters

T	Number of time periods in the planning horizon
H^t	Workforce capacity for performing maintenance in period t (The number of technician teams available)
C	Space capacity of maintenance hangar (The simultaneous number of aircraft that can be serviced)
R^t	Flight demand (flight time to be performed for combat patrol, pilot training etc.) in period t
X_{max}	Maximum assignable flight time of an aircraft in a single period
X_{min}	Minimum assignable flight time of an aircraft in a single period, if assigned
Y_p	Interval of UBMT p (the RFT of an aircraft after maintenance is reset to this original value)
Y_q	Interval of CBMT q (the RCT of an aircraft after maintenance is reset to this original value)
δ_p	Tolerance permitted for advancing the schedule of UBMT p
δ_q	Tolerance permitted for advancing the schedule of CBMT q
G_p	Maintenance duration of UBMT p
G_q	Maintenance duration of CBMT q
G_{pq}	Modified duration of CBMT q (shortened by conducting any UBMT p together)
$A^1_{n,p}$	Availability state of aircraft n at the beginning of the first period with respect to UBMT p
$A^1_{n,q}$	Availability state of aircraft n at the beginning of the first period with respect to CBMT q
$Y^1_{n,p}$	RFT of aircraft n at the beginning of the first period for UBMT p
$Y^1_{n,q}$	RCT of aircraft n at the beginning of the first period for CBMT q
$G^1_{n,p}$	RMT of aircraft n at the beginning of the first period for UBMT p
$G^1_{n,q}$	RMT of aircraft n at the beginning of the first period for CBMT q
L	Lower bound of the total RFT for fleet sustainability

Decision variables

$a^t_{n,p}$	1 if aircraft n is partially available, considering only UBMT p in period t; 0 otherwise
U^t_n	1 if aircraft n is partially available, considering all its UBMTs in period t; 0 otherwise
$a^t_{n,q}$	1 if aircraft n is partially available, considering only CBMT q in period t; 0 otherwise
A^t_n	1 if aircraft n is fully available, considering all its PMs in period t; 0 otherwise
O^t_n	1 if aircraft n is assigned to flight mission in period t; 0 otherwise
$d^t_{n,p}$	1 if UBMT p of aircraft n is completed at the beginning of the period t; 0 otherwise
$d^t_{n,q}$	1 if CBMT q of aircraft n is completed at the beginning of the period t; 0 otherwise
$f^t_{n,p}$	1 if aircraft n gets grounded for UBMT p at the beginning of the period t; 0 otherwise
$f^t_{n,q}$	1 if aircraft n gets grounded for CBMT q at the beginning of the period t; 0 otherwise
$y^t_{n,p}$	RFT of aircraft n in period t of UBMT p

$y^t_{n,q}$	RCT of aircraft n in period t of CBMT q
$g^t_{n,p}$	RMT of UBMT p of aircraft n in period t
$g^t_{n,q}$	RMT of CBMT q of aircraft n in period t
X^t_n	Assigned flight time of aircraft n in period t
$h^t_{n,p}$	1 if a technician team is assigned to UBMT p of aircraft n in period t; 0 otherwise
$h^t_{n,q}$	1 if a technician team is assigned to CBMT q of aircraft n in period t; 0 otherwise
$\lambda^t_{n,p}$	Wasted interval of UBMT p of aircraft n in period t as advancing the check schedule
$\lambda^t_{n,q}$	Wasted interval of CBMT q of aircraft n in period t as advancing the check schedule
$c^t_{n,q}, \alpha^t_{n,q}, \beta^t_{n,q}$	Auxiliary binary variables

An aircraft is unavailable unless all maintenance tasks are completed. For example, if an aircraft is grounded to perform CBMT q_1, it cannot fly even if the RCT of CBMT q_2 is sufficient. This aircraft is partially available for CBMT q_2, but not fully available, as it is partially unavailable for CBMT q_1. After all checks are completed, only then is the aircraft fully available again. We formulated a MILP model for the MAFMP problem. To make this formulation easier to understand, we appended a description that explains its purpose each time we introduce a set of constraints. Moreover, some truth tables are provided in the Appendix to help to demonstrate the relationships, established by the constraints, between the variables.

$$\max \sum_{t=2}^{T+1} \sum_{n\in N} A^t_n \tag{1}$$

$$\text{s.t.} \quad y^{t+1}_{n,p} = y^t_{n,p} - X^t_n + Y_p d^{t+1}_{n,p} - \lambda^t_{n,p} \qquad \forall n\in N, \forall p\in P, t=1,\dots,T \tag{2}$$

$$X_{min} a^{t+1}_{n,p} - X_{min}(1-a^t_{n,p}) \le y^t_{n,p} - X^t_n \qquad \forall n\in N, \forall p\in P, t=1,\dots,T \tag{3}$$

$$y^t_{n,p} - X^t_n \le 1.1 Y_p a^{t+1}_{n,p} + \delta_p Y_p (1-a^{t+1}_{n,p}) \qquad \forall n\in N, \forall p\in P, t=1,\dots,T \tag{4}$$

$$\delta_p Y_p f^{t+1}_{n,p} \ge \lambda^t_{n,p} \qquad \forall n\in N, \forall p\in P, t=1,\dots,T \tag{5}$$

$$d^{t+1}_{n,p} \ge a^{t+1}_{n,p} - a^t_{n,p} \qquad \forall n\in N, \forall p\in P, t=1,\dots,T \tag{6}$$

$$a^{t+1}_{n,p} - a^t_{n,p} + 1.1(1-d^{t+1}_{n,p}) \ge 0.1 \qquad \forall n\in N, \forall p\in P, t=1,\dots,T \tag{7}$$

$$f^{t+1}_{n,p} \ge a^t_{n,p} - a^{t+1}_{n,p} \qquad \forall n\in N, \forall p\in P, t=1,\dots,T \tag{8}$$

$$a^t_{n,p} - a^{t+1}_{n,p} + 1.1(1-f^{t+1}_{n,p}) \ge 0.1 \qquad \forall n\in N, \forall p\in P, t=1,\dots,T \tag{9}$$

$$g^{t+1}_{n,p} = g^t_{n,p} - h^t_{n,p} + G_p f^{t+1}_{n,p} \qquad \forall n\in N, \forall p\in P, t=1,\dots,T \tag{10}$$

The objective function maximizes the cumulative sum of the number of available aircraft, expressed as the sum of the number of available aircraft in each period, as shown in Eq. (1). The availability of the first period is not included in the objective function because it is a given parameter, and the availability of the period $T+1$ is included to ensure a smooth connection to the next planning horizon [25]. Constraint (2) updates the RFT of each aircraft at the beginning of the period $t+1$, based on its RFT at the beginning of period t and the flight time at period t. Constraints (3) and (4) mean that if the RFT of aircraft at the end of period t is less than the minimum flight time, it cannot be assigned to a mission in the next period. Constraint (5) ensures that a wasted interval can occur only when the aircraft is grounded and the wasted value is within the allowable range.

