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Original Research

Optimization of collaborative decision-making during the aircraft pre-flight maintenance

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Abstract: Collaborative decision-making (CDM) protocols improve the efficiency of the air transportation system by uniting the objectives of aircraft and airport operators, air traffic control authorities, maintenance providers, and ground handling personnel. CDM can minimize delays, increase operational reliability, and ensure efficient use of infrastructure. Despite the maturity of CDM, the level of collaboration among aviation professionals in team settings remains inadequate to make well-informed joint decisions. This study analyzed the CDM activities of specialists in aircraft structures and engines, avionics and radio-electronic systems, and cargo ground operations when conducting the pre-flight maintenance on an An-26 aircraft. Structural-time tables and network graphs were developed to map the sequence of actions of maintenance personnel before and after the simulated optimization efforts. The computational analysis using MS Excel and Python language within the Google COLAB platform revealed that pre-flight maintenance is accelerated by 22.42% after optimization with a cargo ground operator compared to the pre-optimization scenario and by 48.81% when compared to the pre-optimization process without a cargo ground operator. The results support the use of refined deterministic CDM models to enhance cooperation among maintenance personnel and reduce the duration of routine aircraft maintenance.

Keywords: Critical path method, Google COLAB platform, Network graph, Python language, Structural-time table

1. Introduction

In the era of advanced technology, speed and mobility are key determinants of efficiency in work, travel, and leisure. Nevertheless, a significant proportion of the public still perceives air travel as unsafe. In contrast, statistical evidence, expert assessments, and technological advancements consistently confirm that aviation is the safest mode of transportation [1]. According to the International Air Transport Association (IATA) Annual Safety Report [2], the global accident rate declined from 3.72 accidents per million sectors in 2005 to 1.13 in 2024, highlighting the effectiveness of continuous safety improvements in commercial aviation. This long-term reduction reflects advances in safety culture, management systems, technology, and training, despite regional differences and a slight increase in fatal accidents in 2024 compared to 2023.

Recent studies indicate that human factors account for approximately 70–80% of aviation occurrences worldwide (including flight crews, UAV operators, air traffic

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controllers, maintenance personnel, flight dispatchers, ground services, and etc.), while only 20% are caused by other factors [3–5]. In Ukraine, 55 civil aviation accidents and incidents were reported in 2024, distributed as follows (Figure 1): 17 (31%) were attributed to human factors (10 (18%) to flight crews and air traffic controllers; 7 (13%) to maintenance personnel), 21 (38%) to technical factors, 12 (22%) to environmental influences (e.g., bird strikes), and 5 (9%) to unidentified causes [6]. These figures underscore the urgent need to strengthen aircraft safety and maintenance protocols.

Modern air transport functions as a highly complex socio-technical system that depends on the coordinated interaction of diverse stakeholders, including airlines, airports, maintenance organizations, and air traffic management. System efficiency relies on timely and accurate decisions made at both strategic and operational levels. Among these, pre-flight maintenance is particularly critical, as delays or failures in this stage propagate throughout the system and lead to schedule disruptions, economic losses, and safety risks. The substantial proportion of incidents linked to maintenance personnel (13%) highlights the critical importance of addressing their role in flight safety.

Preparing an aircraft for flight is part of operational maintenance, which includes identifying and rectifying malfunctions to ensure the safety of passengers and crew [7, 8]. These procedures are relatively low in labor intensity and are usually performed between the arrival of the aircraft and its next departure. They include actions such as connecting ground power units, removing protective covers, de-icing, installing batteries, inspecting doors and hatches, checking the air-conditioning system, and verifying pressure-sensitive devices after exposure to adverse weather.

In cargo operations, pre-flight preparation is more extensive due to the additional tasks performed by the ground operator (GO) and loaders. These tasks include organizing and supervising baggage and cargo loading, checking ramp locks and hooks, verifying carriage brakes, inspecting the ramp after loading, and ensuring the correct securing of freight before flight. These activities are indispensable for flight safety, but inevitably increase the overall duration of maintenance compared to passenger-only operations. Thus, the presence of a GO in the pre-flight team should not be interpreted as a reduction in efficiency; rather, it reflects the inclusion of additional cargo-handling processes. Later in the analysis, the introduction of additional loaders is proposed as a measure to reduce the time required for these tasks without compromising safety.

Following passenger boarding and cargo loading, the maintenance personnel formally hand over the aircraft to the flight crew with the required documentation (e.g., flight log, flight order). Final pre-flight procedures include removing the chocks, towing the aircraft, conducting a visual inspection, connecting the cockpit communications, and supervising engine start-up. These checks are particularly critical for systems such as engines, landing gear, hydraulics, and avionics. Once engines are running, the external power and communication links are disconnected.

Pre-flight maintenance is typically performed by a team of two or three specialists: an aircraft structures and engines specialist (ASES), an avionics and radio-electronic specialist (ARES), and, in the case of cargo flights, a ground operator (GO). Their interaction is governed by operational documentation and collaborative decision-making (CDM) protocols [7, 9–12].

CDM has become an essential framework for improving the efficiency in aviation operations. By facilitating information sharing and joint planning among stakeholders, CDM reduces uncertainty and enables more effective allocation of resources. While CDM has been successfully

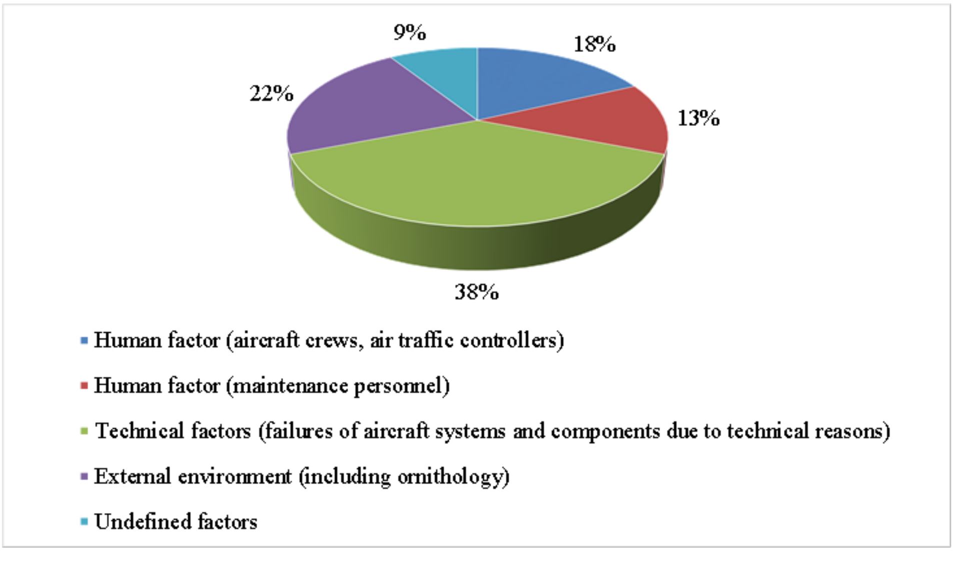

Figure 1. Classification of causal factors for aviation accidents and incidents involving civil aircraft of Ukraine in 2024

applied in domains such as air traffic flow management, slot allocation, and ground operations, its application in aircraft pre-flight maintenance remains limited, although there is an evidence that poor coordination at this stage contributes significantly to delays and operational inefficiencies.

