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A Theoretical Framework of Spare Part Inventory Management for Aging Rotating Equipment: A Case Study

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Abstract. This paper presents a theoretical framework for managing spare parts inventory for aging rotating equipment in the oil and gas industry, focusing on challenges such as unpredictable demand, long lead times, and obsolescence risks. Traditional inventory methods, such as ABC analysis and Economic Order Quantity (EOQ), are insufficient for handling these complexities. The framework integrates demand characteristics, such as usage frequency and criticality, with predictive maintenance and continuous review policies. Data from maintenance management systems also plays a critical role in developing the spare parts control policy. Based on interviews with maintenance experts and inventory analysts, the study findings confirm that unpredictable demand and long lead times are significant challenges. Additionally, flexible contracts and integrated planning between maintenance, inventory control, and suppliers are paramount. Future research should explore dynamic sourcing strategies and machine learning to enhance forecast accuracy and process automation in spare parts management.

Introduction

Traditional inventory management techniques such as ABC classification and Economic Order Quantity (EOQ) have been widely applied to manage spare parts in various industries [1]. However, these methods are often insufficient for managing spare parts for aging equipment, which exhibit erratic demand patterns [2]. [3] Note that the ABC classification does not adequately prioritize parts for aging equipment, where the criticality of parts, rather than their value or historical consumption, should guide stocking decisions. Similarly, EOQ models, which calculate optimal order quantities to minimize holding and ordering costs, fail to address the demand volatility of aging equipment and are not suited to handle the increasing uncertainty in part availability. Moreover, studies suggest that traditional models do not account for the unpredictability of usage and lead times, which are typical of aging equipment [4].

Efficient spare parts inventory management ensures equipment reliability and operational continuity, so the target service level is often set very high [5]. According to [6], inventory typically accounts for one-third of a company's assets, highlighting the importance of optimizing spare parts management for aging equipment. The impact of unexpected failures can be significant, leading to revenue losses and further emphasizing the need for an adequate spare parts management system. Spare parts inventory management involves forecasting, procurement, and stock optimization to ensure the availability of parts when needed while minimizing excess inventory costs. However, as the equipment ages, standard inventory management practices often fail to address specific challenges such as increased unpredictability of engine failure, obsolete spare parts, and erratic demand patterns due to aging equipment experiencing repeated failure or breakdown [7].

Rotating equipment, such as gas compressors and engines, is critical in maintaining operations in mature oil and gas fields. These assets are critical to operational activities such as gas compression, transmission, and processing. As these machines age, they present unique challenges regarding spare part management, leading to operational risks and higher maintenance costs therefore, the purpose of this paper is to analyze the current spare parts control strategy for aging rotating equipment and propose a customized spare parts control policy model, based on a theoretical framework, supported by existing research and results from the interview. The proposed inventory control policy seeks to reduce inventory costs, enhance spare parts availability, and minimize downtime. Additionally, it provides a foundation for management decision-making to optimize spare parts control strategies.

The Case That Motivates This Study

The motivation for this study comes from the growing operational challenges related to managing spare parts for aging rotating equipment, particularly in the oil and gas industry. As equipment such as compressors and engines surpass their designed lifecycle, they become more prone to unpredictable failures and increased maintenance needs. This leads to erratic demand patterns for spare parts, making traditional inventory management strategies like ABC classification and Economic Order Quantity (EOQ) insufficient. Furthermore, spare part obsolescence is adding to the problem, as manufacturers may discontinue production of critical components. The longer lead times required to source or reproduce these parts can result in operational disruptions, increased downtime, and amplified maintenance demand and costs. Based on these complexities, there is an urgent need for a more adaptive spare parts control policy that incorporates demand variability, lead time uncertainties, and criticality of components, ensuring both availability and cost-efficiency in managing aging rotating equipment.

Due to confidentiality, the name of the company is changed to Nusantara. Nusantara is a state-owned company and also a major oil and gas producer in Indonesia that has been operating for more than fifty years in East Kalimantan, with seven areas of operation equal to 1.942 km². Since its first operations, Nusantara has drilled over 1000 wells and produced more than 12.6 trillion cubic feet (TCF) of gas and 0.4 billion barrels of crude oil. During that period, Nusantara installed many rotating equipment to support the production, such as gas compressors and engines. Various types of gas compressors and engines are presented in Table 1.

Table 1. List of Rotating Equipment.

