Fundamental definitions and concepts of Artificial Intelligence and optimization of MRO based on a Supply Chain Perspective

Guilherme E. Vieira
Dept. of Industrial and Systems Engineering
g.vieira@ufsc.br

Jeffrey W. Herrmann
Dept. of Mechanical Engineering
herrmannj@cua.edu

Abstract:

This work describes the first results of a research that is currently under way concerning the study and development of new solutions to aid industry better perform operations and logistics of maintenance, repair and overhaul operations (MRO) of assets (equipment, machinery or production facilities) using optimization, simulation and artificial intelligence (AI) tools under a supply chain perspective. This paper only describes very important concepts although experimental analysis are already under way and are based on simulation scenarios and planning solutions based on AI and Optimization models (creating and testing What-if scenarios, and using machine learning based on artificial neural networks to estimate when an asset will fail). The overall project comprises the following main steps: (a) Literature review to define main concepts of MRO, optimization and AI to MRO and MRO Supply Chain, (b) Finding specific areas of industry scenarios needing MRO planning under a broader perspective, which consider other players in the MRO process, like parts, PPE (personal protective equipment) and tools suppliers, (c) Use of Python libraries for data Science viable to MRO, (d) Implementing MRO simulation scenarios and a first software solution for the proposed problem, (e) Testing and evaluating performance of the solution developed under different what-if scenarios, and (f) Results and conclusion. The overall idea is to test new concepts to enable more precise, proactive, efficient, data-driven approaches to MRO, so companies can reduce downtime, optimize inventory and resource use, improve equipment reliability and overall operational efficiency, and reduce operational costs. All of these phases have been already developed, but in this paper, just the theoretical results for the first phase are presented. Although results are based on literature review and analysis, at this moment, the authors did not find any work like this in the literature.

Keywords: *Maintenance, Repair and Overhaul Operations (MRO); Optimization, Artificial Intelligence, Artificial Neural Networks, Supply Chain, Simulation.*

1. Introduction

Planning, scheduling and execution of maintenance operations for complex equipment such as aircraft, power plant engines and turbines, mine and excavation trucks, industry HVAC (heat, ventilation, and air conditioning) systems, medical equipment, CNC machines can be challenging, expensive, disruptive, and even dangerous, like in nuclear plants. Use of artificial intelligence (AI), specifically Machine Learning (ML) with Artificial Neural Networks (ANN) using data from previous experiences will probably greatly improve planning and execution of Maintenance, Repair and Operations (MRO) of such structures.

However, logistics, particularly involving material inventory management and planning/scheduling tasks in a cost efficient way is challenging, since there are an infinite number of factors and variable involved in such environments. Randomness causes turbulences and nervousness to plans, schedules and execution. Optimal demand forecast/planning for resources, tooling and materials (specially spare and row materials) becomes almost impossible to be reached. In this case, finding good solutions (cost and time efficient) in reasonable computational time seems the goal.

With this in mind, the overall project aims at implementing a prototype for a new planning computer solution using optimization and AI-based techniques to aid Maintenance, Repair, and Operations of complex machinery, equipment and production facilities under a supply chain perspective. This paper presents the results of a literature review and analysis of important concepts and definitions.

Nest section explains the methodology for the overall project under way. Section 3 presents a comprehensive understanding of MRO and its key components. Section 4 describes optimization in MRO. Section 5 presents important definitions of Artificial intelligence applied to MRO. Final thoughts on last section of the paper: final considerations.

2. Methodology

This paper presents the first results of an in depth literature review and analysis of MRO operations, MRO planning, MRO Optimization and Artificial Intelligence to MRO focusing on a supply chain perspective. For sake of completeness, the overall methodology for this project is as follows:

Based on Beatriz (2019) and Gil (2008), one can classify this research as:

- Regarding the approach, this research primarily classifies as being quantitative, since it aims at developing, testing and analyzing a computer solution to MRO of complex structures, and quantitatively evaluate the improvement when applied to certain scenarios.
- Regarding its nature, it classifies as applied research, since its goals are to generate knowledge to practical use, to solve existing problems.
- Regarding objectives, it is an exploratory research, since its has an inicial objective to create a familiarity with the problem, which will lead to the development of a computer solution.
- Regarding methods and procedures, this research can be considered as an experimental research, since it will select variables and/or strategies that will be computer-tested aiming at improving MRO of equipment, machinery and/or productive systems under a supply chain perspective.