Research problem

Although CDM protocols are formally embedded in aviation operations, actual collaboration among maintenance personnel during pre-flight checks remains insufficient. Weak coordination among ASES, ARES, and GO extends maintenance time, wastes resources, and increases the likelihood of delays. This creates a pressing need for optimized CDM models tailored specifically to pre-flight maintenance.

Research hypothesis

The optimization of CDM processes for pre-flight maintenance will:

- improve coordination among different maintenance specialists,
- reduce overall maintenance duration, and
- enhance operational efficiency compared to existing practices.

Research objectives

- to develop deterministic individual and collaborative decision-making models for pre-flight maintenance tasks;
- to apply the Critical Path Method (CPM) and optimization techniques (Python-based algorithms and MS Excel tools) for streamlining pre-flight procedures;
- to show how CDM models can reduce the duration of maintenance by improving coordination among ASES, ARES, and GO;
- to demonstrate the approach using the example of the An-26.

The paper is structured as follows. Section 2 reviews the relevant literature on CDM in aviation and related approaches to decision making. Section 3 describes the methodology, including CPM, expert judgement, and optimization procedures. Section 4 applies the model to An-26 pre-flight maintenance. Section 5 discusses the findings, and Section 6 concludes with concise contributions and recommendations for future research.

2. Analysis of the latest research and publications

Commercial aviation relies upon the safe performance of tasks by multiple specialists, such as flight crew, air traffic controllers, maintainers and ground support personnel. The interaction between these specialists has been identified as a critical factor in improving flight safety. This had led to practical and scientific studies examining the interaction between aviation specialists. The initial research in this field was conducted by the United States National Aeronautics and Space Administration (NASA), which pioneered Crew Resource Management (CRM) to improve cooperation within flight crews [13–15]. This concept has since evolved into an effective mechanism for minimizing human error. Later studies [16–18] investigated the interaction dynamics of air traffic controllers' teams, which differ significantly from cockpit crew coordination. This approach became known as Team Resource Management (TRM). Over time, CRM and TRM principles have been adapted to other industries, including firefighting, naval operations, and healthcare [19].

Building on the foundations of CRM and TRM, the concept of CDM was introduced as a broader framework to address the increasing complexity of interactions across the entire aviation system [20, 21]. Its first major application was in Air Traffic Flow and Capacity Management (ATFCM) [9], where coordination among airlines, airports, and air navigation service providers proved essential to reducing congestion and delays. Subsequently, the International Civil Aviation Organization (ICAO) and the European Organization for the Safety of Air Navigation (EUROCONTROL) developed global CDM frameworks that institutionalized information exchange, stakeholder coordination, and joint decision-making. These initiatives demonstrated measurable improvements in predictability, delay reduction, and system resilience.

Building on these foundations, CDM was extended to airport surface operations, slot allocation, and aircraft turnaround. For instance, the ICAO's Flight and Flow Information for a Collaborative Environment (FF-ICE) initiative [22, 23], based on the concept of System Wide Information Management (SWIM) concept [24], emphasized shared situational awareness as a means of reducing uncertainty. FF-ICE is regarded as the cornerstone of the Performance-Based Approach (PBA) in modern air transport [25]. Similarly, Airport CDM (A-CDM) programs in Europe have demonstrated measurable improvements in punctuality and turnaround efficiency through standardized communication protocols [10–12].

Today, CDM principles are applied well beyond aviation – in transportation [26], logistics [27], management [28], and business [29] – where coordinated action and information sharing are equally critical.

Research on Individual Decision-Making (IDM) in aviation has also gained attention. For example, [30] pilot-copilot synchronization during emergency events (e.g., power supply failures) has been analysed, where cross-monitoring plays a decisive role. Further studies [31–34] extend CDM modeling to mixed teams of aviation stakeholders (pilots, UAV operators, air traffic controllers, flight dispatchers, engineers, emergency services, and etc.), employing deterministic, stochastic, and neural-network-based approaches to optimize collaboration in emergencies. Nevertheless, most CDM applications in aviation still concentrate on traffic flow and operations at airport-level, with limited focus on aircraft maintenance. This gap is critical as maintenance decisions directly affect aircraft readiness, safety, and operational efficiency. Existing approaches often rely on deterministic schedules or expert rules that inadequately capture human error and interdependencies across tasks.

The challenge of optimizing CDM in pre-flight maintenance lies in balancing two objectives: minimizing downtime while ensuring technical readiness. Many conventional models fail to capture the interdependence of the actions by stakeholders. To address this problem, quantitative models that combine expert judgment with advanced scheduling methods are required.

Recent optimization research has introduced various methods. Petri nets and other discrete-event models capture concurrency and synchronization in turnaround and maintenance operations, providing rigorous verification of bottlenecks and resource conflicts. Game-theoretic frameworks model the competing interests of airlines, controllers, and service providers, offering insights into the cooperative versus competitive resource allocation. Agent-Based Models (ABM) simulate heterogeneous actors and negotiation protocols that reflect the decentralized, adaptive nature of aviation systems. Likewise, operations research techniques such as Mixed-Integer Linear Programming (MILP), Resource-Constrained Project Scheduling Problems (RCPSP), and stochastic programming approaches (e.g., Markov Decision Processes (MDPs) and Partially Observable MDPs (POMDPs)) address uncertainty in scheduling under complex constraints.

Despite this methodological diversity, most models target macro-level processes (e.g., airport capacity, flow management, slot allocation) rather than micro-level line maintenance. Furthermore, some approaches are computationally infeasible in real-time (e.g., MILP, stochastic programming), while others lack the transparency required in regulated aviation domains (e.g., ABM, neural networks).

This paper addresses this research gap by focusing on deterministic optimization of CDM in pre-flight maintenance teams. By applying network planning techniques, the proposed model accounts for role substitutability, task parallelization, and critical-path dependencies. The framework is both operationally verifiable and practically implementable, delivering measurable improvements in real maintenance settings.

