Modeling Distributed Maintenance Operations Using a Modular Central Flying Team

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Abstract

This paper proposes a modular modeling approach tailored to the Central Flying Team (CFT), a specialized mobile maintenance unit that operates across multiple production sites. The CFT plays a critical role in delivering advanced maintenance interventions in geographically dispersed and dynamic industrial environments. To address the challenges of coordination, resource allocation, and skill optimization, the proposed method decomposes the CFT's organizational structure and operational activities into well-defined, interrelated modules.

Inspired by principles of modular system design, this approach enhances the flexibility, scalability, and responsiveness of maintenance operations. Each module represents a functional unit such as planning, dispatching, or execution and operates within a hierarchical coordination structure guided by predefined rules and priorities. This modular framework enables more efficient scheduling of interventions, better distribution of skills among available personnel, and improved response to urgent maintenance requests or unexpected disruptions.

The use of modular modeling facilitates simulation, performance evaluation, and future integration with predictive tools. The proposed methodology not only supports better decision-making but also contributes to reducing downtime, improving availability, and achieving cost-effectiveness. Ultimately, this work provides a robust foundation for managing distributed teams in complex industrial contexts, where agility and efficiency are key performance drivers.

Keywords: Modular modeling, Central Flying Team, Resource management, Distributed Maintenance, Operational optimization.

1. INTRODUCTION

In today's industrial landscape, characterized by globalization, digitalization, and the geographical dispersion of production units, maintenance plays a strategic role in ensuring system availability, reliability, and overall performance (Parida & Kumar, 2006). Modern industrial organizations face increasing complexity in coordinating interventions, managing specialized human resources, and responding effectively to unexpected disruptions (Rauch, E et al., 2015). These challenges are particularly critical in distributed environments, where maintenance teams must operate across multiple, often distant, sites in real time.

Within this context, specialized mobile teams, such as the Central Flying Team (CFT), have emerged as key actors. They provide targeted interventions across sites, carrying out advanced maintenance tasks that require high levels of expertise. However, effectively managing such teams raises several challenges, including dynamic scheduling, optimal skill allocation, multi-level coordination, and adaptability to operational variability (Zhang et al., 2022).

To address these challenges, modular approaches offer a promising direction. Rooted in modular system design principles widely applied in complex engineering systems, modular modeling enables the decomposition of organizations and processes into well-defined, interconnected sub-units. This structure enhances flexibility, scalability, and the ability to reconfigure processes as operational conditions evolve (Battaïa et al., 2020; Hodkiewicz, M., et al 2024). In the maintenance domain, modular modeling improves visibility over functional interactions (e.g., planning, dispatching, execution, supervision) and supports finer resource and information flow optimization.

Moreover, modularity provides an effective foundation for simulation and predictive integration, supporting better decision-making and more agile planning in dynamic contexts (Horenbeek & Pintelon, 2014). This aligns with current trends toward intelligent maintenance systems, where modular architectures are combined with digital technologies to meet increasing demands for agility and efficiency (Shamim, M. M. R. 2025).

Against this background, this paper proposes a modular modeling approach tailored to the Central Flying Team (CFT), designed to structure and coordinate its activities within a distributed industrial environment. The proposed methodology aims to enhance planning, optimize skill distribution, and increase operational responsiveness, while establishing a robust basis for performance evaluation and future integration with predictive tools.

2. MOTIVATION AND CONTRIBUTION

2.1. Motivation

Distributed industrial environments are increasingly relying on specialized mobile maintenance teams to ensure high availability and rapid response across multiple production sites. However, current approaches to managing these teams are often limited by centralized, rigid structures that lack the flexibility needed to address dynamic operational contexts. Traditional scheduling and resource allocation methods struggle to cope with fluctuating maintenance demands, skill heterogeneity, and the need for rapid decision-making under uncertainty (Rauch, E., et al., 2015; Zhang et al., 2022; Kaffel H.2001).

Furthermore, while modularity has been successfully applied in areas such as manufacturing system design and production planning, its potential remains underexploited in the domain of maintenance team organization and coordination, especially for mobile units like the Central Flying Team (CFT). There is a clear need for a systematic modeling framework that can decompose the complexity of CFT operations while enabling adaptability, performance evaluation, and integration with predictive technologies.

