TRANSPORT PROBLEMS 2025 Volume 20 Issue 3
PROBLEMY TRANSPORTU DOI: 10.20858/tp.2025.20.3.05

Keywords: smart MRO; planning and scheduling optimization; dynamic maintenance; constraint-based maintenance

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RESHAPING AIRCRAFT MAINTENANCE: A SMARTER SCHEDULING AND PLANNING APPROACH FOR MODERN AVIATION

Summary. The unique and demanding world of aviation always demands better, smarter, and more dynamic solutions for aircraft maintenance. The key driver of the search for new state-of-the-art developments is the need to minimize aircraft downtime. While traditional methods have proven their usefulness with small maintenance hubs, they can struggle to achieve efficient performance in larger operational maintenance environments. Often, real-world scenarios demand multiple dynamic constraints, such as fluctuating delivery dates, resource limitations, material shortages, and work package changes. Ultimately, these changes will require a fast response to accommodate, but at the same time, try to achieve the most efficient way for aircraft redelivery. This paper presents a novel and adaptive module for scheduling and planning designed to reshape how maintenance planning is conducted within the aviation industry. By utilizing constraint programming and modeling, the proposed method aids in making decisions about maintenance planning and scheduling to reduce aircraft downtime by maximizing the utilization of skilled workers, which, in turn, will reflect positively on operational efficiency. This work advances transport planning by providing a scalable, data-driven framework customized to the changing requirements of modern aviation maintenance.

1. INTRODUCTION

In the aviation culture, in which the environment is described as heavily regulated and safety is strongly expected, maintenance, repair, and overhaul (MRO) services are considered indispensable. They ensure that the aircraft remains airworthy, operational, and reliable.

Airports Council International released its bi-annual report, which forecasts that global passenger traffic is expected to reach 9.9 billion, with a 4.8% year-on-year (YoY) growth rate [1], indicating that the aviation market will keep expanding. As the growth continues to affect the aviation industry, airlines' operations will naturally demand all related service providers, such as ground handlers and maintenance providers, to meet the high expectations of the stakeholders and exhibit complete readiness while adhering to the stringent regulatory standards. This means that for any related enterprise to stay relevant in this competitive industry, it must display efficiency, work accuracy, and, in the case of maintenance, high levels of quality and safety, because an aircraft is a high-cost asset that is central to the airline industry. Any delay to the planned downtime can result in significant financial losses, reputational damage, and logistical difficulties [2]. MRO processes and the quality of maintenance services directly affect the reliability, safety, and availability of an aircraft, which harms the operator's reputation and the passengers' trust in the company.

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Conventional MRO approaches are mainly based on inflexible schedules and reactive planning actions [3], which frequently result in operational inefficiencies due to inaccurately planned checks, prolonged aircraft downtime during inspections, and an inability to accommodate unforeseen failures between scheduled service intervals due to a lack of capacity or resources. However, the increasing complexity of contemporary aircraft systems requires a plethora of sophisticated decision-making tools and technologies to improve maintenance workflow and boost maintenance operational robustness.

Despite the immense advancement in the MRO sector over the past decade, there is still a gap in operational planning and scheduling, as well as the tools utilized. The methods employed are largely semi-manual and rely on people's perspectives instead of taking advantage of cutting-edge advances and data-driven approaches [4, 5]. In the race to achieve maintenance operational excellence, MRO companies frequently fail to adequately optimize resources, correct workforce allocation, adapt to unforeseen maintenance occurrences, and adjust to dynamic operating changes. Furthermore, one essential and sometimes overlooked component of these systems is the labor itself, notably the skills and specialties of maintenance professionals. Aligning the appropriate professional with the right work at the right time is an ongoing difficulty in the business. Even when a small group of planners can manage this task appropriately in a small MRO environment, they may struggle to maintain control in larger-scale operations and during the heavy aircraft utilization season such as summer or spring season [6].

Preparing a long-term or short-term plan for maintenance checks in a medium-sized company is challenging, as it requires the maintenance work check package to be performed and the optimization of many dynamic and interdependent variables to be coordinated. Aircraft availability, maintenance deadlines, hangar capacity, material/tools availability, and skilled labour assignment are all inputs and variables in the optimization process. The goal or objective for any MRO is to minimize ground time while maximizing profit by taking on more work and accepting more parallel aircraft maintenance lines using the same resources. Attaining this equilibrium necessitates a shift from reactive, manual planning to smart, automated, and constraint-aware optimization methodologies.