Accordingly, the purpose of this study is to optimize CDM during pre-flight maintenance using network planning methods. The Critical Path Method (CPM) is employed to determine and optimize task sequences, while the Expert Judgment Method (EJM) captures subjective assessments of task durations and priorities. The approach is tested on the An-26 aircraft, with results demonstrating significant gains in coordination and efficiency.

3. Methods

This section outlines the methodological framework used to develop and optimize IDM/CDM deterministic models for aircraft pre-flight maintenance. The approach integrates expert-based data collection, deterministic modeling assumptions, the CPM, and optimization procedures implemented in spreadsheet MS Excel and Python language.

3.1 Data

The durations of the maintenance regulation works (MRWs) was determined using the Expert Judgement Method (EJM) [35]. Thirty experienced airline technicians undergoing advanced training at the Ukrainian State Flight Academy were surveyed to provide estimates of the execution time of MRWs. The test case considered was the Antonov An-26 aircraft, a medium transport aircraft with extensive operational history. Analogues such as the An-32, An-140T, Airbus C295, and Alenia C-27J Spartan were included for comparison of technical parameters.

The EJM is a structured forecasting approach that collects and refines experts' opinions through iterative rounds of questionnaires [35]. After each round, participants receive anonymized feedback summarizing the group’s responses and reasoning and prompting them to reconsider their earlier judgements. This iterative process typically reduces the spread of opinions and steers the group towards convergence. The procedure concludes once a predefined criterion is reached – such as consensus, stability of responses, or a fixed number of rounds – with the final aggregated evaluations determining the outcome.

The algorithm of EJM for obtaining the durations of MRWs [30, 35]:

Questionnaires for experts: m – is a number of experts, $m \geq 30$.

The matrix of individual estimates: R_i – is a system of estimates of i-expert, $i = \overline{1, m}$.

The matrix of group estimates $R = R_j = R_{gr}$ (1):

$$R = Rj = R_{gr} = \frac{\sum_{i=1}^{m} R_i}{m} \quad (1)$$

where $R = R_j = R_{gr}$ – is an opinion of the group of experts, $j = \overline{1, n}$;

n – is a number of MRWs;

m – is a number of experts;

R_i – is a system of estimates of i -expert.
Coordination of a expert's opinion.
Computation of dispersion D (2):

$$D = \frac{\sum_{i=1}^{m} (R_g - R_i)^2}{m-1} \qquad (2)$$

Computation of square average deviation δ (3):

$$\sigma = \sqrt{D} \qquad (3)$$

Computation of variation coefficient v (4):

$$v = \frac{\sigma}{R_g} \cdot 100\% \qquad (4)$$

If $v \leq 33\%$ then the opinion is concerted and a system of experts' estimates has been obtained. If $v > 33\%$ then it is necessary to calculate Kendal's coefficient W (coefficient of concordance) (5):

$$W = \frac{12S}{m^2(n^3 - n) - m\sum_{i=1}^{m} T_i};$$

$$S = \sum_{j=1}^{n} (\sum_{i=1}^{m} R_{ij} - \overline{R})^2;$$

$$T_i = \sum_{i=1}^{m} (t_i^3 - t_i); \qquad (5)$$

$$\overline{R} = \frac{1}{n} \sum_{j=1}^{n} (\sum_{i=1}^{m} R_{ij}),$$

where S – is a generalized dispersion;

t_i – is a number of the same estimates in the i -row which fixed the i -expert.

Kendal's coefficient must be within the limits $0.7 < W \leq 1$. If $W < 0.7$ it is necessary to repeat the interrogation.

Compare the system of estimates R_{gr} and R_i, $i = \overline{1, m}$ based on the Spearman's coefficient R_S (rating correlation coefficient) (6):

$$R_S = 1 - \frac{6\sum_{j=1}^{n} (R_g - R_i)^2}{n(n^2 - 1)} \qquad (6)$$

The significance of the computations.

The significance of the computation of Kendal's coefficient W, criterion x^2 (7):

$$\chi_f^2 = \frac{S}{\frac{1}{2} m(n+1) - \frac{1}{12(n-1)} \sum_{j=1}^{n} R_j} > \chi_t^2, \qquad (7)$$

where χ_f^2 – is an actual value of the variable;

χ_t^2 – is a tabular value of the variable.

The significance of the computation of Spearman's coefficient R_S using Student's t-criterion (8):

$$t_{critical} = R_s \sqrt{\frac{n-2}{1 - R_s^2}} > t_s \qquad (8)$$

where n – is a number of MRWs;

t_{St} – is a tabular value, while the number of degrees of freedom $f = n$ -2 and error α = 5%.

3.2 Model assumptions

The following assumptions were adopted:

- Task durations are deterministic and known in advance.
- MRWs are performed sequentially or in parallel, depending on precedence constraints.
- Safety-critical tasks cannot be shortened; optimization focuses on the non-critical MRWs.

Three categories of maintenance personnel are considered:

ASES – aircraft structures and engines specialist,

ARES – avionics and radio-electronic systems specialist,

GO – ground operator.

The objective is to minimize the critical path duration of the MRW complex while meeting regulatory safety requirements.

3.3 Notation

Table 1 summarizes the notation used throughout the IDM/CDM modeling.

Table 1. Symbols and definitions

Symbol	Definition
t_{ij}	Duration of MRW from event *i* to event *j*
E_{ij}^{S}	Early start time of MRW $i \rightarrow j$
E_{ij}^{F}	Early finish time of MRW $i \rightarrow j$
L_{ij}^{S}	Late start time of MRW $i \rightarrow j$
L_{ij}^{F}	Late finish time of MRW $i \rightarrow j$
EE_{ij}	Early occurrence time of event *j*
LL_{ij}	Late occurrence time of event *j*
R_{ij}	Total time reserve for MRW $i \rightarrow j$
r_{ij}	Free time reserve for MRW $i \rightarrow j$
T_{cr}	Critical path duration of MRWs

3.4 Critical Path Method (CPM)

The Critical Path Method (CPM) was applied to construct network graphs of MRWs. For each task, early and late start/finish times were calculated by forward and backward passes through the network [36, 37].

Forward pass (9):

$$E_j = \max(E_i + t_{ij}), \forall_i \in Predecessors(j) \quad (9)$$

Backward pass (10):

$$L_i = \min(Lj - t_{ij}), \forall_j \in Successors(i) \quad (10)$$

Total time reserve (11):

$$R_{ij} = L_{ij}^{S} - E_{ij}^{S} \quad (11)$$

Free time reserve (12):

$$r_{ij} = EE_j - (E_{ij}^{S} + t_{ij}) \quad (12)$$

An MRW is considered critical if $R_{ij} = 0$.