No	Manufacturer	Unit Type	Unit Average Age (yrs)
1	CTP	Diesel Engine Generator	20.5
		Generator Gas Engine	17.18
		Reciprocating Compressor	28
		Wellhead Compressor	13.18
2	WKS	Generator Gas Engine	18
		Reciprocating Compressor	19.17
		Flare Recovery Unit	10.67
3	DRR	Reciprocating Compressor	30.6
4	ARC	Reciprocating Compressor	16.92
5	FRC	Wellhead Compressor	13.32
Average Age of Rotating Equipment			**18.75**

Significant evidence in the literature shows that equipment older than 10 years is typically considered aging. This is particularly true, where equipment exceeding this age often requires more rigorous maintenance schedules and stricter inventory control policies to mitigate the risks associated with aging. [8] highlight that equipment like gas turbines, pumps, and compressors, commonly found in power generation plants and oil rigs, tends to reach the end of its designed operational lifespan of close to 20 years. This observation aligns with multiple studies suggesting that equipment older than 10 years necessitates increased attention for maintenance and spare parts management [8]. Additionally, research on other industries, such as aviation equipment, shows that the average age of equipment often exceeds 20 years, particularly for older aircraft models, leading to challenges in reliability and performance [9]. In the manufacturing sector, equipment that is over 10 years old is frequently subjected to more rigorous maintenance schedules due to the increased likelihood of failures and performance degradation [10]

As can be seen from Table 1, the average age of rotating equipment is 18.75 years, which, according to previous literature, can be categorized as aging equipment. As equipment ages, it typically experiences increased downtime and, consequently, an increasing demand for spare parts. Research indicates, equipment that is older than 10 years often requires more frequent repairs and replacements, resulting in higher inventory turnover for spare parts [11]. The cost of spare parts can account for a significant portion of the total lifecycle cost of equipment, with estimates suggesting that spare parts consumption can reach up to 2.5% of the original purchase price annually for equipment with a lifespan of around 30 years [11].

The standard for rotating equipment downtime can vary significantly depending on the type of equipment, operational context, and specific industry practices. However, it is generally accepted that minimizing downtime is critical for maintaining operational efficiency and profitability. Previous research indicates that the average downtime for rotating equipment in the oil and gas sector can range from 5% to 10% of total operational time annually. This translates to approximately 18 to 36 days of downtime per year for equipment that operates continuously [12]. Table 2 and Table 3 show the downtime and spare parts consumption for aging rotating equipment.

Table 2. Equipment Downtime (hours)/Year.

Manufacture	Downtime (hours)/Year					Average Downtime Hours/Year	Standard Deviation	Coefficient of Variation
	2020	2021	2022	2023	2024			
CTP	9,783	8,824	4,077	4,372	10,169	7,445	2929	39%
WKS	4,130	3,241	3,443	3,540	5,243	3,919	807	21%
DRR	1,495	377	486	1,565	7,565	2,298	3080	134%
ARC	1,322	2,172	1,782	1,329	1,843	1,690	395	23%
FRC	9,231	7,536	4,683	4,254	5,158	6,172	2144	35%
Total	**25,961**	**22,150**	**14,471**	**15,060**	**29,978**	**21,524**	**6767**	**31%**

As shown in Table 2, which includes standard deviation and coefficient of variation, this provides a deeper understanding of equipment downtime patterns over the five-year period. While the average shows the central tendency of downtime, the standard deviation indicates how widely downtime values fluctuate from year to year, where a higher standard deviation reflects greater inconsistency in performance. For instance, both CTP and FRC units show consistently high average downtime as well as relatively high standard deviation values, confirming their critical status and justifying the need for continuous spare part provisioning to minimize operational risk.

However, the DRR equipment stands out with an extremely high coefficient of variation,134% and a large standard deviation, highlighting not only variability relative to its mean but also absolute volatility over time. This means that while the average downtime of DRR may appear moderate, sudden and severe spikes in failures can create unexpected strain on spare part availability if not anticipated. In contrast, WKS and ARC exhibit lower standard deviation and coefficient of variation values, indicating more predictable demand behavior and enabling leaner inventory approaches. These findings highlight the need for differentiated inventory strategies, ensuring high safety stocks for consistently critical equipment such as CTP and FRC, adaptive contingency planning for high-volatility units like DRR, and streamlined inventory policies for more stable categories such as WKS and ARC. Such an approach balances cost efficiency with risk mitigation in managing spare parts for aging rotating equipment.

