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Overcoming Data Acquisition Challenges in Predictive Maintenance for Military Applications: A Systematic Literature Review

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Contents

List of Tables and Figures

Abstract

In recent years, the military has faced heightened scrutiny regarding its data acquisition methods, which have been criticized for being outdated and time-consuming. These processes have struggled to keep pace with rapid technological advancements. The prolonged durations, often stretching across years, have put the Department of Defense (DoD) in a challenging position, hindering its ability to embrace cutting-edge technologies that could significantly enhance resources available to military personnel. Among these transformative technologies are artificial intelligence (AI) and machine learning, both holding immense potential for revolutionizing military operations. However, the DoD grapples with effectively harnessing these innovations due to the complexities of the acquisition process. This study specifically delves into the challenges faced during the acquisition of Predictive Maintenance Technology (PdM), a field poised to revolutionize military logistics and operational efficiency. The aim is to illuminate these obstacles comprehensively. By thoroughly understanding these challenges, the research endeavors to pave the way for more streamlined, efficient, and responsive acquisition processes. The ultimate objective is to enable the military to adeptly leverage emerging technologies to their fullest potential, providing invaluable support to those on the front lines and empowering the armed forces to effectively meet the demands of contemporary and future warfare. Through this in-depth analysis, the study aspires to offer crucial insights that could reshape the future landscape of military acquisitions. It aims to foster an environment conducive to the seamless integration of transformative technologies into defense operations, contributing significantly to the evolution of military capabilities.

1 Introduction

In this systematic literature review, the interconnected dynamics data acquisition, and predictive maintenance technology within military operations have been analyzed comprehensively. The study reveals that the seamless integration of these elements is imperative for ensuring the optimal functioning of military systems. Effective data management is essential to maintain the functionality, security, and relevance of military applications. Simultaneously, efficient data acquisition processes are crucial for integrating cutting-edge technologies, such as predictive maintenance systems. Predictive maintenance technology, powered by sophisticated software algorithms, plays a pivotal role in forecasting equipment failures and optimizing maintenance schedules. The synthesis of these aspects is vital in enhancing military operational readiness, reducing downtime, and extending the lifespan of critical assets. This review underscores the significance of a holistic approach, where software management, data acquisition, and predictive maintenance technology are tightly interwoven, leading to streamlined and effective military operations.

1.2 Rational

Efficiency is paramount in military operations, and optimizing performance through predictive maintenance is pivotal for operational readiness. Understanding the nuances of data acquisition and predictive maintenance technology enables military organizations to streamline procedures, minimize downtime, and ensure equipment functionality when needed, thus enhancing overall operational efficiency. In the paper titled "Artificial Intelligence in Armed Forces," the author discusses the transformative impact of AI. This aspect holds significant importance for national security, as a military able to swiftly develop and effectively employ such technologies gains a formidable competitive edge {Mallick, 2018 #7}. The president of the United States recently released an executive order on artificial intelligence, and the ethical concerns that face our nation in height of this technology. Additionally In the article Explainable Artificial Intelligence, the article lists some challenges specifically related to artificial intelligence. Some of these challenges include the gap between the research community and business sectors, which impedes the full allocation of the latest technologies of the AI realm. The digital transformation processes technologies have lagged. {Arrieta, 2020 #19}. Furthermore, the complexity and opacity of some AI models, such as Deep Neural Networks, can be incomprehensible to the end user on the model's decision making {Arrieta, 2020 #19}. These challenges also pose significant barriers to achieving transparency and interpretability in AI models. The study's examination of Predictive Maintenance (PdM) equips the Department of Defense (DoD) with invaluable insights, aiding well-informed decisions regarding data acquisition and implementation strategies. Numerous articles describe various technical processes that are involved in predictive monitoring for example, data acquisition, pre-processing, feature processing, and artificial intelligence {Saini, 2022 #60},{Tiddens, 2022 #76}. This knowledge revolutionizes maintenance practices, reducing downtime and improving asset availability. Predictive maintenance not only enhances asset reliability and reduces maintenance expenses but also extends asset lifespan. By optimizing maintenance practices and avoiding costly corrective measures, the Department of Defense can significantly improve operational efficiency, ensuring mission preparedness and reducing related costs. Moreover, predictive maintenance transforms aircraft sustainment and operations by enabling informed decision-making, reducing the risk of failure, and enhancing operational availability. It prevents unplanned maintenance activities, unnecessary inspections, and replacements of undamaged parts, thereby minimizing costs {Scott, 2022 #79}. However, scaling predictive maintenance necessitates embedding it into various decision-making levels, with operational use particularly reliant on trust and acceptance of proposed solutions {Scott, 2022 #79}. Additionally, the following article discusses the challenges associated to maintenance, including the difficulty of accurately predicting the remaining life of a system, the uncertainty associated with predicted service life, and the need to balance maintenance costs with system availability and reliability {Tinga, 2010 #20}. Other challenges include the need to develop accurate models of the system, the need to monitor usage or loading of the system, and the need to develop appropriate maintenance strategies based on the monitored data {Tinga, 2010 #20}. In essence, this research strives to enhance military operational efficiency, promote cost-effectiveness, drive technological innovation, and strengthen national security. By delving into the intricate relationships between data acquisition and predictive maintenance technology, this study provides a foundational framework for informed decision-making within military contexts. Ultimately, these advancements benefit defense capabilities, fortifying national security and readiness.

1.3 Objectives

The research objective is multifaceted, aiming to explore the complex interconnections between data acquisition processes and predictive maintenance technology in military settings. Specifically, the study focuses on the challenges related to data acquisition in predictive maintenance technology within the defense sector. Firstly, the study seeks to comprehensively understand how data acquisition processes are orchestrated, evaluated, and aligned with the deployment of predictive maintenance solutions, emphasizing the intricacies of procurement and integration. This includes investigating how these processes impact operational readiness. Secondly, it aims to identify and analyze challenges related to the procurement and integration of data acquisition systems into military equipment, emphasizing issues such as compatibility, cybersecurity, and data integration in the context of predictive maintenance technology. Thirdly, the research assesses the impact of streamlined data acquisition processes on the operational efficiency of military systems, particularly in terms of reducing downtime, optimizing maintenance schedules, and prolonging the lifespan of critical assets. Navigating the complexities of maintenance systems involves various conflicting factors. My objective is to systematically tackle the challenge of data acquisition using systems theory. I aim to provide a solution by incorporating game theory algorithms, enabling predictions that consider the competing objectives in this intricate process. A methodical strategy for data acquisition will significantly influence how the algorithm is trained, ultimately showcasing the interrelated nature of the process.

2 Background Theory

Systems Theory assumes a vital role by offering a holistic outlook on intricate systems, particularly pertinent in military contexts. Viewing data acquisition processes as interconnected elements within a broader system, Systems Theory enables seamless integration of diverse data sources. This integrated approach empowers the DoD to refine and optimize data acquisition methods, ensuring that collected data is not only accurate but also relevant and actionable within the realm of predictive maintenance. Moreover, the foundational theory underpinning data acquisition challenges within the Department of Defense (DoD) is Game Theory. When applied to predictive maintenance algorithms, Game Theory introduces strategic decision-making concepts. By understanding competitive interactions and incentives among different entities, Game Theory informs the development of algorithms, optimizing decision strategies for maintenance actions. It provides a unique perspective on predictive maintenance, enhancing its efficiency and effectiveness within military applications. The systematic implementation of Game Theory, complemented by Systems Theory insights, is crucial for addressing the distinctive challenges faced by the DoD. Comprehensive documentation, interdisciplinary collaborations, and continuous feedback loops form the core of this systematic approach. These theories create a robust foundation for overcoming data acquisition hurdles, enabling the DoD to adapt to real-world applications and technological advancements effectively. This iterative process of refinement ensures that the DoD remains at the forefront of data acquisition methodologies, enhancing its capabilities and decision-making processes. In summary, the integration of Game Theory and Systems Theory forms a comprehensive background framework supporting the DoD in addressing data acquisition challenges. Adhering to these theories, the DoD can establish systematic and reliable data acquisition processes essential for informed decision-making, operational efficiency, and strategic planning in the context of predictive maintenance algorithms.

3 Research Methods

The systematic literature review followed a rigorous methodology that involved several stages. The review highlights gaps in the research area. In this report, I will follow the PRISMA research methodology.

