

13th CIRP Global Web Conference (CIRPe 2025)

A Data-Driven Scheduling Framework to Optimise Aircraft Line Maintenance

Georgios Karadimas, Emanuele Pagone*, Salah Albakkoush, Konstantinos Salonitis

*Sustainable Manufacturing Systems Centre, Faculty of Engineering and Applied Sciences, Cranfield University, MK43 0AL, UK** Corresponding author. e.pagone@cranfield.ac.uk

Abstract

Ensuring efficient and sustainable aircraft maintenance scheduling is critical for compliance, operational performance, and resource optimisation in Maintenance, Repair, and Overhaul (MRO) operations. This study presents a novel framework integrating mathematical modeling and discrete event simulations to optimise line maintenance scheduling. The Program Evaluation and Review Technique (PERT) is employed to model maintenance task durations, while Monte Carlo Simulations assess uncertainty and resource constraints, particularly tool availability. A case study using real-world data from a commercial MRO operator in Libya validates the framework, demonstrating its potential to reduce downtime, enhance resource utilisation, and improve sustainability in MRO operations. This research contributes to the development of data-driven maintenance strategies, addressing key challenges in airline MRO scheduling and supporting more efficient and resilient aviation maintenance practices.

© 2025 The Authors. Published by Elsevier B.V.

This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>)

Peer review under the responsibility of the scientific committee of the CIRPe 2025

Keywords: Aircraft maintenance, Maintenance, Repair, and Overhaul (MRO) scheduling, Program Evaluation and Review Technique (PERT), Monte Carlo Simulation (MCS), Discrete Event Simulation (DES), Sustainability in aviation.

1. Introduction

Aircraft maintenance plays a vital role in ensuring the safety, regulatory compliance, and operational continuity of commercial aviation. In order to maintain airworthiness and uphold safety standards, airlines must conduct periodic maintenance checks, including transit checks, A-checks (line maintenance), and more intensive C/D-checks. Among these, line maintenance is particularly demanding due to its frequency and the limited time intervals available for completion [1, 2]. Maintenance schedules are often dictated by flight hours (FH), calendar time (CT), or flight cycles (CY), and any deviation from planned maintenance can lead to increased downtime, delayed operations, and reduced fleet availability [3].

Line maintenance operations, usually carried out at airport gates or ramps, require a delicate balance between timeliness

and operational feasibility. These checks often encompass numerous interdependent tasks, and their execution must consider not only workforce and time constraints but also the availability of specialized tools and equipment. Moreover, line maintenance tasks are subject to both planned interventions and unexpected disruptions, which makes scheduling inherently complex [4]. Research shows that accumulated delays during A-checks alone can contribute to nearly a month of operational downtime over the lifecycle of an aircraft, emphasizing the urgent need for optimization in MRO scheduling practices [5].

Despite the development of several maintenance scheduling models in the literature ranging from heuristic algorithms to optimization models such as MILP, genetic algorithms, and system dynamics many of these approaches suffer from notable shortcomings [6–8]. First, they often assume deterministic durations for tasks, thereby ignoring real-world variability.

Second, most models exclude the consideration of critical resource limitations, particularly tool availability. Third, many scheduling frameworks fail to integrate the stochastic and dynamic nature of MRO operations, especially in heterogeneous fleets across geographically and operationally diverse airline networks [9, 10].

These limitations highlight a critical research gap in the development of context-specific, unified frameworks for line maintenance scheduling. There is a lack of comprehensive models that simultaneously account for variable task durations, resource constraints, inter-task dependencies, and the effect of missing tools on scheduling robustness. This gap is especially pronounced in MRO environments operating under limited infrastructure and logistical uncertainty such as in Libya where traditional scheduling approaches prove inadequate [11].

To address these deficiencies, this paper proposes a novel scheduling framework that combines mathematical modeling and computer simulation into an integrated methodology. The model employs the Program Evaluation and Review Technique (PERT) to estimate task durations based on three-point estimates (optimistic, most likely, and pessimistic) and uses Monte Carlo Simulation (MCS) to analyze uncertainty and evaluate the effects of tool unavailability [12, 13]. Discrete Event Simulation (DES) is used to simulate the scheduling environment and validate the robustness of proposed schedules under real-world operational scenarios.