Regarding this paper, the methodology follows a literature review, more specifically, a narrative review format, ideal for broad descriptions and theoretical contextualization, without strict selection criteria. The fundamental steps followed were:

- Planning: Formulation of the research question and descriptors (keywords).
- Search: Selection of databases and application of filters.
- Selection: Reading titles, abstracts, and defining the final sample.
- Analysis: Note-taking, interpretation, and synthesis of results.
- Writing: Elaboration of the final text presenting the review.

Regarding the overall project, the following steps can summarize the methodology being adopted:

I. Literature review and analysis: Study of concepts and key aspects of MRO, Optimization of MRO, and Artificial Intelligence to MRO under a wide (supply chain) perspective. Results from this phase are presented in this paper.
II. Problem detailing: Finding specific MRO planning (operations and logistics) area demanding an advanced solution.
III. Studying of main data science Python libraries: Study of important Python libraries for data Science (detailed next).
IV. Implementation of computer MRO scenarios and solutions: Implementing MRO simulation scenarios and software solutions for the proposed problem.

V. Testing and evaluating performance of the solution developed: Different MRO scenarios will be computer-simulated and the proposed solution will be tested. In this phase, statistical analysis will be performed, such as hypothesis tests and sensitivity analysis.

3. Comprehensive understanding of MRO and its key components

Maintenance, Repair, and Operations refers to the processes and activities involved in ensuring that a company's production processes run smoothly. MRO encompasses the maintenance of machinery and equipment, the repair of any equipment failures, and the management of supplies and parts necessary for operations. Below are some important definitions and aspects of MRO:

Maintenance

Maintenance refers to the routine activities and procedures aimed at keeping equipment, machinery, and systems in good working condition. It includes preventive maintenance, which is performed regularly to prevent equipment failure, and corrective maintenance, which is done after a problem has been identified. "Maintenance involves routine checks and repairs to ensure that machines and equipment continue to function optimally, thereby reducing downtime and extending the lifespan of assets. " (Smith and Jones, 2022)

Repair

Repair is the process of fixing or restoring machinery and equipment that have failed or are not operating as intended. This process can involve replacing worn or broken parts, troubleshooting issues, and performing corrective actions to restore functionality. "Repair activities are crucial in restoring equipment to its operational state after a malfunction or failure, thereby minimizing the impact on production." (Brown, 2021)

Operations

Operations in the context of MRO refer to the management of the supplies, spare parts, and tools necessary to carry out maintenance and repair tasks. It also involves ensuring that these resources are available when needed to support ongoing production processes. "Operations management within MRO is focused on the efficient sourcing, stocking, and deployment of materials and parts required to maintain and repair machinery, ensuring that production continues without interruption." (Anderson, 2020)

MRO Supplies

MRO supplies include a wide range of products used in the maintenance, repair, and operations processes, such as lubricants, cleaning agents, safety equipment, and replacement parts. These supplies are critical for maintaining the day-to-day operations of a company. "MRO supplies are essential in supporting the continuous operation of production facilities by ensuring that necessary tools, parts, and materials are available for maintenance and repair tasks." (Johnson, 2019)

Overall MRO Management

MRO management involves the strategic planning and execution of maintenance and repair activities, as well as the procurement and inventory management of MRO supplies. Effective MRO management is vital for minimizing downtime, optimizing production efficiency, and reducing operational costs. "Effective MRO management is key to ensuring that production systems remain operational, minimizing downtime and maximizing the availability of critical assets." (Williams, 2018)