3.1 Research Questions

In this systematic literature review (SLR), the central inquiry revolves around exploring the integration of predictive maintenance technologies with vital defense processes such as logistics, supply chain management, and mission planning. The central inquiry of any research endeavor, including this study, is the research question. To formulate the research questions, the existing research in predictive maintenance was leveraged, and an initial search on Predictive Maintenance technology within the military domain was conducted. Extracted samples from the selected papers were evaluated to assess the potential relevance of conducting an SLR in this field. The preliminary analysis affirmed the relevance of the topic. Hence, based on these initial findings, the overarching research question (ORQ) that steers this investigation was formulated: Two key research questions guide this comprehensive investigation:

1. "What are the most effective ways to integrate predictive maintenance with other defense processes, such as logistics, supply chain, or mission planning?"
2. "How can we standardize the evaluation metrics and datasets used in predictive maintenance studies to facilitate comparison and generalization of results?"
3. "What method of data acquisition is optimal for predictive maintenance algorithms"?

The integration of predictive maintenance technologies into defense operations is critical for ensuring equipment reliability and mission readiness. This review aims to identify innovative strategies and best practices employed across diverse defense sectors to achieve seamless acquisition and integration effectively. Additionally, it explores the challenges associated with standardizing evaluation metrics and datasets, a crucial aspect for meaningful comparison and generalization of results across studies. The following questions were derived from the ORQ, these questions will be referred to as specific research questions (SRQ)

1. What methodologies have been employed to integrate predictive maintenance with defense logistics systems, ensuring timely and efficient equipment repairs and replacements?
2. How are predictive maintenance insights utilized in mission planning to ensure the availability and reliability of mission-critical equipment during military operations?
3. What types of datasets are typically utilized in predictive maintenance research within defense contexts, and how can these datasets be made publicly available for research purposes?
4. How can data privacy and security concerns be addressed while sharing predictive maintenance datasets, ensuring compliance with regulations and ethical standards?
5. What methodologies have been proposed for the comparative analysis of predictive maintenance techniques, allowing researchers to assess the performance of different algorithms and approaches?

By addressing these specific sub-questions, the systematic literature review can provide a comprehensive understanding of the integration strategies and challenges associated with predictive maintenance in defense processes. This approach also offers insights into standardizing evaluation metrics and datasets for meaningful cross-study comparisons and generalizations.

3.2 Eligibility Criteria

The criteria for inclusion in this review require that the research must be published in a journal and be in the English language. Additionally, the research should be relevant to the defense industry, specifically within the field of aviation. Studies conducted between the present date and the last five years are eligible for consideration. The acceptable study designs include case studies and qualitative research focused on the topic of interest. The context of the research should be its application to defense industries in aviation. Research that is outdated or not conducted within the scope of the U.S. Military will be excluded from the review.

3.3 Information Sources

In this comprehensive literature review, I will employ several sources. I will initiate the search using Compendex (Ei engineering village) and extend the exploration to include IEEE Xplore and Google Scholar. Additionally, I will utilize Endnote and Scopus for citation and result archiving purposes.

3.4 Search Strategy

The modified search approach aims to pinpoint research journals concentrating on predictive maintenance methods in the defense sector. After selecting these journals, I will scrutinize each report to identify challenges or gaps mentioned within. Once I comprehend the existing research and its challenges, I will explore other sectors that might have resolved similar issues. Subsequently, I will examine the supplementary materials cited in the articles. The articles are sorted and selected by most relevant. The data was selected by the title. The title must have relevance to data acquisition of physical sensor or parts that may be utilized for predictive maintenance techniques.

Table 1: Search Strategy

Search Term	Number of Results Returned	Results Filtered on Journal Articles	Articles withing the last five years and in English
“Predictive maintenance" AND “military”	101	28	12
“Data Acquisition" AND "Military”	3,148	935	153
"Game theory" and "Maintenance”	1098	708	257
"Systems Theory" and "Data Acquisition”	132	78	12

3.5 Paper Selection Process

During the paper selection procedure, I will evaluate the titles and abstracts. In the initial phase of the extraction process, two questions must be addressed regarding the title and abstract:

Question	Inclusivity Weight
Question 1: Has the research objective been clearly stated?	1.0
Question 2: Does the research context specifically relate to the military?	2.0
Question 3: Does the research objective pertain to predictive maintenance technology?	2.0
Question 4: Does the report contain information regarding Data Acquisition	3.0

Question 5: Does the report contain information regarding System Theory?	3.0
Question 6: Does the report contain information regarding Game Theory?	3.0

If all the questions receive positive responses, the paper will proceed to a detailed analysis, specifically focusing on the introduction section. The introductions of papers meeting both criteria will be automatically integrated into the literature review. In cases where a response to a question is partly affirmative, an in-depth examination of the report will be carried out for additional evaluation. If the report partially meets the criteria, a comprehensive analysis of the full text will be conducted. If the comprehensive analysis is weighted heavily by the scale listed in the table, the report is included. If the report addresses any of the research questions, it will be included. Papers that do not meet the criteria for both questions will be excluded from further review.

4 Search Outcomes and Prioritization

4.1 Selection Process

The revised search strategy is geared towards identifying specialized research journals focused on predictive maintenance techniques in the defense sector. After the selection of these journals, I will meticulously analyze each paper to pinpoint challenges or gaps mentioned therein. My understanding of the existing research and its associated challenges will lead me to explore analogous issues resolved in other sectors. Additionally, I will scrutinize supplementary materials cited in the articles for further insights. To illustrate, the table below displays the refined results of the initial query. To be included in the literature review, an article must meet the criteria outlined in the first question presented in the table: the research objective must be clearly stated. Subsequent questions carry additional weights, allowing for a comprehensive evaluation. Articles with the highest relevance to all five questions and the highest rankings were meticulously chosen for the review. The last column of the table represents the weighted total of inclusivity. The columns following the title indicate the cumulative weight obtained in Table 1 above. The last column represents the overall scale, encompassing the total weight of the articles examined in this review. The table was condensed due to its extensive length.

Table 2: Selection Process

Title	Q1	Q2	Q3	Q4	Q5	S
Artificial intelligence for predictive maintenance	1	0	2	0	0	3
Towards Data Acquisition for Predictive Maintenance of Industrial Robots	1	0	2	0	0	3
A practical and synchronized data acquisition network architecture for industrial robot predictive maintenance in manufacturing assembly lines	1	0	2	0	0	3
Instrumentation and data acquisition techniques for development of predictive maintenance of load tap changers	1	0	2	0	0	3
Predictive maintenance of military systems based on physical failure models	1	2	2	0	0	5
Predictive Maintenance of Armored Vehicles using Machine Learning Approaches	1	2	2	0	0	5
A Systematic Literature Review of Predictive Maintenance for Defense Fixed-Wing Aircraft Sustainment and Operations	1	2	2	0	0	5
Predictive Maintenance in the Military Domain: A Systematic Review of the Literature	1	2	2	0	0	5
A Predictive Model for Forecasting Spare Parts Demand in Military Logistics	1	2	2	0	0	5
Using big data analytics to create a predictive model for Joint Strike Fighter	1	2	2	0	0	5
Predictive Monitoring of Incipient Faults in Rotating Machinery: A Systematic Review from Data Acquisition to Artificial Intelligence	1	0	2	3	0	6

4.2 Data Extraction

The process of data extraction involved targeted searches for context relevant to the subsequent analysis. The literature review was segmented into distinct components. The initial segment comprised systematic literature reviews conducted on comparable topics within Predictive Maintenance (PdM). Reports that claimed to have performed systematic reviews on predictive maintenance techniques were included in the review, with a focus on highly cited reports. I scrutinized reports cited in these systematic literature reviews that delved into specialized areas. Finally, data pertinent to the application of systems theory in data acquisition and game theory in predictive maintenance were extracted.

4.3 Synthesis and Analysis:

In this review, I organized the chosen academic articles into distinct categories based on their contexts. The initial category encompasses systematic literature reviews, offering comprehensive insights into predictive maintenance techniques within the defense industry. The second category comprises reviews focusing on specific studies that explore the application of predictive maintenance across diverse industries. The third category encompasses journals related to game theory, shedding light on its relevance in predictive maintenance contexts. Another category delves into the characteristics and challenges associated with data acquisition in the predictive maintenance industry. Lastly, to bolster the theoretical framework, I examined articles from the realm of systems theory.

