Advances in Military Technology
Vol. 20, No. 1, 2025, pp. 155-172
ISSN 1802-2308, eISSN 2533-4123
DOI 10.3849/aimt.01956

# Assessing Readiness Levels for Implementation of Industry 4.0 Technologies in Military Maintenance Depots

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The manuscript was received on 6 January 2025 and was accepted
after revision for publication as a case study on 25 April 2025.

**Abstract:**

*Industry 4.0(I4.0) is transforming manufacturing and maintenance processes across various sectors in the world. This paper assesses I4.0 readiness levels in Indian Military Aircraft and Systems Maintenance Depots (MASMDs). Current readiness models often lack dimensions relevant for military maintenance. This research evaluates five diverse MASMDs across different platforms, analyzing data based on aircraft type, systems type, depot size, workload, and technological capabilities. The results reveal varying I4.0 readiness levels among depots and identify critical improvement areas. The findings provide insights for defense organizations planning digital transformation in maintenance facilities. Future research could extend to other military maintenance domains or compare readiness across different nations' armed forces.*

**Keywords:**

*Industry 4.0, maintenance, military repair depots, readiness level*

## 1 Introduction

In today's digital age, Industry 4.0 (I4.0) technologies have revolutionized manufacturing, transforming traditional firms into smart factories [1]. These technologies enable real-time data utilization for planning, logistics, and development [2]. By seamlessly linking systems both within factories and across supply chains, I4.0 facilitates process control optimization and adjustments directly at the execution stage [3]. I4.0 technologies hold the potential to transform military logistics operations by delivering specialized applications and offering substantial benefits. This level of integration significantly enhances operational efficiency and productivity. However, many global firms still lack comprehensive documentation for effectively adopting and implementing I4.0 principles [4].

Industry 4.0 is described by the intensive application of information technologies [5]. It encompasses the rapid digitization of business processes and information, prom-

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ising significant savings in cost and labor. While digital transformation extends beyond industry to impact societies, governments, economies, and education, focus of this research remains on its implications for military aircraft and systems maintenance. I4.0 technologies can be seamlessly incorporated into aircraft and systems manufacturing to improve efficiency, enhance product quality, and optimize operational performance [6]. The aerospace industry is also progressively integrating Industry 4.0 technologies to improve aircraft maintenance, repair, and overhaul (MRO) operations [7].

MASMDs are military maintenance facilities similar to various aircraft and systems Maintenance, Repair, and Overhaul (MRO) facilities. These facilities have been established by military organizations to cater for in house maintenance of aircraft and aircraft support systems which have been procured from foreign countries. This enables cost effective and optimized maintenance for these types of systems. Currently, all MASMDs were established during the procurement of aircraft or systems, utilizing the technology transferred at the time of their initial induction. However, there is significant potential to upgrade these facilities to align with Industry 4.0 standards, enhancing their productivity and operational efficiency.

To effectively navigate this transition, military organizations require robust readiness efforts to serve multiple purposes including determining current Industry 4.0 implementation levels, facilitating self-evaluation to identify needs, enabling benchmarking against civilian aviation and systems maintenance counterparts, and informing strategic planning. This research accesses comprehensive readiness levels comprising seventeen key dimensions, designed specifically to assess the readiness levels of I4.0 in five aircraft and systems maintenance depots.

Our literature review revealed a significant gap in existing readiness models, particularly in bridging academic research with practical military aircraft and systems applications. To address this, we have assessed readiness levels based on critical dimensions often overlooked in previous models for depot level maintenance of military aircraft and systems.

In this paper, we applied a specially developed survey questionnaire to five MASMDs, each responsible for different types of aircraft including fighters, transport and helicopters and systems including aircraft support systems and guided weapons maintenance operations. The questionnaire evaluates seventeen key dimensions of Industry 4.0 readiness. This assessment provided each MASMD with an overall score and individual dimension scores, offering understanding of their strengths and shortcomings for Industry 4.0 adoption.

*Tab. 1 Research Questions for MASMDs*

| Sr. No. | Research Question |
|---|---|
| RQ1 | To assess the current state of digital integration and asset management in depot-level maintenance operations. |
| RQ2 | To evaluate the use and readiness for predictive and intelligent maintenance strategies. |
| RQ3 | To understand the level of workforce readiness and training in adopting I4.0 technologies. |
| RQ4 | To analyze the level of supply chain and process automation within depot operations. |
| RQ5 | To assess security of data and regulatory compliance measures in I4.0 integration. |
| RQ6 | To determine strategic alignment and management readiness for I4.0 initiatives. |
| RQ7 | To examine the use of highly developed technologies for operational optimization in MASMDs. |

Field research of five MASMDs highlighted several key challenges in transitioning to Industry 4.0, notably the predictive maintenance and work force competency surrounding the return on investment for new technologies. To overcome these hurdles, military organizations need clear roadmaps and diagnostic tools to assess their readiness and identify potential obstacles to ensure all military assets are always ready for operations in stipulated timelines.

Based on the preceding discussion, Tab. 1 represents seven research questions to steer the implementation of I4.0 technologies in MASMDs.