Constraints (6)–(9) mean that the aircraft is partially unavailable when a task on the aircraft starts and that the aircraft is partially available when the task is completed. Constraint (10) has a similar logic to Constraint (2). RMT for each aircraft at the beginning of the period $t+1$ is updated based on its RMT at the beginning of period t and on whether or not workforce have been assigned to work on that aircraft during that period.

$$y^{t+1}_{n,q} = y^t_{n,q} - a^t_{n,q} + Y_q d^{t+1}_{n,q} - \lambda^t_{n,q} \qquad \forall n\in N, \forall q\in Q, t=1,\dots,T \tag{11}$$

$$a^t_{n,q} + a^{t+1}_{n,q} - 1 \le y^t_{n,q} - a^t_{n,q} \qquad \forall n\in N, \forall q\in Q, t=1,\dots,T \tag{12}$$

$$y^t_{n,q} - a^t_{n,q} \le 1.1 Y_q a^{t+1}_{n,q} + \delta_q Y_q (1-a^{t+1}_{n,q}) \qquad \forall n\in N, \forall q\in Q, t=1,\dots,T \tag{13}$$

$$\delta_q Y_q f^{t+1}_{n,q} \ge \lambda^t_{n,q} \qquad \forall n\in N, \forall q\in Q, t=1,\dots,T \tag{14}$$

$$d^{t+1}_{n,q} \ge a^{t+1}_{n,q} - a^t_{n,q} \qquad \forall n\in N, \forall q\in Q, t=1,\dots,T \tag{15}$$

$$a^{t+1}_{n,q} - a^t_{n,q} + 1.1(1-d^{t+1}_{n,q}) \ge 0.1 \qquad \forall n\in N, \forall q\in Q, t=1,\dots,T \tag{16}$$

$$f^{t+1}_{n,q} \ge a^t_{n,q} - a^{t+1}_{n,q} \qquad \forall n\in N, \forall q\in Q, t=1,\dots,T \tag{17}$$

$$a^t_{n,q} - a^{t+1}_{n,q} + 1.1(1-f^{t+1}_{n,q}) \ge 0.1 \qquad \forall n\in N, \forall q\in Q, t=1,\dots,T \tag{18}$$

$$g^{t+1}_{n,q} = g^t_{n,q} - h^t_{n,q} + G_{pq}\alpha^{t+1}_{n,q} + G_q \beta^{t+1}_{n,q} \qquad \forall n\in N, \forall q\in Q, t=1,\dots,T \tag{19}$$

$$\beta^t_{n,q} \le 1 - c^t_{n,q} \qquad \forall n\in N, \forall q\in Q, t=1,\dots,T+1 \tag{20}$$

$$\alpha^t_{n,q} \le c^t_{n,q} \qquad \forall n\in N, \forall q\in Q, t=1,\dots,T+1 \tag{21}$$

$$f^t_{n,q} = \alpha^t_{n,q} + \beta^t_{n,q} \qquad \forall n\in N, \forall q\in Q, t=1,\dots,T+1 \tag{22}$$

$$|P|(1-c^t_{n,q}) \le \sum_{p\in P} a^{t+1}_{n,p} \qquad \forall n\in N, \forall q\in Q, t=1,\dots,T \tag{23}$$

$$\sum_{p\in P} a^{t+1}_{n,p} \le |P| - c^t_{n,q} \qquad \forall n\in N, \forall q\in Q, t=1,\dots,T \tag{24}$$

In a similar manner to Constraints (2)–(5), Constraints (11)–(14) update the RCT for each aircraft. The difference is that these are equations for CBMT and are updated based on availability in period t, not the flight time. Constraints (15)–(18) have the same logic as Constraints (6)–(9). Constraint (19) updates the RMT for each aircraft at the beginning of the time period $t+1$ in a similar manner to Constraint (10). Constraints (20)–(24) ensure that maintenance duration of CBMTs can be shortened by conducting UBMTs and CBMTs together on a grounded aircraft. In detail, variable c designates whether any UBMT is in maintenance. If so, c will be 1, and 0 otherwise. In addition, $c=0$ implies $\alpha=0$, and $c=1$ implies $\beta=0$, respectively. Consequently, as f is the sum of α and β, if f has the value of 1, one of α and β should be 1, but not both, depending on UBMTs. Therefore, the maintenance duration can be shortened when α takes the value 1.

$$\sum_{n\in N} X^t_n = R^t \qquad t=1,\dots,T+1 \tag{25}$$

$$\sum_{n\in N}\Big(\sum_{p\in P} h^t_{n,p} + \sum_{q\in Q} h^t_{n,q}\Big) \le H^t \qquad t=1,\dots,T+1 \tag{26}$$

$$|N| - \sum_{n\in N} U^t_n \le C \qquad t=1,\dots,T+1 \tag{27}$$

$$\sum_{p\in P} a^t_{n,p} - |P| + 1 \le U^t_n \qquad \forall n\in N, t=1,\dots,T+1 \tag{28}$$

$$U^t_n \le a^t_{n,p} \qquad \forall n\in N, \forall p\in P, t=1,\dots,T+1 \tag{29}$$

$$1 - a^t_{n,p} \le g^t_{n,p} \qquad \forall n\in N, \forall p\in P, t=1,\dots,T+1 \tag{30}$$

$$g^t_{n,p} \le G_p(1-a^t_{n,p}) \qquad \forall n\in N, \forall p\in P, t=1,\dots,T+1 \tag{31}$$

$$1 - a^t_{n,q} \le g^t_{n,q} \qquad \forall n\in N, \forall q\in Q, t=1,\dots,T+1 \tag{32}$$

$$g^t_{n,q} \le G_q(1-a^t_{n,q}) \qquad \forall n\in N, \forall q\in Q, t=1,\dots,T+1 \tag{33}$$

$$y^t_{n,p} \le Y_p a^t_{n,p} \qquad \forall n \in N,\ \forall p \in P,\ t = 1,\dots,T+1 \tag{34}$$

$$X_{min} a^t_{n,p} \le y^t_{n,p} \qquad \forall n \in N,\ \forall p \in P,\ t = 1,\dots,T+1 \tag{35}$$

$$y^t_{n,q} \le Y_q a^t_{n,q} \qquad \forall n \in N,\ \forall q \in Q,\ t = 1,\dots,T+1 \tag{36}$$

$$a^t_{n,q} \le y^t_{n,q} \qquad \forall n \in N,\ \forall q \in Q,\ t = 1,\dots,T+1 \tag{37}$$

Constraint (25) ensures that the flight demands of each time period are satisfied. Constraints (26) and (27) ensure that the number of workforces assigned to the task are not greater than the workforce capacity, and that the number of grounded aircraft for phase inspection does not exceed the space capacity. Constraints (28) and (29) create the condition in which the aircraft is partially available, considering all its UBMTs only when all the partial availability states of each UBMT are equal to 1. Constraints (30), (31), (34), and (35) ensure that the following relationship holds between $a^t_{n,p}$, $y^t_{n,p}$, and $g^t_{n,p}$, $\forall n, p, t$: $a^t_{n,p} = 0 \Rightarrow g^t_{n,p} \ge 1$, $a^t_{n,p} = 1 \Rightarrow g^t_{n,p} = 0$, $a^t_{n,p} = 0 \Rightarrow y^t_{n,p} = 0$, and $a^t_{n,p} = 1 \Rightarrow y^t_{n,p} \ge X_{min}$. Constraints (32), (33), (36), and (37) have a similar mechanism. These equations guarantee that the following relationship exists between $a^t_{n,q}$, $y^t_{n,q}$, and $g^t_{n,q}$, $\forall n, q, t$: $a^t_{n,q} = 0 \Rightarrow g^t_{n,q} \ge 1$, $a^t_{n,q} = 1 \Rightarrow g^t_{n,q} = 0$, $a^t_{n,q} = 0 \Rightarrow y^t_{n,q} = 0$, and $a^t_{n,q} = 1 \Rightarrow y^t_{n,q} \ge 1$. Constraints (31) and (33)–(37) state the lower and upper bounds of the RFT, RCT, and RMT.

$$X^t_n \le X_{max} O^t_n \qquad \forall n \in N,\ t = 1,\dots,T+1 \tag{38}$$

$$X^t_n \ge X_{min} O^t_n \qquad \forall n \in N,\ t = 1,\dots,T+1 \tag{39}$$

$$O^t_n \le A^t_n \qquad \forall n \in N,\ t = 1,\dots,T+1 \tag{40}$$

$$X^t_n \le y^t_{n,p} \qquad \forall n \in N,\ \forall p \in P,\ t = 1,\dots,T+1 \tag{41}$$

$$h^t_{n,p} \le g^t_{n,p} \qquad \forall n \in N,\ \forall p \in P,\ t = 1,\dots,T+1 \tag{42}$$

$$h^t_{n,q} \le g^t_{n,q} \qquad \forall n \in N,\ \forall q \in Q,\ t = 1,\dots,T+1 \tag{43}$$

$$A^t_n \le a^t_{n,p} \qquad \forall n \in N,\ \forall p \in P,\ t = 1,\dots,T+1 \tag{44}$$

$$A^t_n \le a^t_{n,q} \qquad \forall n \in N,\ \forall q \in Q,\ t = 1,\dots,T+1 \tag{45}$$

$$\frac{\sum_{p\in P} a^t_{n,p}}{|P|} + \frac{\sum_{q\in Q} a^t_{n,q}}{|Q|} - 2 + \frac{1}{|P|+|Q|} \le A^t_n \qquad \forall n \in N,\ t = 1,\dots,T+1 \tag{46}$$

$$\sum_{n\in N} y^t_{n,p} \ge L \qquad \forall p \in P,\ t = 1,\dots,T+1 \tag{47}$$