Figure 1: Synthesis and Results

5 Risk of bias in individual studies

In the study examining the integration of predictive maintenance technologies in defense processes, numerous potential biases could influence the research outcomes. Recognizing and mitigating these biases are essential to ensuring the study's accuracy and reliability. The eligibility criteria established for the review introduce several potential sources of bias. By exclusively considering journal entries, there is a risk of publication bias, potentially overlooking valuable insights from unpublished sources. The restriction to English language publications may introduce language bias, excluding relevant studies published in other languages. Focusing solely on the defense industry might lead to industry relevance bias, disregarding valuable perspectives from related sectors. The temporal restriction, limiting studies to those conducted between the present date and the 2000s, could introduce temporal bias by excluding older studies providing historical context or foundational knowledge. Allowing only case studies and qualitative research poses a risk of study design bias, potentially neglecting experimental or quantitative studies. The specific emphasis on research applied to defense industries in aviation might result in context bias, missing broader insights from other areas within the defense industry. The exclusion of studies not conducted on the U.S. Military could introduce geographical bias, limiting the review to international military contexts. Lastly, excluding outdated research could lead to exclusion bias, potentially overlooking historical studies that provide crucial perspectives on the evolution of practices and technologies in the defense industry. Addressing these biases is vital to maintain the transparency and rigor of the review process. Acknowledging and actively managing these potential biases in research design, data collection, analysis, and interpretation are essential to enhance the robustness and credibility of the study findings. Transparent communication about the limitations and potential biases in the research is pivotal for conducting a comprehensive and unbiased analysis.

6 Literature Review

The review investigates the challenges encountered in predictive maintenance methods, employing a bottom-up strategy. It commences by evaluating the issues related to predictive maintenance technology within the Department of Defense (DoD) and then explores potential solutions through the application of systems theory management and game theory. Initially, the analysis will focus on articles that have conducted systematic literature reviews on predictive maintenance technology. Subsequently, the focus will shift to reports offering solutions to the challenges identified in these reviews. The examination will include how other articles have tackled these challenges and identify any gaps in the existing research. Lastly, the review will assess articles providing supporting data for the theoretical framework. The underlying theory posits that applying systems theory and management processes can overcome challenges in data collection. Additionally, game theory algorithms can enhance maintenance predictions. Game theory has the potential to revolutionize technology by considering multiple data points collectively, such as supply chain demands and actual maintenance needs. However, the diverse priorities and constraints in different industries can lead to conflicts in decision-making. Game theory aims to address these complex interactions by considering the requirements and restrictions of all decision-makers involved.

The primary objective is to investigate research questions related to predictive maintenance algorithms and data management in software systems, especially concerning Department of Defense acquisitions. Several key challenges were identified in the military domain, including issues related to data availability and quality. Limited data availability impacts the construction of effective machine learning models, leading to challenges in dataset quality and prediction accuracy {Carvalho, 2019 #26}. Another study highlighted challenges in implementing data-driven predictive maintenance for aircraft, including data-related risks such as loss, corruption, and transmission delays. Additionally, the lack of standardization in data collection and processing emerged as a significant challenge, affecting the accuracy and reliability of predictive maintenance results. The complexity of machine learning algorithms and the need for substantial data further posed barriers to implementation. Overall, the recurring theme across these studies is the challenge posed by insufficient data to support predictive maintenance methods. In the article titled "Predictive Maintenance in the Military Domain: A Systematic Review of the Literature," several key challenges were identified. According to the study, one of the significant challenges in predictive maintenance in the military domain is related to data availability and quality {Dalzochio, 2023 #10} . The authors noted that constructing effective learning models demands a substantial volume of labeled data for machine learning training. Ensuring this data comprehensively covers all potential failure scenarios is crucial. However, practical limitations often result in a scarcity of information about monitored asset failures, directly affecting dataset quality and, consequently, the accuracy of machine learning-based prediction models. Therefore, further research is needed to develop more effective methods for addressing the challenges of data availability and quality in the military domain. Regarding the limitations of predictive maintenance algorithms, the study notes that there is no universal solution or approach to using predictive maintenance {Dalzochio, 2023 #10}. The authors identified six groups of approaches, including Framework, Model-based, Data-driven, Features Modeling, Maintenance Policy, and Agent software {Dalzochio, 2023 #10}.Each approach has its strengths and limitations, and selecting the most appropriate approach depends on several factors, such as the type of equipment, the available data, and the maintenance objectives. Additionally, the accuracy of predictive maintenance algorithms is directly related to the quality and quantity of the data used to train the models {Dalzochio, 2023 #10}. Another article also suggests a similar framework. In the article exploring predictive maintenance applications in the industry, the framework provides a direct view on the inputs used and results obtained with the various predictive maintenance applications. The four elements are initiation, data collection, maintenance technique selection, and decision-making {Tiddens, 2022 #76}. Each element contains several options, from which one must be selected. The paper notes that the order of the elements is not fixed, and the elements can be considered in a different order. The paper also categorizes maintenance techniques (MTs) on the required input, which can be either data-driven, knowledge- and physical model-based, or a combination of the three {Tiddens, 2022 #76}. Data-driven approaches rely on the assumption that only little changes occur in the statistical characteristics of the data unless a malfunction occurs in the system {Tiddens, 2022 #76}. The efficacy of these models depends, however, severely on the quality and quantity of input data {Tiddens, 2022 #76}. Physical models need an accurate mathematical model, in which the behavior of a failure mode is quantitatively characterized using physical laws {Tiddens, 2022 #76}. Physical models are more complex and require more input data than data-driven models {Tiddens, 2022 #76}. Finally, knowledge-based models rely on expert knowledge and experience to identify potential failure modes and their causes {Tiddens, 2022 #76}. The article titled "A Systematic Literature Review of Predictive Maintenance for Defense Fixed-Wing Aircraft Sustainment and Operations" delves into challenges specifically related to predictive maintenance in defense industries, particularly in the aviation sector. This piece underscores that the challenges mentioned in this paragraph are recurring themes in the broader issues associated with predictive maintenance techniques {Scott, 2022 #79}. It focuses on studies directly linked to fixed-wing aircraft sustainment and operations, providing a detailed understanding of challenges within this specific context, which often goes unnoticed in existing literature {Scott, 2022 #79}. A primary concern highlighted in this research is the availability and suitability of data, encompassing sensor capabilities on aircraft and the supporting data processing infrastructure {Scott, 2022 #79}. Data acquisition proves challenging due to complexities in data acquisition systems or the absence of necessary infrastructure to record and transmit data to maintenance engineers {Scott, 2022 #79}. The lack of standardized techniques or methodologies in Prognostics and Health Management (PHM) poses a significant challenge, particularly when utilizing prognostic data for decision-making purposes {Scott, 2022 #79}. Moreover, there are diverse types of decision-making needs and time dependencies in military contexts. The unique sensor topology or sensor networks specific to certain platforms might hinder the generalization of models to other platforms {Scott, 2022 #79}. Additionally, retrofitting this technology to older aviation platforms presents specific challenges, making the integration process complex and demanding {Scott, 2022 #79}. In summary, the systematic literature reviews highlight the recurring challenges in predictive maintenance within military contexts. Insufficient data availability hampers the construction of accurate machine learning models, affecting prediction accuracy. Standardization gaps in data collection and processing further complicate reliability. The aviation sector faces specific hurdles, including retrofitting challenges and diverse decision-making needs. These findings underscore the crucial need for systematic, standardized data acquisition methods in military predictive maintenance applications. In the following section, I will delve deeper into articles that tackled these challenges using specific approaches and report their outcomes.