This paper offers a new direction for smart aircraft maintenance planning and scheduling processes in the context of constraint programming, tailored to the needs of modern and medium-sized MRO operations. Constraint programming is especially well-suited for this purpose because it can handle complicated and interdependent rules and conditions in a flexible modeling framework. By incorporating both operational limitations and employee competencies, the system can effectively navigate the solution space to identify optimum or near-optimal schedules. Furthermore, the optimization tool minimizes the downtime of the machine by maximizing workers' skills, meaning the most efficient skilled worker is picked to perform each task, thus reducing the task time. By intelligently matching tasks with the most skilled technicians based on availability, the proposed module can reduce labor waste, improve job satisfaction, aid in labor training, and enhance overall productivity.

Enhancing aircraft maintenance by implementing smart scheduling offers both a technological answer to and a strategic perspective for the future of modern MRO operations. As the sector continues to evolve, such innovations will be essential for sustaining safety, efficiency, and competitiveness in a progressively intricate and rapid global market.

2. CURRENT APPROACHES TO MAINTENANCE SCHEDULING AND PLANNING IN THE MRO SECTOR

Heuristic algorithms are among the most commonly used approaches for scheduling problems in general [7]. It is a problem-solving strategy that employs a practical, experience-based approach to obtaining a good answer fast when precise methods are too complex or slow. They do not guarantee the optimal solution, but they can solve the problem at hand feasibly. The literature contains much research that utilizes these algorithms [8-10]. While very popular, this approach may be subject to bias, requires continuous tuning, and, most importantly, is too rigid, meaning adding a new constraint will require redesigning the entire algorithm [11].

In the same context, many researchers have utilized genetic algorithms (GAs), which are a popular type of heuristic algorithms and hybrid methods, to do maintenance scheduling [12, 13]. Similarly, the approach will not be efficient in the case of MRO, even though it can solve problems more quickly. Still, compared to constraint programming (CP), it is weak at handling constraints. Table 1 shows a comparison between the GA and CP methods when used to solve a scheduling problem.

Table 1

Genetic algorithms vs. constraint programming

Feature	Genetic Algorithms (GA)	Constraint Programming (CP)
Approach	Solutions undergo cycles of selection, crossover, and mutation [14]	Fulfils the constraints as the solver finds a valid schedule
Constraint Handling	Weak; constraints need to be handled indirectly using penalties [15]	Strong; constraints are directly modeled and strictly enforced
Solution Quality	Approximate, not always feasible [16]	Feasible and often optimal or near-optimal
Adaptability to New Rules	Requires redesign or retraining [11]	Easy to add new constraints or modify existing ones
Use Case Fit	Good for soft-constrained or highly flexible problems [16]	Best for safety-critical, rule-intensive environments like MRO
Cost	Computationally costly [17]	Suitable computational cost
Scalability	Solution quality degrades rapidly in large, complex scenarios [18]	Solution quality is moderate in large-scale scenarios, can grow slowly, good in multi-constraint problems

In addition to the above, many researchers have investigated different areas and fields for scheduling, such as the tabu search algorithm [19], multi-agent systems (MAS) [20], and ant colony optimization (ACO) [21], among many other methodologies. However, the CP modules exhibit the best performance and have the lowest cost for scheduling and planning, especially in dynamic and hard rule-based environments. Based on the above, in the case of the MRO scheduling and planning problem, CP is the most effective, flexible, and optimal choice [22] and, hence, will be used in the present work.

3. MRO REQUIREMENTS AND PROBLEM DEFINITION

MRO work operations depend heavily on a complex set of operational and technical requirements. The technical aspect involves accurately and compliantly performing maintenance check tasks as per the rules and regulations established by the authorities and manufacturers [23]. The operational approach involves completing the technical part while achieving operational excellence, an optimal schedule that leverages available resources, and a proactive approach to asset management. The aim is to find a solution that integrates the relationship between maintenance activities and project management principles, highlighting the need for structured planning, resource optimization, and continuous improvement.

When an aircraft operator seeks the service of an MRO provider, the rules and the contract define several key points, such as the set of tasks that the MRO agreed to perform, known as the work package (WP). The package contains different tasks and sub-tasks, which the MRO reviews before the aircraft arrives at the hangar and gives a confirmation of the ability to provide a hangar spot, skilled workforce, tools, and materials. The most important factor for both the MRO company and the airline is the check time, otherwise called the turnaround time (TAT) [24].

Often, the MRO firm in a medium-sized scenario will have to do different checks (A-, B-, C-, out of phase, and D-checks) on different aircraft types and different operators [25]. From the airline's point of view, also known as the customer, it is crucial to return the aircraft as soon as possible with a high-quality maintenance job. Customer satisfaction and the guarantee of future cooperation depend on keeping the original agreement. Any package can be easily divided into phases or modules, as shown in Fig. 1.

