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SPARE HARDWARE MANAGEMENT VIA AUTOMATION

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Abstract

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This research focuses on how Industry 4.0 technologies can be applied to manage spare hardware inventory to overcome various challenges associated with the conventional techniques. These include stock discrepancies, slow procurement, and bad forecasting that leads to time wastage and increased costs. A literature-based methodology was employed, analysing peer-reviewed studies and technical papers to examine technologies like IoT, Artificial Intelligence (AI), image processing, and microcomputing (e.g., Raspberry Pi). The study consolidates six major themes: traditional inventory constraints, automation and smart solutions, inventory optimization methods (EOQ, ABC, FSN), condition-based maintenance, cost-efficient automation for SMBs, and integration of ERP systems with AI. Research also shows that the use of automated systems helps in increasing inventory accuracy, decreasing delays in the operation and making accurate decisions as data is captured and analysed in real-time. A conceptual framework of real-time tracking, AI forecasting, and ERP-WMS integration is proposed for an efficient inventory solution. The research also found that automation deployment has beneficial impacts on efficiency, sustainability and competitiveness but that there are still challenges to deployment, including cost and readiness of workforce. As such, this study adds to the existing literature and practice of digital transformation in supply chain and offers specific recommendations to industries that are seeking to digitally transform their inventory management systems to suit the tenets of Industry 4.0.

Keywords: Inventory Optimization, Automation

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List of Abbreviations

Abbreviation	Full Term	Description
ABC	Always, Better, Control	Inventory classification based on consumption value (high to low).
AGV	Automated Guided Vehicle	Mobile robot used in automated warehouses for transport.
AI	Artificial Intelligence	Technology that enables machines to mimic human intelligence.
AS/RS	Automated Storage and Retrieval System	Mechanized system for storing and retrieving inventory items.
EOQ	Economic Order Quantity	Inventory model that determines optimal order quantity to minimize costs.
ERP	Enterprise Resource Planning	Integrated software for managing business operations and data.
FSN	Fast, Slow, Non-moving	Inventory classification based on movement frequency.
IioT	Industrial Internet of Things	Network of smart devices in industrial settings for data exchange.
IoT	Internet of Things	Interconnected network of physical devices with sensors and communication capabilities.
KPI	Key Performance Indicator	Metrics used to evaluate success in achieving specific objectives.
ML	Machine Learning	Subset of AI where algorithms improve through experience/data.
RFID	Radio Frequency Identification	Technology that uses electromagnetic fields to identify and track tags attached to objects.
SME	Small and Medium-Sized	Businesses with limited revenue and workforce

	Enterprise	compared to large corporations.
WMS	Warehouse Management System	Software system for managing warehouse operations, inventory tracking, and order fulfillment.

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Chapter 1: Introduction

1.1 Research Background

Spares management plays a significant role in current industrial processes as it indicates how to manage hardware so that there are as few downtimes as possible. Typically, spare parts Logistic systems have problems normally associated with manual tracking, random stock demands, and poor control measures. The maximum possible advantage of spare hardware management by using Industry 4.0 in automation results in increased accuracy, time, and cost optimization. New research points to EOQ and ABC analysis to enhance the inventory, which is a central topic of interest (Emar et al., 2021). Further, the consequence of fault management has been earmarked on the hardware design to deal with potential dangers yielding from defective network systems (Vitucci et al., 2023). Other works such as image recognition and microcomputer automatic management system have also been suggested in spare part tracking and control (Lee et al., 2023). This paper aims at implementing the process of spare hardware management through the use of these technological advancements in order to enhance efficiency and affordability.

1.2 Problem Statement

Spare hardware management is a crucial aspect necessary to be focused on, especially in industries with a constant need for the continuous production of products and services including manufacturing, IT, and transportation industries. It has been seen that the traditional approach towards the maintenance of the spare parts involves conventional paperwork, and periodic Physical counts of inventories and may be decision-oriented hence causing inefficient control of spare. The current procurement system is prone to errors, takes time to issue procurement, and leads to excessive procurement of stock which organizes the organizational operational cost and resource wastage through the attendant cost of disposal of excess equipment.

With the advancement of Industry 4.0 or the fourth industrial revolution automation as well as smart technologies gives a high advantage in spare hardware control. It has been found that the use of microcomputers and image-processing techniques in tracking spare parts can minimize manual handling (Lee et al., 2023). Further, tools like EOQ and inventory classification namely ABC assist in increasing stock revolutions and resource management (Emar et al., 2021). Nevertheless, current automation is not seamlessly salvable in industries' inventory management because of compatibility problems, implementation costs, and resistance.

This paper aims to analyze the general problems of the spare hardware management process and propose a technological solution to the problem. The work also aims to find out how the implementation of automation can increase the efficiency of operations, save money, and increase operational sustainability. The application of automation in the spare hardware system is the primary focus of this study, which has employed the analysis of performance comparison between automated tracking, fault anticipation, and demand estimation in order to formulate an ideal design of automation integration in an industrial environment.

1.3 Aim and Objectives

The aim of the research is to develop an automated framework for spare hardware management that enhances efficiency, reduces waste, and improves decision-making in industrial operations.

The research objectives are:

- To analyse the limitations of traditional spare hardware management and identify inefficiencies in inventory control.
- To evaluate the impact of automation technologies, such as AI, IoT, and machine learning, on spare parts management.
- To design and propose an automated solution that integrates real-time tracking, predictive analytics, and smart inventory management.

- To assess the feasibility and effectiveness of the proposed automation framework through case studies or simulations.

1.4 Research Questions

The research questions are:

- What are the key inefficiencies in traditional spare hardware management systems?
- How can automation technologies improve the efficiency and accuracy of spare part inventory management?
- What are the technical and operational challenges associated with implementing automation in spare hardware management?
- How can predictive analytics and AI-driven models optimize spare parts forecasting and fault detection?

1.5 Design Solution

The more technical solution includes the use of smart technologies such as IoT sensors, Machine learning analytics and automation for spare hardware management in the company. The system will also track the use of spare hardware in real time and analyse usage and failures; thus, the spare hardware usage will be monitored and any probable shortcoming anticipated. Thus, by using a Raspberry Pi-based microcomputer (Lee et al., 2023) and image Processing, the entering process of spare parts information will be minimized.
Besides, an integration of EOQ models and ABC classification (Emar et al., 2021) will help to achieve strategic inventory management and maintain the critical level of components, which does not allow for holding excessive inventories. Maintenance algorithms will be taken to the next level to enable them predict when a failure is going to occur and suggest the right time for replacement to avert costly downtimes more so in the manufacturing process. It will also be aimed at being scalable and compatible with other ERP systems so that more organizations can adopt the solution. That is why, to positively ascertain the

impact of the automated system integration on inventory, cost and decision-making factors, one will be conducting a case study or simulation.

1.6 Significance of the Research

Thus, this research aims to add on the required body of literature that has sought to address this issue especially in spare hardware management where manual methods of stock management take eons to complete. It will also help in eradicating the mistakes that are made by human beings which are common in most industries, enhance accuracy in the management of stock as well as reducing operational time taken. Use of IoT, artificial intelligence as well as predictive analytics in managing spare parts aligns to Industry 4.0 that sees precise and intelligent management of inventory. Moreover, predictive maintenance and online tracking increase the responsibility of avoiding possible equipment failures with enhancing productiveness and utilization of resources.

Moreover, the analysis will be helpful for the companies planning to implement automation in the SC management and improve the organizational operational readiness. This study proposes solutions to technical and operative issues in order to open up the route to the wide implementation of automated spare hardware solutions making its employees to be long-term competitive in industrial contexts.

Chapter 2: Method and Material

2.1 Introduction

This chapter outlines the research method used in this literature-based study to examine the subject of spare hardware inventory management in the context of Industry 4.0. Since, no survey was conducted and no primary data was collected, the paper relies only on secondary sources such as published journal articles, research papers, technical research papers and white papers. The first section of the chapter overviews the overall qualitative paradigm, then provides the framework for selecting literature from credible databases based on specific criteria. It then outlines the thematic analysis approach used in this study in order to determine patterns, technologies, and frameworks mentioned in other researches.