Table 3. Spare Parts Consumption/Year.

Manufacturer	Spare Parts Consumption/Year					Total
	2020	2021	2022	2023	2024	
CTP	$ 139,291	$ 452,505	$ 236,058	$ 399,302	$ 148,409	$ 1,375,565
WKS	$ 853,534	$ 540,997	$ 174,804	$ 1,738,915	$ 1,281,757	$ 4,590,007
DRR	$ 205,965	$ 226,270	$ 108,006	$ 63,352	$ 72,885	$ 676,478
ARC	$ 14,659	$ 63,974	$ 72,824	$ 33,492	$ 818,243	$ 1,003,192
FRC	$ 282,242	$ 373,240	$ 84,498	$ 1,408	$ 464,747	$ 1,206,135
Total	**$ 1,495,691**	**$1,656,986**	**$ 676,190**	**$ 2,236,469**	**$ 2,786,041**	**$ 8,851,377**

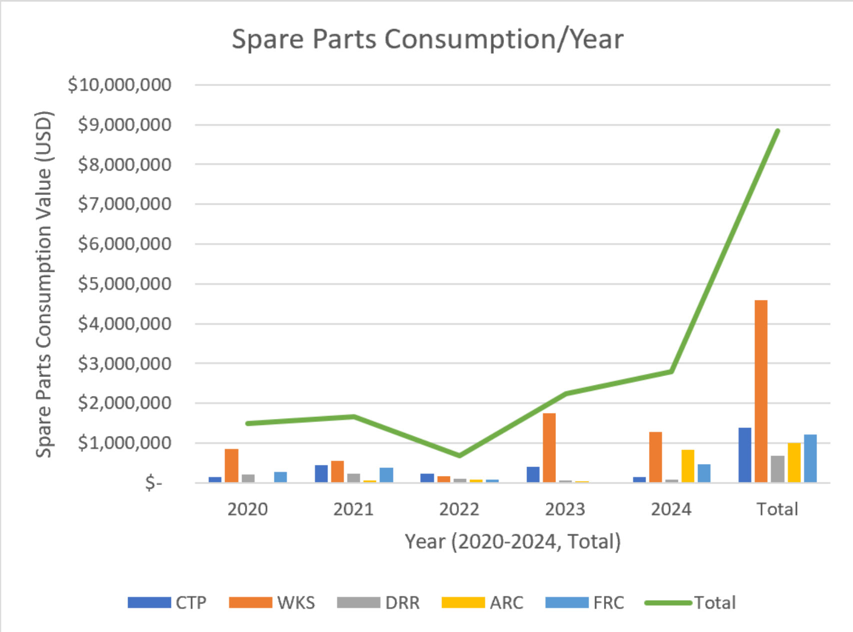

Fig. 1. Graphic Spare Parts Consumption/Year.

Current Maintenance Strategy

Based on interview results with maintenance planning engineers, the existing maintenance strategy approach is preventive maintenance, a combination of periodic and predictive. Periodic maintenance involves performing maintenance at regular intervals to prevent unexpected equipment failure. This approach, also referred to as "time-based maintenance," is widely adopted by firms in the industry, often following manufacturers' recommendations, though it can sometimes lead to unnecessary maintenance activities. On the other hand, predictive maintenance bases maintenance decisions on data collected from specialized instruments such as sensor systems, monitoring technologies, vibration analysis, lubrication testing, and ultrasonic inspection. This method is also known as "condition-based maintenance” [13]

Current Inventory Control Strategy

The current inventory control strategy involves multiple methodologies to manage the 12,795 types of materials. These materials are categorized using the ABC inventory classification, with 1,053 items classified as Class A, 279 as Class B, and 11,463 as Class C. The replenishment process follows a traditional Min-Max inventory approach, whereas when the inventory level reaches the Min point, a replenishment order is placed to refill the stock back to the Max level. Moreover, the Min-Max quantity is determined when registering new spare parts to the Enterprise Resource Planning (ERP) system. The periodic review policy varies between classes, with Class A items reviewed monthly, Class B annually, and Class C every two years or as needed. Additionally, the organization targets a key performance indicator (KPI) of 85% for inventory service level agreements (SLA) related to maintenance, repair, and operations (MRO) materials, ensuring sufficient stock availability for operational needs.