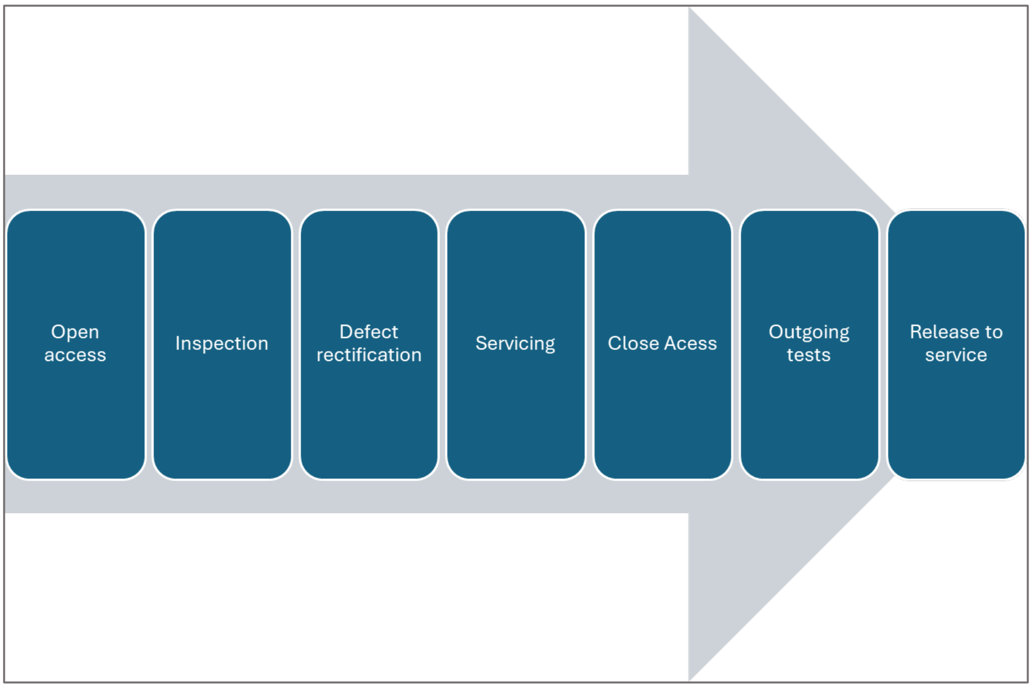


Fig. 1. Maintenance work package phases

Although the tasks are determined before the aircraft arrives at the facility, several circumstances might interconnect and directly influence the efficiency of project execution. For instance, after the inspection, findings, and defect rectification actions are added to the total tasks of the check, material may be required for some of the findings, which can result in additional delays in a single work, subtask, or an entire project line. Hence, the negative effect of a line delay will accumulate and disrupt other lines/checks. Therefore, the timetable will need to be adapted to accommodate changes, particularly if certain maintenance actions are necessary for subsequent operations. Additionally, selecting the appropriate sequence and interdependencies of jobs is a crucial element in the maintenance process. Moreover, disagreements over resources, whether they are tools, materials, or specialists, might compel the MRO to diverge from the established maintenance schedule [26].

The coordination and integration of the above-mentioned requirements is the problem this research addresses. CP the Schedule Optimization Tool for Aircraft Maintenance (SOTAM) will be able to understand the work package, the establishment of correct and logical precedence relationships between the tasks, reach the inspection complete phase as fast as possible to initiate the defect rectification phase, and plan any new actions related to corresponding findings and fault rectification to reach the release to service (RTS) phase. The uncertainties that can emerge during the project's execution include technicians' capacity issues, such as illnesses or overlapping tasks and projects due to delays or other unforeseen circumstances, as well as unforeseen findings that require time to contact manufacturers, suppliers, and/or order materials.

4. METHODOLOGY

This section highlights the methodology used to develop SOTAM and create the proposed scheduling and planning module. It presents the data used as inputs, the constraints and their definitions, the developed model, variable definitions, and the mathematical representation.

4.1. Data Inputs

The data deemed necessary for inclusion in this investigation as inputs were collected by mapping out the workflow of an actual MRO company in Central Europe. The dataset comprises dummy data that, at its core, mimics the real historical records used by the aforementioned MRO firm. The reason for this is the confidentiality agreements between the university and the company. Each record is crucial in modeling a virtual environment that reflects real-life operations.

The first dataset input will be a list of the current aircraft occupying slots in the hangars. These aircraft will be considered fixed slots and not changeable. They can be either pre-agreed on and have reserved their slots, or are amid an ongoing maintenance check, as shown in Table 2. These slots will be uploaded as an Excel file to SOTAM by the planner.