The primary aim of this study is to develop and validate a hybrid framework for scheduling line maintenance in airline MRO operations, with the goal of minimizing downtime, optimizing resource utilization, and enhancing operational resilience. Validation is conducted using real operational data from a commercial airline MRO in Libya. This hybrid approach offers a more realistic and adaptable framework that reflects the constraints and uncertainties encountered in actual airline operations, especially in regions with resource limitations.

By integrating stochastic modeling, real-world constraints, and simulation-based validation, this paper contributes a practical and scalable solution to a pressing issue in aviation maintenance. It supports MRO decision-makers in developing maintenance strategies that not only meet regulatory and operational requirements but also improve sustainability and customer satisfaction.

2. Methodology

This study adopts a structured, multi-phase methodology to develop and validate an integrated framework for line maintenance scheduling in airline MRO operations. The framework comprises three interconnected phases: (1) scheduling plan formulation, (2) probabilistic modeling using PERT and Monte Carlo Simulation (MCS), and (3) performance evaluation through Discrete Event Simulation (DES). These components interact sequentially, with each feeding into the next as seen in Fig 1, enabling both temporal and resource-based uncertainty to be modeled effectively.

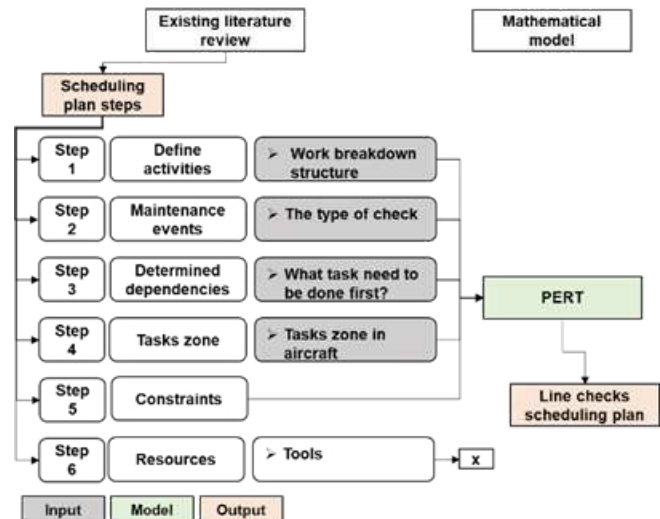


Fig. 1. PERT mathematical model approach.

The first phase involves identifying and organizing key components of the line maintenance process, based on industry practices and existing literature. This includes task grouping, dependency mapping, time intervals (based on FH, CT, CY), and maintenance resource requirements. The outcome is a high-level scheduling structure that informs both mathematical modeling and simulation stages. This ensures that the scheduling framework reflects the realities of operational AMRO environments [14].

To address uncertainty in task durations, the Program Evaluation and Review Technique (PERT) is employed. PERT is a probabilistic method that estimates the duration of each task using three-time estimates as seen in equations (1), and (2):

- T_o : Optimistic time
- T_m : Most likely time
- T_p : Pessimistic time

$$Te = \frac{T_o + 4T_m + T_p}{6} \quad (1)$$

$$a = \frac{T_p - T_o}{6} \quad (2)$$

These estimates form the basis for the Monte Carlo Simulation (MCS), executed using Microsoft Project with Full Monte Add-in. The MCS performs hundreds of replications to derive a distribution of total maintenance duration, capturing variability across scenarios [15]. The standard error of the mean (EM) is computed as:

$$EM = \frac{\alpha}{\sqrt{n}} \quad (3)$$

While PERT and MCS provide temporal insight, they do not account for dynamic operational constraints, such as the unavailability of critical tools or shared maintenance resources. To address this, a simulation-based evaluation is implemented in Phase 3.

In the third phase, a Discrete Event Simulation (DES) model is constructed to evaluate the system under real-world conditions. DES enables modeling of operational interactions

between aircraft, tasks, queues, and limited resources (e.g., specialized tools or personnel), seen in Fig 2. The model uses triangular distributions for task durations, derived from the PERT estimates [16].

The equation for the confidence interval:

$$CI = \bar{X} \pm t_{n-1, \frac{\alpha}{2}} \frac{\alpha}{\sqrt{n}} \quad (4)$$

Where: $t_{n-1, \frac{\alpha}{2}}$ is the value of the t-distribution with $(n - 1)$ degrees of freedom and a significance level of $\frac{\alpha}{2}$, n is the number of replications, $\bar{X}$ is the mean value of the replications, and α is the standard deviation of these output data.