Constraints (38)–(41) allow an aircraft to operate missions only when the aircraft is fully available. They also impose upper and lower bounds on the flight time for a single period. These limitations generally exist for technical and practical reasons. Constraints (42) and (43) ensure that workforces can be assigned only to the aircraft with positive RMT. Constraints (44)–(46) create the condition in which the aircraft is fully available ($A^t_n = 1$) only when all the partial availability states are equal to 1 ($\sum_{p\in P} a^t_{n,p} = |P|$ and $\sum_{q\in Q} a^t_{n,q} = |Q|$). If even one partial state becomes unavailable, the aircraft becomes unavailable. Constraint (47) is a sustainability constraint and imposes a lower bound on the total RFT. This prevents unnecessary backlog of phase inspection and future maintenance bottlenecks.

$$a^1_{n,p} = A^1_{n,p} \qquad \forall n \in N,\ \forall p \in P \tag{48}$$

$$y^1_{n,p} = Y^1_{n,p} \qquad \forall n \in N,\ \forall p \in P \tag{49}$$

$$g^1_{n,p} = G^1_{n,p} \qquad \forall n \in N,\ \forall p \in P \tag{50}$$

$$a^1_{n,q} = A^1_{n,q} \qquad \forall n \in N,\ \forall q \in Q \tag{51}$$

$$y^1_{n,q} = Y^1_{n,q} \qquad \forall n \in N,\ \forall q \in Q \tag{52}$$

$$g^1_{n,q} = G^1_{n,q} \qquad \forall n \in N,\ \forall q \in Q \tag{53}$$

$$\lambda^t_{n,p},\ y^t_{n,p},\ g^t_{n,p} \ge 0 \qquad \forall n \in N,\ \forall p \in P,\ t = 1,\dots,T+1 \tag{54}$$

$$\lambda^t_{n,q},\ y^t_{n,q},\ g^t_{n,q} \ge 0 \qquad \forall n \in N,\ \forall q \in Q,\ t = 1,\dots,T+1 \tag{55}$$

$$a^t_{n,p},\ d^t_{n,p},\ f^t_{n,p},\ h^t_{n,p} \in \{0,1\} \qquad \forall n \in N,\ \forall p \in P,\ t = 1,\dots,T+1 \tag{56}$$

$$a^t_{n,q},\ d^t_{n,q},\ f^t_{n,q},\ c^t_{n,q},\ \alpha^t_{n,q},\ \beta^t_{n,q},\ h^t_{n,q} \in \{0,1\} \qquad \forall n \in N,\ \forall q \in Q,\ t = 1,\dots,T+1 \tag{57}$$

$$A^t_n,\ O^t_n,\ U^t_n \in \{0,1\} \qquad \forall n \in N,\ t = 1,\dots,T+1 \tag{58}$$

Constraints (48)–(53) initialize the state of the aircraft at the first period of the planning horizon. Finally, Constraints (54)–(58) are non-negativity and integrality constraints, respectively.

4. Heuristic algorithms

As Peschiera [17] showed that the MAFMP problem is NP-hard, the problem we are taking into account is also NP-hard. Considering that the branch-and-bound algorithm, which commercial solvers usually implement, has an exponential complexity, the computational effort required for the MAFMP model to find an optimal solution with a solver increases rapidly with the problem size. In the early stage of planning, where multiple alternatives needed to be considered, and in situations where plans need to be revised urgently, managers need to be able to quickly find and compare solutions. In this case, endeavoring to find optimal solutions of large problems may not be suitable. Therefore, we developed two heuristics to find a good solution within a reasonable time. The heuristics are a fleet-split heuristic (FSH) and a sequential-decision heuristic (SDH), which are described as follows.

4.1. FSH

The first heuristic, which is a matheuristic relying on the divide-and-conquer strategy, is based on a straightforward observation and idea. We observed that the solver is generally faster in solving for instances with smaller numbers of aircraft. Therefore, we split an instance into several subproblems and solved each of them sequentially. Flight requirements and maintenance capacity were divided into several groups using this split skill.

A subproblem may become infeasible if the number of available aircraft or the total RFT does not meet the flight requirements. Hence, it is essential to divide the original problem by considering the balance between demand and capacity to ensure the feasibility of each subproblem. In this paper, we divided the original problem in such a way that the sum of the initial RFT, which has the most significant influence on the feasibility, is similar for each subproblem. After that, based on this value, flight demand and maintenance capacity were allocated to each subproblem.

We divided the original problem by considering the balance between demand and capacity to ensure the feasibility of each subproblem. The idea of dividing the original problem into smaller subproblems and solving them sequentially, was presented in the work of Marlow and Dell [2] as a heuristic algorithm. This algorithm solved the subproblems independently. However, we found that this independence wastes the residual capacities of each subproblem, resulting in poor solution quality. In addition, in some cases, the constraints of a subproblem may not be satisfied, making the instance infeasible. Therefore, we added a simple procedure to share the residual capacities and overachieved requirements from the previous subproblem to the next subproblem. This procedure allows decentralized subproblems to use the entire resource more efficiently, thereby reducing the loss of objective function value and mitigating instances from becoming infeasible. Once all subproblems are solved, the results of subproblems can be recombined to produce a heuristic solution.

In preliminary experiments, we measured the performance of the FSH by varying the size of the subproblem. We observed a trade-off relationship in that the greater the number of subproblems, the lower the computation times and the lower the solution quality. In addition, if the size of the subproblem becomes excessively small, the effect of one aircraft on the problem increases, and the number of instances in which the subproblem is infeasible increase. This result means that the size of the subproblem should be determined considering the nature of the problem and the required performance. If the size of the subproblem is smaller than six aircraft, the FSH is inferior in solution quality to the SDH. Therefore, for the practicality of the FSH, it is necessary to set the size of the subproblem to 6 or more aircraft, and a size of 10 or less is recommended so that the solver can solve it relatively quickly. We set each subproblem to 10 aircraft in this paper, considering these experimental results and the fact that the number of aircraft in a fighter wing is typically a multiple of ten.

The following summarizes the procedure for the heuristic. In the procedure, K denotes the total number of subproblems, Z denotes the number of unsolved subproblems, and S_k denotes the set of aircraft in the kth subproblem. F_k denotes the flight requirements (flight demand and a lower bound of total RFT for each period) met by S_k, and C_k denotes the maintenance capacities used by S_k. F_o and F_r represent the flight requirements of the original problem and the remaining flight requirements, respectively. Similarly, C_o and C_r represent the maintenance capacities of the original problem and the remaining maintenance capacities.

Procedure(*FSH*)

Step 1	Let $Z \leftarrow K$ and let $F_r \leftarrow F_o$ and let $C_r \leftarrow C_o$
Step 2	Split the fleet into K subsets of aircraft and let $k \leftarrow 1$
Step 3	Divide F_r and C_r by Z to calculate the flight requirements and available maintenance capacity for the kth subproblem
Step 4	Solve the MAFMP model for the kth subproblem. If the result is infeasible, then go back to *Step* 2 and apply another split method; otherwise let $F_r \leftarrow F_r - F_k$ and let $C_r \leftarrow C_r - C_k$
Step 5	If k is not equal to K, let $k \leftarrow k+1$ and let $Z \leftarrow Z-1$ and go to *Step* 3; otherwise, terminate

4.2. SDH

The second heuristic we developed follows the decision flow and criteria used by field operators. The basic idea of this heuristic is based on the aircraft flowchart heuristic [24]. However, the model in this paper differs from previous studies in many areas, such as objective function, CBMT, and tolerance, so we modified and extended the aircraft flowchart heuristic to fit our model. In particular, the main difference is that it reflects two major rules practically used in maintenance sites of the ROKAF, which will be introduced later.