Table 2

Current aircraft positioning in the hangars and their slots

ID	MSN	Registration	Manufacture	Type	Customer	Starting Date	TAT	Slot
1	XXX0	A-AAA	Airbus	A320	Cust_1	01/04/2025 07:00:00	65	5
2	XXX1	A-AAB	Airbus	A319	Cust_1	05/04/2025 07:00:00	17	3
3	XXX2	A-AAC	Boeing	B767-200	Cust_1	19/04/2025 07:00:00	17	4
4	XXX3	A-AAD	Airbus	A380	Cust_2	07/05/2025 07:00:00	17	2
5	XXX4	A-AAE	Boeing	B737-400	Cust_2	01/04/2025 07:00:00	60	1
6	XXX5	A-AAF	Boeing	B767-300	Cust_3	15/04/2025 07:00:00	45	6
7	XXX6	A-AAG	Airbus	A321	Cust_3	25/04/2025 07:00:00	40	8
8	XXX7	A-AAH	Airbus	A320	Cust_4	01/04/2025 07:00:00	15	7

The user must then upload the list of newcomers' aircraft (i.e., the aircraft that the company wants to schedule) to the already agreed schedule, as demonstrated in Table 3. The table also shows the registration number, the aircraft manufacturer, the type of aircraft, the customer, the expected starting date, and the TAT, among other data that the program considers in determining the possibility of placing the new incomers based on size in the first round and the theoretical insert possible slot.

The hangar's layout is provided to the program as a combination of allowed and mixable aircraft types, categorized by size. This layout is input as conditions, as shown in Table 4, and includes all possible combinations of aircraft types. The empty representation means that the slot will be left empty because there are no further possibilities to allocate any more aircraft due to the size limitations. For example, Hangar 2 can only fit B767-200 + B737-300 at the same time, and the third slot remains empty. These data are flexible and can be customized to any MRO depending on its layout and the number of hangars.

For the employee calendar, the program can generate a random dataset for each employee every 10-minute interval, where 0 indicates the employee is busy and 1 indicates the employee is free. For the real-time application, the human resources (HR) department, in cooperation with production management, will need to input this data according to the actual situation. Similarly, the list of tools is created as a calendar with the same 0 or 1 logic.

Table 3

New aircraft specifications

ID	MSN	Registration	Manufacture	Type	Customer	Starting Date	TAT	Slot
1	XXX8	A-AAI	Airbus	A320	Cust_1	10/04/2025 07:00:00	25	Unknown
2	XXX9	A-AAJ	Airbus	A319	Cust_2	05/04/2025 07:00:00	30	Unknown
3	XX10	A-AAK	Airbus	A321	Cust_4	19/04/2025 07:00:00	35	Unknown

Table 4

Hangar layout and aircraft possible combination based on type and size

Hangar	Cases
1	B737-400+B737-400+B737-300
1	B737-400+B737-400+B737-700
1	B737-500+B737-500+B737-500
2	B767-200+B737-300+EMPTY
2	B767-200+B737-400+EMPTY
2	B767-200+B737-500+EMPTY
3	3A321+2A320
3	3A321+A320
3	B752+B752+B752+EMPTY+EMPTY

As for the people skill matrix, in which the SOTAM builds the optimization, management is required to evaluate all employees for each one of the tasks that the company has previous experience with as demonstrated in Table 5, the evaluation is represented by a key performance index (KPI) number from 0–9, where 0 means the employee is not experienced in a specific task and 9 means the employee is very experienced. In time, this table serves as the basis of the optimization. This table needs to be reevaluated and updated after each training or in case of any changes, preferably on a yearly or semi-yearly basis.

Table 5

Example of employee KPI based on the skill, task, and previous experience

EMPLOYEE_ID	SKILL	TYPE	HIRE_DATE	WORK_SHIFT	LEVEL	TASK	KPI
EMP_i	MECH	Airbus	21-Jun-07	A	B1	T1	1
EMP_{i+1}	INT	Boeing	17-Sep-03	A	B1	T1	0
EMP_{i+2}	PAI	Airbus Boeing	17-Aug-05	A	B1	T2	9
EMP_{i+3}	AVI	Boeing	07-Jun-02	A	B2	T3	8
EMP_{i+4}	MECH	Airbus	07-Jun-02	A	B1	T1	9
EMP_{i+5}	SHM	Airbus	21-Sep-05	A	-	T2	0
EMP_{i+6}	MECH	Airbus	03-Jan-06	B	-	T3	0
EMP_{i+7}	AVI	Boeing	25-Jun-05	B	-	T4	0
EMP_{i+8}	MECH	Airbus	07-Feb-07	B	B1	T3	9
EMP_{i+9}	SHM	Airbus	16-Aug-02	B	B1	T4	7

4.2. Mathematical Model for SOTAM

In preparation for the optimization, which is the last and main step in SOTAM, the following parameter set needs to be identified:

- T: the set of maintenance tasks, indexed by t,
- W: the set of workers, indexed by w, and $|W|$ is the total number of workers,
- $d_t \in N$: the duration in minutes of a task t,
- $s_{tw} \in \{0,9\}$: the KPI and skill level of a worker for worker w to perform task t,
- $D \in N$: the deadline for the schedule (TAT).