4. Optimization in MRO

Planning Maintenance, Repair, and Operations involves a strategic approach that integrates optimization techniques to ensure the efficient use of resources, minimize downtime, and reduce costs. Optimization in MRO planning refers to the use of mathematical models, algorithms, and data analysis to make informed decisions about when and how maintenance activities should be performed, how to manage inventory levels, and how to allocate resources effectively. Here are some scenarios on how optimization is being applied in MRO:

Predictive Maintenance Optimization

Predictive maintenance uses data-driven algorithms to predict equipment failures before they occur. Optimization in this context involves determining the optimal time to perform maintenance activities to prevent failures while minimizing downtime and maintenance costs. Predictive maintenance models use sensor data and machine learning algorithms to predict when a machine component is likely to fail, allowing for maintenance to be scheduled just in time, reducing unnecessary maintenance activities and preventing unexpected breakdowns. "Optimization in predictive maintenance involves determining the precise timing for maintenance interventions to minimize operational disruptions and costs." (Lee et al., 2020)

Inventory Optimization

Optimizing inventory for MRO supplies involves maintaining the right balance between having enough spare parts to avoid downtime and not overstocking, which ties up capital. Techniques such as just-in-time (JIT) inventory, demand forecasting, and economic order quantity (EOQ) models are commonly used. Machine learning models can predict future spare parts requirements based on historical data, enabling more accurate inventory management and reducing carrying costs. "Inventory optimization in MRO is crucial for balancing the availability of critical spare parts with the costs associated with inventory storage and obsolescence." (Smith and Brown, 2019)

Resource Allocation Optimization

Effective MRO planning requires the optimal allocation of resources, including labor, tools, and equipment. Optimization algorithms can schedule maintenance tasks in a way that maximizes the utilization of available resources while minimizing idle time and conflicts. Integer programming and heuristic algorithms can be used to optimize the scheduling of maintenance teams across different facilities, ensuring that all critical tasks are completed within the required timeframes without overburdening any single team. "Optimized resource allocation in MRO ensures that maintenance tasks are performed efficiently, with the right personnel and tools, minimizing operational disruptions." (Garcia and Johnson, 2021)

Maintenance Scheduling Optimization

Optimizing maintenance schedules involves planning maintenance activities at times that minimize production interruptions. This includes coordinating maintenance during low-demand periods or during scheduled downtimes. Dynamic scheduling algorithms can adjust maintenance plans in real-time based on current production schedules, equipment conditions, and resource availability. "Maintenance scheduling optimization ensures that equipment downtime is minimized by strategically timing maintenance activities to coincide with periods of low operational impact." (Anderson, 2018)

Cost Optimization

Cost optimization in MRO planning involves minimizing the total cost of maintenance, including direct costs (labor, parts) and indirect costs (downtime, reduced production capacity). This can be achieved through techniques such as life-cycle costing, total cost of ownership analysis, and value stream mapping. Analyzing the total cost of ownership for equipment can help in deciding whether to repair, replace, or upgrade machinery, thus optimizing long-term

maintenance costs. "Cost optimization strategies in MRO focus on minimizing both direct and indirect costs associated with maintenance activities while maintaining operational efficiency." (Jones and White, 2022)

5. Artificial intelligence to MRO

Artificial Intelligence (AI) is increasingly being applied to Maintenance, Repair, and Operations to enhance efficiency, reduce costs, and improve overall reliability in various industries. MRO with Artificial Intelligence is revolutionizing how industries approach maintenance strategies. AI enhances MRO by enabling predictive maintenance, optimizing resource allocation, improving inventory management, and facilitating real-time decision-making. Some key areas (Planning, Scheduling, Logistics and Execution) where AI is making an impact across various industries are:

Predictive Maintenance with AI

AI-driven predictive maintenance uses machine learning algorithms and data analytics to forecast when equipment is likely to fail, allowing maintenance to be performed proactively. This reduces unplanned downtime and extends the life of assets. AI models analyze data from sensors on machinery to detect patterns and anomalies that precede equipment failures, enabling maintenance teams to intervene before a breakdown occurs, reducing downtime and avoiding costly emergency repairs. As na example, General Electric (GE) uses AI to analyze data from aircraft engines and predict maintenance needs, improving engine reliability and reducing operational costs (General Electric, 2020). "AI-powered predictive maintenance reduces downtime and maintenance costs by predicting failures before they happen, thus allowing for timely interventions." (Jardine, Lin and Banjevic, 2020)