Fig. 3 shows the flow of the SDH. The SDH consists of four sequential decisions for each period. The first decision is to generate maintenance plans that assign workforces to the grounded aircraft. Workforces are assigned priorities, starting with the aircraft with the lowest total RMT, in order to quickly reduce the number of grounded aircraft. This decision affects available space capacity and flight plans for the following period. For example, if there is no space capacity available in the next period, less or no flight time should be allocated to an aircraft with little RFT. On the other hand, if there is space available in the hangar and more aircraft need to be serviced to meet the sustainability constraints, more flight time should be assigned to those aircraft. Therefore, the information about the residual space capacity in the next period is transferred to the next step, and the information about workforce assignment is passed to the fourth step, where it is used to update the status of the aircraft in the next period.

The second decision is to generate flight plans. The modified aircraft flowchart technique is used to determine the flight time of each available aircraft for the current period t. The aircraft flowchart (also known as sliding scale scheduling) is widely used by the ROKAF and many other air forces worldwide to establish aircraft flight and maintenance plans [24]. Let W be the aircraft set with a positive RFT, regardless of availability by state of the CBMTs in period t. Additionally, we sorted these aircraft in non-decreasing order of their RFT at the beginning of period t. The index i of each aircraft denotes its relative order in the sorted set. $Y_p/|W|$ is the ideal slope of the diagonal, as the difference in the RFT of each aircraft must be properly spaced to prevent the aircraft from becoming unavailable at the same time. Therefore the RFT of aircraft n at the beginning of period $t+1$ should ideally be equal to $Y_p/|W|(i-1)$. Fig. 4 shows an example of the application of the aircraft flowchart technique. The blue line with the ideal slope of the diagonal becomes the target line for each aircraft's RFT. If an available aircraft has more RFT than the blue line, as more flight time as possible should be assigned so that the RFT in the next period is closer to the blue line; otherwise, less flight time should be assigned. For example, in Fig. 4, aircraft with indices 1 to 29 should have more flight time.

In contrast, aircraft with indices greater than 30 should be assigned less flight time. Eventually, the distribution of RFT for each aircraft can be approximated to the target line using the aircraft flowchart technique.

Thus, the problem of generating flight plans is reduced to a least-squares problem that minimizes the deviation between the ideal RFT and the actual RFT at the beginning of the next period. Then, the nonlinear optimization problem is as follows.

$$\min \sum_{n\in W}\sum_{p\in P}\left(y_{n,p}^{t+1} - (Y_p/|W|(i-1))\right)^2 \tag{59}$$

$$\text{s.t.} \quad y_{n,p}^{t+1} = y_{n,p}^{t} - X_n^t \qquad \forall n \in W, \forall p \in P \tag{60}$$

$$X_{min} O_n^t \le X_n^t \qquad \forall n \in W \tag{61}$$

$$X_n^t \le X_{max} O_n^t \qquad \forall n \in W \tag{62}$$

$$O_n^t \le A_n^t \qquad \forall n \in W \tag{63}$$

$$X_n^t \le y_{n,p}^t \qquad \forall n \in W, \forall p \in P \tag{64}$$

$$\sum_{n\in W} X_n^t = R^t \tag{65}$$

$$A_n^t, O_n^t \in \{0,1\} \qquad \forall n \in W \tag{66}$$

$$X_n^t \ge 0 \qquad \forall n \in W \tag{67}$$

In Eq. (59), the total deviation index at the beginning of the next period is minimized. Constraint (60) updates each aircraft's RFT at the beginning of the next period, based on its RFT at the beginning of the period t and the flight time assigned for the same period. Constraints (61)–(64) ensure that flight time can be assigned only

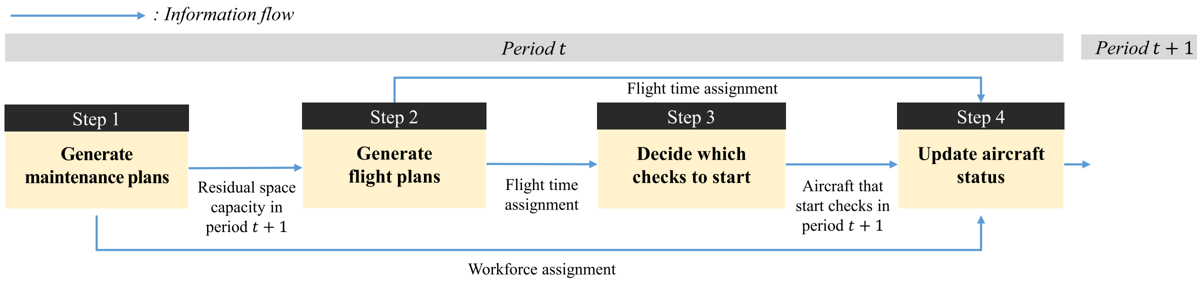

Fig. 3. The flow of the SDH.

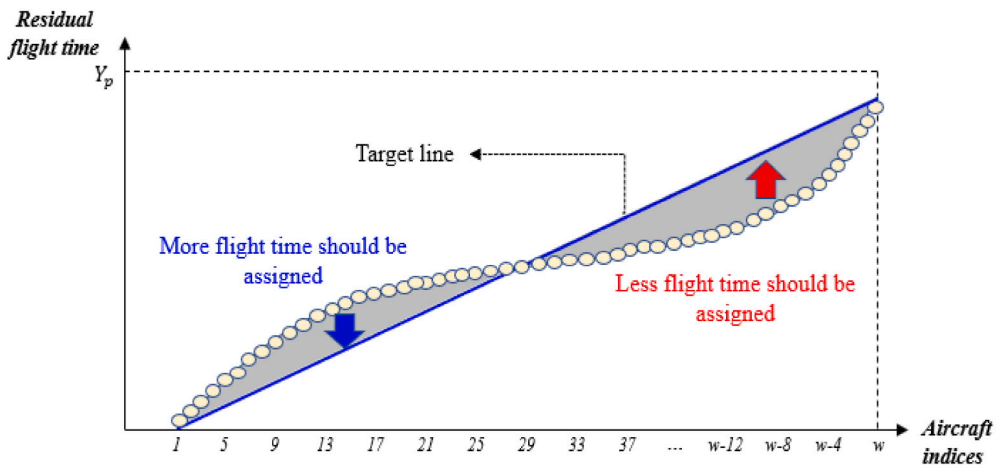

Fig. 4. An example of the application of the aircraft flowchart technique.

to available aircraft and limit the lower and upper bound of flight time. Constraint (65) ensures that flight demands for each period are satisfied. Additionally, the last expression is an integrality constraint. Because this quadratic problem with linear constraints can be easily solved [24], we solved this problem using a solver. As mentioned above, the aircraft flowchart technique aims to minimize the total deviation index rather than maximize fleet availability. Therefore, the solution found does not represent the optimal solution for maximizing fleet availability. Because of this, we focused on solving this quadratic problem quickly by setting the optimality gap tolerance to 10 percent in the solver options. The flight time determined through the aircraft flowchart technique is adjusted in consideration of the maintenance space available and the sustainability constraint, and the corresponding information is transferred to the next step.