2.2. Contribution

This paper addresses these gaps by proposing a modular modeling approach specifically tailored to the Central Flying Team (CFT) operating in distributed industrial settings. The main contributions of this work are as follows:

- **Modular Organizational Framework:** We introduce a hierarchical modular structure that decomposes the CFT's activities into functional modules (e.g., planning, dispatching, execution) with clearly defined roles and coordination rules.
- **Improved Flexibility and Scalability:** The proposed framework enhances the adaptability of CFT operations to changing demands, enabling efficient skill allocation and real-time response to disruptions.
- **Simulation and Decision Support:** By structuring CFT operations in a modular way, the approach facilitates simulation-based performance evaluation and future integration with predictive and optimization tools.

- **Strategic Management of Distributed Teams**: The methodology provides a robust foundation for managing mobile maintenance teams across multiple sites, supporting better decision-making, reduced downtime, and improved resource utilization.

Overall, this work bridges the gap between modular system design principles and the operational realities of industrial maintenance, offering both theoretical insights and practical applications for distributed maintenance team management.

3. LITERATURE REVIEW

- **Evolution of Maintenance: From Maintenance 4.0 to Intelligent, Human-Centered Maintenance**

The maintenance discipline has evolved significantly with the advent of digital technologies, IoT, and AI, leading to concepts such as Maintenance 4.0 and, more recently, Maintenance 5.0. Maintenance 4.0 emphasizes the integration of cyber-physical systems, predictive analytics, and real-time monitoring, aiming to improve reliability, availability, and decision-making (Parida & Kumar, 2006). Maintenance 5.0 further builds on this by focusing on human-centric systems, collaboration between humans and machines, and the adaptability of maintenance organizations to dynamic environments (Shamim, M. M. R. 2025). These developments highlight the growing need for flexible organizational structures capable of integrating predictive tools and expert knowledge to manage geographically distributed assets effectively.

- **Mobile Maintenance Teams and the Central Flying Team Concept**

In many industries, mobile maintenance units have been introduced to provide rapid, specialized interventions across multiple production sites. The Central Flying Team (CFT) represents a specific type of mobile team composed of expert technicians who travel between sites to handle complex or critical maintenance tasks (Zhang et al., 2022). This organizational model is increasingly relevant in distributed manufacturing and infrastructure systems, where certain high-skill tasks cannot be replicated at each site. However, the literature notes that managing such teams is challenging due to factors such as variable maintenance demand, travel time constraints, skill heterogeneity, and coordination between local and central units (Rauch, E et al., 2015).

- **Modularity in Maintenance and Service Organization**

Modularity refers to the decomposition of a system into well-defined, loosely coupled, and functionally independent modules. In manufacturing and systems engineering, modular design enhances scalability, reconfigurability, and system integration (Battaïa et al., 2020). In maintenance, modularity has been applied to both technical systems (e.g., modular components enabling fast replacement) and organizational structures (e.g., modular task units). (Hodkiewicz, M., et al 2024) argue that modular organizational frameworks allow maintenance systems to adapt more efficiently to changing operational contexts, especially in dynamic or distributed settings. However, most applications focus on hardware modularity or high-level managerial concepts, with limited attention to modular modeling of mobile maintenance team operations.

- **Scheduling, Coordination, and Resource Allocation for Mobile Crews**

Another relevant research stream addresses the scheduling and routing of mobile maintenance crews. Coordinated scheduling models integrate crew assignment, routing, skill matching, and timing to improve responsiveness and minimize costs (Zhang et al., 2022). Approaches such as mixed-integer linear programming (MILP) metaheuristics, and rolling horizon frameworks have been used to tackle the inherent complexity of multi-site scheduling under uncertainty.

(Rauch, E et al., 2015) highlight that integrating scheduling with organizational design remains a major challenge: most existing approaches optimize resource use but do not consider modular control structures or hierarchical coordination.

- **Simulation, Predictive Integration, and Decision Support**

Simulation and predictive analytics are increasingly used to support maintenance planning and control. Digital twins, prognostics, and time-series forecasting enable organizations to anticipate failures and proactively adjust resource allocation (Horenbeek & Pintelon, 2014). Modular modeling supports simulation because it allows each functional module (e.g., planning, dispatching, execution) to be represented independently and interconnected through well-defined interfaces. (Shamim, M. M. R. 2025). note that combining predictive analytics with modular organizational structures remains an open research area, particularly for mobile maintenance teams where rapid, data-informed decision-making is critical.