This research paper is structured into different sections. Section 1 covers the introduction aspects of the paper including key factors of Industry 4.0, MASMDs and approach for conducting readiness levels in these depots, Section 2 contributes to the background, Section 3 covers the literature review, Section 4 outlines our research methodology, Section 5 deals with the data analysis, Section 6 covers the methodology for calculation of readiness levels of MASMDs, Section 7 analyzes the results and findings from our field research, and Section 8 identifies the key strengths and shortcomings and offers concluding remarks.

## 2 Background

### *2.1 Military Aircraft and Systems Maintenance Depots*

MASMDs are specialized facilities crucial to keeping nations' defense assets and related systems in top operational condition. These depots serve as centralized hubs for conducting complex maintenance, repair, and overhaul operations on a wide range of military hardware. From fighter jets and transport planes to helicopters, aircraft systems, and guided weapons, these facilities are equipped with advanced tools, technology, and skilled personnel to handle everything from routine inspections to major overhauls.

All the MASMDs considered in the paper are responsible for different types and categories of maintenance operations. Tab. 2 summarizes different types of MASMDs and their roles in maintenance operations.

### *2.2 Industry 4.0 for Aircraft and Systems Maintenance*

Industry 4.0 (I4.0) remains a growing field, bringing key enabling technologies that aim to transform organizations with isolated systems and legacy maintenance process I4.0 is driving a considerable transformation in industrial operations. The enabling technologies of I4.0, including the Internet of Things (IoT), Big Data and Analytics, Artificial Intelligence (AI), Cyber-Physical Systems (CPS), Cloud Computing, 3D Printing, Augmented and Virtual Reality (AR/VR), Robotics and Automation, Blockchain, and Digital Twins, are the backbone of this transformation. Some of the key I4.0 technologies being extensively used in different aircraft and systems maintenance applications and depot level maintenance operations are illustrated in Tab. 3.

The transition to Industry 4.0 in military contexts requires collaborative efforts and supportive national policies to overcome structural challenges. This is particularly true for legacy aircraft and systems maintenance, where resource constraints, spare part availability, and outdated tooling can pose significant obstacles to digital transformation. Despite these challenges, I4.0 technologies offer substantial possibilities for performance improvement and efficient operations in military aircraft and systems maintenance [12].

*Tab. 2 Different types of MASMDs and their roles*

| MASMD | Depot Type | Role in Maintenance Operations |
|---|---|---|
| MASMD 1 | Fighter Aircraft Depot | - To perform deep maintenance and structural repairs on fighter jet aircraft<br>- To carry out disassembly and assembly of fighter aircraft<br>- To conduct overhaul of aircraft controls<br>- To upgrade avionics and weapons systems<br>- To undertake engine overhauls and life-extension modifications<br>- To execute airframe fatigue testing and repairs |
| MASMD 2 | Transport Aircraft Depot | - To execute heavy maintenance checks on large transport planes<br>- To carry out disassembly and assembly of transport aircraft<br>- To conduct overhaul of aircraft controls<br>- To perform cargo systems overhaul and modernization<br>- To undertake airframe corrosion treatment and prevention<br>- To upgrade communication and navigation systems |
| MASMD 3 | Helicopter Aircraft Depot | - To perform comprehensive rotary wing maintenance<br>- To carry out disassembly and assembly of transport aircraft<br>- To conduct overhaul of aircraft controls<br>- To undertake dynamic component overhauls (rotors, transmissions)<br>- To conduct avionics upgrades and weapons integration<br>- To execute airframe life-extension programs |
| MASMD 4 | Aircraft Support Systems Depot | - To conduct overhaul and repair of modernized airfield systems including navigational aids<br>- To execute diagnostics and rectification of runway and taxi lights<br>- To perform component software updates and cybersecurity enhancements<br>- To calibrate and repair runway precision instruments and sensors<br>- To undertake disassembly and repair of major communication components |
| MASMD 5 | Military Guided Weapons Depot | - To conduct routine maintenance and testing of guided missiles<br>- To perform software updates and guidance system calibrations<br>- To execute warhead and propulsion system inspections<br>- To carry out overhaul of GW vehicles and launch platforms<br>- To undertake refurbishment of GW missiles<br>- To manage weapon storage, handling, and transportation logistics |

## 3 Literature Review

A comprehensive review of Industry 4.0 readiness assessment frameworks reveals several notable models that have contributed to the field. The IMPULS framework [13] established foundational metrics for European manufacturing industries, while PwC's Industry 4.0/Digital Operations Self-Assessment [14] provided a practical self-evaluation approach across various sectors. The structured Maturity Model [15] and SIMMI 4.0 [16] both offered systematic methods for evaluating organizational readiness, with the latter specifically focusing on smart factory implementations. The Connected Enterprise Maturity Model [17] developed by Rockwell Automation emphasized connectivity and security aspects, while specialized regional studies like the Nepal adoption readiness assessment [18] highlighted unique challenges in developing economies. The Industry 4.0 Readiness Calculation framework [19] further contributes by providing a transitional strategy for traditional industries undergoing digital transformation, demonstrating the evolution of readiness assessment methodologies across various contexts and requirements.