4.2.1. Variables

Also, the following are SOTAM's defined decision variables:

- $x_{tw} \in \{0,1\}$: equals 1 if task t is assigned to worker w, 0 otherwise,
- $s_t \in R_{+}$: the start time of task t,
- $e_t \in R_{+}$: the end time of task t, where $e_t = s_t + d_t$,
- $l_w \in R_{+}$: the total workload assigned to worker w.

4.2.2. Constraints

The following constraints are used in the code:

1. Each task must be assigned to only one worker:

$$\sum_{w \in W} x_{tw} = 1, \quad \forall t \in T \tag{1}$$

2. Only qualified workers can be assigned:

$$x_{tw} = 0 \ if \ s_{tw} = 0 \tag{2}$$

3. There are no overlapping tasks for any worker. For any two different tasks ($t_1 \neq t_2$), if both are assigned to the same worker w:

$$x_{t1w} + x_{t2w} = 2 \ \Rightarrow \ e_{t1} \leq s_{t2} \quad or \quad e_{t2} \leq s_{t1} \tag{3}$$

4. Load calculation for worker w:

$$l_w = \sum_{t \in T} d_t . x_{tw}, \quad \forall w \in W \tag{4}$$

5. Workload balancing (between 80% and 120% of the average):

$$\text{If } \bar{L} = \frac{\sum_{t \in T} d_t}{|W|}, \text{ then:} \tag{5}$$

$$0.8\,\bar{L} \leq l_w \leq 1.2\,\bar{L}, \quad \forall w \in W \tag{6}$$

6. Task deadlines:

$$e_t \leq D, \quad \forall t \in T \tag{7}$$

4.2.3. Objective Function of the Optimization

The multi-objective minimizes the following parameters:

1. The maximum finish time of all tasks.
2. The workload imbalance, which is interpreted as the difference between the maximum and minimum worker load.

At the same time, it maximizes the skill or KPI used by assigning tasks to highly qualified people, which also decreases the time (see Eq. (8)).

$$\min\left(max_{t\in T}\, e_t + \left(max_{w\in W}\, l_w - min_{w\in W}\, l_{w_t}\right) - 0.01 \sum_{t,w\,\in\, allocs} s_{tw}\, x_{tw}\right) \tag{8}$$

In Eq. (8), 0.01 is a weight in the objective function that is used to balance the importance of maximizing the skill with the rest of the goals.

5. CASE STUDY OF SOTAM AND EXPERIMENTAL MILESTONES

The SOTAM module and program were tested by conducting a case study to verify the optimizer on a real case scenario example. The tables presented in Section 4.1 were uploaded to the optimizer to provide theoretical insertion possibilities of the new aircraft indicated in Table 3. Fig. 2 illustrates the program's interface after the files were uploaded. The right side of the figure shows the possible and impossible solutions for the insertion and the reason behind it.