3.5 Optimization process

The optimization of deterministic IDM/CDM models was performed in three stages [38]:

Redistribution of reserves – sequential adjustment of non-critical MRW durations within safety limits (13):

$$t_i^{k-1} < t_i^{k} < t_i^{k+1} \quad (13)$$

where $t_i^{k-1} = max\,min\,t_i^{k}$ – is a minimum time while ensuring maximum flight safety;

$t_i^{k+1} + \min\max t_i^{k}$ – is a critical time of the longest (critical) path;

t_i^{k} – is an optimal time, $i = \overline{1, m}; k = \overline{1, K}$.

Parallelization of tasks – simutaneously executing non-critical MRWs by multiple personnel (e.g., ASES + ARES).

Consolidation of CDM models – integrating individual networks (IDM_A, IDM_B, IDM_C) into a single collaborative deterministic model to minimize the overall T_{cr}.

Implementation was carried out using spreadsheet in MS Excel (network diagrams) and Python language in Google COLAB platform (algorithmic calculation of T_{cr}).

4. Results

This section presents the application of the IDM/CDM deterministic models to the case of aircraft pre-flight maintenance. Network graphs, critical paths, and optimization outcomes are reported.

4.1 Individual decision-making (IDM) results

Deterministic modeling of IDM during pre-flight maintenance was carried out separately by each maintenance specialist:

IDM_A – aircraft structures and engines specialist (ASES);

IDM_B– avionics and radio-electronic system specialist (ARES);

IDM_C – ground operator (GO).

Using CPM, the following outputs were obtained under each IDM model:

- Shortest execution time of the MRW complex.
- Identification of critical MRWs (with $R_{ij} = 0$).
- Start/finish times of each MRW.

Network graphs for each specialist are shown in Figure 2. These results form the baseline for evaluating collaborative optimization.

4.2 Collaborative decision-making (CDM) results

The deterministic CDM model integrates individual network graphs into a single framework. The objective is to minimize the critical path duration (T_{cr}) by exploiting time reserves and parallel execution.

Three optimization strategies were tested:

- Redistribution of reserves – adjusting non-critical MRWs while maintaining safety (Eq. 13). Figure 3 illustrates the optimized CDM network with coordinated time reserves.

Critical path (MRW_{cr}) d_1, d_2, d_5, d_6, d_8, (14):

$$T_{cr} = t_1(d_1) + t_2(d_2) + t_5(d_5) + t_6(d_6) + t_8(d_8). \quad (14)$$

Non-critical arcs ($MRWncr$) d_3, d_4, d_7.

Time reserves (MRW_R) (15)–(16):

$$R_3 = (t_1 + t_2) - t_3; \quad (15)$$

$$R_5 = t_5 - t_4 \quad (16)$$

- Parallel execution – assigning two or more specialists to perform MRWs simultaneously (e.g., ASES + ARES).
- Network consolidation – restructuring the sequence of MRWs to align personnel activities and reduce idle times.

Optimal consolidated time for joint execution of j-MRW by the maintenance specialists at k-stage of CDM is within the range (17):

$$t^k_{jCDM} = \left[\max\min t_j^{k-1}, \min\max t_j^{k+1}\right] \quad (17)$$

$$j = \overline{1,n}; k = \overline{1,K}.$$

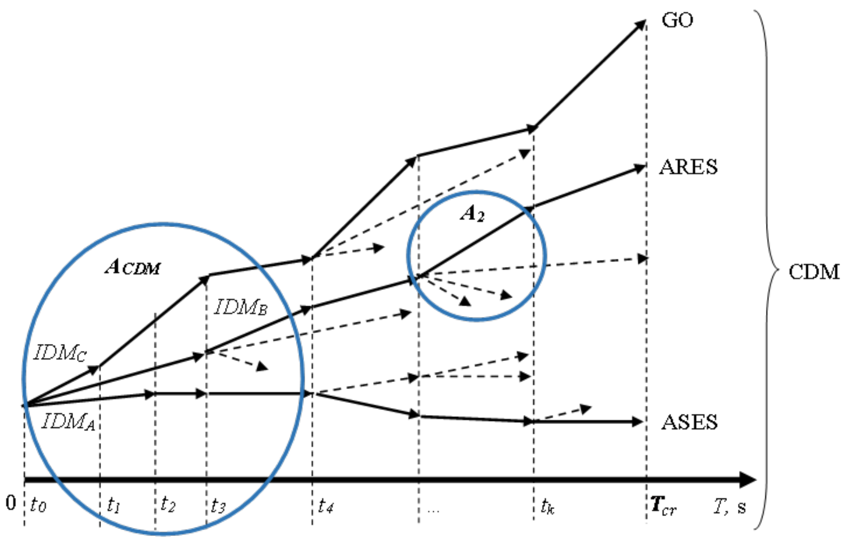

Figure 2. Network graphs of MRWs for individual maintenance specialists IDM_A (ASES), IDM_B (ARES), and IDM_C (GO): A_{CDM} – alternative collaborative MRW complexes for the maintenance specialists ASES, ARES, and GO; A_2 – alternative MRWs for ARES at k-stage; t_k – time for completing MRWs at k-stage; T_{cr} – critical time of the collaborative MRWs for the team of maintenance specialists ASES, ARES, and GO

Then consolidated time for consolidated execution of MRWs by the team of the maintenance specialists with limited maintenance factual time to complete the complex of works t_{MFT}, which does not exceed the maintenance regulations time t_{MRT}, equals (18):

$$A(t)_{opt} = \sum_{k=1}^{K} \sum_{j=1}^{n} t_{jCDM}^{k} \qquad (18)$$

subject to limitation $t_{MFT} \leq t_{MRT}$,
where k – is a CDM stage.

By aligning non-critical arcs and coordinating time reserves for each maintenance specialist (ASES, ARES, and GO), a common deterministic model is obtained – CDM model under certainty with a common critical path (MRWs). The model was tested in MS Excel and Python (Google COLAB). Both methods consistently identified the same critical paths and reserves.

When analyzing the complex of works in a common decision (A_{IDM}, B_{IDM} , C_{IDM}), each maintenance specialist determines their actions to solve the task S. The MRWs of the maintenance specialists in the deterministic model can be multi-alternative, unambiguously uncertain (S_1, S_2, S_3) (Figure 4).