The review of existing frameworks for evaluation of readiness levels for Industry 4.0 has revealed variability in the number of dimensions. While frameworks with fewer dimensions may suffice for specific sectors or specialized cases, they often lack the robustness required for comprehensive analysis in complex environments like military aircraft and systems maintenance. Our literature review also noted that despite differences in nomenclature, many dimensions across various models serve similar analytical purposes. For instance, dimensions labeled as "employees", "personnel", or "human resources" often address the same core aspect of organizational readiness.

*Tab. 3 Key Industry 4.0 technologies for aircraft and systems depot level maintenance operations*

| Technology | Description | Application in depot level maintenance operations | Ref. |
|---|---|---|---|
| Digital Twin | Virtual replicas of physical assets, systems and processes that can be used to run simulations before actual devices are built and deployed. | Real time data monitoring from sensors, simulation of maintenance procedures, behavior and performance of aircraft and systems components, performance analysis of aircraft and other systems followed by predictive maintenance. | [8] |
| Artificial Intelligence (AI) and Machine Learning (ML) | AI replicates human intelligence processes by computer systems. ML involves the use of algorithms to parse data, learning from it, and making well informed decisions. | Automated defect detection by images and sensor data, identifying anomalies and indications of wear and tear which cannot be examined by naked eye, predictive analysis to clearly bring out component failure based on historical data and current operating conditions, and optimization of maintenance schedules and processes. | [9] |
| Additive Manufacturing (3D Printing) | Process of fabricating articles in three-dimensional solid form by adding layer-wise material using a digital print. | Prototyping and manufacturing of aircraft and systems components and spare parts with optimized designs, reduced weight, low cost, and production as per demands. | [10] |
| Augmented Reality (AR) and Virtual Reality (VR) | AR clearly surfaces digitized information onto the physical world, while VR creates a real-world stimulating environment. | Technician training by AR with real-time guidance, information and step-by-step instructions to perform complex maintenance procedures. VR offers immersive training environments that simulate actual scenarios for aircraft and systems technicians to practice maintenance procedures in a secured and well-defined environment, enhancing their skills and confidence along with remote assistance and troubleshooting of aircraft and systems snags. | [8] |
| Big Data Analytics | It involves the use of well-developed analytical techniques to process and analyze large datasets to reveal trends, interactions, and insights, especially relating to human associations and their behavior. | Analyzing maintenance parameters to uncover trends and insights that are not immediately visible but will lead to unexpected future failures in aircraft and systems performance, and additionally optimizing inventory management of spares for maintenance operations. | [11] |
| Augmented Reality (AR) and Virtual Reality (VR) | IoT and Smart Sensors involve a network and software that connect various devices and systems through the internet, allowing seamless communication and sharing data. | IoT enabled smart sensors installed on various aircraft and systems components to monitor their real-time condition, such as temperature, pressure, and vibration, and other critical parameters providing a continuous stream of information about the health of the aircraft or systems and it facilitates predictive maintenance before an aircraft or system component or spare is likely to fail. | [11] |

## 4 Research Methodology

This research was intended to achieve an assessment of readiness levels in a detailed manner for I4.0 implementation in depot level maintenance within military organizations. To accomplish these objectives, a structured methodology was employed that integrated both qualitative and quantitative approaches [19].

A survey-based research design was chosen, utilizing a comprehensive questionnaire specifically developed for this research which was distributed to personnel across multiple MASMDs responsible for diverse military aircraft and systems maintenance operations. Responses were collected to assess current practices, readiness levels, and potential shortcomings to I4.0 adoption. The survey encompassed selection of seventeen critical dimensions for calculation of readiness levels.

Methodology for determining Industry 4.0 Readiness Level in MASMDs involves a multi-step approach that integrates both qualitative and quantitative assessments. Initially, a structured survey was developed based on established I4.0 maturity models. The survey targets seventeen key dimensions critical to operations, each representing a critical aspect of Industry 4.0 readiness. Respondents, including maintenance engineers, technicians, and IT specialists from MASMDs, were asked to evaluate their current practices on a 5-point Likert scale.

### *4.1 Research Design*

The research is structured to provide valuable insights tailored to the MASMDs. Following the creation of well-designed questionnaire, data was collected and analyzed, enabling the grouping of emergent dimensions to determine readiness levels of MASMDs. Fig. 1 illustrates the various phases of research design for identifying readiness levels of MASMDs.


*Fig. 1 Research design*

### *4.2 Identification of Dimensions for Calculating Readiness Levels in MASMDs*

Common dimensions across most readiness models include technology, people, strategy, leadership, processes, and innovation, though they may appear under different labels. Based on this analysis and the specific needs of military aircraft and systems depot-level maintenance, this paper proposes seventeen dimensions to assess I4.0 readiness in MASMDs. These dimensions have been selected using literature review and interviews of specialists in this area.

These dimensions can be used to develop a customized readiness assessment tool for each MASMD facility, assisting it for identification of strengths, gaps, and opportunities for advancing towards complete I4.0 implementation. The selected dimensions, their description and MASMD assessment focus are explained in Tab. 4.