Continuing from the challenges outlined in the previous article, I will analyze three additional articles concerning military predictive maintenance technology. In the following section, I will assess the data sources utilized, offer a comprehensive explanation of the models applied to these sources, and present the outcomes derived from the analysis {Lee, 2023 #44} . These articles discuss the approaches employed to overcome the challenges faced. In a similar study conducted in the field of aviation, the authors highlighted 20 hazards associated with data-driven predictive aircraft maintenance {Lee, 2023 #44}. These hazards pertain to data accuracy, algorithm reliability, agent communication, and trust in new data-driven technologies. Among these, four hazards were specifically related to the accuracy of diagnostic and prognostic algorithms and their outcomes, with erroneous diagnostics and prognostics identified as the most critical risks {Lee, 2023 #44}. Possible causes of Hazard H05, making diagnostic/prognostic results erroneous, were also recognized as hazards (H02 and H03), which address errors in the data {Lee, 2023 #44}. Additionally, the algorithm itself might be unreliable (H06) {Lee, 2023 #44}. The authors utilized an agent-based algorithm to generate these hazards, where agents, defined as independent entities making decisions based on specific rules, interact with one another, and have individual goals. The study suggests that enhancing the reliability of condition monitoring systems and diagnostics/prognostics algorithms, ensuring timely and precise communication between agents, and establishing trust among stakeholders in new data-driven technologies are pivotal challenges that must be tackled to ensure the secure and efficient implementation of data-driven predictive aircraft maintenance. In the upcoming article titled "A Predictive Model for Forecasting Spare Parts Demand in Military Logistics," the aim is to develop a range of spare parts demand forecasting models employing qualitative techniques, including time series and data mining models, using our spare parts demand dataset. The objective is to pinpoint the most effective predictive model among those developed. The authors observe that spare parts demand in military logistics often displays erratic, intermittent, infrequent, or irregular patterns. Regarding the data, biases are present in how it was mined, particularly in the incorporation of natural language processing techniques on comment data. These biases originate from the assumption that specific textual elements (specific words) might exist in the comments data within the target dataset, aiding in forecasting the demand for each spare part. The data for this study was sourced from DELIIS (Defense Logistics Integrated Information System) of ROK-MND (Republic of Korea-Ministry of National Defense). Although time series analysis has been widely used in previous spare part demand forecasting models, these methods require improvement in terms of prediction accuracy. Inaccurate forecasts leading to erroneous business decisions can incur significant costs and result in substantial sales loss, potentially causing organizational challenges {Hanjun, 2018 #37}. In contrast, the subsequent article reviews predictive maintenance concerning inventory policies. In the article "Simultaneous Predictive Maintenance and Inventory Policy in a Continuously Monitoring System Using Simulation Optimization," the authors employ a different model from the one previously discussed. They introduce a maintenance model that incorporates real-time degradation information and inventory policy within a series-parallel system with multiple machines {Liu, 2023 #9}. The proposed maintenance model addresses a crucial research gap by considering stochastic degradation, spare parts inventory management, and imperfect maintenance simultaneously. Previous studies have primarily focused on either predictive maintenance or inventory management independently, with few exploring both simultaneously. Therefore, the proposed maintenance model bridges this gap by integrating both predictive maintenance and inventory policies in a series-parallel system with multiple machines. However, the authors highlight the need for improvement in incorporating more realistic details within the proposed model. The article does not explicitly provide extensive information about the data mining or data selection processes {Liu, 2023 #9}. In summary, the first article underscored key hazards in the field. The subsequent study presented a practical implementation of predictive maintenance, albeit with gaps in time series utilization. The final article proposed a solution by combining predictive maintenance methods with inventory management. Notably, the first study employed an algorithm for data collection, the second study potentially mitigated model bias, and the third study lacked extensive information on the data acquisition process. In the upcoming section, I will further outline the reports pertaining to data acquisition, systems theory, and game theory. This detailed examination will shed light on the methodologies employed in these areas, providing a comprehensive understanding of how these fundamental aspects are integrated into the context of military predictive maintenance technology. The upcoming section will scrutinize articles that specifically address data acquisition concerning predictive maintenance technology. This section holds significant importance, considering that data acquisition has been a recurrent challenge highlighted in previous sections.