Optimal decisions for unambiguously uncertain actions can be determined using non-stochastic/stochastic CDM models under conditions of complete (non-stochastic) uncertainty/risk.

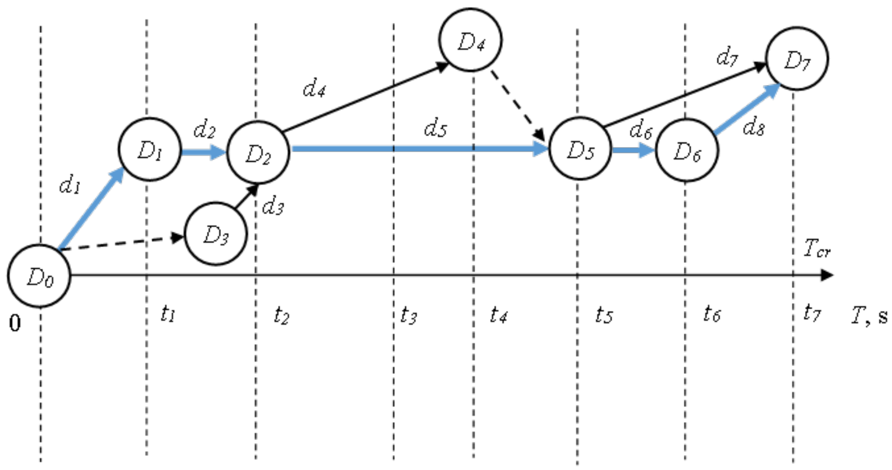

Figure 3. Optimized CDM network graph for ASES, ARES, and GO: $CDM_D = (D,d)$ – collaborative network graph of the MRW complexes for the team of maintenance specialists ASES, ARES, and GO; t_k – time for completing MRWs at k-stage; T_{cr} – critical time of the collaborative MRWs for the team of maintenance specialists ASES, ARES, and GO

4.3. Illustrative example of collaborative decision-making (CDM) during the pre-flight maintenance of the An-26 aircraft

Let us consider the illustrative example of CDM during the pre-flight maintenance of the aircraft Antonov-26 (An-26). The An-26 is a medium-sized multi-purpose transport (military transport) aircraft of the third class; its main characteristics are listed in Table 2 [39, 40]. A total of 1,398 aircraft were produced. Despite its versatility, the An-26 is currently facing the problem of aging, as many aircraft have already reached the end of their service life. The age of this aircraft means that its long-term operation is becoming increasingly expensive and problematic due to natural wear and tear, outdated avionics, unavailability of spare parts, etc.

Analogs of the An-26 aircraft were selected based on similar tasks, and their characteristics were compared (Table 2).

An-32. A direct development of the An-26, designed to improve performance in hot climates and high altitudes. 361 aircraft were produced.

An-140T. A transport modification of the An-140 aircraft. Domestic companies refuse to operate this type of aircraft, primarily due to their high cost, which has increased by almost 2.5 times compared to the cost of the first models produced. A total of 35 aircraft were produced, with approximately 10-15 aircraft remaining in service worldwide.

Airbus C295. A modern European transport aircraft that is actively replacing the An-26 in the air fleets of many countries. It is known for its versatility, equipped with new avionics, excellent performance, and low operating costs. A total of 220 aircraft have been produced.

Alenia C-27J Spartan. A modern Italian-American tactical medium military transport aircraft, distinguished by its exceptional performance, robust construction, and ability to operate in extreme conditions. It has one of the

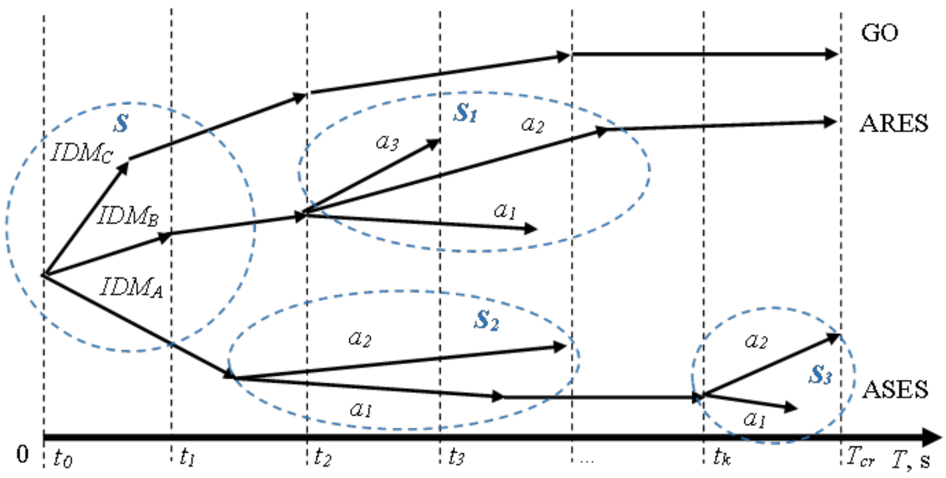

Figure 4. Deterministic multi-alternative model for the team of maintenance specialists IDM_A (ASES), IDM_B (ARES), and IDM_C (GO): a_1, a_2 – alternative MRWs for ASES, ARES, and GO at k-stage; t_k – time for completing MRWs at k-stage; T_{cr} – critical time of the collaborative MRWs for the team of maintenance specialists ASES, ARES, and GO; S – common task for the team of maintenance specialists ASES, ARES, and GO; S_1, S_2, S_3 – unambiguously uncertain MRWs for the maintenance specialists during solving the common task S

Table 2. Comparative characteristics of the An-26 and its analogues

No.	Parameters	An-26	An-32	An-140T	Airbus C295	Alenia C-27J Spartan
1	Maximum useful load (kg)	5,500	6,700	6,000	9,000	11,300
2	Range with maximum load (km)	1,100-1,240	800	1,300	1,300	1,852
3	Overflight range (km)	2,200-2,660	2,500	3,700	5,400	5,926
4	Cruising speed (km/h)	435	470-530	460	480	583-602
5	Maximum take-off weight (kg)	24,000	27,000	21,000	23,200	31,800
6	Engine type	2 turboprop (AI-24VT)	2 turboprop (AI-20DM)	2 turboprop (TV3-117VMA-CBM1)	2 turboprop (PW127G)	2 turboprop (Rolls-Royce AE 2100D2A)
7	Required runway length for take-off (m)	780-870	760-880	880	670	500
8	Ability to operate from unpaved runways	Yes	Yes	Yes	Yes	Yes
9	Start year of operation	1970	1984	1999	2001	2006

largest cargo compartments in its class. 117 aircraft have been produced.