2.2 Research Design

The research design for this study is a literature-based review, which is appropriate when a conceptual approach is needed to systematically review theories and new technologies without conducting original empirical research. This is especially true in places that are undergoing the technological transformation such as inventory management and Industry 4.0 implementation (Zhang et al., 2021). A literature-based approach enables the identification of the research gaps, comparison of the existing models, and the development of further conceptual solutions based on the literature studies. The starting point of the study was built based on the realization of various shortcomings of the conventional spare parts inventory management systems. These are frequent stock-outs, procurement issues, high operating costs, and maintenance that are more of crisis than preventive (Madamidola et al., 2024). From this understanding, the foundation for exploring how IoT, AI, and machine learning can be leveraged to enhance inventory accuracy and operational resilience was created.

A literature review was then conducted and the sources included journal articles, conference papers, and technical papers centered on spare parts logistics, automation in a warehouse, and predictive maintenance and inventory management models (Imarah and Jaelani, 2020; Sodiya et al., 2024). The type of analysis done was thematic as the goal was to determine the best practice and present the most effective automations. The findings from the review as also applied in construction of a conceptual framework. This model shows real time monitoring, fault detection, and demand driven procurement which is as per the industry 4.0 technology (Carpitella & Izquierdo, 2025).

2.3 Literature Sources and Selection Criteria

The sources used in the literature review for the current study included peer-reviewed journals, conferences, technical papers, and white papers and reports from reliable industries. To maintain the academic viability and relevance to the themes of the book, a systematic approach was used to select the articles. To conduct the literature search, several databases including IEEE Xplore, ScienceDirect, SpringerLink, MDPI, Google Scholar, SSRN, and ResearchGate were used. Different search terms were used in order to encompass the various aspects of spare parts inventory management and its relation with automation technologies. These were “spare parts inventory management,” “warehouse automation,” “Industry 4.0 and logistics,” “predictive maintenance,” “IoT in supply chain,” “Raspberry Pi and image processing inventory system,” and “ERP and automation integration.” The inclusion criteria focused on literature published between 2010 and 2025, with a strong emphasis on recent studies to reflect the rapidly evolving technological landscape. However, some important pieces that have set out to define inventory management theory and practice were exempted.

The selected literature had to address at least one of the following thematic areas: traditional inventory issues and problems, considerations of Industry 4.0 and automation, methods of inventory management and optimization including EOQ and ABC analysis, condition-based maintenance, image recognition solutions, and integration of ERP and AI systems. To ensure the quality of the sources, only articles that were published in refereed journals or reviewed by industry specialists were used. These were systematic overviews of spare parts inventory management policies (Zhang et al., 2021) and research on the impact of IIoT on warehouses (Khan et al., 2024). Studies on AI automation revealed enhanced stock accuracy and operation effectiveness (Sodiya et al., 2024). Inventory control was also a major concern with the authors exploring the applicability of EOQ and ABC techniques in the current supply chain environment (Imarah and Jaelani, 2020).

Literature on predictive maintenance presented AI and digital twins in relation to asset management (Rojas et al., 2025). Further, the possibility of low-cost automation using image processing and Raspberry Pi was also reviewed as a feasible solution for SMEs (Kawanaka and Kudo, 2018). Finally, sources explaining ERP system integration provided insights into how the use of AI in the platform helps in real-time updates of the inventory and decision-making process (Pokala, 2024).

2.4 Analytical Method

The studies reviewed during the review process were analyzed using a thematic synthesis approach of the articles. Thematic synthesis is a qualitative approach that allows for the categorisation, analysis and integration of patterns, concepts or relationships that are germane to a given field. It is particularly useful in literature-based research where multiple academic and industrial views have to be synthesized in order to form a coherent understanding of a subject matter. Consequently, the use of thematic synthesis enabled combining technological, operational and strategic aspects of spare hardware inventory into a single analysis framework for this study. The study found six major themes, which reflected six key domains in the development and advance of inventory systems. All these features are closely connected to the modern problems of traditional systems and the novelties prompted by automation and Industry 4.0 solutions.

Theme 1: Challenges in Traditional Spare Hardware Management

Traditional inventory management processes are often characterized by data entry incompatibilities, lack of transparency, slow updates, and reactive acquisition. Some of these shortcomings include overstocking or understocking that cause production hold up, high operating costs, and compromised service delivery. Previous studies have been praised inadequate in addressing the speed and accuracy that is needed in current manufacturing processes (Zhang et al., 2021). Real time data and automation is missing in the process and there is a big gap between usage and record, which has triggered the need for digital transformation.

Theme 2: Automation and Industry 4.0 Technologies

Smart inventory systems are brought about by automation technologies such as the Internet of Things (IoT), Radio Frequency Identification (RFID), and Artificial Intelligence (AI). These enable real-time tracking, ordering, and even decision-making if the platform possesses the ability to order products on its own. For instance, sensors can monitor the quantity and usage pattern of stock and order stock without the interference of human beings (Atieh et al., 2016). Carpitella and Izquierdo (2025) also pointed out that automation also enables sustainable management of resources and the reduction of waste. The integration of Industry 4.0 technologies increases the precision of the processes, decreases the need for manpower, and improves the flexibility of the supply chain.

Theme 3: Inventory Optimization Models

Traditional inventory control models, such as Economic Order Quantity (EOQ) and ABC classification, continue to play a crucial role when combined with modern technologies. These models help in strategic management decisions about the type and frequency of orders for the stocks in question. Integrated into digital systems, they offer more flexible and data-driven value. For example, EOQ can be made dynamic when used as a technique for adjusting the usage rate of inventory, whereas ABC analysis can be used to target the most sensitive items for better control (Emar et al., 2021). This approach combines traditional theory with newfangled flexibility, which makes for better and more specific inventory planning.

Theme 4: Predictive Maintenance and Fault Detection

Predictive maintenance adds a preventive aspect to inventory management since it uses sensors and AI to determine when equipment is likely to fail. This makes it possible to order and replace critical components on time and in a more strategic manner than having to make emergency purchases (Rojas et al., 2025). Lee et al. (2019) established that predictive models can enhance part availability by predicting when spare part demand will occur not through fixed schedules. This means that maintenance requirements can now be tied to inventory management, a major step in preparedness and budgetary responsibility.

Theme 5: Image Processing and Raspberry Pi Applications

Cost-effective technologies for image processing and Raspberry Pi make it possible to implement effective automation solutions, especially for SMEs. These tools are able to support visual inspection, barcode scanning and object identification, thus minimizing the amount of work done by hand and the error frequency (Kawanaka and Kudo, 2018). Szabó and Gontean (2016) illustrated that Raspberry Pi is a suitable foundation for implementing lightweight, programmable systems that can interface with other warehouse management systems applications. These technologies make it easier to automate and bring more businesses into the digital fold.

Theme 6: ERP and AI Integration

Enterprise Resource Planning (ERP) systems are central to many industries today with its definition referring to the management of an organization's resources. This means that it provides real-time visibility, real-time stock management, and demand forecasting through integration with AI. Pokala (2024) also said that the ERP platforms are self-sourced procurement, alerts and performance analyses based on historical data. According to Syreyshchikova et al. (2020), such integrations facilitate communication between departments, enhance timely response, and minimize bureaucracy. ERP integrated with AI enables the efficient, smart, and centralized management of inventory at a large level.

2.5 Reliability and Validity

When conducting literature-based research, criteria such as reliability and validity must be met to warrant the credibility and scholarly nature of the study. As there was no quantitative data collection in this research, the approach was standardised to ensure reliability, dependability and replicability.

Reliability

Reliability was maintained by using a uniform and clear method for picking the literature. Only articles published between 2010 and 2025, that deal with topics relevant to the subject and that are credible, were included in this review. Using academic databases such as IEEE Xplore, ScienceDirect, MDPI and SpringerLink, the research looked for study results using high-quality materials. Literature was grouped into key themes that supported the research objectives, even though no formal coding was done. Grouping the findings in this way helped us reduce the chance of subjective opinions from reviewers. While it could not always be repeated as a scientific procedure, researcher worked hard to keep consistency and clarity and preserve academic standards during the study.

Validity

Validity refers to the extent to which the study accurately reflects the real-world phenomenon it intends to investigate. To enhance construct validity, the themes identified in the literature were aligned closely with the research objectives and questions. Although triangulation was not strictly used, various theoretical, empirical and industry sources were incorporated to strengthen the analysis. This allowed to understand the same subjects from different angles and lower the chances of bias. Supporting content validity, the review covered both traditional theories and the current state of spare parts inventory automation.