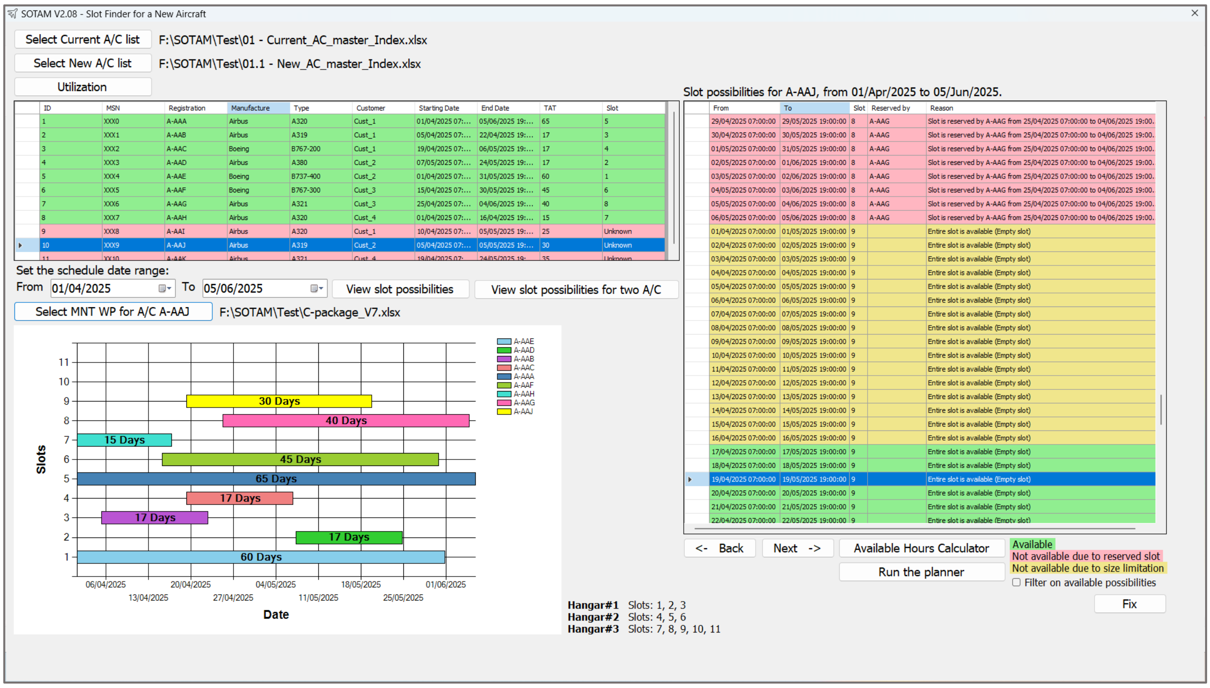


Fig. 2. All possible and impossible solutions for the selected aircraft theoretical insertion in the hangar slots

The company needs to prioritize customers who require the earliest slots, and the scheduler should run accordingly. Then, after choosing a feasible solution and uploading the relevant work package, the planner program can be initiated. The next step is to check if the selected slot has the necessary tools, parts, and materials available.

Additionally, when the planner is initiated, the uploaded work package will be divided into smaller modules and phases. Some modules can run in parallel, like the airframe, avionics, modifications, engines, and replacements. However, inside each main module, the prioritization of tasks is realized in sub-phases, as shown in Fig. 3.

As shown in Fig. 3, the aircraft identification is clearly displayed, along with the total labor required for the package and each module. For tooling problems, the sub-phase is highlighted in yellow. Unavailable parts are indicated in pink. A simultaneous shortage of tools and parts is indicated as a blue sub-task. The user/planner must decide whether to keep the aircraft in the same predetermined slot or move it to a new one. In case the tools and parts shortage are accepted in the specified slot, the planners can proceed to the next step, which is the capacity allocation. However, if it is not accepted, the next feasible theoretical slot should be chosen and the planner should be run again to check the tools and materials until a slot can be found for which all materials, parts, and tools are available.