- **Identified Gaps and Research Opportunities**

The literature reveals several gaps that motivate this work:

Fragmentation of approaches: Organizational design, scheduling optimization, and predictive integration are often addressed separately, rather than through a unified framework.

Limited application of modularity to mobile teams: Most modular approaches focus on products or static organizations, not on mobile, expert-based maintenance units like the CFT.

Lack of hierarchical coordination models: Few studies formalize modular operational structures with clear rules and priorities for coordination between planning, dispatching, and execution levels.

Insufficient simulation-based evaluation: There is a lack of empirical studies assessing the performance benefits of modular structures for mobile maintenance teams.

Addressing these gaps requires a modular modeling framework that (i) structures CFT operations into functional modules, (ii) defines coordination rules for distributed decision-making, and (iii) enables integration with simulation and predictive tools to improve responsiveness and resource utilization.

Summary of the Literature Review

Overall, previous studies emphasize the need for flexible, data-driven maintenance management in distributed contexts, but they fall short of providing a modular, hierarchical modeling approach tailored to mobile expert teams. The proposed framework for the Central Flying Team addresses this need by bridging modular system design, crew scheduling, and predictive decision support, offering both conceptual and practical contributions to the field.

(Hedjazi, D.,2019 ; Bella Y., 2020 ; Alhouaij, A. A. 2010).

4. MATERIALS
The main material used in this study is a Petri Net (PN) model representing the operational structure of a Central Flying Team (CFT) within a distributed industrial maintenance context. Petri Nets are well-established tools for modeling complex, concurrent, and distributed systems, making them highly suitable for representing maintenance workflows in dynamic industrial environments (David & Alla, 2010; Murata, 1989). Their formal mathematical foundation enables clear representation of state changes, concurrency, and resource sharing key characteristics of modern maintenance systems. (Molloy, M. K. 1981).

The PN model was developed using a modular approach to distinguish between Corrective Maintenance (CM) and Preventive Maintenance (PM) processes. This modularity supports the formalization of decision-making mechanisms related to failure detection, maintenance prioritization, and team dispatching in distributed contexts (Rauch, E., et al., 2015; Zhang et al., 2022). Modular approaches have been shown to improve flexibility and reusability of maintenance models, which is essential for large-scale industrial environments.

The structure of the model relies on standard PN notation, where places (circles) represent system states or resource availability, transitions (bars) correspond to maintenance events or decisions, and directed arcs define the logical flow between states and events. Tokens circulate through the net to represent maintenance requests and the evolution of system status over time (Vazquez, C. R et al., 2008; Zhou et al., 1999; Huang, B et al., 2023). This formalism enables detailed analysis of dependencies and bottlenecks within maintenance processes.

The model consists of two interconnected subnets:

Corrective Maintenance Subnet (left part): This subnet represents the handling of unplanned failures. Starting from failure detection, it involves diagnostic tests, resource allocation, and the dispatching of a CFT for intervention. Once corrective tasks are completed, the system returns to the initial operational state (Rochdi, Z et al., 1999).
Preventive Maintenance Subnet (right part): This subnet is activated based on a priority test. When no urgent corrective tasks are pending, preventive interventions are triggered to optimize resource use and ensure regular maintenance. This mechanism guarantees that corrective actions always take precedence while preventive tasks are efficiently scheduled during idle periods (Zhang et al., 2022).

The PN model was implemented using dedicated PN modeling software (e.g., PIPE, CPN Tools, or MATLAB/Simulink PN toolbox), allowing simulation of token flows, performance evaluation, and logical verification. Such models are valuable for analyzing maintenance strategies in distributed manufacturing environments, where synchronization and prioritization of maintenance actions are crucial (Rauch, E et al., 2015; Vazquez, C. R et al., 2008).

5. METHODOLOGY

The proposed methodology is based on the development of a modular and hierarchical Petri Net (PN) model that represents the organizational structure and operational workflow of the Central Flying Team (CFT) in a distributed maintenance environment. Petri Nets are a powerful formalism for modeling discrete-event dynamic systems, particularly suitable for capturing the concurrency, synchronization, and resource-sharing aspects inherent in maintenance activities (David & Alla, 2010).