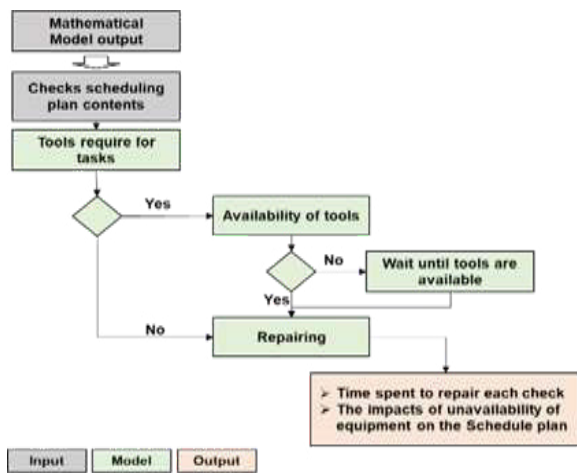


Fig. 2. DES model approach.

This phase allows modeling of tool unavailability scenarios, which are injected into the simulation by randomly removing resource access during key tasks, thus capturing a common operational disruption in AMRO practice [17].

The framework's final structure is a unified pipeline, where the scheduling structure is modeled probabilistically via PERT-MCS and then evaluated using DES to incorporate real-world constraints. The integrated model is validated using real operational data from a Libyan AMRO provider, which includes historical check durations, task sequences, and tool usage logs. This ensures contextual relevance and enhances the framework's generalizability for deployment in similarly constrained MRO environments.

The simulation was based on six years of operational data, applying triangular PERT distributions with precedence rules (FS for LG, EN, WH; SS otherwise) and tool outages derived from historical logs. More than 10,000 replications were executed with fixed seeds using MS Project with Full Monte and a discrete-event simulation engine, ensuring a margin of error below 2%.

3. Data Collection

3.1. Case Study from Libyan Airline MRO

To validate the proposed scheduling framework, empirical data were collected from a commercial Airline Maintenance, Repair, and Overhaul (AMRO) operator in Libya, referred to here as X Airline MRO. This section describes the procedures undertaken to extract, structure, and analyze operational data related to line maintenance checks over a six-year period (2013–2019). The data form the foundational inputs for the mathematical and simulation models developed in this study.

The data collection process began by developing a Work Breakdown Structure (WBS) for each of the three types of scheduled line maintenance checks. This included identifying individual tasks, their dependencies, and locations across aircraft zones as seen in Fig 3 below. Each task was annotated with a due date, determined by a combination of calendar time (M/CT), flight hours (FH), or flight cycles (CY) the standard industry parameters for maintenance scheduling [18].

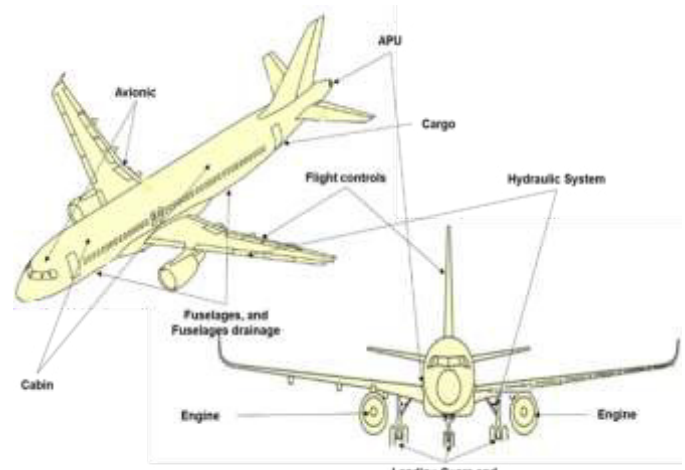


Fig. 3. Aircraft maintenance zones.

The three check types identified from the maintenance records were:

- **A-check** (First-level check): Triggered at 400–600 FH, 4 M/CT, or 500–700 CY.
- **A+-check** (Second-level check): Triggered at 700–750 FH, 6 M/CT, or 1,000 CY.
- **A++/A+++check** (Third-level or composite check): Performed at 1,000–1,200 FH, 12 M/CT, or 1,500 CY.

Table 1. Average number of tasks and repair time for each check type.