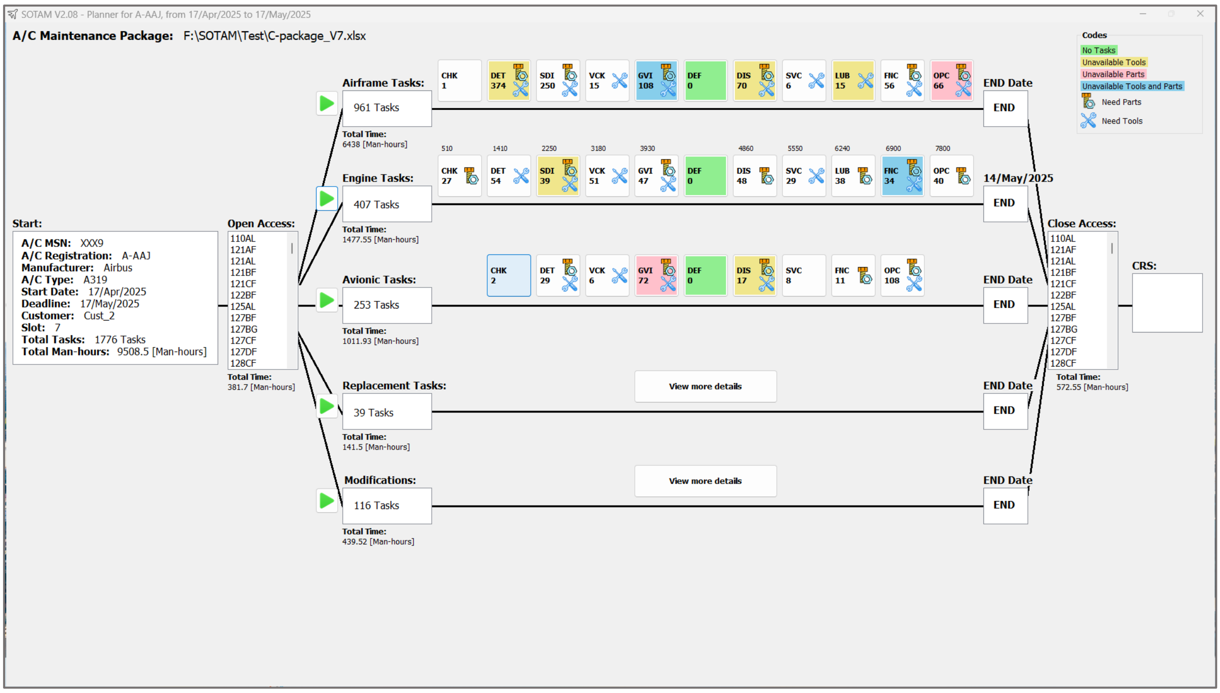


Fig. 3. The planner structure and interface

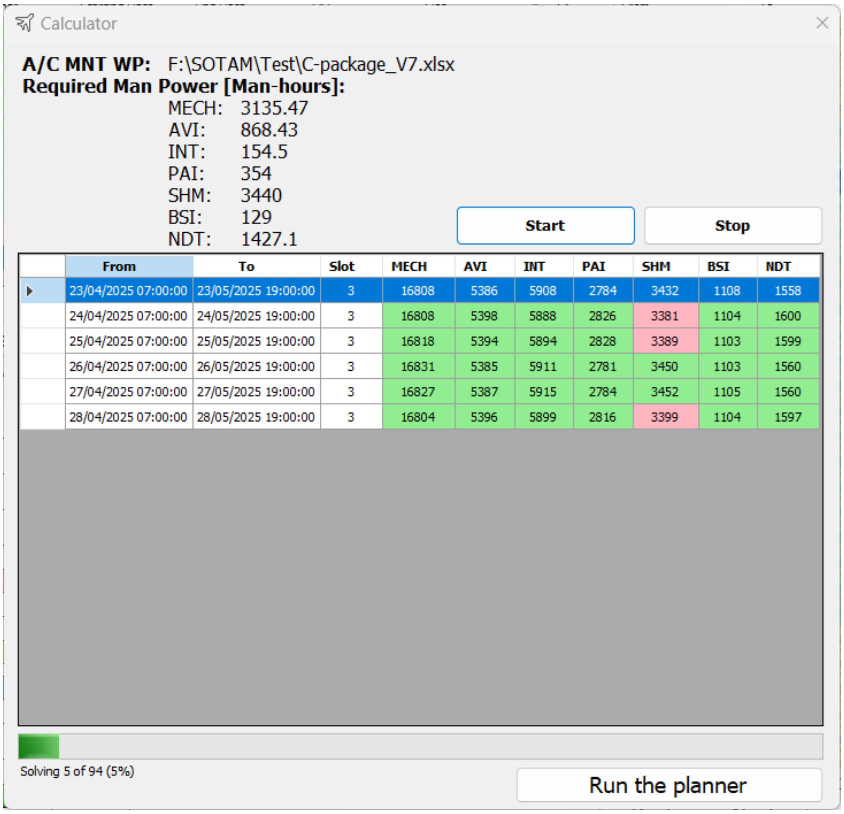
The next step is to check the calendar to determine if there is a possibility of accepting the job in the selected slot, taking into account people's availability. For this, SOTAM conducts a cross-check of the package hours with the sub-phases' hours and the people's availability hours, as illustrated in Fig. 4. A green background means there is availability, and pink represents the lack of human resources in that specific area or shop (which can be resolved by hiring extra workers, such as contractors, or moving to another slot).

People scheduling and the final table of capacity distribution are calculated to ensure that the objective of the optimization process is met. The calendar of available people is taken from the free capacity as uploaded by the HR in the input files. After that, SOTAM runs the optimizer to select people according to the set objective, which is to maximize the performance of the planning and scheduling of the tasks using the uploaded skill KPIs while minimizing the work span (check time TAT) and balancing the workers' workload. The results are presented in Fig. 5 as a calendar illustrating the allocation of resources to individuals. Each sub-phase has its own mini-Gantt chart, which can be viewed by clicking on the corresponding sub-phase.

6. CONCLUSIONS

This research introduces a novel constrained programming approach for aircraft maintenance scheduling and planning that aligns the operational and technical aspects of a mid-sized MRO company. The Schedule Optimization Tool for Aircraft Maintenance (SOTAM) can solve real-life problems, ranging from slot allocation to capacity optimization, thereby promoting the vision of a smart, competitive MRO that can stay relevant in the aviation industry. The optimizer assigned diverse maintenance tasks to a limited workforce with varying skill and experience levels based on qualification and availability.