2.6 Summary

This chapter provides an overview of the study’s approach, which is an exploratory, qualitative research conducted from a review of literature. Describes a sequential and rigorous approach with an emphasis on a systematic review of articles and thematic synthesis to establish automation in spare parts inventory management. The databases were searched for relevant sources based on clear criteria for inclusion. Six core themes emerged: The areas of interest include traditional inventory issues, Industry 4.0 technologies, inventory optimization methods, predictive maintenance, image processing using Raspberry Pi, and ERP-AI integration. These themes guided the establishment of a conceptual framework of smart inventory systems. For reliability, procedures were kept constant, and for validity, the research objectives were followed along with multiple sources and focusing on practical relevance. The approach gives a good starting point to studying and developing automated inventory systems.

Chapter 3: Current State Analysis / Project Specifications

3.1 Introduction

This chapter will include a detailed evaluation of the current spare hardware inventory management system and will examine the system to define operational issues, obsolete procedures, and processes with no recorded use of technology. It is necessary to find out the current issues that are still a problem with inventory management like manual data entry, little planning, and non-integrated systems. Inventory control of spare parts is one of the most vital activities that determine maintenance plans, equipment availability, and expenses. However, in its current state, the system does not provide real-time visibility or ability to plan ahead. Based on this analysis, a potential, broader solution that is grounded in automation is proposed that would meet the requirements of Industry 4.0. As a result, the chapter is intended to justify the necessity of the integrated approach to inventory control that would enhance the accuracy of data and make the processes more efficient.

3.2 Current IT System and Inventory Management Practices

The case company mainly uses a legacy ERP system and ad hoc methodology for the management of the inventory, where manual records and spreadsheets are used. One of the major problems is that the ERP platform is not fully integrated with the warehouse; this makes the inventory process fragmented and reactive. As Sudarmi and Sunaryo (2024) pointed out ERP systems in the early stages were more focused on supporting transactions and did not support real-time analysis or interface with the outside world. As for spare parts, lack of real-time visibility into stock data slows down acquisition and distorts inventory (Mehrotra and Sehgal, 2023). Additionally, in many cases, such as those in a warehouse, the inventory movement is documented after the actual movement takes place, which causes additional time and errors that affect the dependability of operations. According to Odeyinka and Omoegun (2023), such conventional warehousing structures are incompatible with dynamic contexts particularly those that require accurate supply chain or maintenance-requiring part stock availability.

There is always a variance between the recorded stock and the actual stock, which is very dangerous since they entail certain costs. Both situations are expensive to the business since they indicate that the business has too much stock or not enough stock.

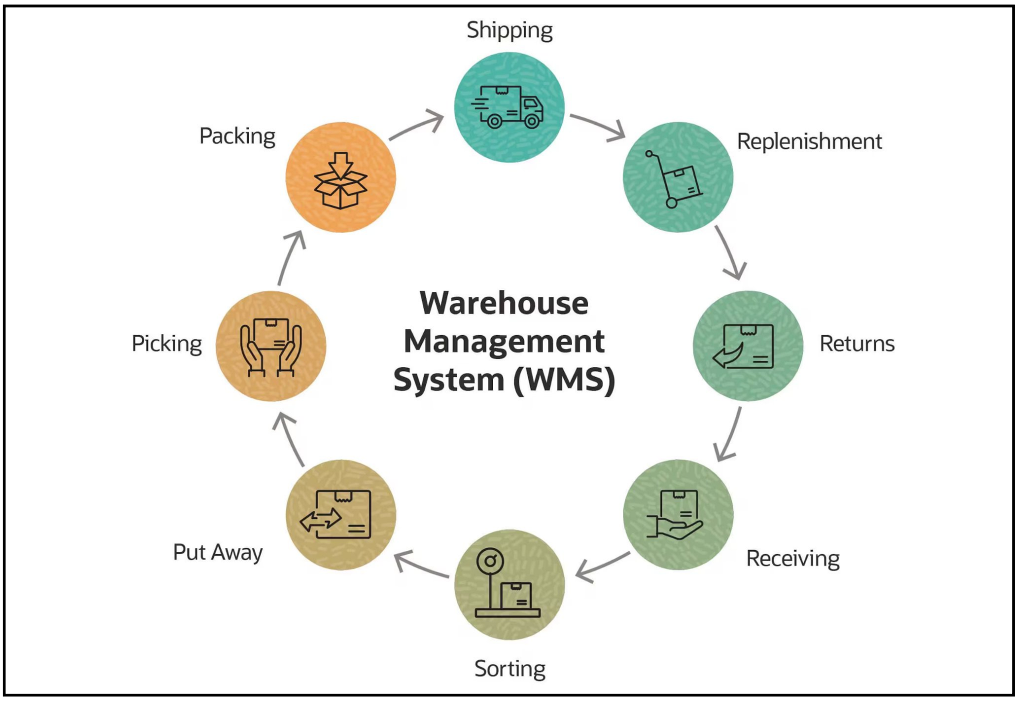

Figure 1: Warehouse Management System

(Source: Odeyinka and Omoegun, 2023)

3.3 Identified Challenges in the Current System

3.3.1 Manual Data Entry and Stock Inaccuracy

One of the main problems of the current system is that it fails to provide automatic inputs and thereby, there is a disparity between the physical stock and the records. This brings in human intervention and thereby delays the updates of the stock quantity (Mehrotra and Sehgal, 2023). Thus, maintenance departments undergo unscheduled downtime due to missing parts that were supposed to be in store.

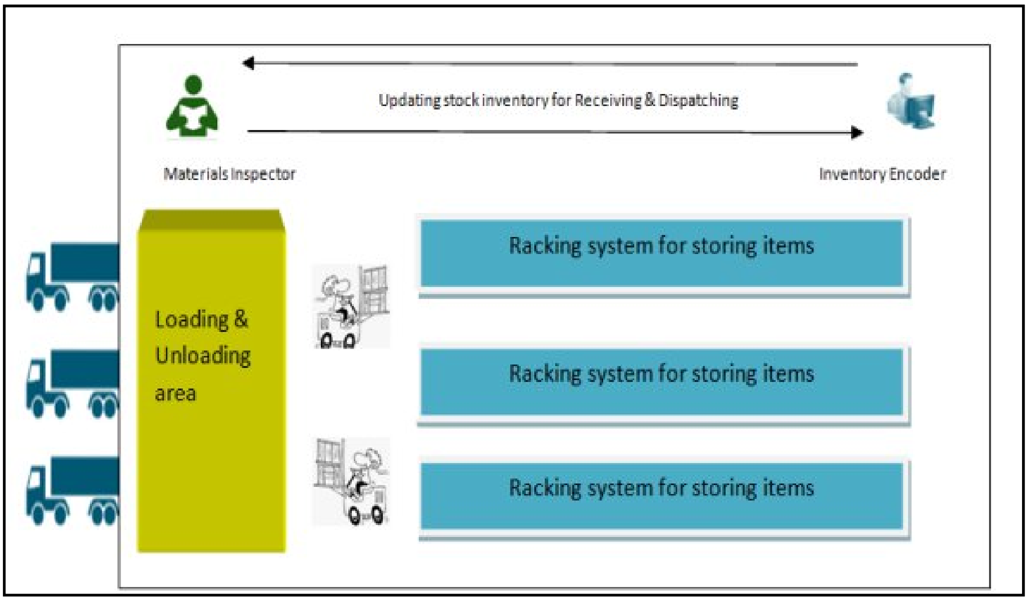

Figure 2:The Layout of a Traditional Warehouse

(Source: Mehrotra and Sehgal, 2023)

3.3.2 Limited Demand Forecasting Capabilities

The current ERP system lacks the functionality of predictive modeling or usage in the past. Other than that, procurement lacks forecasting and as a result it will either use reactive restocking or over ordering which are costly and time wasting. For instance, according to Adur Kannan et al (2020), machine learning and AI are more efficient in forecasting sporadic demand than is currently possible in the system.

3.3.3 Lack of Warehouse Automation

Some of the warehouse functions that include part picking, location identification, and replenishment are done manually. These processes are rather lengthy and ineffective. Odeyinka and Omoegun (2023) explain how the use of technologies such as barcode scanners and Automated Storage and Retrieval Systems (AS/RS) can increase the rate of pick up and decrease the rate of errors.

3.3.4 System Silos and Lack of Integration

Another major challenge is the disconnection between the ERP and other subsystems. It also runs in near real-time, so while inventory data is updated when new inventory arrives or is moved, the data at the central location is not updated in real-time. According to Tong et al. (2023), the co-ordination of ERP and WMS is crucial in order to ensure that the activities of all the departments are in harmony and decisions that are made are informed.