Check Type	Avg. No. of Tasks	Avg. Repair Time (hrs)
A-check	56	9.61
A+-check	96	16.91
A++/A+++check	189	36.81

To enhance scheduling efficiency, individual maintenance tasks were grouped into ten standardized work packages based

on functional similarity and spatial proximity within the aircraft. These include Landing Gear (LG), Wheels (WHs), Engines (ENs), Hydraulic Systems (HYs), Flight Controls (FLc), Fuselage (FUs), Cargo (CRg), Cabin (CAb), Avionic Systems (AVi), and Auxiliary Power Unit (APU). Each package maps to specific zones (e.g., LG tasks in Zones 731 and 741) and contains multiple interrelated tasks. In compliance with FAA safety regulations, certain packages such as LG, WHs, and ENs must not be serviced simultaneously due to technician access constraints and operational dependencies [19].

Historical maintenance reports also indicated tool dependencies for several packages. In particular, LG, EN, FLc, FUs, and APU tasks required specialized tools, and tool unavailability frequently led to scheduling delays. These dependencies are modeled explicitly in the simulation phase to reflect operational realities.

To support PERT-MCS modeling, six years of maintenance records were used to compute the three-point duration estimates for each package within every check type.

The estimates reflect task-level variability across A-, A+-, and A++/A+++ checks and form the statistical input for the Monte Carlo Simulation. This dataset provides a realistic basis for simulating line maintenance scheduling under practical constraints.

4. Framework Implementation and Results

The proposed framework was implemented using six years of data from X Airline MRO in Libya. Maintenance parameters such as task durations and resource constraints were structured using a Work Breakdown Structure (WBS) and modeled with PERT. Due to operational limitations, three critical work packages Landing Gear (LG), Engines (EN), and Wheels (WHs) were treated with a Finish-to-Start (FS) dependency, while all other packages followed a Start-to-Start (SS) relationship.

Using three-point estimates for each package, PERT was used to calculate task durations and standard deviations. These were then applied in a Monte Carlo Simulation (MCS) with a triangular distribution and 95% confidence level. Replication sizes exceeded 2.47 million for the first and second checks and 4.1 million for the third to ensure a margin of error below 2%.

The results of the simulation are summarized in Table 2, showing the estimated repair time and uncertainty (α) for each check type.

Table 2. Estimated repair time and uncertainty (α) for each check type.

Check Type	Time Spent to Repair (hrs)	α (Standard Deviation)
A-check	3.84	2.45
A+-check	7.64	3.63
A++/A+++check	14.74	5.49

The simulation also identified critical packages by calculating the Percentage of Critical Tasks (PCT) and Sensitivity Index (SI). ENs, WHs, and LGs were consistently critical across all checks, while CRg (Cargo) became

significant in the third check. Less impactful packages included APU, HYs, and AVi.

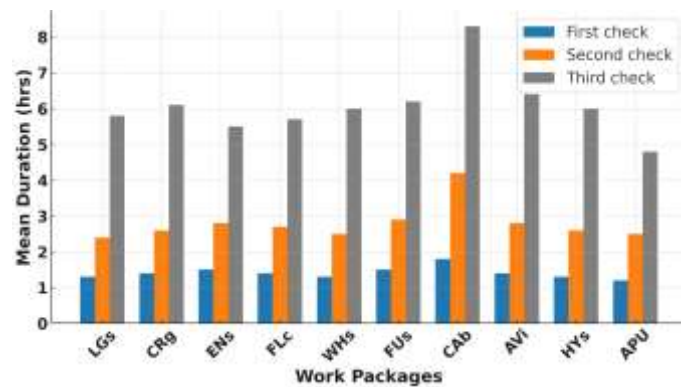


Fig. 4. Mean duration (hrs) to repair each package.

The bar chart analysis clearly illustrates an increasing trend in mean duration for each Work Package (WP) from the first to the third check, reflecting cumulative complexity or expanded task scopes over time. The WP "CAb" demonstrates notably higher mean durations at all assessment points, indicating this area consistently requires greater time investment, and thus may benefit from targeted process optimization or resource enhancement. Conversely, "APU" shows the lowest mean durations across all checks, suggesting efficient handling or simpler task structures within this package.

Compared with CPM and a greedy dispatcher baseline, the proposed framework produced more robust schedules under conditions of tool unavailability.

4. Conclusion

This study introduced a practical, simulation-driven framework for optimizing line maintenance scheduling in airline MRO operations. By integrating PERT, Monte Carlo Simulation, and Discrete Event Simulation, the model accounts for uncertainty, resource constraints, and safety-critical task dependencies issues often neglected in existing approaches.