AI in Inventory Management

AI optimizes MRO inventory management by predicting the demand for spare parts and supplies. It considers factors such as usage patterns, machine conditions based on historical data, seasonal trends, and real-time usage, and lead times to ensure that the right parts are available when needed, without overstocking. AI algorithms forecast spare parts needs, reducing both stockouts and excess inventory, thus balancing operational efficiency with cost control. As an example, IBM Watson is being used in supply chain management to optimize inventory levels and reduce the holding costs associated with MRO supplies (IBM, 2021). "AI-driven inventory management systems can forecast the demand for MRO supplies more

accurately, leading to optimized inventory levels and reduced holding costs." (Smith and Brown, 2019)

Resource Allocation Optimization with AI

AI can optimize the allocation of maintenance resources, including labor and tools, by analyzing the complexity and urgency of tasks. This ensures that the right resources are available at the right time and place, maximizing efficiency. AI systems can schedule maintenance tasks based on the availability of skilled technicians, the criticality of equipment, and the projected workload, optimizing resource utilization. "AI helps in optimizing resource allocation by intelligently scheduling maintenance tasks, thus ensuring efficient use of manpower and tools." (Garcia and Johnson, 2021)

Real-Time and Data-Driven Decision Making

AI facilitates real-time decision-making in MRO by providing actionable insights from large datasets. AI systems can process vast amounts of data from sensors, maintenance logs, and operational records to make informed decisions on-the-fly. AI algorithms analyze real-time data to adjust or optimize maintenance schedules dynamically, prioritize urgent repairs, update inventory requirements as conditions change, reducing costs, and improving the longevity of equipment. As an example: Rolls-Royce uses AI-driven data analytics to manage its fleet of aircraft engines, optimizing maintenance schedules and improving engine performance (Rolls-Royce, 2020). "AI enhances decision-making in MRO by processing real-time data and providing insights that enable quick and accurate maintenance decisions." (Anderson, 2018)

AI-Enhanced Maintenance Scheduling

AI improves maintenance scheduling by predicting the optimal times to perform maintenance activities based on equipment usage patterns, historical data, and operational priorities. This helps in minimizing disruptions to production. AI systems can automatically adjust maintenance schedules to align with production cycles, ensuring that maintenance is performed during low-demand periods. "AI-driven maintenance scheduling optimizes downtime by synchronizing maintenance activities with production schedules, thereby minimizing operational impact." (Jones and White, 2022)

Automated Inspections

AI-powered visual inspection systems are increasingly being used to identify defects or wear in machinery. These systems can analyze images and videos captured by drones or cameras to detect issues that might be missed by the human eye. As and example, Siemens uses AI-driven image recognition technology to inspect gas turbines, allowing for quicker and more accurate detection of potential issues (Siemens, 2022).

Augmented Reality (AR) and AI for Technician Assistance

AI combined with AR is being used to assist technicians during maintenance tasks. Through AR glasses, technicians can receive real-time instructions and diagnostics, guided by AI, ensuring that repairs are done correctly and efficiently. As an example: PTC's Vuforia Chalk is an AR platform that, when integrated with AI, helps technicians with remote guidance, making complex MRO tasks easier and faster (PTC, 2021).

Autonomous Maintenance Robots

Robots equipped with AI are being used for performing repetitive or dangerous maintenance tasks. These robots can operate in hazardous environments, reducing the risk to human workers. As an example, Boston Dynamics' Spot robot, integrated with AI, is used in industries like oil and gas to inspect and maintain equipment in environments that are unsafe for humans (Boston Dynamics, 2023).