3.4 Areas Identified for Improvement

3.4.1 Real-Time Tracking Using IoT

Specifically, the use of IoT devices such as RFID scanners and environmental sensors can help keep track of spare parts in real-time without interruptions. This integration also avoids data latency issues, minimises manual data entry mistakes, and offers real-time visibility of movements and inventories of parts. Automated internet of things (IoT) based inventory has been known to enhance the flow of data accuracy and timeliness in warehouse operations (Sahara and Aamer, 2022).

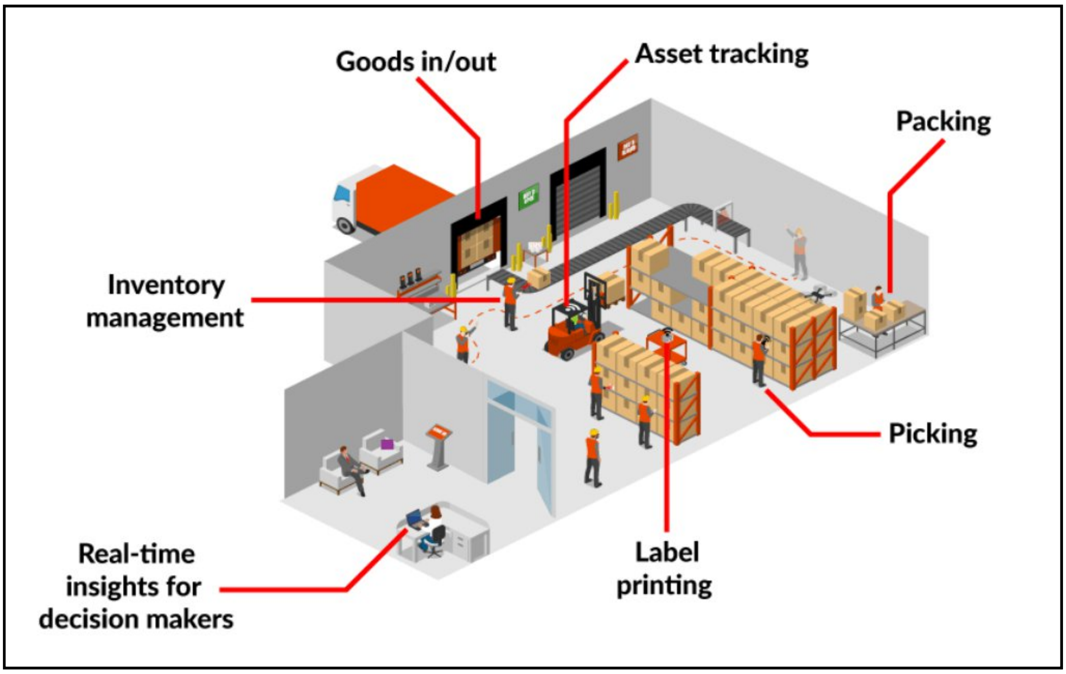

Figure 3: IoT-Based Smart Inventory Tracking Setup

(Source: Sahara and Aamer, 2022)

3.4.2 Warehouse Process Automation

Some of the automation technologies include the Automated Storage and Retrieval Systems (AS/RS) that help in reducing the cycle time of several warehouse operations including picking, placing and replenishment. These systems decrease dependence on people, decrease the likelihood of errors and increase the velocity of inventory in the warehouse. With the integration of the technology in smart warehousing, they are seen as an important factor in spare parts operations (Deepika and Vinoline, 2025).

3.4.3 AI-Powered Demand Forecasting

The utilization of AI and machine learning in demand forecasting help the organizations to predict the requirements of spare parts more accurately, especially for slow-moving and fluctuating products. The usage frequency data, when processed using predictive analysis, ensures that there are no cases of overstock and stock out at any given point in time. Research also shows that the use of AI in demand forecasting increases supply chain responsiveness and holding costs (Alalawin et al., 2021).

3.4.4 Full ERP-WMS Integration

In order to ensure system-wide consistency and reduce data silos, seamless integration between the Enterprise Resource Planning (ERP) system and Warehouse Management System (WMS) is essential. Integrated solutions allow for consistent changes across departments, more accurate decisions, and real-time tracking of stocks and transactions.Integrated systems have been shown to enhance organizational coordination and operational efficiency (Sudarmi and Sunaryo, 2024).

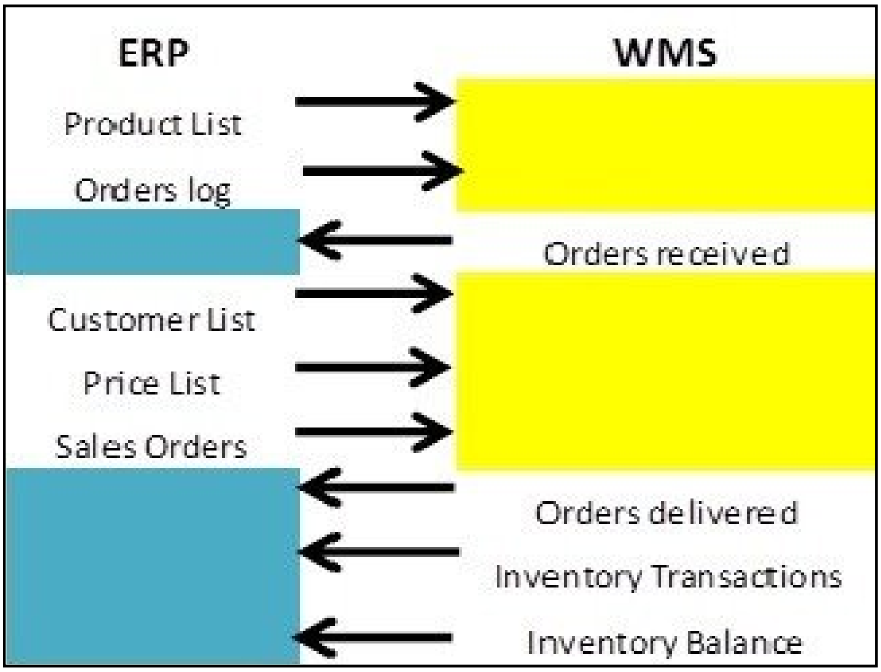

Figure 4: ERP-WMS Integration Flowchart

(Source: Sudarmi and Sunaryo, 2024)

Chapter 4: Theoretical Background

4.1 Introduction

Inventory of spare parts is a crucial element of effective asset management and business continuity, especially in the industries that rely on the use of various assets. Most inventory systems were in the past, paper based or simple computerized tracking and planning tools, which are gradually being replaced by the industry 4.0 tools. Technologies such as automation, IoT, AI, as well as ERP in integration with WMS are revolutionizing how spare parts are managed, forecasted and replenished. These technologies offer accurate time control, forecast and automation of inventory procedures, which in turn increases productivity and minimizes disruptions. Since spare parts are usually characterized by high cost and low turnover, effective supply management is crucial to achieving an optimal balance between service levels and inventory expenses. The following chapter presents the theoretical framework for explaining these technological developments and their applicability to automated spare parts management. The ideas presented here will form the foundation for the framework outlined in the remaining sections of this dissertation.

4.2 Spare Parts Inventory Management

4.2.1 Inventory Models and Importance

Spare parts inventory management is crucial to reducing product downtime and enhancing reliability across industries like manufacturing, energy, and logistics industries. As Bounou et al. (2017) have pointed out, spare parts should be managed as a different class of inventory from the regular inventory that is non-cyclically ordered, costlier, and indispensable for a system to operate efficiently. They contend that the existing forecasting models are quite inadequate for spare parts, especially spare parts that are demanded infrequently. According to Yavuz (2020), poor spare parts planning leads to either a surplus inventory or a critical shortage. For example, an automotive company's analysis of spare parts found that more than 40% of those in inventory were idle for 12 months, which meant resources were frozen in those stocks. On the other hand, lack of necessary spare parts caused 9 hours of production loss per each instance and the company lost thousands of dollars.