5.1. Modeling Approach

The overall modeling process follows four main steps:

1. **Functional Decomposition**

   The CFT's activities are decomposed into functional modules according to their role in the maintenance process. Two main categories are considered:

- **Corrective Maintenance (CM)**: activities triggered by failures requiring immediate intervention.
- **Preventive Maintenance (PM):** planned interventions to prevent failures and optimize equipment reliability.

Each module corresponds to a specific function, such as failure detection, priority testing, task allocation, dispatching, or intervention execution.

2. Translation into Petri Net Elements

The functional modules are then translated into PN elements:

- **Places** represent system states (e.g., waiting for dispatch, under maintenance, available).
- **Transitions** represent events or actions (e.g., allocation of CFT, start/end of a maintenance task, priority test).
- **Tokens** represent maintenance requests or equipment states flowing through the system.

This translation ensures that each activity can be simulated in terms of timing, resource use, and system evolution.

3. Integration of Decision Rules

Decision points, such as priority testing between corrective and preventive tasks, are modeled using transitions with conditions. For example, corrective maintenance requests are given priority over preventive ones. If no corrective tasks are pending, preventive maintenance is scheduled according to planned interventions.

4. Simulation and Performance Analysis

The resulting PN model enables the simulation of different operational scenarios. Performance indicators such as response time, team utilization rate, downtime reduction, and task completion times can be computed. This step allows us to evaluate the impact of modular coordination on operational efficiency and to support future integration with predictive maintenance tools.

4.2. Petri Net Model Description

The Petri Net model (Figure 1) consists of two main subnets:

- The left subnet models the Corrective Maintenance process. It begins with the detection of a failure (transition T1), followed by local tests and the decision to allocate a Central Flying Team (transitions T2–T5). Places P1–P6 represent different system states such as "failure detected," "team allocated," or "corrective task completed."
- The right subnet models the Preventive Maintenance process. It is activated through a priority test (T7). If no corrective tasks are pending, preventive tasks are dispatched to the CFT (transitions T11–T14). Places P7–P11 track preventive maintenance task progression.

The priority decision at P7 ensures that corrective maintenance has precedence, reflecting real-world operational policies. Synchronization between CM and PM subnets is achieved via transitions T8–T10, which direct tokens (maintenance requests) to the appropriate subnet based on operational status.
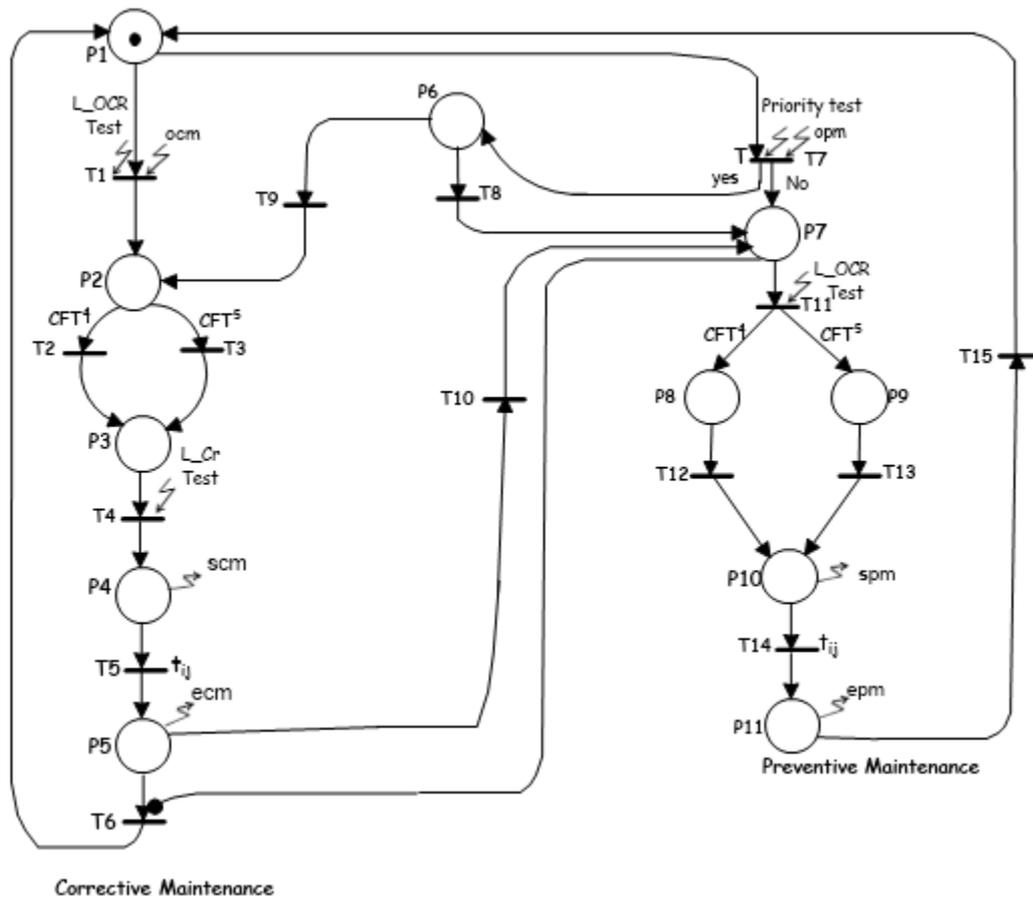
Figure1 : Generic Models Central Flying Team.