*Tab. 4 Dimensions for Industry 4.0 applications for MASMDs*

| Sr. No. | Dimension | Description | Assessment Focus |
|---|---|---|---|
| 1. | Digital Asset Management | Evaluate the extent to which aircraft and systems components are digitally tracked and managed throughout their lifecycle. This includes the use of RFID tagging, and other IoT-based asset tracking systems. | How well are digital records of components maintained? Is there real-time visibility into the condition and location of assets? |
| 2. | Predictive Maintenance | Assess the implementation of predictive maintenance technologies using data analytics, machine learning, and IoT sensors to predict and prevent failures before they occur. | To what extent are predictive analytics used to optimize maintenance schedules? Are systems in place to monitor equipment health in real-time? |
| 3. | Automation of Inspection Processes | Examine the use of automated inspection technologies, such as drones, robots, and AI-based image recognition, to conduct aircraft and engine inspections. | Are inspections automated using AI-based systems? How much human intervention is required during inspections? |
| 4. | Vertical and Horizontal Integration | Assess the integration of operations across different layers (vertical) and with suppliers, manufacturers, and customers (horizontal). This includes the integration of enterprise resource planning (ERP) systems with shop floor operations and external stakeholders. | To what extent are the processes integrated from the shop floor to the enterprise level? How well does the facility coordinate with external partners and suppliers? |
| 5. | Workforce Training and Competency | Evaluate the readiness and skill level of the workforce in handling advanced digital tools, automation systems, and data analytics relevant to operations. | How regularly are employees trained in new technologies? Is there a structured program for continuous learning and upskilling? |
| 6. | Supply Chain Integration | Assess the degree of integration and automation in the supply chain, including inventory management, parts ordering, and logistics. | Is the supply chain digitally connected? Are inventory levels optimized using real-time data? |
| 7. | Quality Management Systems (QMS) Automation | Evaluate the automation and digitalization of quality management processes, including the capture and analysis of quality data and the automation of compliance reporting. | How automated are quality assurance and compliance processes? Is data captured digitally and analyzed in real-time? |
| 8. | Customer and Partner Collaboration Platforms | Assess the use of digital platforms for collaboration with customers, OEMs, and regulatory bodies. This includes platforms for sharing data, reporting, and receiving feedback. | How integrated are customer and partner interactions? Are digital platforms used to facilitate real-time communication and data sharing? |

| Sr. No. | Dimension | Description | Assessment Focus |
|---|---|---|---|
| 9. | Facility and Energy Management | Examine the implementation of smart building technologies to optimize energy use, HVAC systems, lighting, and overall facility management. | How automated is the facility management? Are energy use and environmental conditions optimized using real-time data? |
| 10. | Regulatory Compliance and Reporting Automation | Evaluate the extent to which regulatory compliance processes are automated and integrated with maintenance operations. This includes the automatic generation and submission of compliance reports. | Are compliance processes automated? How seamlessly do they integrate with operational data? |
| 11. | Data Security and Cyber-Physical Security | Assess the security measures in place to protect digital assets, data, and connected systems from cyber threats. | How robust is the cybersecurity infrastructure? Are there measures in place to protect against unauthorized access and data breaches? |
| 12. | Smart Inventory and Parts Management | Evaluate the implementation of smart inventory systems that use IoT and data analytics to manage parts availability, optimize inventory levels, and predict parts demand. | Are inventory levels managed using real-time data? How effectively is parts management integrated with overall maintenance operations? |
| 13. | Intelligent Decision Support Systems | Assess the use of AI and ML to provide decision support for maintenance operations, such as scheduling, resource allocation, and risk assessment. | Assessment Focus: Are intelligent systems used to assist in decision-making? How integrated are these systems with real-time data feeds? |
| 14. | Lifecycle Data Management | Examine how lifecycle data for aircraft and systems components is captured, stored, and analyzed. This includes tracking maintenance history, usage patterns, and component wear and tear. | How comprehensive is the lifecycle data management system? Are digital twins or similar technologies in place to stimulate components behavior? |
| 15. | Advanced Analytics for Operational Optimization | Assess the use of advanced analytics, including big data and machine learning, to optimize maintenance operations, reduce aircraft and systems downtime, and improve efficiency. | How extensively are advanced analytics used? Are they integrated into daily operations to drive continuous improvement? |
| 16. | Augmented Reality (AR) and Virtual Reality (VR) in Training and Maintenance | Evaluate the use of AR and VR technologies for training technicians, conducting remote inspections, and providing real-time assistance during maintenance tasks. | Are AR and VR technologies deployed in the maintenance processes? How effectively do they enhance training and operational efficiency? |
| 17. | Strategic Alignment and Management Planning | Measure the alignment of Industry 4.0 initiatives with overall military objectives and operational requirements for aircraft and systems. | Is there a documented strategy to modernize maintenance operations in MASMDs? Are long term initiatives of MASMD aligned with overall strategy for robust operations? |

### *4.3 Questionnaire Design*

The development of a structured and well-developed questionnaire was important to collect appropriate relevant data for assessing I4.0 readiness levels in MASMDs [20]. A thorough review of existing literature informed the designers of the questionnaire to ensure clarity and relevance, allowing respondents to provide articulate and meaningful answers [21]. To mitigate potential ambiguity or biases, all questions were rigorously reviewed by domain experts and professionals within the military aviation and systems maintenance domains, with revisions implemented accordingly [22].