In the upcoming articles of this section, the focus will be on how authors have successfully addressed challenges related to data acquisition in the context of predictive maintenance techniques. This section aims to illustrate how these approaches can be adapted and implemented within the defense industry. As discussed in the preceding section, the complexities in this technology stem from conflicting factors. Maintenance involves a multitude of variables. Take, for instance, the maintenance of vehicle tires. Replacing a tire could be prompted by a sensor warning, the tire's physical condition (such as being bald and in need of replacement), or weather conditions necessitating specialized tires like snow tires. Predictive maintenance might involve a time series anticipating when the tire needs replacement. Inventory levels also play a role; if there's low stock of the required tire, adjustments must be made. Additionally, the user might opt to replace only one out of four tires. From a predictive maintenance perspective, these intricate factors highlight the challenges associated with data acquisition in this industry. In the report titled "Data Acquisition for Simulation-Based Predictive Energy Calculation," the authors aim to address a crucial concern in the electric vehicle industry: predictive energy calculation {Hellwig, 2019 #57}. Ensuring an electric vehicle's battery does not deplete before reaching the destination is of paramount importance. Achieving a high level of accuracy in predictions is essential. To tackle this challenge, the authors employed a model-based approach. An algorithm predicts the electric vehicle's velocity by analyzing the journey in advance {Hellwig, 2019 #57}. Relevant route data, obtained from online sources, is processed to calculate energy consumption over the covered distance, as described in chapter IV-A {Hellwig, 2019 #57}. The predicted velocity is then utilized to estimate the upcoming journey's average energy consumption, allowing for the prediction of the State of Charge (SOC) at the destination and the extrapolation of the vehicle's range {Hellwig, 2019 #57}. The data sourced from online databases includes details like length, slope, legal speed limits, corners, intersections, and traffic lights. Google Maps, a popular navigation app, was employed for this purpose. The data was stored topologically, representing geographic features such as roads and railways as nodes, ways, and relations. This topological representation maintains spatial relationships between features rather than focusing on their physical attributes. The report compares three model equations: closed-loop vehicle simulation, the feed-forward approach, and sequential calculation. The closed-loop simulation, being the most complex, utilizes a driver model as a speed controller and analyzes component interactions, ensuring high accuracy {Hellwig, 2019 #57}. The feed-forward approach, while less complex, interprets the provided driving cycle as the actual vehicle velocity, estimating energy consumption with sufficient accuracy. The sequential calculation further reduces computational time, allowing energy consumption and driving time calculation for sections of the driving cycle with constant acceleration {Hellwig, 2019 #57}. The report concludes that the proposed simulation-based approach significantly reduces the variation in range prediction for electric vehicles {Hellwig, 2019 #57}. It involves online data acquisition for velocity prediction and the implementation of a predictive method based on the energy balance of the traction battery {Hellwig, 2019 #57}. The study shows that the model-based prediction method, relying on the remaining range at the destination, is highly desirable, and the correction method ensures precise vehicle SOC prediction {Hellwig, 2019 #57}. The report also discusses various model approaches for predicting energy consumption and range, including closed-loop simulation, the feed-forward approach, and sequential calculation. Notably, weather conditions and live traffic, which are inherently time-variant information, pose challenges for data acquisition in this context {Hellwig, 2019 #57}. The following article adopts a practical approach to address data acquisition challenges by installing sensors to facilitate data monitoring on a manufacturing assembly line. The Intelligent Manufacturing Production Line Data Monitoring System offers several benefits to discrete manufacturing enterprises. The system provides real-time monitoring of production line data, which can help enterprises respond to diversified demands in a timely manner, adjust the production process, shorten the production cycle, and ensure product quality. The collected data can also provide a powerful decision-making basis for upper-level planning management departments. The system is effective in the monitoring of production line data, which can help enterprises improve their monitoring and management of the discrete manufacturing workshop, a problem that has always plagued the enterprise. The Intelligent Manufacturing Production Line Data Monitoring System, with its real-time monitoring capabilities and predictive analytics, offers valuable insights that can revolutionize defense predictive maintenance strategies. Like its application in discrete manufacturing, this system can be adapted for defense equipment. By continuously monitoring the health and performance of military machinery, it can detect anomalies and predict potential failures before they occur, ensuring optimal operational readiness. Utilizing predictive analytics algorithms, historical data from defense equipment can be analyzed to identify patterns and trends, enabling accurate predictions of maintenance needs. This proactive approach allows defense forces to schedule maintenance activities effectively, reducing downtime and ensuring mission-critical equipment is always operational. Additionally, integrating real-time condition monitoring and prescriptive maintenance techniques can further enhance the defense predictive maintenance framework. By embracing these technologies, defense organizations can optimize their maintenance processes, improve equipment efficiency, and ultimately enhance their overall operational capabilities and preparedness. The Intelligent Manufacturing Production Line Data Monitoring System, with its real-time monitoring capabilities and predictive analytics, offers valuable insights that can revolutionize defense predictive maintenance strategies. Like its application in discrete manufacturing, this system can be adapted for defense equipment. By continuously monitoring the health and performance of military machinery, it can detect anomalies and predict potential failures before they occur, ensuring optimal operational readiness. Utilizing predictive analytics algorithms, historical data from defense equipment can be analyzed to identify patterns and trends, enabling accurate predictions of maintenance needs. This proactive approach allows defense forces to schedule maintenance activities effectively, reducing downtime and ensuring mission-critical equipment is always operational. Additionally, integrating real-time condition monitoring and prescriptive maintenance techniques can further enhance the defense predictive maintenance framework. By embracing these technologies, defense organizations can optimize their maintenance processes, improve equipment efficiency, and ultimately enhance their overall operational capabilities and preparedness. The article also mentions that manufacturing is facing severe pressure to survive in the context of economic globalization, where market competition has expanded from regional to global. To address these challenges, the article proposes the use of industrial IoT technology and its application in manufacturing workshops to achieve intelligent production. However, the article also acknowledges that achieving intelligent production requires further exploration in the areas of manufacturing IoT technology, artificial intelligence algorithms, and machine learning. Incorporating IoT technology in this context involves employing IoT platforms designed to facilitate effortless connectivity and communication among devices and systems. These platforms streamline data exchange, empowering manufacturers to remotely monitor and manage production processes in real-time {Wu, 2017 #110}. In the next article, the authors discuss a relative field and how data acquisition is collected for predictive maintenance in industrial robots. The objective of the proposed architecture is to enable the effective predictive maintenance of industrial robots in real production environments. The authors propose a solution to overcome the issue of identifying anomalies in the behavior of a robot if there is no clear distinction between different routines and working conditions {Izagirre, 2022 #62}. In summary, routines pertain to the specific tasks or activities individuals or organizations regularly engage in, while working conditions encompass the overall environment, both physical and social, in which these routines take place. Working conditions significantly impact the effectiveness of routines carried out in the workplace. The data acquisition process involves selecting a robot and its routine for monitoring in a data server. The server communicates with the Programmable Logic Controller (PLC) to confirm the routine's initiation. Signal acquisition occurs in a separate network from the control layer, ensuring signals don't pass through PLCs {Izagirre, 2022 #62}. Collected signals are stored in the data server and can be supplemented with information from external sources like sensors or databases. Synchronization with PLCs enables simultaneous data collection from external sensors during routine execution. The database stores robot signals and metadata, and the visualization layer utilizes software to display analysis results and predictions. This architecture enables individual-level analysis with predictive maintenance models and Remaining Useful Life (RUL) estimation and provides a global view of the entire robot fleet. The authors used two models to test the feasibility of one-class models to detect deviations in this particular use case: Support Vector Regression (SVR) and Extreme Learning Machine (ELM) {Izagirre, 2022 #62}.. These models have shown good results in modeling non-linear systems and are therefore suitable to test the feasibility of one-class models to detect deviations in this particular use case. The models were trained with healthy state data and tested with both healthy and faulty state data. The data acquisition network architecture is listed in figure 2 of the appendix. The results of the feasibility test are presented in appendix. The results of the feasibility test are presented in Figure 3 of the appendix. The table shows the root mean squared error (RMSE) and mean absolute error (MAE) of the predictions for both models with healthy and degraded state data. The results show that one-class anomaly detection models can be trained to model the healthy behavior of the robots when data is captured with the proposed architecture. Moreover, RMSE and MAE metrics can be used as an indicator of the deviation of the monitored data and thus automatically detect a possible mechanical degradation in the joints of the robots. The study concludes that this architecture facilitates efficient predictive maintenance for industrial robots operating in genuine production environments {Izagirre, 2022 #62}. The fundamental technical stages of a predictive monitoring system include Data Acquisition, Pre-processing, Feature Processing, and Artificial Intelligence. During the data acquisition phase, information is gathered from a variety of sensors, which presents a challenge due to their sheer number. Successful predictions often depend on integrating data from multiple sensors, underscoring the importance of their seamless coordination. Ensuring the accuracy and reliability of each sensor is crucial for obtaining high-quality data, essential for accurate predictions. Pre-processing is necessary to clean, transform, and prepare the collected data for analysis. Feature processing involves selecting and engineering pertinent features from the data, optimizing it for predictive algorithms. Artificial Intelligence techniques are then applied to process the refined data, enabling accurate predictions and proactive decisions based on the acquired information. This structured framework forms the backbone of predictive monitoring systems, maximizing the utilization of sensor data for valuable insights and informed decision-making. In the article titled "Predictive Monitoring of Incipient Faults in Rotating Machinery: A Systematic Review from Data Acquisition to Artificial Intelligence," the main challenge revolves around dealing with multiple sensors and limited data availability. Limited sensor data can stem from factors such as newly commissioned machines, restricted data storage capacity, or limited access to the machine. In these situations, drawing conclusions about a machine's health status based on limited data points becomes challenging. One potential solution is the application of transfer learning, utilizing past mathematical models from similar machines. To address the issue of multiple sensors, researchers have developed sensor data fusion approaches, amalgamating data from various sensors to assess a machine's health. In Industry 4.0 settings with multiple sensor sources from diverse machines, a new challenge arises concerning the management of large data chunks. In such cases, researchers and industrial professionals must carefully sift through meaningful fault-related information. While AI can handle this complexity, adhering to the principle of "Garbage In, Garbage Out" is crucial. This principle emphasizes the significance of filtering out noisy, irrelevant, or inaccurate data during the preprocessing stage to ensure the accuracy and reliability of the data used for analysis. The authors employed denoising mechanisms to remove noise from the signal data. The journal article highlights key aspects of predictive monitoring for incipient faults in rotating machinery. It stresses the importance of this approach in preventing unexpected failures and reducing downtime. Vibration analysis, coupled with advanced signal processing techniques, enhances fault detection accuracy. Data preprocessing, utilizing denoising mechanisms, is pivotal, and artificial intelligence techniques, including machine learning and deep learning, play a crucial role in analyzing sensor data and predicting faults. The interdisciplinary collaboration of experts in mechanical engineering, electrical engineering, and data science is essential. Overall, the article provides a comprehensive overview of technical processes, emphasizing their vital role in ensuring industrial machinery's reliability and efficiency {Saini, 2022 #60}. Transitioning from the discussion on predictive monitoring for rotating machinery, this article delves into a cloud-based solution tailored to manage the substantial data generated by UAV sensors. This innovative approach integrates terrestrial cloud computing capabilities with UAV systems, enabling these vehicles to offload data processing and storage tasks to the cloud {Feng, 2019 #102}. The article focuses on modeling the UAV cloud control system (CCS) akin to a network control system (NCS) {Feng, 2019 #102}. It establishes stable conditions by analyzing the impact of time delays on the control of cloud-based multi-UAV systems. The article further explores the on-demand service capability of the UAV front-end, considering wireless environment influences. Through rigorous simulations, the study verifies the relationship between data generation rates and system stability, offering valuable insights into this cutting-edge technology {Feng, 2019 #102}. The article mentions that one critical theoretic issue in the proposed cloud-based UAV system is how to acquire the big data generated by the sensors while guaranteeing a stable operation state of the system. The article further explains that the complete control of multiple UAVs requires the combination with the UAV front-end and the GSC, and the performance of the UAV control depends on the on-demand service capability of these two parts {Feng, 2019 #102}. The article also mentions that a large amount of data may be transmitted to the GSC from the UAV front-end through wireless radio frequency, and the computing results should also be sent back to the UAV front-end to fulfill the complete control of the multi-UAV system {Feng, 2019 #102}. Therefore, the data acquisition challenges in the proposed cloud-based UAV system include ensuring stable operation while acquiring and transmitting large amounts of data between the UAV front-end and the GSC {Feng, 2019 #102}. The study presents a network control system (NCS) model called UAV Cloud Control System (CCS) for analyzing the stability of cloud-based UAV systems {Feng, 2019 #102}. The CCS operates via a shared digital communication network, involving sensors, operators, and controllers {Feng, 2019 #102}. Modeled as a switched control system, stable conditions are derived considering the impact of time delays on multi-UAV control {Feng, 2019 #102}. The cloud-based multi-UAV system is conceptualized as an open Jackson network, with its service capability quantified in the context of wireless environmental effects {Feng, 2019 #102}. This comprehensive approach enables analysis of the UAV cloud control system's stability and service capability, offering valuable insights into the technology's functionality. In the explored articles, two critical aspects of modern technology are discussed: predictive monitoring systems and cloud-based solutions for UAV data management. The first article elucidates the intricate stages of predictive monitoring systems, underscoring the challenges in harmonizing diverse sensors and ensuring data accuracy. It emphasizes the indispensable role of AI techniques, while also highlighting the significance of high-quality input data, as indicated by the principle "Garbage In, Garbage Out." Denoising mechanisms are employed to enhance data quality, illustrating the need for interdisciplinary collaboration for success. Transitioning to the cloud-based UAV system article, a pioneering approach is introduced, integrating terrestrial cloud computing with UAVs. The focus centers on modeling the UAV cloud control system (CCS) as a network control system (NCS) and analyzing the impact of time delays on multi-UAV control. Challenges arise in maintaining system stability while managing significant data transmission between the UAV front-end and the Ground Station Controller (GSC). The study's comprehensive analysis provides valuable insights into this innovative technology, addressing vital theoretical and practical aspects of cloud-based UAV systems {Feng, 2019 #102}.