The third step is to decide which check to start, and the following two rules need to be applied: First, if an aircraft is grounded, then as many checks as possible should be performed in parallel to reduce the number of groundings in the future. Second, a maintenance plan that exceeds the workforce capacity should be avoided, as it prolongs unavailability. These rules are consistent with the current practice of the ROKAF maintenance field, which promotes efficient operation and strongly avoids maintenance bottlenecks and delays. The proposed algorithm differs from the previous studies based on the aircraft flowchart heuristic, in that it is structured to consider both UBMT and CBMTs together and has applied the ROKAF practice of determining when to initiate maintenance. In addition, depending on the tolerance parameter value, maintenance tasks can be conducted earlier than their interval. Therefore, determining when and which checks to start significantly affects the fleet availability. Grounding the aircraft is not recommended if maintenance is expected to be delayed because of a lack of workforce. We can easily predict delays by simulating maintenance plans for the following period. Through the previous step, we can gain information about the aircraft that will continue to be grounded in the next period because of pending work. We also can gain information about the aircraft that will be newly grounded in the next period because of the exhaustion of the RFT or RCT. Based on this information, the third step can be summarized as follows.

Step 3-1	Subtract the workforce needed for the number of pending tasks from the capacity for the next period. Check the result, and if the result is positive, go to the next step; otherwise terminate.
Step 3-2	Subtract the number of tasks that must be started in the next period because of exhaustion of the RFT or RCT from the remaining workforce capacity. Check the result, and if the result is positive, go to the next step; otherwise terminate.
Step 3-3	Advance the check schedules that are within the tolerance and subtract that number from the remaining workforce capacity. Apply this process first to an aircraft that should be grounded in the next period, and then to available aircraft. This process is repeated until the remaining workforce capacity becomes zero.

In the final step, the aircraft status at the beginning of the next period is updated using the decisions made in the previous steps. The above procedure is repeated for each period of the entire planning horizon to make flight and maintenance plans for all aircraft. The SDH is a heuristic algorithm developed based on the aircraft flowchart technique used by many air forces. Because it is not based on a mathematical model, it can be used as a benchmark for the model. This heuristic is simple and can be easily applied to problem instances. Thus, it can be used as an alternative if the instance is difficult to solve with a solver.

5. Computational experiments

In this section, we verified the model and analyzed the effects of the maintenance policies (size of workforce capacity and tolerance) on fleet availability. We also conducted experiments to evaluate the performance of the two heuristics presented above for large problems in which a solver cannot find an optimal solution within a time limit. The experiments were conducted on a personal computer with an Intel Core i5 processor with 2.9 GHz and 16 GB RAM. Moreover, a single-thread option was set in IBM ILOG CPLEX Optimizer 20.1.

Because the data about real-world instances of the ROKAF are confidential, we generated random instances whose size and characteristics are similar to real-world instances. We used these instances to demonstrate the applicability of MILP model and heuristic algorithms. In practice, some parameters, such as the number of PM tasks, the intervals between maintenance, and the maintenance duration, do not change significantly. Thus, we set the parameters to realistic values (i.e., $Y_p = [400]$, $Y_q = [28, 48, 48, 96, 240, 288, 576, 672, 672, 768]$, $G_p = [4]$, $G_q = [1, 1, 1, 1, 2, 2, 2, 2, 2, 2]$, $G_{pq} = [1, 1, 1, 1, 1, 1, 1, 2, 2, 2]$, $X_{max} = 8$, $X_{min} = 3$, $L = (Y_p + X_{min})((|N| - C)/2)$. We generated and solved 30 random instances for each instance type. Random instances were generated using a method similar to that of Gavranis and Kozanidis [25]. The space capacity of the hangar was set as equal to $0.06|N|$ and rounded up to the nearest integer. A discrete probability function randomly generated the initial number of grounded aircraft in the hangar with integer values between 0 and C. The initial RFT and RCT of each aircraft were random numbers uniformly distributed over the intervals $[X_{min}, Y_p]$ and $[1, Y_q]$, respectively. The initial RMT for UBMT was a random number uniformly distributed over the interval $[1, G_p]$. We assumed that there were no grounded aircraft for CBMTs initially, so the initial RMT for CBMTs was set to 0. The flight demand for each period was generated as a uniform random number over the interval $[3.1|N|, 3.8|N|]$. Because each initial value was randomly taken over specific ranges, various scenarios that may occur in the real world could be generated. This is the reason why we generated 30 random instances. If the total RFT of the fleet is less than the flight demand, or the sustainability constraints may not be met, the instance becomes infeasible. When generating the random instances for each instance type, we discarded infeasible instances and generated more instances until we found 30 feasible instances. By generating a wide range of instances for each problem size, we can ensure that the various cases (even tight ones) that can occur in the real world are covered.

The experiments were divided into two main categories. First, we verified that the model worked as intended and solved small problems with a solver. Additionally, parameter analysis was performed. Second, we used two heuristic algorithms to solve large problems and evaluated their performance.

5.1. Experiment 1

We performed experiment 1 to verify that the model works as intended. Fig. 5 shows the recommended optimal flight and maintenance plan to maximize fleet availability in a Gantt-chart. Each row is an aircraft, and each column represents a time period. The number in the green boxes indicates the flight time consumed by the aircraft assigned to the mission. The letter M in red boxes means the aircraft is grounded for maintenance. This plan maximizes the number of available aircraft while meeting various constraints such as space, workforce, and flight demands for each period.

Sensitivity analysis was performed on the problem of 10 aircraft and a three-month planning horizon. The time limit was set to 1800 s. The experimental results are summarized in Table 2. Table 2 shows the experimental results with varying workforce capacity and tolerance. The values in the table are the average values of the results of 30 random test problems generated for each instance type. More specifically, the second column of this table shows the maximum fleet availability achieved through optimization of flight and maintenance plans. We calculated the fleet availability as follows.

$$\text{Availability} = \frac{\text{Cumulative sum of the number of available aircraft}}{\text{Cumulative sum of the total number of aircraft}} \times 100(\%) \tag{68}$$

Fleet availability increases as workforce capacity and tolerance increase. The increased workforce capacity allows more tasks to be performed in parallel, reducing the time the grounded aircraft waits for maintenance. The increased tolerance provides greater flexibility for when to start checks. This avoids the maintenance bottlenecks caused by the concentration of tasks in a specific period and provides more opportunities to reduce the maintenance duration by merging tasks. This prevents work delays and allows a large amount of work to be serviced within the planning horizon, thereby increasing the fleet availability. Military operators can use these results as a basis for determining appropriate workforce capacity and tolerance in flight and maintenance planning. In addition, a maintenance policy can be established to meet the target availability through what-if analysis for each situation. For example, if the target availability is 89.00 percent, the operator can achieve the goal by setting the workforce capacity to 3 and the tolerance to 5.0 percent, as shown in Table 2. At this time, if the workforce capacity is limited to 2, the operator can meet the target availability by increasing the tolerance to 7.5 percent. However, as shown in Fig. 6, fleet availability does not increase proportionally with the increase or increase rate of workforce capacity and tolerance. It is challenging to increase availability even with additional resources, so operators should set achievable target availability considering this result.

Advancing the check schedule wastes the residual life of the parts and results in the need to perform checks more frequently in the future. Muchiri and Smit [37] used the concept of additional labor costs associated with inspections being conducted more frequently than necessary. In this paper, we calculated these additional costs using the unused interval and maintenance interval for each task as follows.

$$\text{Wasted interval} = \frac{\text{Maintenance interval - used interval after last check}}{\text{Maintenance interval}} \times 100(\%) \tag{69}$$

To focus on the tendency of wasted intervals, we did not precisely reflect the man-hours for each task and the unit price of the replaced parts. The third column of Table 2 shows that the larger the capacity, the more effectively the tolerance could be utilized, and the wasted interval increases. In addition, the increase of the tolerance had a great effect on the increase of the wasted interval. The field operator could schedule flight and maintenance plans under cost management by reflecting replacement cost and man-hours information for each task in the model. The increase of the tolerance must be decided carefully, as it results in drastic increases in the wasted interval (additional cost) and significantly impacts future flight and maintenance plans. The fourth column shows that the tightness of the workforce capacity and the size of the tolerance make a difference in computation times. The tighter the capacity and the larger the tolerance, the longer the computation times to find the optimal solution. In particular, the tightness of the capacity greatly affects the computation times. The fifth column shows the average availability of each instance without merging. In addition, the last column presents the gain of merging in terms of availability. It is easily shown that merging tasks promises gains in fleet availability. Moreover, it is conspicuous that as the workforce capacity decreases and the tolerance level increases, the gain of merging increases.