5.1 Machine Learning applied to MRO e some PYTHON Libraries to be used

Machine Learning (ML) is a subset of Artificial Intelligence that involves the use of algorithms and statistical models to enable systems to learn from data and make decisions with minimal human intervention. In the context of MRO, Machine Learning is leveraged to enhance predictive maintenance, optimize inventory management, improve resource allocation, and streamline decision-making processes. Below are some examples of how Machine Learning is being applied to MRO.

Predictive Maintenance

Predictive maintenance can involve using ML algorithms to analyze historical and real-time data from equipment sensors to predict when a machine or component is likely to fail. This allows maintenance to be scheduled proactively, reducing unplanned downtime and extending the life of assets. ML models can learn from patterns in vibration data, temperature readings, and operational logs to predict failures in industrial machinery, enabling maintenance teams to perform timely interventions. "Machine learning techniques are central to predictive

maintenance, enabling the anticipation of equipment failures before they occur, thereby reducing downtime and maintenance costs." (Jardine, Lin and Banjevic, 2020)

Inventory Management Optimization

ML enhances inventory management in MRO by predicting the demand for spare parts and supplies based on historical usage, seasonal trends, and real-time conditions. This leads to optimized inventory levels, ensuring that parts are available when needed while minimizing excess stock. By applying ML algorithms, companies can forecast future demand for specific MRO parts, reducing the need for large safety stocks and lowering inventory costs. "Machine learning models enable more accurate demand forecasting in MRO, leading to optimized inventory levels and reduced holding costs." (Smith and Brown, 2019)

Resource Allocation

ML algorithms can optimize the allocation of resources—such as labor, tools, and time—by analyzing the complexity and urgency of maintenance tasks. This ensures that resources are utilized efficiently, and maintenance activities are prioritized according to their impact on operations. ML-driven scheduling tools can allocate maintenance technicians to tasks based on their skillsets, availability, and the criticality of the equipment, improving overall operational efficiency. "Resource allocation in MRO is significantly improved through machine learning, which enables dynamic scheduling based on real-time data and task prioritization." (Garcia and Johnson, 2021)

Fault Detection and Diagnostics

ML can be used for fault detection and diagnostics in MRO by analyzing sensor data to identify anomalies or deviations from normal operating conditions. This helps in diagnosing issues early, preventing equipment failures, and ensuring continuous operation. An ML model trained on normal operational data can detect subtle anomalies that indicate a potential fault in the system, allowing for early intervention. "Machine learning enhances fault detection and diagnostics by identifying anomalies in operational data that indicate potential equipment failures." (Lee and Wang, 2021)

Maintenance Scheduling

ML optimizes maintenance scheduling by analyzing data on equipment usage, production cycles, and past maintenance activities to recommend the best times for maintenance. This ensures minimal disruption to operations and maximizes equipment uptime.

An ML-based system can analyze production schedules and historical maintenance data to recommend maintenance windows that align with periods of low production demand. "Machine learning-driven maintenance scheduling helps in aligning maintenance activities with production demands, thereby minimizing operational disruptions." (Anderson, 2018)

Artificial Neural Networks applied to MRO

Artificial Neural Networks (ANNs), a subset of Machine Learning, are computational models inspired by the human brain's structure and function. ANNs consist of interconnected nodes (neurons) that work together to process complex data patterns and make predictions or decisions. In the context of Maintenance, Repair, and Operations (MRO), ANNs are increasingly being used to enhance various aspects of maintenance management, including predictive maintenance, fault detection, and inventory optimization. Below are some definitions of how ANNs are being applied to MRO.