The proposed framework integrates a multi-objective function (three goals) into a single complex model. The ultimate goal is to minimize the total maintenance completion time and maximize the people's skills while keeping a balanced workload utilization to promote fairness and training for less experienced technicians. The problem was modeled using the IBM CP Optimizer [27, 28] as variables and constraints, enhanced by the objective. SOTAM was able to assign tasks feasibly and intelligently.



From	To	Slot	MECH	AVI	INT	PAI	SHM	BSI	NDT
23/04/2025 07:00:00	23/05/2025 19:00:00	3	16808	5386	5908	2784	3432	1108	1558
24/04/2025 07:00:00	24/05/2025 19:00:00	3	16808	5398	5888	2826	3381	1104	1600
25/04/2025 07:00:00	25/05/2025 19:00:00	3	16818	5394	5894	2828	3389	1103	1599
26/04/2025 07:00:00	26/05/2025 19:00:00	3	16831	5385	5911	2781	3450	1103	1560
27/04/2025 07:00:00	27/05/2025 19:00:00	3	16827	5387	5915	2784	3452	1105	1560
28/04/2025 07:00:00	28/05/2025 19:00:00	3	16804	5396	5899	2816	3399	1104	1597

Fig. 4. Hours calculation

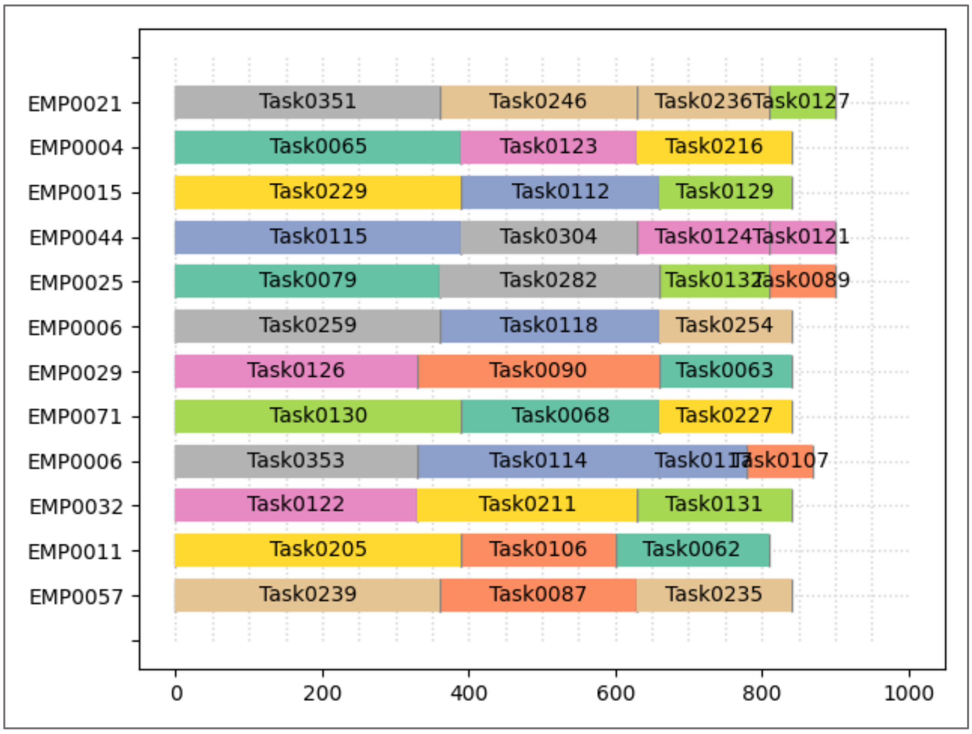


Fig. 5. Results of the workers' schedule in one of the sub-phases

For visualization and user interaction purposes, the module was programmed in Visual Studio as a combination of C# and Python to ensure easy and flexible file uploading by planners or management while also providing a transparent board to view the results. The results of our case study and experiment confirm that SOTAM can generate a high-quality schedule for tasks, people, tools, and checks within a couple of minutes while utilizing a standard CPU. The model is extremely flexible and adaptable, allowing for the integration of additional constraints if management decides to integrate them; these include shift limits, priority tasks enhanced by artificial intelligence [29], and even new task dependencies.

This study transforms maintenance planning in aviation by demonstrating how smart scheduling techniques may improve operational readiness, resource efficiency, and service quality. As MROs face mounting pressure from airlines to reduce the TAT while upholding safety and performance requirements, optimization-based solutions are set to become indispensable tools in contemporary aviation management.

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Received 09.05.2024; accepted in revised form 19.08.2025