4.2.2 Inventory Classification Techniques

In order to tackle these problems, the most common approach is classification methods. Pandya & Thakkar (2016) point out that in ABC analysis, inventory is classified according to consumption value: A items are 70–80% of the annual consumption value but only 10–20% of the items. XYZ analysis, on the other hand, sorts inventory according to the degree of demand variation. Products with a stable demand pattern are classified as "X" while those with highly fluctuating demand are classified as "Z." Yavuz (2020) also supports the continuing of FSN analysis that will help to distinguish between Fast, Slow and Non movers to minimize obsolete inventory. When combined, these classification models provide a richer perspective that can be used by organizations to better manage their inventory, distribute their resources, and enhance the dependability of their services.

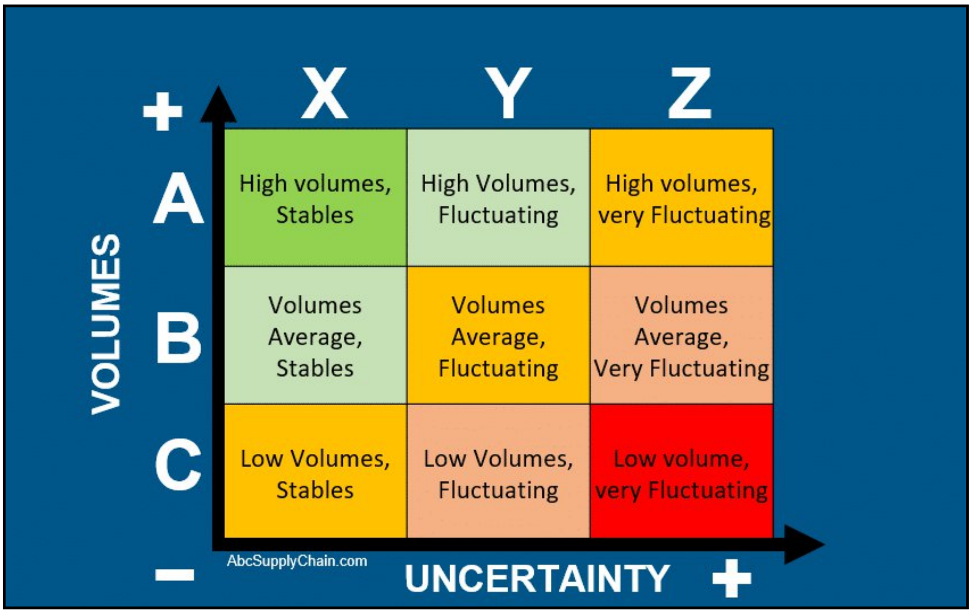

Figure 6: ABC XYZ Analysis in Inventory Management

(Source: Yavuz, 2020)

4.3 Warehouse Automation Technologies

4.3.1 Automated Storage and Retrieval Systems (AS/RS)

Automated Storage and Retrieval Systems (AS/RS) is the core of the new high-efficiency warehouses replacing the traditional conventional methods of storage. According to Hameed et al. (2019), AS/RS refers to the computer-based systems that are used to store and retrieve inventory with minimal human interaction. These systems can accommodate any number of applications, from handling large pallets in high throughput environments to picking small valued goods and spare parts in mini load conditions. In spare parts warehousing, AS/RS are well suited because of the high variability, low volume characteristics of inventory to ensure that there is accurate storage and timely picking of the spare parts. Bremer et al. (2024) conducted a study on robotic AS/RS performance analysis based on the system theory and observed that the throughput increased by more than 30% after the compact warehouse adopted AS/RS automation. This also concluded that they achieved an improved picking accuracy which cut down on order error by up to 25%.

These improvements will have a direct effect on operational efficiency since they help minimize downtime and increase services offered. According to Torchio (2023), AS/RS integration also benefits from robotics concerning labor and the use of the vertical dimension. Their doctoral studies prove that robotic systems can minimize the needed warehouse space by 40% while simultaneously increasing or at the very least, maintaining productivity. Furthermore, automated systems deliver predictable performance and accountability – elements that are pivotal for spare parts logistics where misplacing or delaying spare parts is likely to affect a range of maintenance schedules.

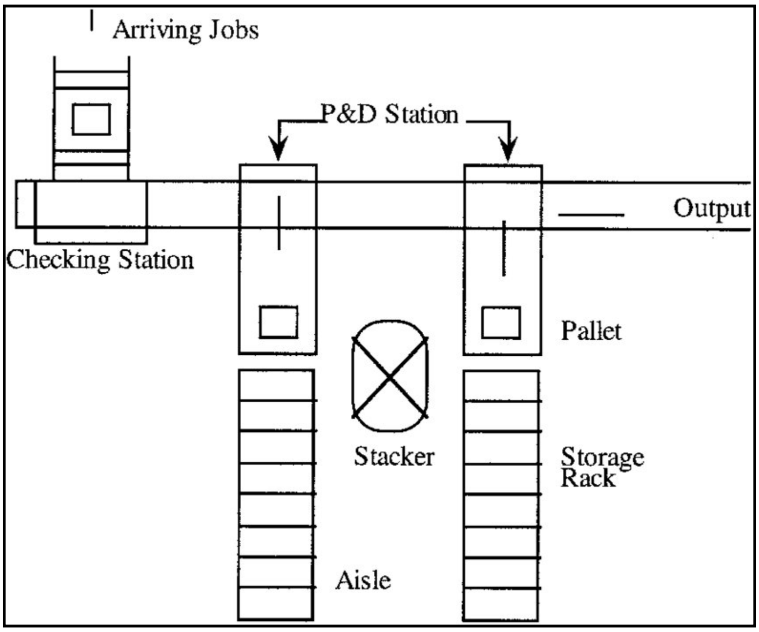

Figure 7:AS/RS Workflow Diagram

(Source: Torchio, 2023)

4.3.2 Robotics and Conveyor Systems

Robotics and conveyor systems complement AS/RS by automating material movement and handling within the warehouse. As Dhaliwal (2020) notes, industries are increasingly turning to Automated Guided Vehicles (AGVs), robotic arms, and conveyor systems as a way to reduce the dependency on manual handling. He also adds that these systems lead to higher throughput while decreasing the occurrence of errors that come with human interaction, especially helpful in cases where the components are visually similar or require a high level of precision. Conveyor systems can be well-suited for routine, high-throughput applications; however, robotic arms are better for pick-and-place or sorting and assembling of parts. In automated warehouses, these technologies are applied to reduce cycle times and increase productivity and work safety by minimizing the human-element exposure to dangerous procedures. Together, AS/RS, robotics, and conveyor systems are the building blocks of the modern warehouse where speed, precision, and flexibility of scale are critical to efficient spare parts storage and distribution.

Figure 8: Robotics and Conveyor Systems

(Source: Dhaliwal, 2020)

4.4 Internet of Things (IoT) in Inventory Management

4.4.1Real-Time Tracking

According to Mashayekhy et al. (2022), IoT is considered a disruptive technology in inventory management since it allows for the tracking of stock levels through sensors, RFID, and connected platforms. They state that companies employing IoT as a means of tracking inventory management saw their errors in this aspect cut by more than one-third. As Nguyen (2023) demonstrated in the case, deploying IoT in spare parts warehouses results in improved forecasting of parts demand, as well as real-time visibility into the part’s movement, which facilitates quicker maintenance decisions.

4.4.2 Predictive Maintenance with IoT and ML

Teoh et al. (2021) propose a predictive maintenance model combining IoT and fog computing with machine learning. They continue to state that using sensor data and data analytics in localized locations allows for early detection of component failure hence minimizing on machine downtime. This is supported by Kalusivalingam et al. (2020) in showing how the use of IoT data analytics in manufacturing contexts enables the prediction of equipment breakdowns and appropriate stocking of raw materials.