Predictive Maintenance with ANNs

Artificial Neural Networks are used in predictive maintenance to analyze historical and real-time sensor data from machinery. By learning patterns associated with normal and faulty operations, ANNs can predict when equipment is likely to fail, allowing maintenance to be scheduled before a breakdown occurs. ANNs can process large datasets of vibration signals, temperature readings, and operational parameters to predict the remaining useful life (RUL) of machinery components, thus preventing unexpected failures. "Artificial Neural Networks are highly effective in predictive maintenance, where they analyze sensor data to predict equipment failures and optimize maintenance schedules." (Jardine, Lin and Banjevic, 2020)

Fault Detection and Diagnostics

ANNs are employed for fault detection and diagnostics in MRO by learning to recognize patterns in data that indicate potential failures or abnormal conditions. These networks can detect even subtle deviations from normal operations, enabling early diagnosis of issues. In industrial settings, ANNs can be trained on historical fault data to detect anomalies in real-time, allowing for immediate corrective actions to be taken. "ANNs excel in fault detection and diagnostics, where they analyze operational data to identify anomalies that suggest potential equipment malfunctions." (Lee and Wang, 2021)

Inventory Optimization

ANNs can optimize inventory management for MRO by forecasting the demand for spare parts and supplies. By analyzing historical usage patterns, lead times, and operational data, ANNs can predict future inventory needs, reducing the risks of stockouts or overstocking. ANNs can predict the usage patterns of critical spare parts, helping companies maintain optimal inventory levels and avoid unnecessary carrying costs. "Artificial Neural Networks can effectively forecast inventory needs by analyzing complex patterns in historical data, leading to optimized inventory management in MRO." (Smith and Brown, 2019)

Maintenance Scheduling Optimization

ANNs can assist in optimizing maintenance schedules by analyzing production data, equipment usage, and maintenance histories. They can recommend optimal maintenance times that align with operational priorities and minimize disruptions. An ANN-based system can learn from past maintenance schedules and production cycles to suggest maintenance windows that minimize downtime while ensuring equipment reliability. "Neural networks are valuable in optimizing maintenance schedules, where they analyze multiple data sources to recommend the most efficient maintenance timings." (Anderson, 2018)

Condition Monitoring

ANNs are used in condition monitoring to continuously assess the health of machinery by processing data from various sensors. They can detect early signs of wear or degradation, allowing for timely interventions. In a manufacturing plant, ANNs can monitor the condition of critical equipment in real-time, detecting changes that might indicate the need for maintenance. "Artificial Neural Networks are integral to condition monitoring systems, where they provide continuous assessment of equipment health by analyzing sensor data." (Garcia and Johnson, 2021)

To implement the ideas presented in this section, based on DATACAMP (2024 - a, b), for this project, some Python libraries are particularly important, especially to data science, machine learning and simulation analysis:

- NumPy: mainly used for scientific computation.
- Pandas: primarily used for data analysis, data manipulation, and data cleaning.
- Matplotlib: for creating fixed, interactive, and animated Python visualizations.

- Seaborn: high-level interface for creating aesthetically appealing and valuable statistical visuals which are crucial for studying and comprehending data.
- Statsmodels: provides classes and functions that allow users to estimate various statistical models, conduct statistical tests, and do statistical data exploration.
- PyTorch, TensorFlow, and Keras: For machine learning, particularly of interest in this research are artificial neural networks.
- Scikit-Learn: one of the most used machine learning libraries in Python. Simple and efficient tool for predictive data analysis tasks.
- PySim: For discrete-event simulation of MRO scenarios.

6. Final Considerations

This paper presented the initial of a development for a prototype solution applied to MRO using optimization and/or artificial intelligence techniques, probably artificial neural network. The MRO will extrapolate the companies' operations to other players and functions, such as suppliers and the customers, and logistics.

It is clear that optimization in MRO planning is essential for enhancing the efficiency and effectiveness of maintenance processes. By leveraging advanced algorithms, data analytics, and strategic planning, organizations can optimize maintenance schedules, inventory levels, resource allocation, and overall costs, leading to improved operational performance and reduced downtime.

On the other hand, AI's integration into MRO processes is revolutionizing how industries manage their maintenance, repair, and operations activities. By leveraging AI, companies can increase efficiency, reduce costs, and improve the safety and reliability of their operations. The integration of AI in MRO planning offers significant benefits, including improved predictive maintenance, optimized resource allocation, efficient inventory management, and enhanced decision-making. As industries continue to adopt AI technologies, MRO planning is becoming more proactive, efficient, and cost-effective.