Section 1 covered 16 questions for technical domain for Industry 4.0 and two general questions specific to type of MASMD and experience of experts. Section 2 encompassed 34 questions with a set of two questions for each dimension to evaluate the readiness level. These questions were designed to assess various levels of maturity, from Band 0 (Initial) to Band 4 (Automated), reflecting the extent to which processes are automated, integrated, and optimized using advanced digital technologies. The questionnaire was designed to gather both quantitative data (through Likert-scale responses) and qualitative insights (through open-ended interactions and discussions).

### *4.4 Data Collection Phase*

A descriptive research approach was adopted to investigate the readiness and implementation of I4.0 principles in MASMDs [23]. Data collection was conducted using a well-structured questionnaire designed to capture insights from 30 respondents across key functional areas, such as operations, logistics, and maintenance planning. A high response rate of 99 % was achieved, underscoring the relevance of the topic and the engagement of the target population [24].

The data collected from the questionnaire responses was analyzed using content analysis technique to identify recurring patterns, themes, and challenges [25]. To ensure the robustness of the findings, subject matter experts reviewed and validated the proposed recommendations, providing critical feedback and adjustments.

### *4.5 Sampling*

Sampling technique (purposive) was used to select respondents who are directly involved in operations, including senior maintenance and logistics officers, aircraft and systems technicians, and IT professionals. The sample included a diverse range of organizations, from small facilities for systems to large depots for aircraft, to ensure that the findings are generalizable across different types of maintenance operations. A sample size of 35 personnel in fighter MASMD, 37 in transport, 34 in helicopters, 32 in aircraft support systems and 31 in Guided weapons MASMD participated in the survey.

### *4.6 Survey Administration*

The survey was administered through an online platform, ensuring easy access for participants across various locations. Respondents were provided with detailed instructions explaining the purpose of the research, the meaning of each readiness level (Bands 0-4) as per readiness level percentage, and instructions on how to complete the survey. This ensured that participants had a clear understanding of the criteria used to assess their organization’s readiness. To understand the different levels of readiness for Industry 4.0 in military aircraft and systems, the bands considered for MASMDs with their current readiness status in adopting Industry 4.0 technologies and practices are explained below:

- **Band 0 (0 to 20 %) – Initial**: No formal processes, technologies, or systems in place. Operations are mainly manual with little to no digital integration.

- **Band 1(21 to 40 %) – Defined**: Basic processes and systems are in place, often supported by manual or partially automated tools. Some digital technologies are beginning to be adopted.
- **Band 2 (41 to 60 %) – Digitalized**: Systems and processes are digitalized and supported by data, but integration between systems is limited. There is some automation, but it is not widespread.
- **Band 3 (61 to 80 %) – Integrated**: Systems and processes are fully integrated across the organization, with data flowing seamlessly between them. Automation is common, and digital tools are widely used.
- **Band 4 (81 to 100 %) – Automated**: Operations are highly automated with minimal human intervention. Systems can autonomously make decisions based on real-time data.

### *4.7 Mapping of Research Questions with Dimensions*

The questions along with their purpose were mapped with dimensions of Industry 4.0 in respect of MASMDs as elaborated in Tab. 5.

### *4.8 Follow-Up Interviews*

To complement the quantitative survey data, follow-up interviews were conducted with a subset of participants. These interviews aimed to explore the context behind the survey responses, allowing for a deeper understanding of the challenges and opportunities related to Industry 4.0 adoption in maintenance operations. The interviews were semi-structured, focusing on areas where participants indicated lower readiness levels.

## 5 Data Analysis Phase

### *5.1 Quantitative Data Analysis*

Survey responses were analyzed using descriptive statistics to determine the average readiness level across each dimension. The data was then categorized into the predefined bands (0-4), allowing for a clear visualization of the overall readiness of each MASMDs. Frequency distributions and mean scores were calculated to identify common trends and areas of strength or weakness.

### *5.2 Qualitative Data Analysis*

The qualitative data from the open-ended survey questions and follow-up interviews with depot experts were analyzed using thematic analysis. This involved coding the responses to identify recurring themes related to challenges, success factors, and readiness barriers. The qualitative data provided context to the quantitative findings, explaining why certain dimensions may have lower readiness levels and suggesting possible interventions.

### *5.3 Integration of Findings*

The final step involved integrating the quantitative and qualitative data to produce a comprehensive assessment of Industry 4.0 readiness in MASMD operations. The integration was achieved through triangulation, comparing the survey results with the insights gained from interviews. This approach allowed for the validation of findings and provided a nuanced understanding of the readiness landscape.