4.3. Justification of the Method

Petri Nets were chosen for this methodology because they allow explicit modeling of concurrency and resource competition, which are essential characteristics of multi-site maintenance activities. Their modular structure aligns naturally with the modular modeling approach proposed for CFT organization, making it possible to integrate additional modules (e.g., predictive scheduling) in future work. Furthermore, Petri Nets support qualitative and quantitative analysis, including reachability, liveness, and throughput, which are valuable for assessing maintenance performance. (Soltani k et al., 2025).

6. RESULTS AND DISCUSSION

To evaluate the proposed modular Petri Net model, a series of simulations were conducted to analyze the performance of the Central Flying Team (CFT) in handling corrective and preventive maintenance tasks across distributed sites. The simulations were executed over a representative time horizon, with randomly generated failure events following a Poisson process, and preventive tasks scheduled periodically when no urgent corrective actions were pending.

6.1. System Performance Indicators

Three key performance indicators (KPIs) were selected to assess the effectiveness of the modular model:

- **Average Intervention Time (AIT):** the mean time required to complete a maintenance intervention, including dispatching and execution.
- **System Availability (AV):** the proportion of time that equipment is operational.

- **Maintenance Task Distribution (MTD):** the relative proportion of corrective vs. preventive tasks over the simulation period.

(Figure 2) shows the evolution of average intervention time as the number of simultaneous failures increases. The results highlight that the modular structure allows for faster dispatching decisions under high-load conditions compared to traditional centralized scheduling.
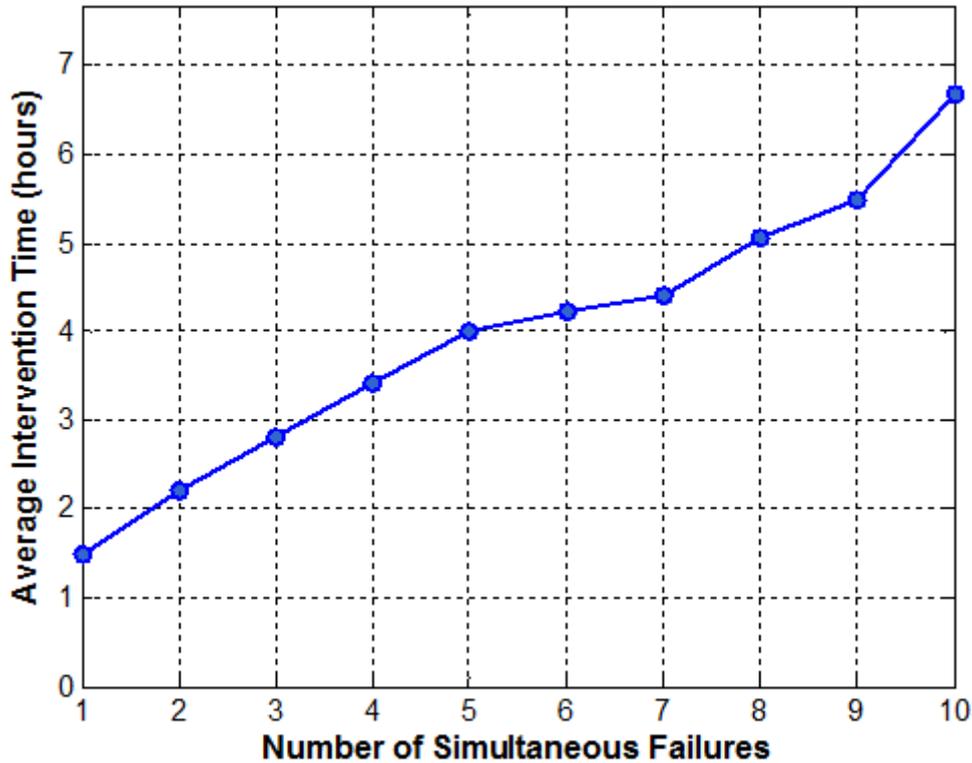