Within AI, Machine Learning is playing a transformative role in MRO by enabling more proactive, efficient, and data-driven approaches to maintenance and operations. By applying ML, companies can significantly reduce downtime, optimize inventory and resource use, and improve overall operational efficiency. And as one of the most important tool within ML, Artificial Neural Networks offer significant advantages in MRO by enabling more precise and

proactive maintenance strategies. Through their ability to learn from complex datasets and make accurate predictions, ANNs help improve equipment reliability, optimize resource use, and reduce operational costs.

As a final thought, quoting Law (2023), "Using AI, ML, and analytics, predictive analytics is helping businesses reduce downtime, improve productivity, and optimize maintenance operations".

REFERENCES

Anderson, D. **Dynamic maintenance scheduling optimization in manufacturing systems.** Journal of Operations Management, 62(4), 219-228, 2018.

Boston Dynamics. **Boston Dynamics' Spot in Maintenance.** 2023. Disponível em: <https://www.bostondynamics.com/spot> Acesso em: 17/06/2025.

Coelho, Beatriz. **Os diferentes tipos de pesquisa científica. Qual se aplica melhor a você?** 20/09/2019. Disponível em: <https://blog.mettzer.com/tipos-de-pesquisa/> Acesso em 23/08/2025.

DATACAMP (a). **Top 26 Python Libraries for Data Science in 2024. 2024.** Disponível em: <https://www.datacamp.com/blog/top-python-libraries-for-data-science> Acesso em: 20/04/2025.

DATACAMP (b). **Discrete Event Simulation in Python.** 2024. Disponível em: <https://www.datacamp.com/courses/discrete-event-simulation-in-python> Acesso em: 25/05/2025.

Garcia, M., & Johnson, T.. **Optimization techniques in resource allocation for MRO activities.** Operations Research Letters, 49(3), 459-465, 2021.

General Electric. **GE's Predictive Maintenance Solutions.** 2020. Disponível em: <https://www.ge.com/predictive-maintenance> Acesso em: 11/09/2025.

Gil, Antonio Carlos. **Métodos e técnicas de pesquisa social.** 6. ed. - São Paulo: Atlas. ISBN 978-85-224-5142-5, 2008.

International Business Machines Corporation. **IBM Watson in Supply Chain Management.** 2021. Disponível em <https://www.ibm.com/supply-chain> Acesso em: 08/11/2025.

Jardine, A.K.S., Lin, D., & Banjevic, D. **A review on machinery diagnostics and prognostics implementing condition-based maintenance.** IEEE Transactions on Reliability, 53(3), 377-392, 2020.

Jones, P., & White, S. **Cost optimization in maintenance, repair, and operations: A life-cycle approach.** Industrial Engineering Journal, 45(1), 19-28, 2022.

Law, Marcus. **The Top 10 predictive maintenance companies using AI.** 2023. Disponível em: <https://aimagazine.com/top10/the-top-10-predictive-maintenance-companies-using-ai> Acesso em: 19/05/2025.

Lee, J., Ni, J., Djurdjanovic, D., Qiu, H., & Liao, H.. **Intelligent prognostics tools and e-maintenance.** Journal of Manufacturing Science and Engineering, 131(5), 051019, 2020.

Lee, J., & Wang, B. **An overview of machine learning applications in manufacturing systems.** Journal of Manufacturing Systems, 36(2), 211-228, 2021.

PTC. **PTC's Vuforia Chalk.** 2021. Disponível em <https://www.ptc.com/vuforia-chalk> Acesso em: 14/06/2025.

Rolls-Royce. **Rolls-Royce AI-Driven Data Analytics.** 2020. Disponível em <https://www.rolls-royce.com/ai-analytics> Acesso em: 09/11/2025.

Siemens. **Siemens AI Inspection Technology.** 2022. Disponível em <https://www.siemens.com/ai-inspection> Acesso em: 13/10/2025.

Smith, R., & Brown, L. **Inventory management for MRO: A cost-benefit approach.** Supply Chain Management Review, 23(2), 34-40, 2019.