*Tab. 5 Research questions and mapping with dimensions of Industry 4.0 in MASMDs*

| Research Question (RQ) | Dimension(s) Covered | Mapping Details |
|---|---|---|
| **RQ 1.** Assess the current state of digital integration and asset management in depot-level maintenance operations. | - Digital Asset Management<br>- Automation of Inspection Processes | Focuses on how well depot operations have digitized their processes, ensuring real-time tracking and use of advanced technologies. |
| **RQ 2.** Evaluate the use and readiness for predictive and intelligent maintenance strategies. | - Predictive Maintenance<br>- Intelligent Decision Support Systems<br>- Lifecycle Data Management | Aims to assess how effectively predictive analytics and decision support systems are utilized for maintenance strategies, reducing unplanned downtime and improving operational efficiency. |
| **RQ 3.** Understand the level of workforce readiness and training in adopting Industry 4.0 technologies. | - Workforce Training and Competency<br>- Augmented Reality (AR) and Virtual Reality (VR) in Training and Maintenance | Looks at the readiness of the workforce in adopting new technologies and how well they are trained to leverage tools like AR/VR in maintenance tasks. |
| **RQ 4.** Analyze the level of supply chain and process automation within depot operations. | - Supply Chain Integration<br>- Smart Inventory and Parts Management<br>- Facility and Energy Management | Focuses on the integration and automation of the supply chain and internal processes to enhance efficiency, part management, and facility operations. |
| **RQ 5.** Assess data security and regulatory compliance measures in Industry 4.0 integration. | - Data Security and Cyber-Physical Security<br>- Regulatory Compliance and Reporting Automation | Evaluates the robustness of the depot's cybersecurity measures and the automation of regulatory compliance to meet the stringent demands of military operations. |
| **RQ 6.** Determine strategic alignment and management readiness for Industry 4.0 initiatives. | - Strategic Alignment and Management Planning<br>- Vertical and Horizontal Integration | Reviews how well Industry 4.0 initiatives are aligned with the organization's overall mission and long-term objectives, with a focus on integration across the supply chain and vertical levels. |
| **RQ 7.** Examine the use of advanced technologies for operational optimization. | - Advanced Analytics for Operational Optimization<br>- Quality Management Systems (QMS) Automation | Assesses the use of advanced analytics and automated systems to drive improvements in operational processes, particularly in quality management and real-time decision-making. |

### *5.4 Reporting*

The findings were reported in a structured manner, with each dimension of Industry 4.0 readiness discussed in detail. The report included visual representations, such as radar charts and heat maps, to illustrate the distribution of readiness levels across the sampled MASMDs. Recommendations were provided based on the identified gaps, suggesting specific actions that organizations could take to advance their Industry 4.0 maturity.

# 6 Methodology for Calculation of Military Readiness Levels for Industry4.0

## *6.1 Readiness Levels Based on Becker's Process*

Readiness levels were established on the basis of Becker's step-by-step process [26] The levels were conceptualized by synthesizing several established Industry 4.0 readiness frameworks. Each literature source contributed unique elements that collectively form a robust methodology for assessing the readiness of Military Aircraft and Systems Maintenance Depot (MASMD) organizations for Industry 4.0 adoption.

## *6.2 Calculations of Readiness Levels*

The calculation of readiness levels in respect of all MASMDs was carried out by band scores analysis, average band score and readiness percentage calculations explained as follows:

a) **Band Score Calculation Method**: Each band was allotted with a score points as Band 0, 1, 2, 3 and 4 with 0, 1, 2, 3 and 4 points respectively.

b) **Average Band Score Calculation**: Average score represents the dimension's technological readiness across survey respondents. Formula used for average band score calculation is:

$$\text{Average Band Score} = \frac{\sum \text{Band Scores for a Specific Dimension}}{\text{Total Number of Responses}}$$

Example illustration for band average calculation in respect of dimension Digital Asset Management:

- Total Band Scores: 32,
- Total Responses: 30,
- Average Band Score: 32 ÷ 30 = 1.06.

c) **Readiness Percentage Calculation**:

$$\text{Readiness Percentage} = \frac{\sum \text{Band Scores for a Specific Dimension}}{\max\left\{\text{Possible Band Score} \cdot \text{Number of Responses}\right\}} \cdot 100\ \%$$

Example illustration for Readiness Percentage Calculation in respect of dimension Digital Asset Management:

- Max Possible Band Score per Response = 4.
- Max Possible Total Band Score = 4 · 30 = 120.
- Actual Total Band Score = 32.

Readiness Percentage = (32 / 120) · 100 = 26.67 %

# 7 Results and Discussion

Aircraft Support Systems demonstrate significantly superior readiness levels, averaging 44.35 % across all dimensions, with particularly strong performance in Supply Chain Integration (53.34 %), Lifecycle Data Management (53.34 %), and AR/VR Training (53.34 %). This suggests a mature digital infrastructure and advanced technological integration in these systems. In contrast, Helicopters show the lowest overall readiness at 7.68 %, indicating a substantial technological gap, with critical areas like

Predictive Maintenance at just 6.67 %. Fighter Aircraft maintain a moderate but consistent readiness level (21.44 % average), showing relative strength in Data Security (28.34 %) and Digital Asset Management (26.67 %). The Transport Aircraft category (10.24 % average) and Guided Weapons (18.84 % average) fall between these extremes, with Guided Weapons showing notable strength in Workforce Training and Competency (27.5 %). A concerning pattern emerges in Facility and Energy Management, which shows consistently low readiness across all categories except Aircraft Support Systems.