In this section, we explored how advanced technologies reshaped predictive maintenance and data management in various industries. Predictive maintenance, crucial for preventing unexpected failures, involved analyzing complex data from multiple sensors. Maintaining a vehicle's tires, for example, wasn't just about replacing them when worn but also considering sensor warnings, weather conditions, and inventory. This complexity highlighted the challenges of data acquisition. One study focused on electric vehicles, predicting their energy consumption. Researchers used algorithms and online data to calculate energy needs, employing models like closed-loop simulation and sequential calculation. Another approach involved real-time monitoring of manufacturing processes. The Intelligent Manufacturing Production Line Data Monitoring System allowed real-time adjustments, ensuring product quality and efficient production cycles. In the defense sector, similar technologies were vital. An architecture was proposed for predictive maintenance in industrial robots, where anomalies were detected by monitoring routines and working conditions. Applying AI, historical data from defense equipment could predict maintenance needs, optimizing schedules and reducing downtime. Shifting to UAVs, a cloud-based solution integrated cloud computing with UAVs, offloading data tasks. Challenges included stable data transmission between UAVs and control systems. The study analyzed this issue, emphasizing stable operation amid large data transfers. In summary, these articles showcased how predictive maintenance and innovative data management strategies transformed industries. From electric vehicles to defense equipment and UAVs, advanced technologies revolutionized how we monitored, predicted, and maintained crucial systems, ensuring efficiency and reliability. As discussed in prior sections, the varied priorities and limitations across industries often result in decision-making conflicts. Game theory offers a solution to navigate these intricate interactions by considering the needs and constraints of all stakeholders involved. The following topic defines what Systems and Game theory is, and how it applies within the context of predictive maintenance for defense.

Implementing systems theory principles in the process of data acquisition provides a comprehensive framework for understanding the complex network of interconnected elements. This approach allows maintenance systems to be analyzed as unified entities, considering not just individual components but also their interactions and dependencies. By embracing systems theory, the relationships between data sources become clearer, leading to a more nuanced comprehension of the overall information landscape.

The upcoming articles focus specifically on engine health monitoring for air vehicles (AV). Their objective is to introduce a real-time engine health monitoring system using a technique referred to as WOANN {Balakrishnan, 2021 #17}. A summary of the article reveals its success in achieving an impressive 95% accuracy rate. The authors conducted extensive data collection from 45 flights involving eight distinct engines {Balakrishnan, 2021 #17}. Challenges outlined in the articles include the development of an integrated system encompassing sensing, data processing, diagnostics, and prognostics to enable real-time conditional monitoring. Additionally, the articles address the knowledge gap regarding turbo engine deterioration mechanisms. Subsequently, these upcoming articles will illustrate how Dynamical Systems theory was applied to tackle these complex issues. Systems theory provides a structured methodology to model, analyze, and optimize data acquisition strategies. By viewing the data acquisition process as a system, we can systematically identify the inputs, processes, and outputs involved. This perspective enables the identification of potential bottlenecks, inefficiencies, and gaps in the data collection process. Additionally, systems theory allows for the integration of diverse data sources, ensuring a more comprehensive and diverse dataset for analysis. One prominent issue highlighted is the dynamic nature of supply chain management; the system evolves over time. In the subsequent article, I will explore how systems theory is employed in machine learning to tackle predictive maintenance, specifically in detecting cascade flutter in turbo engines. Early detection of cascade flutter is crucial, as it can lead to a sequence of stalled or surging airfoils, resulting in performance degradation. The article employs dynamical systems theory, a branch of mathematics that examines the behavior of intricate systems over time {Hachijo, 2020 #338}. It focuses on the study of systems undergoing changes, such as physical, biological, and economic systems. In this context, dynamical systems theory is utilized to gauge the determinism in recurrence plots for strain fluctuations on turbine blades, capturing significant changes in the dynamical state during a transition to cascade flutter time {Hachijo, 2020 #338}. This methodology is subsequently employed to categorize the feature space into three dynamical states: a stable state, a transition state, and a cascade flutter state {Hachijo, 2020 #338}. These states are plotted and fit to a Support Vector Machine model as a methodology proposed to detect a precursor of cascade flutter {Hachijo, 2020 #338}. In this context the Dynamical systems theory can be applied to a model to analyze the behavior of mechanical systems. Dynamical systems theory can optimize data acquisition processes by identifying the most critical variables and parameters that influence the system's behavior. By focusing data collection efforts on these key aspects, engineers can gather relevant information efficiently, ensuring that the acquired data is highly informative for analysis and prediction purposes. Many real-world systems are interconnected and influence each other's behavior. Dynamical systems theory provides tools to analyze the interactions between different components within a system over a series of time. By acquiring data from multiple interconnected sources, engineers can gain insights into how changes in one part of the system affect other components, leading to a more comprehensive understanding of the entire system's behavior. Recognizing the intricacies of the anomaly described, a transitional phase from Systems Theory to Game Theory becomes imperative to enhance the problem-solving approach. Systems Theory, with its holistic perspective on complex interactions, lays the foundation for understanding the intricacies of the any system in this context an air vehicle. However, integrating Game Theory introduces a strategic dimension, considering the interactions between different entities within the system as strategic "players" with conflicting interests and goals. The following sections describes what game theory is and how the models are used in this context. Like systems theory, Game theory is a mathematic framework used to study the specific interactions between rational decision makers. The next article this theory is applied to predictive maintenance technologies by integrating the system dynamics and game theory models. In this article, game theory, specifically evolutionary game theory (EGT), is used to model the strategic interactions and decision-making processes related to the adoption of predictive maintenance technology {Meng, 2022 #137}. The authors integrate EGT with system dynamics (SD) to optimize the investment strategies for predictive maintenance technology {Meng, 2022 #137}. They use EGT to model the feedback relationship between costs and benefits, and to determine the optimized strategies from the perspective of the governmental authority {Meng, 2022 #137}. Additionally, the evolutionary stability strategy (ESS) and replicator dynamics, which are fundamental concepts in EGT, are employed to embody the decision-making processes and strategic interactions involved in the adoption of predictive maintenance technology {Meng, 2022 #137}. Therefore, game theory, in this case, is used to model and analyze the strategic interactions and decision-making processes related to technology adoption and investment strategies. The articles present a figure that outlines the SD process referred to in the figure 4 and framework of the integrated methodology processes figure 5. The application of Darwin's theory of evolution in the context of the article is related to the concept of replicator dynamics in evolutionary game theory. According to Darwin's theory of evolution, individuals within a population evolve based on the returns they receive from their strategies, and the proportion of strategy selection changes accordingly. This changing speed is proportional to the product of the strategy selection proportion and the difference between the current revenue and the average revenue {Meng, 2022 #137}. The replicator dynamic, as defined in the paper, captures this evolutionary process of strategy selection and change based on the concept of evolutionary stability strategy (ESS) proposed to embody Darwin’s theory of evolution {Meng, 2022 #137}. Therefore, the application of Darwin's theory in this context is related to the modeling of strategic interactions and decision-making processes within a population, where individuals evolve their strategies based on the returns they receive, like the concept of natural selection in biological evolution {Meng, 2022 #137}. The key outcome of this report is the selection of economic evaluation metrics, including incremental cost, incremental benefit, and return on investment (ROI) to gauge the economy of predictive maintenance technology {Meng, 2022 #137}. Having established the essential economic evaluation metrics for predictive maintenance technology, the focus now shifts to exploring another strategic approach in the maintenance domain. The upcoming article will delve into the application of game theory, providing insights into how this method enhances maintenance strategies and decision-making processes within complex systems. In the forthcoming article, game theory is employed to formulate a bilevel mathematical model for managing multiplayer pavement maintenance {Ji, 2021 #231}. This model integrates principles from both Stackelberg and Nash game models, common frameworks in game theory used to depict interactions and conflicts among decision-makers {Ji, 2021 #231}. The Stackelberg game, functioning as a leader-follower strategy model, addresses the unequal competition between leading (highway agency) and following (service providers) decision-makers {Ji, 2021 #231}. Conversely, the Nash game represents a non-cooperative scenario where all players independently maximize their own gains see Figure 6 in the appendix. By merging these two game models, the proposed bilevel model optimizes pavement maintenance strategies by accounting for intricate interactions among multiple decision-makers {Ji, 2021 #231}. In the context of pavement maintenance management, the complex interactions refer to the conflicts and dependencies among the highway agency and service providers. For example, the highway agency is responsible for developing maintenance strategies, while the service providers are responsible for implementing these strategies. However, service providers may have different priorities and constraints, such as budget limitations, equipment availability, and workforce capacity. These differences can lead to conflicts among service providers and between service providers and the highway agency {Ji, 2021 #231}. Moreover, the interactions among decision-makers are not always straightforward. For instance, the highway agency may choose to outsource maintenance tasks to multiple service providers to increase competition and reduce costs {Ji, 2021 #231}. However, this decision may also increase the complexity of coordination and communication among the service providers, leading to delays and quality issues. The proposed bilevel mathematical model based on game theory aims to address these complex interactions by considering the requirements and restrictions of all decision-makers and finding an equilibrium solution that satisfies all parties {Ji, 2021 #231}. The computational results from the model provide insights into the optimal maintenance mileage allocated to service providers at different periods, as well as the detailed distribution of fitness values of the upper-level model. These results help in understanding the decision-making advantage of the highway agency and the strategies adopted by service providers to maximize profits while accomplishing the assigned maintenance tasks. In summary, the outcome of the proposed model is a feasible solution to the dynamic long-term problem of multiplayer pavement maintenance, which considers the complex interactions and conflicts among the decision-makers involved. Some challenges in this article included Data Availability and Accuracy, Model Complexity, and conflicting objectives. Lastly the final article will analyze how game theory is applied to fleet level dispatch. Fleet-level selective dispatch refers to the process of selecting a subset of equipment from a fleet to be dispatched for a mission {Yuling, 2020 #232}. This process is related to maintenance strategy decision-making because the maintenance strategy is determined and performed during the mission preparation period to satisfy the mission reliability requirement. The maintenance strategy considers the number of dispatched equipment, the number of key parts in each equipment, and the imperfect maintenance level of each part {Yuling, 2020 #232}. The goal is to enhance the equipment probability and ensure that the mission reliability requirement is met. Co-petition game theory is a concept introduced in the article. It is a game theory framework that combines elements of both cooperation and competition among players {Yuling, 2020 #232}. In the context of the article, co-petition game theory is used to model the interactions between different maintenance strategies and equipment within a fleet. The game theory framework allows for the optimization of maintenance strategies by considering both cooperative and competitive aspects, leading to the development of effective strategies for fleet maintenance. The proposed evolutionary co-petition game algorithm in the article leverages this framework to iteratively optimize maintenance strategies for the fleet {Yuling, 2020 #232}. The method unfolds in three stages: evaluating initial equipment statuses, creating available maintenance strategies, and implementing cooperative and competitive game algorithms {Yuling, 2020 #232}. The cooperative game algorithm is applied to the dispatch group, while a competitive game algorithm operates between the dispatch and standby groups, ultimately refining the dispatch group's optimization {Yuling, 2020 #232}. This approach demonstrates effectiveness and remarkable computational efficiency in addressing fleet-level selective dispatch and imperfect maintenance challenges {Yuling, 2020 #232}. In the context of optimizing fleet maintenance strategies, the outcomes of a game theory analysis include the optimal maintenance strategies for each piece of equipment, the expected costs and benefits of those strategies, and the expected reliability and availability of the fleet under different scenarios {Yuling, 2020 #232}. In the report there were multiple data frames considered including the age of the equipment, and time and cost ration under different maintenance levels {Yuling, 2020 #232}. In summary, this section discusses the application of various game theory methods in predictive maintenance, aiming to address competing factors and improve accurate predictions. These approaches offer solutions to challenges within the Department of Defense's predictive maintenance domain.