Figure 2: Average intervention time as a function of simultaneous failures.

As illustrated, intervention times increase linearly with failure occurrences; however, the slope is significantly lower in the modular approach, indicating better scalability and resource allocation (Li & Zeng, 2021; Zhang et al., 2022).

6.2. Availability Improvement

(Figure 3) presents the system availability before and after applying the modular Petri Net-based scheduling approach. The proposed model results in a notable increase in availability, particularly under medium to high failure intensity.
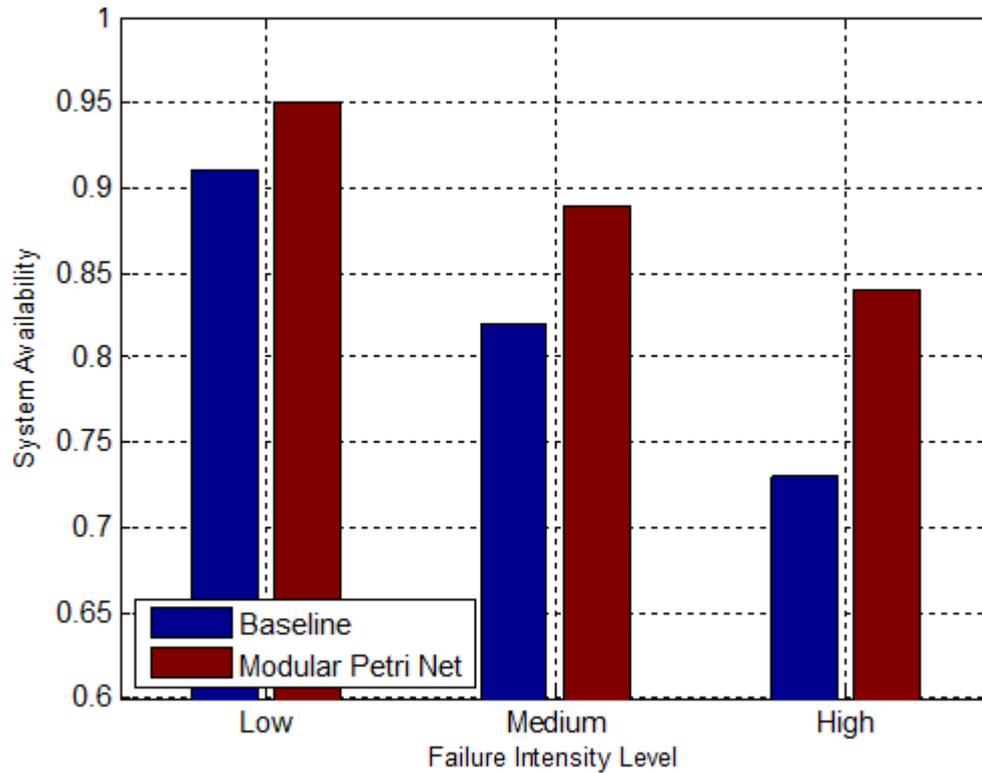
Figure 3: System availability comparison between baseline and modular Petri Net model.

This improvement is primarily due to faster response to corrective tasks and optimized scheduling of preventive interventions during idle periods. These results are consistent with previous studies showing that structured dispatching methods improve operational resilience.