Xian Y-7H. A Chinese licensed version of the An-26 aircraft, with the same characteristics but a different name.

In our example, the pre-flight maintenance of the An-26 aircraft is executed by the aircraft structures and engines specialist S_{ASES} (ASES), avionics and radio-electronic systems specialist S_{ARES} (ARES), and ground operator S_{GO} (GO).

The structural-time table of maintenance personnel actions during pre-flight maintenance of the An-26 by the aircraft maintenance regulations [41] is given in Table 3, and the network graph is given in Figure 5.

Table 3. The structural-time table of maintenance personnel actions during pre-flight maintenance of the An-26 (before optimization)

No.	Work content	Preliminary work	Duration of work, hours	Human resources	Additional resources
1	Connecting the aerodrome power supply		0.10	S_{ARES}	Aerodrome power supply, cable
2	Uncovering the aircraft	1	0.28	S_{ASES} or S_{ARES}	Tools for removing covers
3	Preparing for fueling	2	0.22	S_{ASES}	Fueling equipment, tools for draining
4	Removing plugs and covers, removing the grounding cable	17	0.25	S_{ASES} or S_{ARES}	Tools, plugs
5	Checking the completeness and handing over the aircraft	4; 14	0.13	$S_{ASES} + S_{ARES}$	Logbook, check equipment
6	Towing the aircraft to the engine start location	5	0.25	S_{ASES} or S_{ARES}	Towing vehicle
7	Final inspection	6	0.03	S_{ASES} or S_{ARES}	Aircraft intercom (AIC)
8	Establishing communication and monitoring engine start	7	0.27	S_{ASES} or S_{ARES}	Tools
9	Disconnecting the AIC and power source	8	0.02	S_{ARES}	Communication equipment
10	Taxiing control	9	0.20	S_{ASES} or S_{ARES}	Water, equipment
11	Filling the electric thermos and kettle	16	0.15	S_{ASES} or S_{ARES} or S_{GO}	Checking tools
12	Checking the ramp locks	15	0.12	S_{ASES} or S_{ARES} or S_{GO}	Checking tools
13	Checking the ramp after loading	11	0.01	S_{ASES} or S_{ARES} or S_{GO}	Checking tools
14	Checking the carriage brakes	13	0.03	S_{ASES} or S_{ARES} or S_{GO}	Checking tools
15	Checking the hooks	14	0.03	S_{ASES} or S_{ARES} or S_{GO}	Loading equipment, loaders
16	Loading baggage	1	0.80	S_{ASES} or S_{ARES} or S_{GO}	Fuel
17	Fueling	3	0.25	S_{ASES}	Towing vehicle

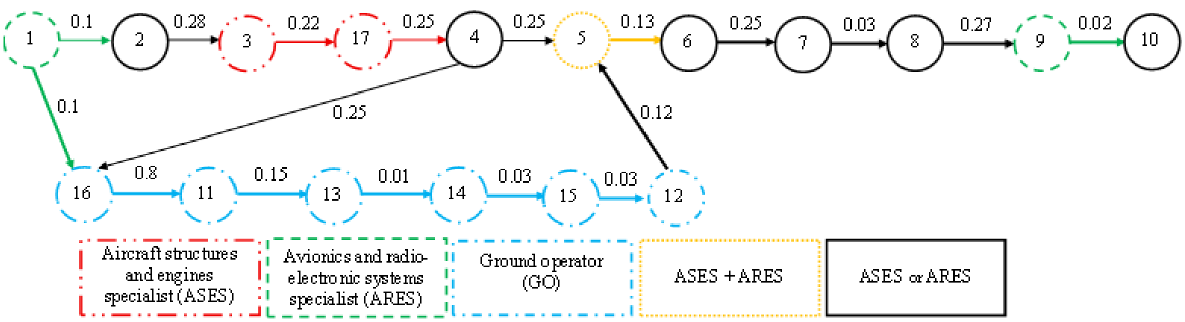

Figure 5. Pre-optimization network graph of An-26 pre-flight MRWs

Table 4. The structural-time table of maintenance personnel actions during pre-flight maintenance of the An-26 (after optimization)

No.	Work content	Preliminary work	Duration of work, hours	Human resources	Additional resources
1	Connecting the aerodrome power supply		0.10	S_{ARES}	Aerodrome power supply, cable
2	Uncovering the aircraft	1	0.14	$S_{ASES} + S_{ARES}$	Tools for removing covers
3	Preparing for fueling	2	0.22	S_{ASES}	Fueling equipment, tools for draining
4	Removing plugs and covers, removing the grounding cable	11; 17	0.125	$S_{ASES} + S_{ARES}$	Tools, plugs
5	Checking the completeness and handing over the aircraft	4; 12	0.13	$S_{ASES} + S_{ARES}$	Logbook, check equipment
6	Towing the aircraft to the engine start location	5	0.25	S_{ASES}	Towing vehicle
7	Final checking	6	0.03	S_{ARES}	Aircraft intercom (AIC)
8	Establishing communication and monitoring engine start	6	0.27	S_{ASES}	Tools
9	Disconnecting the AIC and power source	7; 8	0.02	S_{ARES}	Communication equipment
10	Taxiing control	9	0.20	S_{ASES}	Water, equipment
11	Filling the electric thermos and kettle	2	0.15	S_{ARES}	Checking tools
12	Checking the ramp locks	15	0.12	S_{GO}	Checking tools
13	Checking the ramp after loading	16	0.01	S_{GO}	Checking tools
14	Checking the carriage brakes	13	0.03	S_{GO}	Checking tools
15	Checking the hooks	14	0.03	S_{GO}	Loading equipment, loaders
16	Loading baggage	1	0.80	S_{GO}	Fuel
17	Fueling	3	0.25	S_{ASES}	Towing vehicle