4.5 ERP and WMS Integration

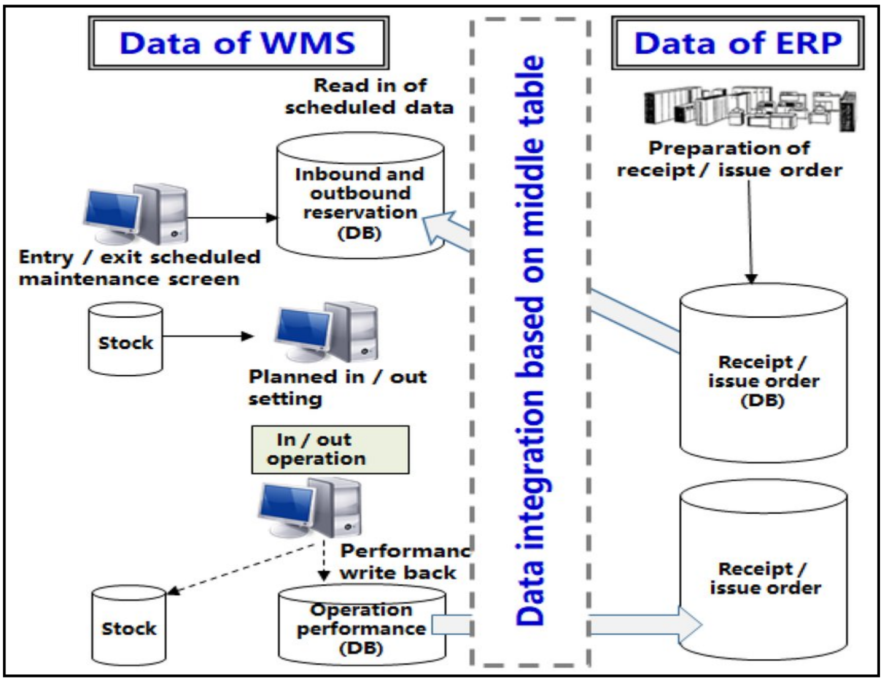

Figure 9: ERP-WMS Integration Architecture

(Source: Adeosun and Chukwunweike, 2023)

4.5.1 Importance of ERP Systems

Enterprise Resource Planning (ERP) systems are known to be the central nervous system of a business organization since they provide an interface for inventory, procurement, finance, and maintenance. Adeosun & Chukwunweike (2023) posited that ERP systems are useful tools for controlling spare parts in industries with diverse configurations. But they admit that typical ERP applications do not capture operational transparency of activities at the warehouse level. Specifically, more than half of the firms in the study stated that inadequate ERP data refresh frequency negatively impacted stock accuracy and procurement scheduling (Adeosun and Chukwunweike, 2023). This leads to situations where products are ordered too late, stocked in large quantities or leading to product down time.

4.5.2 Warehouse Management System (WMS) Synergy

The integration of Warehouse Management Systems (WMS) with ERP platforms allows organizations to have the latest information on the status of their inventory and other departments in real-time. According to Adeosun and Chukwunweike (2023), such integration minimizes the problem of data silos, increases forecast accuracy by 30%, and enhances order delivery time by 25%. It also contributes to more accurate demand forecasting and inventory management thus making the supply chain more flexible.

4.6 Artificial Intelligence in Inventory Optimization

4.6.1 Demand Forecasting

According to Sekhar (2022), conventional forecasting methodologies are not effective in dynamic markets. However, forecasting demand is more precise using a neural network, decision trees, and time series algorithms. Kumar et al. (2024) also looks at how AI can predict demand patterns even for occasional or seasonal spare part demands. Their model improved demand prediction accuracy by over 20% compared to traditional methods.

4.6.2 AI in Stock Optimization

Kumar et al. (2024) also finds that with the help of AI, stock optimization decreases the carrying costs of inventory and the service level constraints. Their strategy was based on the direct implementation of AI tools into ERP systems for ordering points and safety stock determination.

4.7 Industry 4.0 Technologies and Their Integration

Industry 4.0 technologies have revolutionized how warehouses function especially in managing spare parts since precision, speed, and responsiveness are crucial. Tikwayo and Mathaba (2023) performed a systematic review of integration of cyber-physical systems, digital twin, Internet of Things (IoT), and machine learning. They note that these technologies give rise to real-time business environments where decision making is done on operational data in real-time. From their survey, they note that AI and IoT can support change in warehouse operation, demands, and part upkeep requirements. For example, while ordering new parts can be automated through predictive algorithms, IoT sensors allow real-time visibility into inventory movements. By integrating such systems, adaptability is achieved, overall production time is minimized, and the supply chain becomes more robust. Tikwayo and Mathaba (2023) argues that such fragmentation of technology systems could slow the large-scale implementation of the systems if there is no compatibility and standardization achieved. They note that successful implementation depends on the commitment of funding to the procurement and adoption of integrated digital solutions and integration middleware that can link these tools together.

4.8 Implementation Challenges

Several challenges still exist when implementing automation and Industry 4.0 technologies in spare parts inventory management across various organizations in terms of size and capability.

- **Large Capital Expenditure and Infrastructure Transformation:** The cost of procuring and implementing robotic AS/RS and IoT is high. These systems need to replace existing layouts and workflows by integrating more automated equipment and support systems. This is a challenge that has a financial and implementation implication; especially to organizations that are financially challenged (Bremer et al., 2024).
- **Scalability Issues for SMEs:** Automating business processes can be a challenge for small and medium-sized enterprises because they lack the capital, physical room, and technology resources to pursue automation effectively. Another challenge is the relatively small number of competent personnel to attend to and manage such technologies (Torchio, 2023).
- **Workforce Readiness and Resistance:** Technology comprises a critical part of organizational effectiveness, and its efficient implementation is contingent upon engagement and flexibility of the workforce. If the workforce is not trained and engaged, it shall act as an impediment to integration. It is most evident in ERP-WMS integration; it is essential to note that these changes occur in the system frequently due to the nature of its operations. These are critical barriers that need to be addressed through workforce reskilling to enhance the chances of these programs' sustainability in the long run (Adeosun and Chukwunweike, 2023).

4.9 Summary

This chapter has outlined the theoretical background of the use of Industry 4.0 technologies in the modernization of spare hardware inventory management.

Issues like inventory categorization techniques, automation of warehouses, integration of ERP with WMS, IoT in tracking, condition-based monitoring, and predictive maintenance, and AI-aided solutions were also the talk of the town. From the literature, it is evident that there is a trend towards interconnected smart systems that increase productivity, minimize operational mistakes and facilitate evidence-based decision making. Other potential concerns which were also outlined include the high implementation costs, compatibility of the system and the ability to train the human resources to adapt to the change. The understanding arrived at in this chapter provides the foundation for the creation of a practical framework that will be expanded on in the following chapters to propose an effective and sustainable automated spare parts inventory management system.

Chapter 5: Results and Analysis

5.1 Introduction

This chapter provides the findings and thematic synthesis of the literature on modern spare parts inventory management. Using a qualitative approach and drawing on available literature, this study distils six key areas of focus, namely classification models, automation technologies, integration with IoT, AI in forecasting, integration of ERP and WMS systems, and implementation issues. For each theme, existing literature is reviewed to examine the implications of emerging technologies on operations, costs, and services in industries. The findings are synthesized from recent peer-reviewed articles, case studies, and systematic reviews, offering both theoretical insights and practical implications.

5.2 Theme 1: Challenges in Traditional Spare Hardware Management

The conventional spare parts inventory management is normally associated with manual data collection, use of isolated spreadsheets, and periodic physical counts. Such methods are insecure, involve data duplication, are time-consuming, and outdated when it comes to the current operational needs. It was found that one of the most common problems is the data discrepancy, which results in contradictory record inventory. This leads to overstocking which results in high holding costs or understocking which interferes with regular maintenance. Yavuz (2020) pointed out that in the manufacturing organization under investigation, more than 40% of the spare parts inventory was classified as Obsolete or over 12 months of inactivity. Furthermore, approximately 10% of all urgent maintenance work could not be performed due to missing spare parts, which impacted production availability and dependability. Manual systems also do not have real-time traceability, this makes it difficult to track misplaced or stolen components and time taken to search for them. These systems are integrated with procurement, finance, or maintenance planning platforms, creating a lack of visibility across departments. This results in lack of coordination, reactive rather than proactive ordering and few analysis capabilities. These limitations highlight the importance of using automation, system integration and real time access to remove the barriers to the effectiveness, efficiency and speed of spare hardware inventory.

5.3 Theme 2: Automation and Industry 4.0 Technologies

Automation and Industry 4.0 technologies have emerged as an influential driver for change, revolutionising spare parts inventory management. For instance, Automated Storage and Retrieval Systems (AS/RS) have taken over from manual raking and picking in favor of systems that allow for more storage density and faster picking. The literature review by Hameed et al. (2019) suggested that implementation of AS/RS can lead to up to 50% cut in warehouse labor expenses in addition to enhancing the pick accuracy by over 25%. According to Bremer et al. (2024) in their on-performance comparison of robotic AS/RS systems they noted that the robotic systems enhanced overall throughput by 30% and reduced the time taken to retrieve inventory by 22% than in the semi-automated warehouses. Furthermore, the percentage of order errors reduced by 18%, which enhanced customer satisfaction and minimized the amount of rework.