In addition, we analyzed the experimental results in terms of workforce assignment and utilization. In optimal solutions, there were periods in which all workforce capacity was used up, but not all workforce capacity was used in most periods. Table 3 shows the number of periods

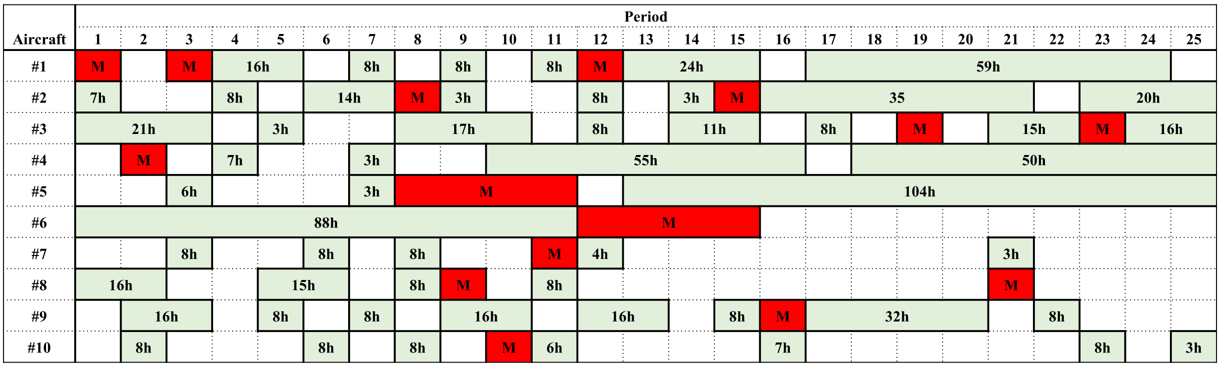

Fig. 5. Example of an optimal flight and maintenance plan in Gantt-chart form.

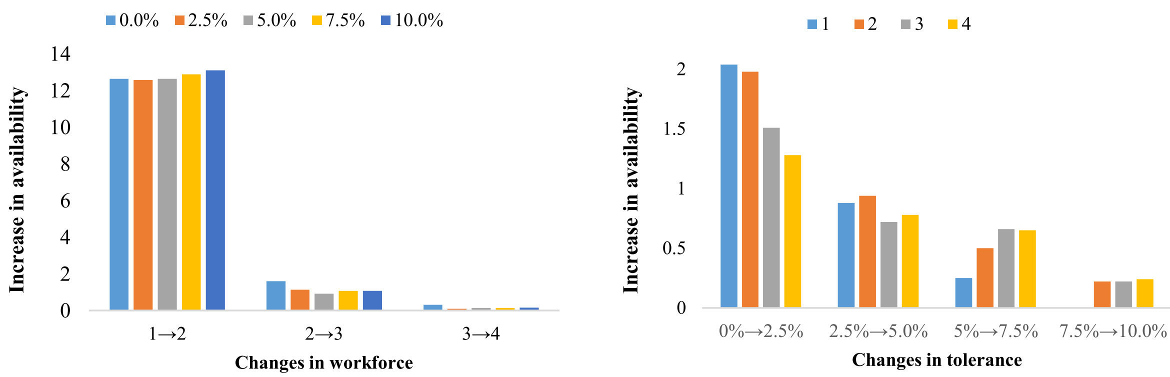

Fig. 6. Comparison of increase in availability based on changes in workforce and tolerance.

Table 2
Experimental results with varying workforce capacity and tolerance.

Instance[a]	Average availability (%)	Average wasted interval (%)	Average computation times (s)	Average availability without merging (%)	Gain of merging (%)
1; 0.0	73.07	0.00	7.35	69.34	5.38
1; 2.5	75.11	1.15	46.65	71.05	5.71
1; 5.0	75.99	2.87	133.75	71.66	6.04
1; 7.5	76.24	3.84	418.56	71.74	6.27
1; 10.0	76.24	4.68	904.39	71.67	6.38
2; 0.0	85.71	0.00	0.81	82.11	4.38
2; 2.5	87.69	1.46	21.77	83.74	4.72
2; 5.0	88.63	3.95	44.79	84.38	5.04
2; 7.5	89.13	6.39	125.05	84.76	5.16
2; 10.0	89.35	7.35	245.79	84.88	5.27
3; 0.0	87.32	0.00	0.62	84.44	3.41
3; 2.5	88.83	1.65	3.10	85.72	3.63
3; 5.0	89.55	4.30	7.82	86.24	3.84
3; 7.5	90.21	6.99	13.31	86.69	4.06
3; 10.0	90.43	7.95	26.21	86.81	4.17
4; 0.0	87.64	0.00	0.65	85.54	2.45
4; 2.5	88.92	1.66	2.61	86.61	2.67
4; 5.0	89.70	4.51	6.20	87.19	2.88
4; 7.5	90.35	7.14	9.50	87.64	3.09
4; 10.0	90.59	8.71	35.62	87.87	3.10

[a]Workforce capacity; Tolerance (%).

by the number of workforces assigned to tasks as a proportion of the entire planning horizon. The values in the table are the average values of the results of 30 random test problems generated for each instance type. For example, 10.40 percent in the last column of the last row means that the average number of periods using four workforces is 10.40 percent of the total 25 periods. As workforce capacity increases, the number of periods with no or little workforce assigned increases, reducing workforce utilization. For capacity 2, about 18 percent of the total period is a period with no workforce assigned. However, it increases to 24–31 percent for capacity 3 and 26–34 percent for capacity 4. This result is because a large workforce capacity is better suited to periods with peak demands of aircraft maintenance. Unlike the total workforce capacity of each period, the aircraft maintenance demands fluctuate and can be concentrated in a specific period, exceeding the capacity. In this case, an aircraft cannot be assigned to a workforce, and thus, the grounded time increases. In addition, the workforce must perform maintenance on this standbying aircraft after completing the previously working one. Therefore, the workforce will be continuously assigned without an idle period. However, as the peak demand periods are better handled with a larger workforce capacity,

Table 3
Proportion of planning horizon by the number of workforces assigned to tasks.

Instance[a]	Number of workforces assigned to tasks				
	0	1	2	3	4
1; 0.0	4.80%	95.20%	–	–	–
1; 2.5	2.40%	97.60%	–	–	–
1; 5.0	1.20%	98.80%	–	–	–
1; 7.5	0.80%	99.20%	–	–	–
1; 10.0	0.53%	99.47%	–	–	–
2; 0.0	18.40%	33.07%	48.53%	–	–
2; 2.5	17.87%	30.67%	51.47%	–	–
2; 5.0	18.67%	28.00%	53.33%	–	–
2; 7.5	17.20%	28.13%	54.67%	–	–
2; 10.0	18.80%	26.93%	54.27%	–	–
3; 0.0	24.80%	35.47%	22.93%	16.80%	–
3; 2.5	26.53%	32.53%	21.60%	19.33%	–
3; 5.0	27.07%	30.53%	22.00%	20.40%	–
3; 7.5	31.07%	25.20%	20.00%	23.73%	–
3; 10.0	31.60%	24.80%	20.67%	22.93%	–
4; 0.0	26.00%	35.87%	23.20%	10.27%	4.67%
4; 2.5	27.73%	34.93%	19.07%	11.73%	6.53%
4; 5.0	29.20%	31.73%	20.93%	11.07%	7.07%
4; 7.5	33.87%	28.40%	16.13%	11.73%	9.87%
4; 10.0	34.80%	26.53%	16.93%	11.33%	10.40%

[a]Workforce capacity; Tolerance (%).

several aircraft can be serviced simultaneously. Consequently, the number of periods with no workforce assigned, after these peak demand periods, increases. Such analysis can be usefully applied in workforce management. Many workforces are often deployed to achieve target availability when tolerance cannot be increased in the real world. In this case, the operator should develop a plan to efficiently utilize the idle workforce, such as assigning them tasks other than PM or technical training on non-working days.