Validated with real data from a Libyan MRO, the framework identified high-impact maintenance packages and provided accurate repair time estimates across check types. The results offer clear, actionable insights to improve scheduling efficiency and reduce aircraft downtime.

This work bridges a key gap in MRO planning research and sets a foundation for future development of adaptive, cost-aware, and fully integrated maintenance optimization systems.

Further research will focus on integrating cost optimization, dynamic rescheduling, and real-time operational data to enhance the framework's adaptability and decision support capabilities. While this study focused on a probabilistic and simulation-based approach for clarity and applicability in resource-limited MRO settings, more advanced methods such as reinforcement learning and metaheuristics (e.g., genetic algorithms, simulated annealing) hold strong potential. Future work will explore these techniques to enhance adaptability and scalability of the scheduling framework.

References

- [1] Kroes M, Wild T, Watkins F. *Aircraft Maintenance & Repair*. 7th ed. New York: McGraw-Hill Education; 2013.
- [2] Pleumpirom N, Amornsawadwatana S. Airline MRO industrial development: A review and research framework. *Int J Prod Econ* 2012;140(2):757–68.
- [3] Muchiri P, Smit J. Maintenance operations in the aviation sector. *J Qual Maint Eng* 2009;15(3):272–82.
- [4] Sriram S, Haghani A. An optimization model for aircraft maintenance scheduling and operations. *Eur J Oper Res* 2003;140(2):469–89. [3]
- [5] Lagos S, Pagone E, Salonitis K. Evaluating aircraft check duration using permutations and simulation. *J Air Transp Manag* 2020;89:101894.
- [6] Papakostas N, Mourtzis D, Chrysosolouris G. Aircraft maintenance task scheduling under availability constraints. *Comput Ind* 2010;61(5):452–60.
- [7] Deng X, Santos B. Simulation-based optimization for MRO scheduling. *Transp Res Part C Emerg Technol* 2022;138:103586.
- [8] Maher SJ, Desaulniers G, Soumis F. Aircraft routing and maintenance planning using extended integer programming models. *Transp Sci* 2018;52(2):376–93.
- [9] Albakkoush S, Pagone E, Salonitis K. An approach to airline MRO operators' planning during line maintenance checks using discrete event simulation. *Procedia Manuf* 2021;54:160–5.
- [10] De Bruecker P, Beliën J, Van den Bergh J, Demeulemeester E. Workforce scheduling in MRO operations: A review. *Comput Oper Res* 2018;95:78–95.
- [11] Albakkoush S, Pagone E, Salonitis K. Scheduling challenges within MRO operations in civil aviation. *SSRN Electron J* 2020.
- [12] Zareei A. Evaluation of maintenance project scheduling using PERT and stochastic modeling. *Int J Proj Manag* 2018;36(3):354–65.
- [13] Mattila V, Virtanen K. Stochastic modeling for MRO resource allocation. *J Air Transp Manag* 2014;34:101–8.
- [14] Efthymiou M, et al. Key challenges in maintenance scheduling for airline operations. *J Air Transp Manag* 2022;103:102221.
- [15] Law AM, Kelton WD. *Simulation Modeling and Analysis*. 4th ed. New York: McGraw-Hill; 2007.
- [16] Sala-Diakanda DM. Evaluating maintenance process simulations using discrete-event modeling. *Simul Model Pract Theory* 2021;108:102234.
- [17] Banks J, Carson JS, Nelson BL, Nicol DM. *Discrete-Event System Simulation*. 5th ed. Boston: Pearson Education; 2010.
- [18] Rodrigues L, Lavorato M. Maintenance strategies in aviation: Concepts and decision support tools. *J Qual Maint Eng* 2016;22(2):190–210.
- [19] Federal Aviation Administration (FAA). *Maintenance Technician Handbook – Airframe, Volume 2*. Washington, D.C.: U.S. Department of Transportation; 2020.



DSPACE

<https://dspace.org/>

A data-driven scheduling framework to optimise aircraft line maintenance

Karadimas, Georgios; Pagone, Emanuele; Albakkoush, Salah Muftah M.; Salonitis, Konstantinos

2025-10-17

Elsevier

<https://doi.org/10.1016/j.procir.2025.09.034>

Karadimas G, Pagone E, Albakkoush S, Salonitis K. (2026) A data-driven scheduling framework to optimise aircraft line maintenance. *Procedia CIRP*, Volume 139, 2026, pp. 251-255