7 Answers to research questions

In response to the research question, "What are the most effective ways to integrate predictive maintenance with other defense processes, such as logistics, supply chain, or mission planning?" the findings indicate that integrating real-time condition monitoring and prescriptive maintenance techniques significantly enhances the defense predictive maintenance framework. Through continuous monitoring of military machinery's health and performance, potential anomalies and failures can be predicted before they occur, ensuring optimal operational readiness. By leveraging predictive analytics algorithms to analyze historical data from defense equipment, patterns and trends can be identified, enabling accurate predictions of maintenance needs. This proactive approach enables defense forces to efficiently schedule maintenance activities, minimizing downtime and ensuring continuous operational functionality of mission-critical equipment. Hence, integrating real-time condition monitoring, prescriptive maintenance techniques, and predictive analytics algorithms emerges as an effective strategy to integrate predictive maintenance with other defense processes. Building on the challenges of data standardization and its impact on predictive maintenance accuracy, the question arises: "How can we standardize the evaluation metrics and datasets used in predictive maintenance studies to facilitate comparison and generalization of results?" The response highlights the significant challenge posed by the lack of standardization in data collection and processing, affecting the accuracy and reliability of predictive maintenance outcomes. The article, "Predictive Maintenance in the Military Domain: A Systematic Review of the Literature," emphasizes the need for extensive labeled data for effective machine learning training {Dalzochio, 2023 #10}. This comprehensive dataset should encompass all potential failure scenarios. However, practical constraints often limit access to information about monitored asset failures, leading to data scarcity and, subsequently, reduced accuracy in machine learning-based prediction models. Thus, standardizing data collection and processing methods and ensuring comprehensive coverage of potential failure scenarios emerge as crucial steps to facilitate result comparison and generalization in predictive maintenance studies. Delving into the intricacies of data acquisition for predictive maintenance algorithms, the discussion shifts to the question: "What method of data acquisition is optimal for predictive maintenance algorithms?" The response underscores the complexity involved in predictive maintenance, necessitating the analysis of intricate data streams from diverse sensors. For instance, in the realm of electric vehicles, researchers utilized algorithms and online data to calculate energy requirements, employing sophisticated models such as closed-loop simulation and sequential calculation. Additionally, real-time monitoring systems like the Intelligent Manufacturing Production Line Data Monitoring System enabled dynamic adjustments in manufacturing processes, ensuring both product quality and efficient production cycles. In the defense sector, historical data from defense equipment proved invaluable in predicting maintenance needs, facilitating optimized schedules and reduced downtime. Hence, the optimal method of data acquisition for predictive maintenance algorithms hinges on the specific equipment, the nature of available data, and the objectives of the maintenance process.

8 Future Work

In the realm of predictive maintenance, several intriguing avenues for research and innovation have emerged. One significant area of focus involves delving into technologies with potential to enhance data security, transparency, and traceability within predictive maintenance systems. Additionally, researchers are keen on integrating predictive maintenance with various defense processes like logistics, supply chain, and mission planning, aiming to optimize operational readiness and minimize downtime effectively. To establish a strong foundation for comparative studies, there's a drive to develop comprehensive frameworks that standardize data collection and processing methods. Game theory algorithms are being investigated to enhance maintenance predictions by considering diverse data points such as supply chain demands, and actual maintenance needs collectively. Augmented reality (AR) and virtual reality (VR) technologies are also under exploration, showing promise in enhancing training and maintenance activities. Beyond defense, predictive maintenance is being explored in renewable energy systems like wind turbines and solar panels, offering avenues to optimize energy production and reduce maintenance costs. To extend the applicability, research is extending into areas such as smart cities, healthcare, and transportation systems like trains and airplanes, aiming to optimize infrastructure maintenance schedules and minimize downtime effectively. These multifaceted research directions signify a robust pursuit toward enhancing the efficiency and reliability of predictive maintenance across diverse sectors.

9 Conclusion

In conclusion, the evolution of predictive maintenance and data management through advanced technologies has profoundly reshaped industries, addressing complex challenges and ensuring the efficiency and reliability of critical systems. The intricacies of predictive maintenance were illuminated in contexts as diverse as electric vehicles, manufacturing, defense equipment, and UAVs. These applications emphasized the multifaceted nature of data acquisition, where factors like sensor warnings, weather conditions, and inventory levels played pivotal roles. The integration of sophisticated algorithms and real-time monitoring systems enabled precise predictions, optimizing maintenance schedules, and reducing downtime significantly. The transformative power of predictive maintenance was demonstrated in the military maintenance industry. In manufacturing, real-time adjustments facilitated by the Intelligent Manufacturing Production Line Data Monitoring System streamlined production cycles and ensured product quality, showcasing the impact of predictive maintenance on efficiency. In the defense sector, innovative architectures were proposed, enabling the proactive monitoring of industrial robots. By focusing on routines and working conditions, anomalies were detected, and predictive maintenance models were employed, optimizing defense equipment schedules, and enhancing operational readiness. UAVs benefited from cloud-based solutions, where stable data transmission between UAVs and control systems was crucial. Through comprehensive modeling and analysis, the integration of cloud computing with UAVs showcased the potential of offloading data tasks and ensuring stable operation. These advancements underscored the importance of interdisciplinary collaboration, where experts in mechanical engineering, electrical engineering, and data science joined forces. The successful implementation of predictive maintenance systems depended not only on advanced algorithms but also on the quality of input data. Moreover, challenges such as managing significant data transmission and ensuring stability in complex systems were addressed through innovative solutions. The integration of systems theory and game theory in predictive maintenance offers one innovative solution that should be further analyzed. Systems theory provides a holistic approach, allowing for the analysis of complex interconnected elements, ensuring a nuanced understanding of data sources. Transitioning to game theory introduces a strategic dimension, modeling interactions between decision-makers as rational players with conflicting interests. In essence, the exploration of these technologies exemplified the continuous pursuit of enhancing predictive maintenance methodologies. By leveraging cutting-edge tools, defense industries can proactively address potential issues, optimize operational efficiency, and ultimately thrive in an ever-evolving technological landscape. As these technologies continue to evolve, the future holds even more promising prospects for predictive maintenance, ensuring the seamless functioning of vital systems across diverse sectors. The d