Torchio (2023) pointed out that the application of technologies in smart warehouses including robotics and automation technologies, vision-based picking system and real-time inventory scan increases traceability and operational transparency. Dhaliwal (2020) proved that by imploring Automated Guided Vehicles (AGVs) and conveyor networks, material handling velocity was enhanced by 40% with fewer accidents and ergonomic mishaps from manual lifting. These technologies all collectively bring the warehouse ecosystems into the modern age, enhancing spare hardware performance, safety and real time responsiveness.

5.4 Theme 3: Inventory Optimization Models

Robust inventory optimization models form the backbone of efficient spare parts management, particularly in environments where demand is irregular and the cost of downtime is high. Some of the traditional tools that are used to classify the stocks include the ABC analysis, which classifies stock based on its daily consumption value, and the XYZ analysis which categorises the stock based on the variability in demand. ABC classification uses the Pareto principle in that it categorizes items in the inventory with the 10-20% most valuable items needing a high level of control (Pandya & Thakkar, 2016). XYZ analysis, on the other hand, focuses on the consistency of item consumption to allow for forecast modification based on the variability. Yavuz (2020) used a FSN (Fast, Slow, Non-moving) technique in a manufacturing company case and was able to purge 15% of the stock that was not needed, thus creating more space and better inventory replenishment.

ABC XYZ and FSN allow inventory control to be constructed in a way that involves multi-dimensions, which will help the inventory managers to devise very special control measures for various categories of items. However, traditional models such as the Economic Order Quantity (EOQ) are equally applicable when digitized. Emar et al. (2021) have shown that when EOQ is aligned with real-time demand data, organizations can cut carrying costs by as much as 18%. These are useful data-oriented methods that assist in bringing procurement tactics more in touch with real time operations, improving flexibility and precision in spare parts requirements planning.

5.5 Theme 4: Predictive Maintenance and Fault Detection

Predictive maintenance (PdM) is changing the approach to spare parts management, from reactive or time-based to condition-based maintenance routines. By using IoT sensors, machine learning, and real-time monitoring, preventive maintenance can be detected from the patterns in the equipment. This enables maintenance activities to be planned and the procurement of spare parts to be timed accurately to meet demand, thus cutting down on the amount of time that an organization's machinery is out of order and the costs incurred in reacting to emergencies. Rojas et al. (2025) conducted a study and showed that the incorporation of predictive analytics in maintenance processes significantly reduced the duration of unplanned equipment downtime by 28% and spare part stock out by 21%. This is done by receiving real-time condition information (vibration, temperature, and load cycles) and feeding it into algorithms that prompt inventory actions at certain conditions.

Lee et al. (2019) also stressed the transition from the time-based approach; it was also revealed that different actual usage patterns of spare parts improved their availability through the usage of predictive models. According to their research, they were able to identify that facilities that implemented predictive maintenance systems had a 17% increase in part availability and a decreased inventory holding cost by 11%. When maintenance forecasts are integrated with inventory management, an organization optimizes its working capacity, minimizes spare inventory, and averts avoidable interruptions thereby making predictive maintenance a key component of current spare parts planning.

5.6 Theme 5: Image Processing and Raspberry Pi Applications

The combination of the image processing system and Raspberry pi microcomputers has made it possible to offer automation solutions that are affordable to small to medium enterprises especially in the spare parts management. These technologies include features such as object recognition, barcode scanning, quality inspection using vision, and inventory management with relatively low investment on hardware and code complexity. Kawanaka and Kudo (2018) have shown that the identification of inventory satisfaction could also be done using image processing and deep learning models. In their implementation, storage bins were observed by cameras that were connected to Raspberry Pi units, this enabled detection of parts and stock. It also lowered dependence on manual audits by more than 40% and increased the accuracy of real-time stock.

According to Szabó and Gontean, 2016, Raspberry Pi platforms are suitable to operate in decentralized warehouses. Their work involved the use of Raspberry Pi units to control and report on inventories via Wi-Fi to a central system; it provided a 30% improvement in visibility of stock for decentralised inventories. These technologies are particularly useful to SMEs as they cannot afford to invest in expensive systems of ERP or robotics. Raspberry Pi systems allow for software which is accessible to the public meaning that the errors that may occur when the operations are done manually are greatly minimized. In general, image processing with low cost microcomputing means more companies can afford to automate their spare hardware inventory systems and minimize human error.

5.7 Theme 6: ERP and AI Integration

Enterprise Resource Planning (ERP) systems have become the core technological platforms for the new-generation industrial value chain, enabling instant communication between inventory, procurement, finance, and maintenance divisions. Not only do ERP platforms consolidate data, but when linked with AI, they also improve decision-making through automation, analytics, and insights. According to Pokala (2024), contemporary ERP systems are characterized by the integration of AI that supports features like auto-start of procurement, exception reporting, and performance prediction based on past consumption behavior. These insights can then be used by inventory managers to have real-time visibility into trends, trends that can be used to predict shortages, and trends that can be used to make restocking decisions without input from a human being. According to Syreyshchikova et al. (2020), ERP-AI integration is critical to enhancing cross-functional communication across departments. Through integration with other applications, the company is able to reduce the time taken to respond to maintenance needs as well as improve on the accuracy of demand forecasts.

In their research, the authors discovered that organizations that adopted AI integrated ERP systems had a 25% increase in inventory accuracy and a 20% decrease in inventory operations time. Furthermore, modules incorporated in the ERP system can simulate different supply chain conditions and offer inventory management strategies that are cheaper to implement but meet service requirements. This capability is particularly useful in strategic planning, especially where spare parts critical to business operations are involved. Consequently, integration of ERP with AI helps organizations to better control spare hardware stocks, to be more reactive, and to adapt to the growing industrial context.

5.8 Summary of Thematic Findings

This thematic analysis conducted throughout this chapter shows a progression in the management of spare hardware inventory from the conventional static and reactive to smart, anticipative, and automated systems. Research has indicated some of the drawbacks of manual tracking and integrated systems such as; inaccurate information, overstocking, and slow response. Some of these limitations are, however, being mitigated by implementation of Industry 4.0 technologies. Technologies such as AS/RS, AGVs and robots have improved the efficiency of the warehouse, and accurate maintenance solutions which are based on AI and IoT have optimized part replacement and maintenance which in turn reduce cases of unexpected equipment failure. Furthermore, inventory optimization models such as the ABC-XYZ-FSN and EOQ are still core but with advanced digital capabilities for flexibility. On a related note, the availability of low-cost products and services such as Raspberry Pi and image recognition makes the usage of automation more attainable for SMEs.

The integration of ERP with AI will result in real-time data sharing and forecasting of the procurement, maintenance and the warehouse. These strategies contribute to improved inventory control, lower costs, and quicker decision-making, which make up the basis for the effective spare parts inventory systems today.

Summary of Thematic Findings

Theme	Key Contribution
Traditional Management Challenges	Identified data errors, stockouts, and inefficiencies
Automation & Industry 4.0	Increased speed, accuracy, and reduced labor dependency
Inventory Optimization Models	Improved classification and dynamic stock control
Predictive Maintenance	Reduced downtime and proactive part ordering
Image Processing & Raspberry Pi	Cost-effective automation for SMEs
ERP and AI Integration	Centralized control, forecasting, and decision support

5.9 Summary

This chapter has summarised the pertinent literature findings by focusing on the evolution of spare hardware inventory management through technology and methods. The thematic analysis highlights the importance of automating procedures, the use of predictive analysis and integrated systems in order to eliminate traditional difficulties and enhance the inventory processes. These insights are used in the subsequent chapters to construct frameworks and guidelines for implementation that improve spare hardware inventory management within the industry 4.0 framework.

Chapter 6: Discussions and Conclusions

6.1 Introduction

This chapter provides an overview of the major themes discussed in chapter 4 regarding spare hardware inventory management within the framework of Industry 4.0. This study examines how the use of technologies such as automation, IoT, predictive analytics, and AI-based ERP systems are revolutionizing inventory management and operational excellence. As for the analysis of the discussed innovations, it focuses on their applicability, effectiveness in terms of cutting costs, and potential for enhancing the accuracy of decision-making processes. In addition, the chapter also explores the challenges and constraints that organisations experience when adopting such technologies, particularly for the small to medium-sized enterprises (SMEs). It also provides recommendations for future studies and practical application in different industrial settings at the end.