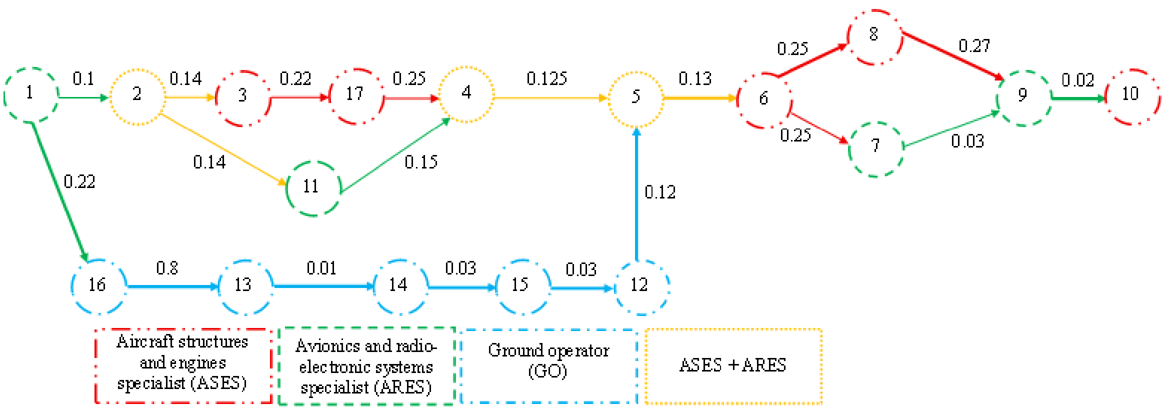

Figure 6. Post-optimization network graph of An-26 pre-flight MRWs

The critical path of MRWs execution before optimization passes through the following nodes:

- with the participation of the GO:

1→16→11→13→14→15→12→5→6→7→8→9→10 (1.94 hours);

- without the participation of the GO:

1→2→3→17→4→16→11→13→14→15→12→5→6→7→8→9→10 (2.94 hours).

The structural-time table of maintenance personnel actions during pre-flight maintenance of the An-26 after optimization is listed in Table 4, and the network graph is shown in Figure 6.

The critical path of MRWs execution after optimization with the participation of the GO passes through the following nodes:

1→16→13→14→15→12→5→6→8→9→10 (1.76 hours).

For non-critical MRWs No. 2 and No. 4, a 50% reduction in duration was achieved by having them executed simultaneously by two maintenance specialists (ASES + ARES). It is not possible to reduce the time required to perform critical tasks. Two different maintenance specialists (ARES and ASES) can execute non-critical MRW No. 7 and critical MRW No. 8 not sequentially, but in parallel.

If additional loaders are used, the critical path can be shortened even further after optimization:

1→2→3→17→4→5→6→8→9→10 (1.51 hours).

The average time for executing MRWs before and after optimization was obtained using the algorithm of EJM [37] from point 3.1: a survey was conducted on thirty experienced airline technicians who underwent advanced training at the Training and Retraining Center for Aviation Personnel of the Ukrainian State Flight Academy.

Computational analysis was carried out using spreadsheet in MS Excel and the Python language in the Google COLAB platform, with consistent results achieved across both tools. A fragment of Python code for calculating the critical path of MRWs execution during pre-flight maintenance of the An-26 is shown below.

```
# Input data on project tasks
tasks = [
{'id': 1, 'name': 'Connecting the aerodrome power supply', 'duration': 0.1, 'predecessors': []},
{'id': 2, 'name': 'Uncovering the aircraft', 'duration': 0.14, 'predecessors': [1]},
{'id': 3, 'name': 'Preparing for fueling', 'duration': 0.22, 'predecessors': [2]},
{'id': 4, 'name': 'Removing plugs and covers, removing the grounding cable', 'duration': 0.125, 'predecessors': [11, 17]},
{'id': 5, 'name': 'Checking the completeness and handing over the aircraft', 'duration': 0.13, 'predecessors': [4, 12]},
{'id': 6, 'name': 'Towing the aircraft to the engine start location', 'duration': 0.25, 'predecessors': [5]},
{'id': 7, 'name': 'Final checking', 'duration': 0.03, 'predecessors': [6]},
{'id': 8, 'name': 'Establishing communication and monitoring engine start', 'duration': 0.27, 'predecessors': [6]},
{'id': 9, 'name': 'Disconnecting the AIC and power source', 'duration': 0.02, 'predecessors': [7, 8]},
{'id': 10, 'name': 'Taxiing control', 'duration': 0, 'predecessors': [9]},
{'id': 11, 'name': 'Filling the electric thermos and kettle', 'duration': 0.15, 'predecessors': [2]},
{'id': 12, 'name': 'Checking the ramp locks', 'duration': 0.12, 'predecessors': [15]},
{'id': 13, 'name': 'Checking the ramp after loading', 'duration': 0.01, 'predecessors': [16]},
{'id': 14, 'name': 'Checking the carriage brakes', 'duration': 0.03, 'predecessors': [13]},
{'id': 15, 'name': 'Checking the hooks', 'duration': 0.03, 'predecessors': [14]},
{'id': 16, 'name': 'Loading baggage', 'duration': 0.8, 'predecessors': [1]},
{'id': 17, 'name': 'Fueling', 'duration': 0.25, 'predecessors': [3]},
]
```

After optimization, the pre-flight maintenance of the An-26 will be 22.42% and 48.81% faster, respectively, with and without the participation of the GO.

The presented optimization of CDM during pre-flight maintenance of the An-26 is based on several assumptions and has certain limitations that should be considered when interpreting the results.

Aircraft type specificity. The study focuses on the An-26, a third-class military transport aircraft with specific operational and maintenance characteristics. While analogues such as the An-32, An-140T, Airbus C295, and Alenia C-27J Spartan have similar roles and design principles, but their avionics, maintenance documentation, and ground support requirements differ. Thus, a direct transfer of the proposed optimization approach to other aircraft types may require adaptation.

Maintenance regulation constraints. The structural-time tables and network graphs were constructed strictly according to the An-26 aircraft maintenance regulations. Any modification of the workflow was limited to the parallelization of tasks that are officially permitted to be performed simultaneously by qualified personnel. Therefore, the optimization does not consider potential regulatory updates or alternative maintenance standards used by other aviation authorities.

Assumptions on personnel and resources. It is assumed that all maintenance specialists (ASES, ARES, GO) are available, fully qualified, and capable of working in parallel without communication delays or coordination errors. In practice, variations in skill levels, staffing shortages, or communication breakdowns may reduce the achievable efficiency gains.

Simplified computational model. The optimization relies on deterministic task durations obtained from expert surveys of experienced technicians. The variability caused by human factors, unexpected technical issues, or environmental conditions (e.g., weather, lighting, runway availability) was not included in the model. A stochastic or simulation-based approach could capture these uncertainties more realistically.

Scalability and generalizability. The optimization demonstrates potential efficiency gains (22.42% and 48.81% depending on the scenario) within the context of the An-26. However, scaling the method to larger, more complex aircraft (e.g., wide-body commercial jets) or to teams with different organizational structures requires validation with real-world data, additional resources, and possibly more advanced optimization tools (e.g., Petri nets, agent-based simulation, or artificial intelligence-supported scheduling).