The bar chart depicting the results in Fig. 2 provides a clear comparative overview of overall readiness across different systems. Its vertical format emphasizes the stark contrast between Aircraft Support Systems (44.35 %) and other categories, particularly the notably low readiness of Helicopters (7.68 %). This visualization effectively communicates the significant readiness gaps between different system categories at a glance, making it valuable for high-level strategic planning and resource allocation decisions. This analysis reveals a clear need for targeted improvement initiatives, particularly in helicopter systems, while suggesting that the successful digital transformation strategies employed in Aircraft Support Systems could serve as a blueprint for enhancing readiness levels across other categories.

The radar chart depicting the results in Fig. 3 offers a multidimensional perspective, revealing the relative strengths and weaknesses across all dimensions simultaneously. The pentagon-shaped plot lines for each category demonstrate how Aircraft Support Systems (in green) consistently outperform other categories across most dimensions, forming a larger footprint. The overlapping patterns help identify specific dimensions where multiple categories face challenges or show strengths, making it particularly useful for identifying common areas needing improvement or potential best practices that could be shared across categories.

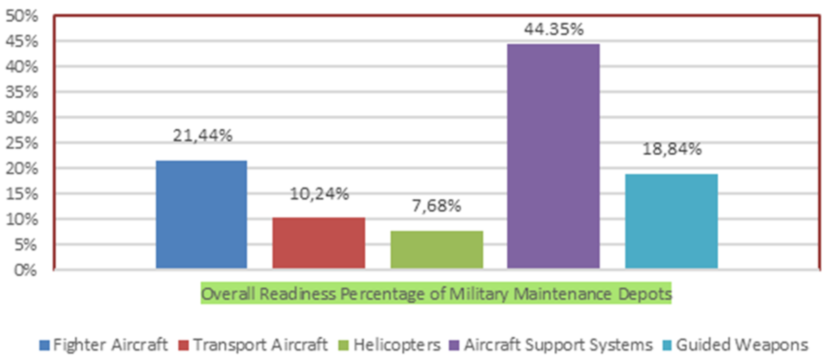


*Fig. 2 Results of readiness levels for MASMDs*

The heat map depicting the results is shown in Tab. 6. The red-shaded heatmap provides the most detailed view of the data, with pink and white colors indicating higher readiness levels in Aircraft Support Systems MASMD. This granular visualization allows for precise identification of specific strengths and weaknesses within each category-dimension combination. The color gradient makes it easy to spot patterns and outliers, such as the consistently high performance of Aircraft Support Systems (shown in white) and the generally lower readiness levels in Helicopters (darker shades). This format is particularly valuable for detailed analysis and identifying specific areas requiring intervention or investment.

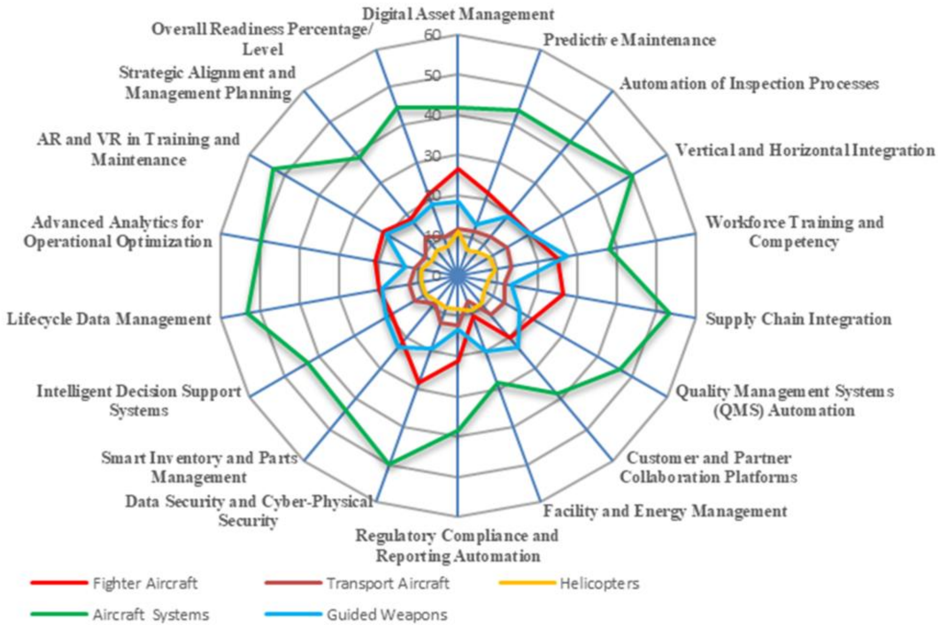


*Fig. 3 Radar chart for readiness of MASMDS*

### *7.1 Limitations and Future Research*

**a) Limitations**

It is important to acknowledge that the assessment results may be influenced by subjective approaches of respondents, potentially concerned about damaging the reputation of their depots. To mitigate this potential bias, we employed anonymous data collection methods and conducted validation interviews with multiple stakeholders at each depot. Despite these efforts, some degree of subjectivity in self-assessment remains a limitation of this study.