At the same capacity, the larger the tolerance, the more effective the use of workforce capacity. As the tolerance increases, the period of maximum workforce assignment increases. A higher tolerance allows more flexibility in the start date of each task. This flexibility reduces bottlenecks by expanding the opportunities for merging tasks. Therefore, by working together on the upcoming maintenance tasks in advance, an aircraft being grounded again in the near future can be prevented. Moreover, independent tasks that cannot be staffed due to the shortage of workforce capacity are appropriately advanced to a period when a workforce is available. Thereby, the given capacity is utilized effectively.

Multiple scenarios with other parameters (except for the workforce capacity), such as flight demand or the condition of each aircraft, maintaining the same values, can be generated. Moreover, several combinations having the same value of the sum of the workforce capacities for the entire planning horizon, but with a different arrangement of the workforce capacities for each period, can exist. Table 4 shows a simple example of such a case assuming 5.0 percent tolerance. It is easily shown that a flexible workforce can also guarantee the optimal objective function value. However, although Scenario 2 and Scenario 3 both have the same value of the sum of the workforce capacities as 28, the objective function value of Scenario 3 was only 93 percent of that of Scenario 2. This example shows the efficiency of a flexible workforce that can be optimized for each situation. In addition, it indicates that a proper arrangement of a flexible workforce is crucial.

5.2. Experiment 2

We conducted Experiment 2 to evaluate the performance of the proposed heuristic algorithms on large problems. Eight scenarios were made for the number of aircraft in four levels (20, 40, 60, 80) and the workforce capacity tightness in 2 levels (tight, loose), and the tolerance for advancing checks was set at the middle level (5.0 percent). The tight case of workforce capacity was set to the nearest integer rounded up from $0.15|N|$, and the loose case was set to the nearest integer rounded up from $0.20|N|$.

Table 5 shows the experimental results of straightforward MILP solving with CPLEX and heuristics for each instance with a three-month planning horizon. The time limit was set to 1800 s. The values in the table are the average values of the results of 30 random test problems generated for each instance type. Solution quality shows the optimality gap of straightforward MILP solving with CPLEX and heuristic solutions, along with the number of instances that could not find a feasible solution within a time limit. The optimality gap between the best bound obtained by straightforward MILP solving with CPLEX and the best solution obtained by each solution methodology, which is calculated as follows.

$$\text{Optimality gap} = \frac{\text{Best bound - best solution}}{\text{Best bound}} \times 100(\%) \tag{70}$$

In general, straightforward MILP solving with CPLEX found better solutions than heuristic algorithm. The FSH has lower solution quality than straightforward MILP solving with CPLEX because it is challenging to share resources perfectly between subproblems. There are two main reasons why the SDH has a relatively low solution quality. First, it is not easy to cooperate perfectly with flight plans and maintenance plans, because of the sequential decision-making structure. Straightforward MILP solving with CPLEX can find better solutions that simultaneously establish flight and maintenance plans. In addition, it is possible to make a cooperative plan, such as by increasing or decreasing the flight time of an aircraft in consideration of the schedule for various maintenance tasks. On the other hand, the SDH causes a loss of availability because each step is performed sequentially. This loss represents the limitations of sequential decision-making in the real-world field. Second, the MAFMP model tends to inhibit grounding aircraft that will not complete their service by period $T+1$ [24]. This may adversely affect aircraft availability in the next planning horizon but effectively maximizes availability up to period $T+1$. On the other hand, the SDH, which makes flight plans using the aircraft flowchart technique, has long-term sustainability, but it is difficult to find an optimal solution that maximizes the fleet availability within the planning horizon.

The average optimality gap of the two heuristics was in the range of 0.80 to 6.14 percent. In the tight case of workforce capacity, the optimality gap of the FSH was 2–3 percent, and that of the SDH was 4–6 percent. In the loose case, the optimality gap of the FSH was within 1 percent, and that of the SDH was around 2 percent. Table 5 also shows the number of instances that could not find a feasible solution within a time limit. In the problem of 80 aircraft, there were instances where the FSH could not find a feasible solution, whereas the SDH found a feasible solution in all instances. Note that the average optimality gap of the FSH is calculated by excluding the instances in which the FSH could not find a feasible solution within the time limit and utilizing only the remaining 27 instances. In addition, the computation time of the SDH is not significantly affected by the tightness of workforce capacity and the number of aircraft. The superiority of the SDH is that it always finds good solutions in a few seconds, which becomes even more evident when the planning horizon is extended to six months ($T = 50$).

In the $T = 50$ problem, even with ten aircraft, the optimal solution could not be found with a commercial solver within 3600 s in most instances. As a result, the FSH is not practical for the $T = 50$ problem, so we only conducted experiments on straightforward MILP solving with CPLEX and the SDH. Table 6 shows the experimental results of straightforward MILP solving with CPLEX and the SDH for each instance with a six-month planning horizon. The time limit was set to 3600 s. Straightforward MILP solving with CPLEX could not find feasible solutions for many instances within a time limit. In contrast, the SDH always found a good solution in a few seconds. Again, the average optimality gap of straightforward MILP solving with CPLEX is calculated only with the instances that were able to find a feasible

Table 4
A simple example of time-varying workforce capacities.

Scenario	Workforce capacity for each period																									Objective
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	function value
1	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	229
2	1	2	1	0	0	0	0	1	4	4	4	2	1	1	2	2	0	0	1	0	1	0	1	0	0	229
3	2	1	1	0	1	1	2	1	1	1	2	2	1	2	2	2	0	1	1	1	1	0	1	0	1	213

Table 5
Performance of the heuristic algorithms on large problems ($T = 25$).

Instance[a]	Solution quality[b]			Average computation times (s)		
	CPLEX[c]	FSH	SDH	CPLEX[c]	FSH	SDH
20; tight	0.77; 0; 18	2.47; 0; 1	6.14; 0; 0	963.78	293.73	0.39
20; loose	0.03; 0; 29	0.80; 0; 3	2.51; 0; 0	297.94	162.62	0.44
40; tight	1.03; 0; 2	3.85; 0; 0	5.91; 0; 0	1719.98	588.02	0.56
40; loose	0.12; 0; 15	0.86; 0; 2	2.01; 0; 0	1284.69	132.11	2.70
60; tight	0.75; 0; 1	3.35; 0; 0	4.82; 0; 0	1756.59	514.37	1.33
60; loose	0.16; 0; 9	0.89; 0; 0	2.01; 0; 0	1530.90	142.67	1.13
80; tight	0.70; 0; 0	3.14; 3; 0	4.22; 0; 0	>1800	621.34	1.41
80; loose	0.17; 0; 3	0.85; 0; 0	2.04; 0; 0	1721.65	149.17	8.00

[a]Number of aircraft; tightness of the workforce capacity.
[b]Average optimality gap (%); number of instances that could not find a feasible solution; number of instances that the solution method found the optimal solution.
[c]Straightforward MILP solving with CPLEX.

Table 6
Performance of the SDH on large problems ($T = 50$).