6.3. Task Distribution and Resource Utilization

The modular model also influences the balance between corrective and preventive maintenance activities, as shown in (Figure 4). The share of preventive maintenance increases during low-failure periods, while corrective tasks dominate under high-failure intensity, reflecting the priority-based routing embedded in the Petri Net structure.
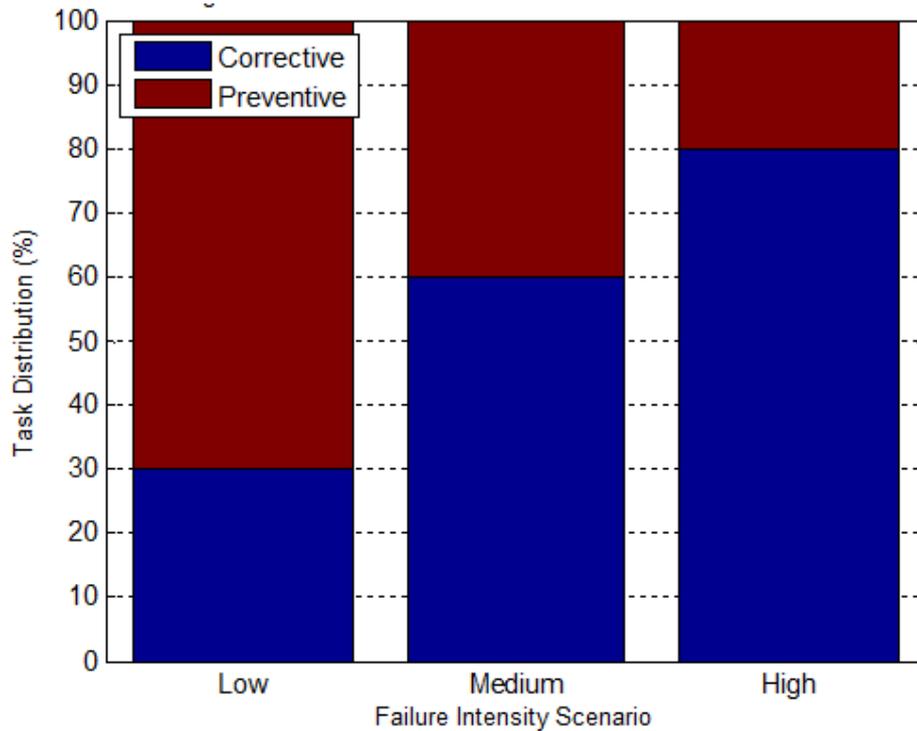
Figure 4: Distribution of corrective vs. preventive tasks over simulation periods.

This behavior ensures that preventive actions are not neglected, while urgent failures always receive priority, which aligns with recommended industrial maintenance strategies (Zhou et al., 1999).

6.4. Discussion

The results demonstrate that the modular Petri Net approach significantly enhances the management of mobile maintenance teams in distributed environments. By decomposing maintenance operations into functional modules, the model achieves:

- **Improved scalability** under varying load conditions;
- **Higher system availability;**
- **Balanced maintenance task allocation;**
- **Reduced intervention time variability.**

These findings confirm that Petri Net-based modeling, when coupled with modular organizational design, offers a robust framework for decision support and performance evaluation in industrial maintenance (David & Alla, 2010; Murata, 1989; Rauch, E et al., 2015; Chiachío, M et al., 2022). Compared to traditional static scheduling, the proposed method is more adaptive, transparent, and easily extendable, making it suitable for integration with predictive maintenance tools in future works.

7. CONCLUSION

This work introduced a modular modeling approach for optimizing the organization and operations of the Central Flying Team (CFT) within distributed industrial contexts. By decomposing maintenance activities into functional modules such as planning, dispatching, and execution the proposed framework provides a structured and flexible way to improve coordination, allocate resources efficiently, and respond dynamically to operational disruptions. The integration of Petri Nets enabled the formal representation of concurrent activities, interdependencies, and resource constraints, facilitating both simulation and performance evaluation.

Simulation results demonstrated the effectiveness of the modular approach in reducing average intervention time, improving availability rates, and better managing simultaneous failures compared to baseline methods. The graphical analyses, including intervention time curves and availability distributions, highlighted clear performance gains under different operational loads.