**b) Future Research**

Future research directions could extend this work to other military maintenance domains or compare readiness levels across different nations' armed forces. Additionally, integrating newer technological dimensions such as blockchain for secure asset tracking or digital twins for lifecycle management could further refine readiness models. Longitudinal studies tracking the impact of incremental Industry 4.0 adoption on maintenance efficiency and operational readiness would enable more adaptive strategies in military depot maintenance operations.

## 8 Conclusion

This research provides a comprehensive assessment of I4.0 readiness levels across five Military Aircraft and Systems Maintenance Depots (MASMDs), offering valuable insights into the current state of digital transformation in military maintenance operations. Through our evaluation of seventeen key dimensions specifically tailored for military applications, we have identified both strengths and critical gaps that require strategic intervention.

The findings are intended for MASMDs which are planned for transition to I4.0. These findings reveal significant disparities in readiness levels among the assessed depots, with most operating at an “Initial” level of Industry 4.0 implementation. This indicates that while there is awareness and some preliminary adoption of advanced technologies, comprehensive integration remains limited. Notable strengths identified across several depots include progress in Lifecycle Data Management, AR and VR in Training and Maintenance, and Supply Chain Integration. However, substantial shortcomings persist in critical areas such as Predictive Maintenance, Facility and Energy Management, and Quality Management Systems (QMS) Automation.

These findings serve as an essential benchmark for military organizations planning their transition to Industry 4.0. The assessment framework provides a diagnostic tool that enables MASMDs to identify their current position and develop targeted strategies for digital transformation. For key managers of government and military institutions, these results offer practical guidance when procuring new aviation equipment and managing the operation of existing aircraft and other systems to align with Industry 4.0 criteria.

Implementation strategies should prioritize dimensions with the lowest readiness scores while leveraging existing strengths. Military organizations can use this assessment to develop phased transformation roadmaps, allocate resources effectively, and establish realistic timelines for upgrading their maintenance capabilities to meet I4.0 standards.

*Tab. 6 Heatmap for readiness in MASAMDS*

| Dimensions | Military Aircraft and Systems Maintenance Depots | | | | |
|---|---|---|---|---|---|
| | **Fighter Aircraft** | **Transport Aircraft** | **Helicop-ters** | **Aircraft Support Systems** | **Guided Weapons** |
| Digital Asset Management | 26.67 | 11.67 | 10.83 | 41.67 | 18.33 |
| Predictive Maintenance | 21.67 | 11.67 | 6.67 | 43.67 | 13.33 |
| Automation of Inspection Processes | 20.00 | 12.50 | 7.50 | 43.34 | 19.17 |
| Vertical and Horizontal Integration | 20.83 | 14.17 | 9.17 | 50.00 | 20.83 |
| Workforce Training and Competency | 25.00 | 13.33 | 9.17 | 38.34 | 27.50 |
| Supply Chain Integration | 26.67 | 11.67 | 7.50 | 53.34 | 13.33 |
| Quality Management Systems (QMS) Automation | 21.67 | 13.33 | 7.50 | 46.66 | 17.50 |
| Customer and Partner Collaboration Platforms | 20.00 | 12.5 | 9.17 | 38.34 | 23.33 |
| Facility and Energy Management | 10.83 | 6.67 | 9.17 | 28.34 | 20.00 |
| Regulatory Compliance and Reporting Automation | 21.25 | 12.5 | 8.33 | 38.34 | 13.33 |
| Data Security and Cyber-Physical Security | 28.34 | 12.5 | 8.33 | 50.00 | 19.17 |
| Smart Inventory and Parts Management | 21.67 | 9.17 | 8.33 | 43.67 | 23.33 |
| Intelligent Decision Support Systems | 19.17 | 12.5 | 9.17 | 43.24 | 20.83 |
| Lifecycle Data Management | 20.00 | 12.5 | 9.17 | 53.34 | 19.17 |
| Advanced Analytics for Operational Optimization | 20.83 | 10.83 | 9.17 | 50.00 | 13.33 |
| AR and VR in Training and Maintenance | 21.67 | 9.17 | 7.50 | 53.34 | 20.83 |
| Strategic Alignment and Management Planning | 18.33 | 12.50 | 8.33 | 38.34 | 17.50 |
| Overall Readiness Percentage/ Level | 21.44 | 10.24 | 7.68 | 44.35 | 18.84 |

By addressing the identified gaps and building upon existing strengths, military organizations can enhance their maintenance capabilities, improve asset availability, and ultimately strengthen their operational readiness in an increasingly digital environment.

## Declaration of Conflicting Interests

All authors declare no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

## Acknowledgement

The work presented in this article has been completed by authors without any external support. Authors received no financial support for research, authorship and/or publication of article.

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