Despite these limitations, the proposed method provides a structured framework that can serve as a basis for further research on CDM optimization across various aircraft types and operational contexts. Future work should incorporate uncertainty modeling, human factor considerations, and validation on modern aircraft fleets to enhance the robustness and generalizability of the approach.

5. Results and discussion

Deterministic IDM models were developed separately for ASES, ARES, and GO. CPM was used to calculate the critical MRWs, total reserves, and execution times. The deterministic CDM model combines IDM networks. Optimization was carried out by redistributing the reserves, introducing parallel MRWs, and restructuring the network topology. The durations of MRWs were obtained using the EJM.

The CDM activities during pre-flight maintenance were analyzed for the An-26 aircraft with the participation of an ASES, an ARES, and a GO. Structural-time tables and network graphs mapped the sequence of actions by maintenance personnel before and after the optimization. The computational analysis carried out in MS Excel and Python (Google COLAB platform) produced consistent results.

The critical path before optimization with GO was 1.94 hours, without GO it was 2.94 hours. After optimization, the critical path with GO was 1.76 hours. The duration of two non-critical MRWs could be reduced by 50% reduction by assigning two specialists (ASES + ARES) perform them simultaneously. Additionally, different specialists could perform the non-critical MRWs and the critical MRWs in parallel. With additional loaders, the critical path was further reduced to 1.51 hours. After optimization, An-26 pre-flight maintenance with GO involvement was accelerated by 22.42% compared to pre-optimization, and by 48.81% compared to pre-optimization without GO.

These results demonstrate that the presence of the GO increases the number of tasks (particularly cargo-handling and loading), which extends the baseline duration of pre-flight maintenance compared to passenger operations. However, optimization through CDM significantly reduces this time, and additional loaders provide further efficiency gains. Thus, the GO and loaders should not be seen as reducing efficiency, but as reflecting the specific operational requirements of cargo aircraft.

From a CDM perspective, the results emphasize:

- the criticality of task duration and start/finish times: altering the critical task durations directly impacts the overall schedule, while non-critical tasks offer optimization opportunities;
- the importance of parallel execution: deterministic models highlight how tasks can be rescheduled or reassigned to shorten the overall critical path without compromising safety;
- cargo-specific challenges: cargo aircraft inherently presents fewer optimization opportunities because of the additional GO-dependent procedures, making collaboration and planning particularly vital.

Therefore, collaboration amoung stakeholders is crucial for planning and executing pre-flight maintenance. Effective communication between maintenance personnel, ground operators, and loaders is critical to support the CDM plan, especially for cargo operations where delays in one task ripple throughout the system. This emphasizes the operational value of CDM protocols to ensure synchronized decision-making among stakeholders.

These findings are important for aviation maintenance policy and the design of related systems. By demonstrating a measurable increase in efficiency through optimized CDM, the results indicate the value of integrating scheduling and workflow optimization tools directly into maintenance regulations or digital maintenance management systems. Organizations and regulators could incorporate these deterministic models into training programs so that maintenance personnel are prepared to anticipate task interdependencies and coordinate their actions effectively during time-critical preflight operations.

From an operational perspective, time optimization leads directly to safety and economic benefits. Reduced turnaround times lower the risk of flight delays and cancellations while also improving aircraft utilization rates for both military and commercial fleets. At the same time, identifying critical versus non-critical tasks ensures that safety is never compromised in the pursuit of efficiency. A more balanced task allocation across ASES, ARES, and GO personnel reduces fatigue and minimizes likelihood of errors, contributing to both safer and more sustainable maintenance operations.

Future validation efforts should extend beyond deterministic models by including stochastic task variability and human-in-the-loop experiments. Real-world trials or high-fidelity simulations, in which maintenance teams adhere to optimized schedules under realistic conditions will help to assess how communication delays, human factors, or environmental constraints affect the outcomes. Such validation would not only confirm the reliability of the proposed model but also facilitate the development of intelligent real-time dashboards to guide maintenance teams in practice.

6. Conclusions

This study makes three main contributions. First, it develops deterministic CDM models for pre-flight maintenance tasks using the CPM, providing a structured and verifiable framework for analyzing interdependencies among maintenance specialists. Second, the illustrative application to the An-26 demonstrates significant efficiency gains – up to 22.42% with a ground operator and 48.81% without – while maintaining safety requirements. Third, the study highlights the potential for role parallelization and workflow optimization as a practical means of enhancing cooperation among line maintenance teams.

The results suggest that deterministic CDM models can be readily integrated into maintenance planning, training, and digital decision-support systems. At the same time, the limitations related to human variability, environmental uncertainty, and aircraft-specific regulations underscore the need for further research. Future work should focus on:

- extending deterministic models with stochastic and simulation-based approaches to capture uncertainty;
- developing intelligent real-time dashboards for maintenance scheduling, and
- validating the models through human-in-the-loop testing with modern aircraft fleets.

Together, these efforts will support the evolution of hybrid human-machine decision-making systems that are capable of improving both safety and efficiency in aviation maintenance.

List of abbreviations

ABM – Agent-Based Modeling
ARES – Avionics and Radio-Electronic Specialist
ASES – Aircraft Structures and Engines Specialist
ATFCM – Air Traffic Flow and Capacity Management
CDM – Collaborative Decision-Making
CPM – Critical Path Method
CRM – Crew Resource Management
EUROCONTROL – European Organization for the Safety of Air Navigation
GO – Ground Operator
FF-ICE – Flight and Flow Information for a Collaborative Environment
ICAO – International Civil Aviation Organization
IDM – Individual Decision-Making
IATA – International Air Transport Association
MDP – Markov Decision Process
MILP – Mixed-Integer Linear Programming
MRW – Maintenance Regulations Work
NASA – National Aeronautics and Space Administration
NTIB – National Transportation Investigation Bureau
POMDP – Partially Observable Markov Decision Process
PBA – Performance-Based Approach
RCPSP – Resource-Constrained Project Scheduling Problems
SWIM – System Wide Information Management
TRM – Team Resource Management

Authors' contributions

Tetiana Shmelova: Conceptualization, Methodology, Validation, Formal analysis. Yuliya Sikirda: Conceptualization, Methodology, Validation, Writing - Original Draft, Project administration, Writing - Review & Editing Igor Syroizhka: Software, Investigation, Visualization, Resources.

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Availability of data and materials

The data presented in this study are available in this article.

Declaration of generative AI and AI-assisted technologies in the writing process

We confirm that none of the original ideas of this research were generated from any artificial intelligence-generated tools.

Informed consent statement

Not applicable.

Competing interests

The authors claim no conflict of interest.

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