6.2 Interpretation of Key Findings

6.2.1 Transition from Traditional to Automated Systems

The analysis revealed that traditional inventory management systems, characterized by manual recordkeeping and isolated software platforms, are increasingly inadequate in meeting the demands of modern industries. Yavuz (2020) pointed out that 40% of spare parts stored in the organization were obsolete or inactive which causes organizational wastage and additional expenses. The increase in the adoption of automation, such as AS/RS and robots, has shown enhanced precision, velocity, and personnel productivity (Hameed et al., 2019; Bremer et al., 2024).

6.2.2 Integration of Industry 4.0 Technologies

Introduction of Industry 4.0 technologies including the Internet of Things (IoT), Artificial Intelligence (AI), and machine learning has transformed inventory management. These technologies allow for continuous monitoring, condition-based monitoring, and real-time decision making, which improve operational flexibility and adaptability (Torchio, 2023; Dhaliwal, 2020).

6.2.3 Inventory Optimization Models

ABC, XYZ, and FSN classification models are still useful when combined with digital systems. These models allow the inventory management to be less prescriptive and more responsive to the current usage rates and fluctuations in demand (Pandya and Thakkar, 2016; Emar et al., 2021).

6.2.4 Predictive Maintenance and Fault Detection

Predictive maintenance, with the help of sensors and AI, helps in ordering and replacement of spare parts in advance and is not an emergency purchase which makes maintenance more efficient (Rojas et al., 2025). According to Lee et al., (2019), reserve stock supply availability is enhanced since it is not scheduled based on fixed time, but reliance on a prediction system based on equipment usage is adopted.

6.2.5 Cost-Effective Automation for SMEs

New technologies such as image processing and Raspberry Pi have enabled automation for SMEs at an affordable price range. These tools enable simple observation, barcode recognizing and object detecting, helping to lessen manual inputs and decrease errors (Kawanaka and Kudo, 2018).

6.2.6 ERP and AI Integration

When integrated with AI, ERP systems offer firms real-time information visibility, stock control, and demand forecasting. Such integrations create interconnectivity between departments, improve response time, and reduce bureaucracy, which results in efficient, intelligent, and centralised inventory management (Adeosun and Chukwunweike, 2023).

6.3 Implications for Practice

The study highlights the need for industries to source more efficient spare hardware inventory management through technology integration. Digitization and adoption of Industry 4.0 solutions can create considerable benefits that relate to productivity and precision, as well as cost advantage. A case of Raspberry Pi shows that despite resource constraints, there are automation tools that can be adopted by SMEs to help them close the technology divide and compete in the digital age.

6.4 Limitations of the Study

The study offers a wealth of information regarding the implementation of advanced technologies in inventory management, the research is more theoretical in nature and involves a literature review. The studies' failure to present real-world evidence may restrict the generalization of the results. As such, future research should investigate these areas through case studies and empirical analyses of the theoretical frameworks considered here.

- **Long-Term Impact Evaluation:** Despite the theoretical benefits of adopting Industry 4.0 technologies highlighted in current literature as a short-term gain, more research should be conducted about the long-term impacts upon the KPIs such as cost, time to failure, and service quality. Longitudinal research might help to uncover the specifics of the sustainability and profitability of automation tools, AI-driven ERP systems, and predictive maintenance solutions for spare parts inventory (Rojas et al., 2025).
- **Industry-Specific Challenges and Enablers:** There is also a need for expanded study on the contextual factors that contribute to successful implementation across different organizational sectors. For example, the issues affecting giant manufacturing firms may not be the same as those

affecting firms that are small or medium-sized. It is important to understand these differences toward creating a specific approach to take when deploying (Szabó and Gontean, 2016).

- **Development of Integration Standards:** There is currently a gap in the literature concerning the best practices or guidelines for the integration of IoT, AI and ERP systems. Future research should shift towards finding solutions to overcome the problems of heterogeneity and establishing high levels of integration between systems with different middleware solutions without vendor lock-in and ensuring scalability (Syreyshchikova et al., 2020).

6.5 Conclusion

The evolution from conventional, manual inventory systems to technologically advanced, automated solutions marks a pivotal shift in how industries manage spare hardware. Traditional systems characterized by delayed updates, isolated data silos, and reactive procurement are no longer adequate in environments that demand high precision, speed, and adaptability. From this study, it is clear that the implementation of Industry 4.0 technologies such as IoT, AI, machine learning, and robotics, enhances real-time tracking, analysis, and intelligent stock control. Predictive maintenance and digital demand forecasting reduce time loss and resource wastage, and affordable automation devices like Raspberry Pi along with image processing make it easier for SMEs. The adoption of AI into ERP systems helps in the flow of information between departments and provides the best decision support for the supply chain. Despite the challenges that are associated with implementation of such systems including; financial constraints, lack of skilled personnel and integration complexities the benefits of such systems outweigh the challenges. The use of technology in an organization in a way that supports the organizational strategy will enhance the chances of attaining firm-wide resilience, sustainability, and cost-efficiency in the long run. However, to sustain this development, future empirical studies and large-scale pilot tests are required. Industries can fine-tune their inventory systems and stay relevant in a digital and automated global economy.

Chapter 7: Summary

The purpose of this research was to identify how spare hardware inventory management can be enhanced through the application of Industry 4.0 technologies. The study adopted a literature review approach and integrated findings from a variety of scholarly and industrial sources that focused on the research themes. The study revealed six broad categories that together raise awareness of the current issues and opportunities related to inventory management. The first theme highlighted areas of waste that the current systems were characterized by; overstocking, understocking, delayed procurement, and inaccurate data. These, according to Yavuz (2020), are anchored in manual documentation and the lack of instant data transfer among organizational departments. Following themes confirmed the disruptive effects of automation and the industry 4.0 technologies. In AS/RS, robotics, and IoT-powered tools, the efficiency, speed, and accuracy are tremendously increased. Bremer et al. (2024) indicated that the robotic AS/RS systems can enhance the retrieval time and inventory accuracy by more than 20% thus reducing time lost during production.

The basic models like EOQ, ABC and FSN are still used but they are even more effective when incorporated into decision support systems that use consumption data in real-time for forecasting and ordering. Decision support through AI and sensors helps to avoid urgent buys and at the same time, allows for better planning of spare parts. Among the most beneficial for the SMEs were the low-cost automation with the help of such devices as Raspberry Pi microcontrollers and image processing systems. Additionally, when ERPs are used in conjunction with AI, their capabilities for providing insight, optimizing planning, and facilitating interdepartmental collaboration are boosted. This study shows that the implementation of automation, IoT, and predictive maintenance using AI enhanced ERP systems can greatly improve spare hardware inventory management. These tools move activities from being reactive and paper-based to proactive, lean, intelligent tools that provide enhanced productivity, precision, and timeliness.

There are still implementing barriers such as financial issues, technical difficulties, and changes in human resources especially for SMEs while realizing its long-term advantages of adopting these technologies strategically.

Increased efficiency, decreased time lost, better stock management, and better utilization of resources are some of the benefits. The integration of Industry 4.0 solutions continues to gain popularity among industries; thus, the adoption of new inventory systems remains not only advantageous but also imperative.

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Appendix

Responsible Use of AI in the Thesis

This thesis acknowledges the responsible and transparent use of Artificial Intelligence (AI) in accordance with the Metropolia University of Applied Sciences' guidelines titled *"Guidelines for the Use of Artificial Intelligence in Learning Activities and Theses"* (8 August 2024).

AI tools were used in a supportive role during the thesis writing process, specifically in the following ways:

- **Structuring and Planning**: AI was consulted to brainstorm and refine the structure of the thesis and to formulate potential research questions.
- **Language and Clarity**: AI-assisted tools were used to improve the grammar, phrasing, and clarity of the text, especially in the early drafting stages.
- **Conceptual Support**: AI was used for ideation regarding models, use cases, and theoretical comparisons, which were then validated using scholarly sources.
- **Technical Editing**: AI helped improve the flow and consistency of terminology throughout the text.

No AI-generated content was used as a primary source. All scientific claims and conclusions in this thesis are supported by peer-reviewed academic literature and properly cited references. AI outputs were reviewed, critically assessed, and modified by the author to ensure alignment with good scientific practice.

Tool Used:

- **OpenAI. (2024). ChatGPT (May 2024 version) [Large language model].** https://chat.openai.com/chat

As the author of this thesis, I am responsible for all the content.