10 Appendix

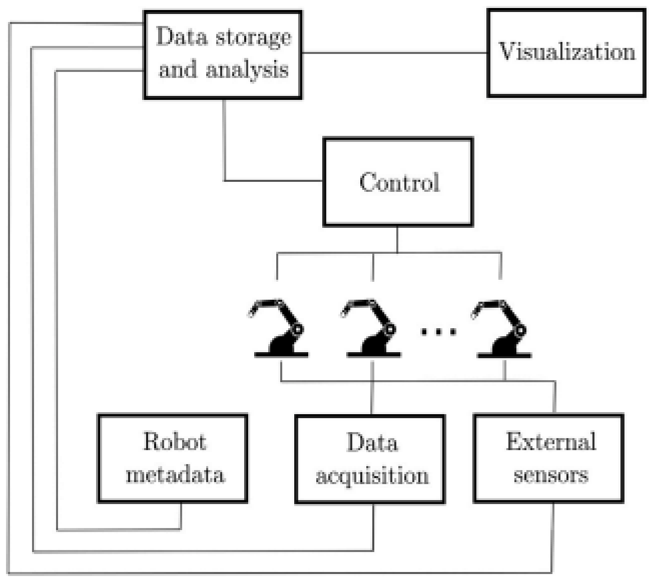

Fig. 1. The data acquisition network architecture.

Figure 2: (Izaguirre) Data acquisition Network

Table 4
RMSE and MAE metrics of the predictions of the models.

	SVR	ELM
RMSE healthy	**0.12**	**0.071**
RMSE degraded	1.201	0.141
MAE healthy	**0.015**	**0.005**
MAE degraded	1.44	0.019

Figure 3: (Izaguirre) Outcomes of Predictions for Models Analyzed

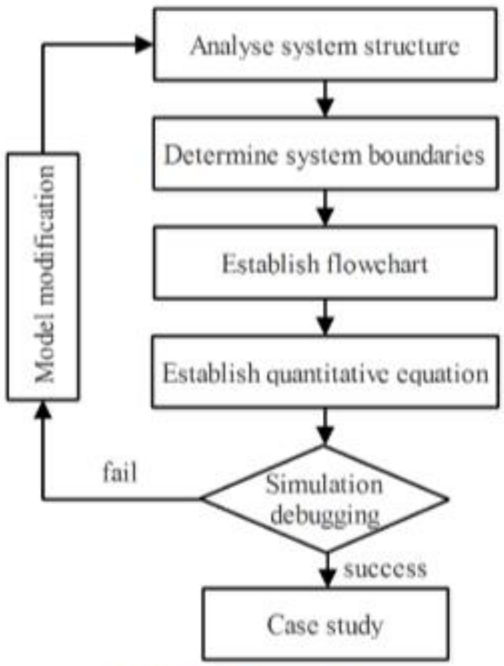

Fig. 1. Process for SD modelling.

Figure 4: Process for SD Modeling (Meng)

ng et al. Reliability Engineering and System Safety 222 (2022) 108424

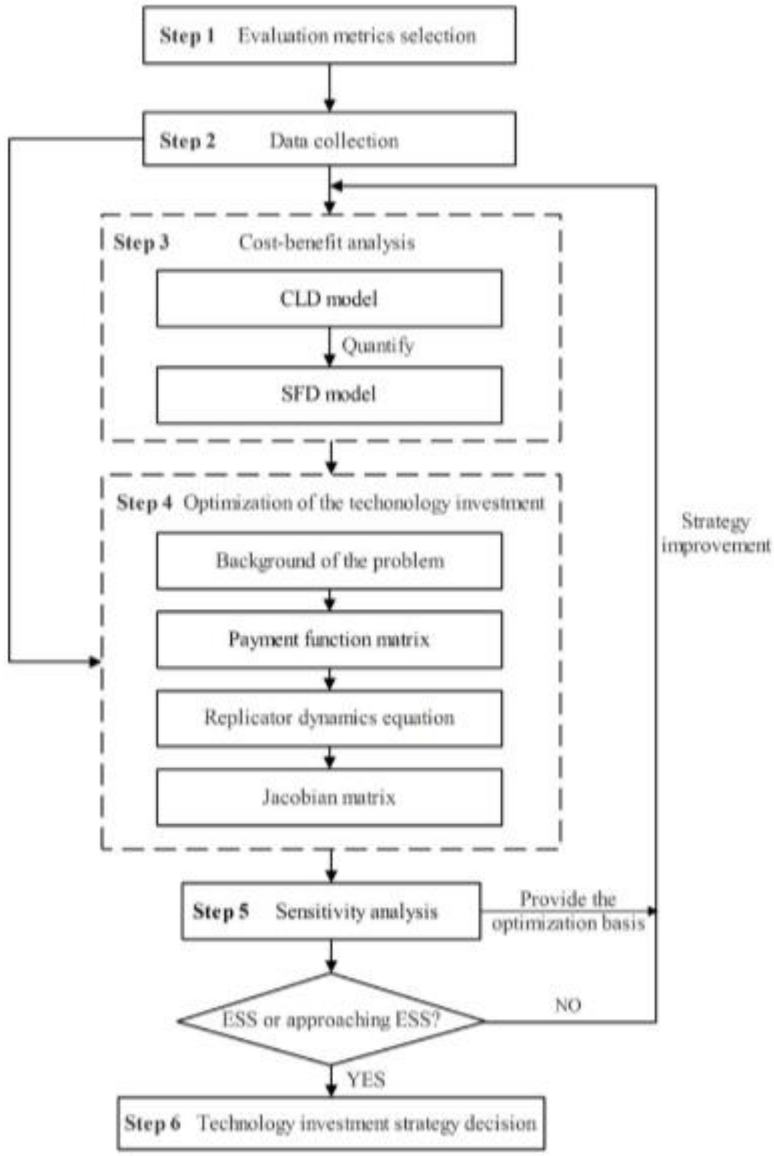

Fig. 2. The framework of the integrated methodology.

Figure 5: Integrated Methodology (Meng)

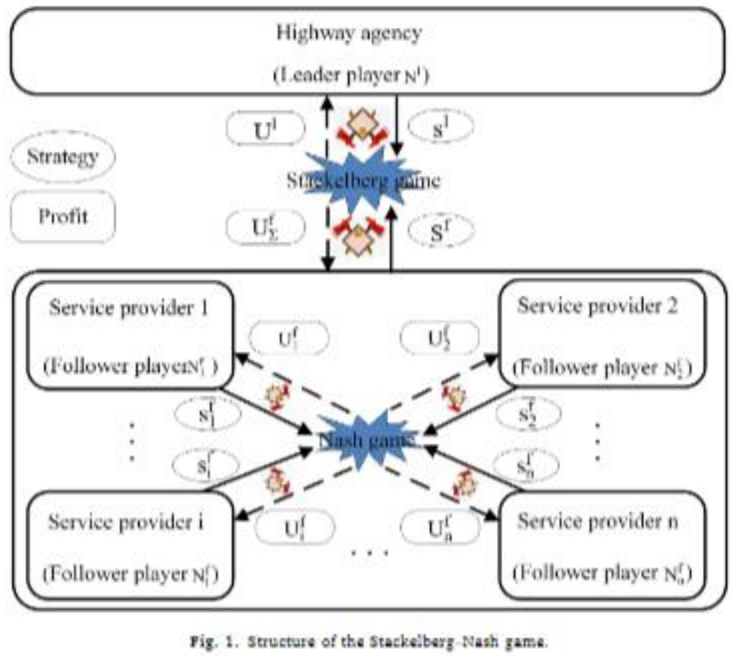

Figure 6: Stackelberg and Nash Game (Ji)

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