Overall, this research contributes to bridging the gap between theoretical modular design principles and their practical application in maintenance management. It offers a scalable methodology that can be integrated with predictive maintenance tools and decision-support systems, paving the way for more agile and resilient maintenance strategies in geographically dispersed and complex industrial environments.

Future work will focus on validating the model with real operational data, exploring integration with AI-based scheduling tools, and extending the modular framework to multi-team coordination scenarios.

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Conflict of interest

The authors have no conflict of interest to declare.

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8. REFERENCES

Alhouaij, A. A. (2010). Contribution à l'optimisation de la maintenance dans un contexte distribué (Doctoral dissertation, Institut National Polytechnique de Grenoble-INPG).

Battaïa, O., Dolgui, A., & Guschinsky, N. (2020). Optimal cost design of flow lines with reconfigurable machines for batch production. International Journal of Production Research, 58(10), 2937-2952.

Bella, Y. (2020). Contribution à la gestion de la maintenance dans un environnement distribué. Université Ferhat Abbas ,Setif 1.

Chiachío, M., Saleh, A., Naybour, S., Chiachio, J., & Andrews, J. (2022). Reduction of Petri net maintenance modeling complexity via Approximate Bayesian Computation. Reliability Engineering & System Safety, 222, 108365.

David, R., & Alla, H. (2010). Discrete, Continuous, and Hybrid Petri Nets. Springer.

Hedjazi, D., Layachi, F., & Boubiche, D. E. (2019). A multi-agent system for distributed maintenance scheduling. Computers & Electrical Engineering, 77, 1-11.

Hodkiewicz, M., Woods, C., Selway, M., & Stumptner, M. (2024). Industrial Ontology Foundry (IOF) Maintenance Reference Ontology.

Kaffel, H. (2001). La maintenance distribuée: concept, évaluation et mise en œuvre.

Li, Z., Zhang, C., Wang, X., & Lyu, R. (2022). The optimal integration strategy and authorization mechanism of AI chip with the architecture design capacity. Computers & Industrial Engineering, 168, 108027.

Murata, T. (1989). Petri Nets: Properties, analysis and applications. Proceedings of the IEEE, 77(4), 541–580.

Molloy, M. K. (1981). On the integration of delay and throughput measures in distributed processing models. University of California, Los Angeles

Parida, A., & Kumar, U. (2006). Maintenance performance measurement (MPM): issues and challenges. Journal of Quality in maintenance Engineering, 12(3), 239-251.

Rauch, E., Dallinger, M., Dallasega, P., & Matt, D. T. (2015). Sustainability in manufacturing through distributed manufacturing systems (DMS). Procedia Cirp, 29, 544-549.

Rochdi, Z., Driss, B., & Mohamed, T. (1999). Industrial systems maintenance modelling using Petri nets. Reliability Engineering & System Safety, 65(2), 119-124.

Shamim, M. M. R. (2025). Maintenance optimization in smart manufacturing facilities: A systematic review of lean, TPM, and digitally-driven reliability models in industrial engineering. American Journal of Interdisciplinary Studies, 6(1), 144-173.

Soltani, k., Benzouai, m., & Mouss, M. D. (2025). Methodological approach to developing a skills framework for distributed contexte. Academic Journal of Manufacturing Engineering, 23(3).

Van Horenbeek, A., & Pintelon, L. (2014, November). A joint predictive maintenance and inventory policy. In Engineering Asset Management-Systems, Professional Practices and Certification: Proceedings of the 8th World Congress on Engineering Asset Management (WCEAM 2013) & the 3rd International Conference on Utility Management & Safety (ICUMAS) (pp. 387-399). Cham: Springer International Publishing.

Vazquez, C. R., Recalde, L., & Silva, M. (2008, December). Stochastic continuous-state approximation of markovian Petri net systems. In 2008 47th IEEE Conference on Decision and Control (pp. 901-906). IEEE.

Venkatesh, K., & Zhou, M. (1999). Modeling, simulation, and control of flexible manufacturing systems: a Petri net approach (Vol. 6). World Scientific.

Huang, B., Zhou, M., Lu, X. S., & Abusorrah, A. (2023). Scheduling of resource allocation systems with timed Petri nets: A survey. ACM Computing Surveys, 55(11), 1-27.