Instance[a]	Solution quality[b]		Average computation times (s)	
	CPLEX[c]	SDH	CPLEX[c]	SDH
20; tight	3.73; 9; 20	9.12; 0; 10	>3600	0.84
20; loose	1.37; 0; 30	3.59; 0; 0	>3600	0.95
40; tight	8.32; 22; 4	7.75; 0; 26	>3600	4.02
40; loose	2.37; 10; 18	3.29; 0; 12	>3600	1.22
60; tight	–; 30; 0	7.14; 0; 30	>3600	1.82
60; loose	6.88; 29; 0	3.84; 0; 30	>3600	1.84
80; tight	–; 30; 0	7.23; 0; 30	>3600	3.36
80; loose	–; 30; 0	4.02; 0; 30	>3600	7.85

[a]Number of aircraft; tightness of the workforce capacity.
[b]Average optimality gap (%); number of instances that could not find a feasible solution; number of instances that the solution method found the best solution.
[c]Straightforward MILP solving with CPLEX.

solution within the time limit. Table 6 also shows the number of instances that each solution method found the best solution. Although the solutions from straightforward MILP solving with CPLEX were better than the heuristic solutions in the $T = 25$ problem, the solutions from the SDH outperformed the solutions of straightforward MILP solving with CPLEX for most instances of the $T = 50$ problem.

In practice, military operators who need to solve MAFMP problems may choose a more appropriate method, depending on the size of the problem, the quality of the desired solution, and the allowed time. Operators can use straightforward MILP solving with CPLEX or the FSH to find a better solution to the $T = 25$ problem. However, when a solution to a large problem (particularly, $T = 50$ problem) needs to be obtained quickly, the SDH can be considered the best method. Suppose the operator wants to find a better solution than the SDH while always looking for a feasible solution. In that case, a mixed approach can be used by applying the SDH in advance and then implementing a warm start for straightforward MILP solving with CPLEX. However, an appropriate choice is required because such a mixed approach does not always guarantee a better solution than straightforward MILP solving with CPLEX. In addition, military operators can choose the appropriate method for each planning stage. In the final stage, it may be adequate to find a better solution using straightforward MILP solving with CPLEX, although it may take a little longer. On the other hand, in the intermediate stage, there is a process of adjusting parameter values such as flight demand and available capacity by analyzing various scenarios. In this process, heuristics that can quickly find and compare solutions can be implemented usefully.

5.3. Managerial insights

We derived the following managerial insights for military operators from the above experiments:

- Increased capacity and tolerance help enhance the fleet availability but incur additional costs. Moreover, the increase in availability Is not proportional to the increase in workforce and tolerance. The amount of increase in availability has been decreased. Therefore, analyzing flight and maintenance requirements to determine the achievable target availability and establishing the appropriate workforce capacity and tolerance are critical to increasing fleet availability and reducing costs.
- Larger tolerance can create a higher fleet availability with the same workforce capacity. Because of military security, hiring external technicians for aircraft maintenance is limited, and it takes much time to train new skilled technicians. Therefore, it is difficult to increase the workforce capacity in a short time. In this case, increasing the tolerance can be an effective alternative to meeting the target availability.
- Flexible workforce capacity is more effective than increased workforce capacity. Table 3 shows that the period required for total capacity is relatively short. In other words, just adding a team for a short period can have the same effect as increasing the capacity. Therefore, it is necessary to flexibly increase or decrease the capacity for each period by using the personnel responsible for tasks other than PM.
- The larger the tolerance, the more effective the use of workforce capacity. In addition, within sufficient capacity, idle workers and no-work periods inevitably occur. We recommend using these characteristics for vacation planning, shift work, and technical training for idle workers.

6. Conclusions

In this paper, we proposed a MILP model for the MAFMP problem. Practical factors, such as heterogeneous maintenance tasks, advancing

Table A.1
Truth table of UBMT related variables.

$a^t_{n,p}$	$a^{t+1}_{n,p}$	$f^{t+1}_{n,p}$	$\lambda^t_{n,p}$	$d^{t+1}_{n,p}$	X^t_n	$y^t_{n,p}$	$y^{t+1}_{n,p}$	$g^t_{n,p}$	$g^{t+1}_{n,p}$	$h^t_{n,p}$
0	**0**	0	0	0	0	0	0	≥1	≥1	≥0
0	**1**	0	0	1	0	0	Y_p	≥1	0	$g^t_{n,p}$
1	**0**	1	$y^t_{n,p} - X^t_n$	0	≥0	$\geq X_{min}$	0	0	G_p	0
1	**1**	0	0	0	≥0	$\geq X_{min}$	$y^t_{n,p} - X^t_n$	0	0	0

Table A.2
Truth table of CBMT related variables.

$a^t_{n,q}$	$a^{t+1}_{n,q}$	$f^{t+1}_{n,q}$	$\lambda^t_{n,q}$	$d^{t+1}_{n,q}$	$y^t_{n,q}$	$y^{t+1}_{n,q}$	$g^t_{n,q}$	$g^{t+1}_{n,q}$	$h^t_{n,q}$
0	**0**	0	0	0	0	0	≥1	≥1	≥0
0	**1**	0	0	1	0	Y_q	≥1	0	$g^t_{n,q}$
1	**0**	1	$y^t_{n,q} - 1$	0	≥1	0	0	G_{pq} or G_q	0
1	**1**	0	0	0	≥1	$y^t_{n,q} - 1$	0	0	0

Table A.3
Truth table of variables related to advancing the schedule.

$\sum_{p \in P} a^{t+1}_{n,p}$	$c^t_{n,q}$	$\alpha^t_{n,q}$	$\beta^t_{n,q}$
$<\vert P\vert$	1	≥0	0
$\vert P\vert$	0	0	≥0

the check schedule, and merging between tasks, which were lacking in previous studies, were included in the model. We demonstrated the applicability of the model by experimenting with realistic problem cases. Because our model is based on practical factors in the ROKAF, it can be instantly applied to real instances. In addition, the characteristics of the model are similar to those of operation and maintenance planning problems for various equipment, not only in the military but also in other applications. Thus, the model can be easily implemented in other problems through some modifications. Moreover, the model also has the advantage of ensuring the optimality and validity of the revised plan when rescheduling is required. If the users want to base the existing plan, some variables can be fixed with the previous optimal solution, and partial adjustments can be made by calculating the unfixed variables. This is an option that can be obtained by applying this model practically.

We derived managerial insights on maintenance policies and workforce management from experiments with varying workforce capacity and tolerance. These insights would be beneficial to military operators. It is very time-consuming to obtain optimal flight and maintenance plans while taking into account various factors. Our model can significantly reduce the workload required to create plans. In addition, the model can be used to assess or analyze various maintenance policies, as described in Experiment 1.

We also developed two heuristic algorithms to help military operators make decisions quickly on large problems. Experiment 2 showed that heuristics can solve large problems in a short time. It can be used to adjust plans frequently if weather conditions require flight plans to be changed or if unexpected failures are discovered while conducting inspections. Our heuristic algorithms can be easily applied to various problems and used to develop efficient algorithms.

This study can be extended in several promising directions. Based on deterministic models, stochastic models can be developed that accommodate uncertainties, such as unpredictable aircraft failures and flight cancellations due to weather conditions. In addition, a more precise and realistic maintenance plan can be established by reflecting on the differences in the types and levels of technicians' skills, which is not considered in this paper. We also propose to develop the MAFMP model into a multi-objective model that maximizes fleet availability while reducing maintenance costs in the future. Unifying the units of fleet availability and maintenance costs, which may include the costs caused by the wasted intervals and the workforce-related costs, can be one way to comprise a single-objective function and, thus, handle the multi-objective model. For example, the cost of the wasted intervals can be quantitatively calculated according to the type of maintenance task, including the costs of parts for the task or the opportunity costs added by the wasted intervals. On the other hand, workforce-related costs can be measured by considering the cost of workforce management, such as the labor costs of technician teams. Meanwhile, the change in fleet availability can be quantified as a cost considering the economic utility of aircraft availability. Finally, previous studies have developed various heuristic methods for the MAFMP problem, but most of them were constructive heuristic algorithms to find feasible solutions, and studies using meta-heuristic methods were insufficient. Meta-heuristic algorithms should be considered to find better solutions than constructive heuristic algorithms.

CRediT authorship contribution statement

Guesik Cha: Writing – original draft, Methodology, Investigation, Conceptualization. **Junseok Park:** Writing – review & editing, Validation, Methodology, Investigation. **Ilkyeong Moon:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix

See Tables A.1–A.3.

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