Inventory Replenishment Process

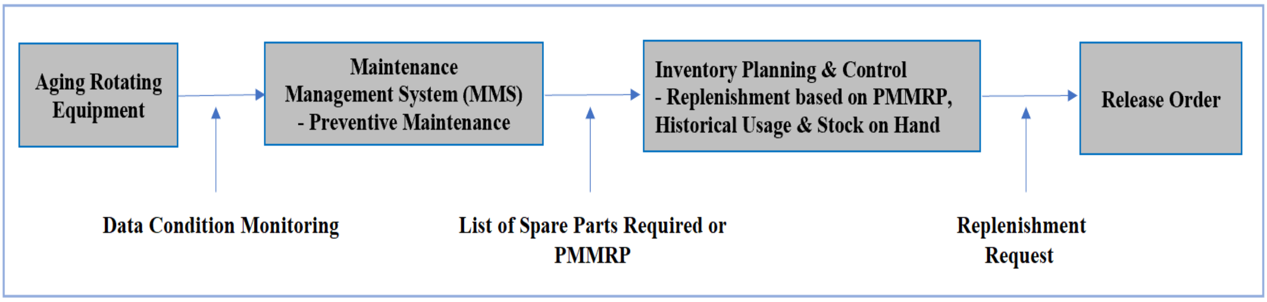

Fig. 2. Inventory Replenishment Process.

Based on previous literature, common inventory management methods such as ABC class, replenishment policy, and periodic review policy are not fully adequate to handle the complexities associated with aging equipment. These methods can lead to increased downtime, higher inventory costs, and inefficiencies in the supply chain.

Literature Review

Inventory Management for Aging Equipment

The oil and gas sector is highly dependent on critical rotating equipment. As equipment gets old, the need for spare parts grows significantly. Managing spare parts for aging equipment presents unique challenges, as older machines are often less efficient and more prone to breakdowns. Studies have shown that the lack of reliable inventory control for such equipment can lead to excessive downtime and high inventory costs. Traditional inventory management methods, such as ABC classification and Economic Order Quantity (EOQ), have long been used to optimize spare part inventories. ABC classification ranks inventory based on consumption value, with "A" items being the most valuable and frequently used, while "C" items are less critical and consume fewer resources [2, 3]. EOQ models are designed to minimize the total cost of ordering and holding inventory by determining the ideal order quantity for each item [1]. These methods work well for managing spare parts for new equipment with predictable usage patterns, as they rely on historical demand data and established lead times. [7] point out that ABC classification focuses primarily on part value and consumption frequency, but fails to account for the criticality of spare parts required for aging equipment. Similarly, [14] argues that EOQ models overlook the increased demand volatility and longer lead times associated with parts for older equipment. As equipment ages, spare part requirements often become more erratic, and the risk of obsolescence rises, making it difficult for these models to ensure adequate inventory levels.

Although compressors, gas engines, and pumps are standard equipment with well-documented average life expectancies provided by manufacturers, forecasting their actual operational age presents significant challenges. This difficulty arises from variations in operating conditions such as temperature, pressure, and exposure to corrosive fluids. Furthermore, equipment obsolescence and lack of available spare parts may shorten effective lifetime, sometimes forcing earlier replacement independent of physical wear-out. These combined uncertainties explain why forecasts based solely on nominal average life are often unreliable for aging rotating equipment. [15] further explore the complexities of maintaining aging equipment, noting that traditional inventory systems are not designed to handle the irregular demand patterns associated with aging assets. Their study suggests that spare part inventory management must evolve to include more flexible, real-time forecasting tools to better anticipate part failures and account for the unique needs of older equipment. Another significant challenge is the risk of obsolescence. As equipment ages, manufacturers may discontinue certain spare parts, making it increasingly difficult to source them when needed. This situation necessitates organizations to maintain a delicate balance between having enough inventory to avoid downtime and managing the risk of holding obsolete parts that may never be used [16, 7].

In summary, managing spare parts for aging equipment in the high capital industry requires a shift from traditional inventory methods, such as EOQ and ABC classification, to more adaptive strategies. Challenges such as part obsolescence and lead time variability continue to pose significant risks for aging equipment. Therefore, an alternative approach is needed to explore new inventory models that can address these challenges and optimize spare part management for aging equipment.

Demand Characteristics in Spare Part Management

Demand characteristics are critical in managing spare parts, especially for aging rotating equipment, such as gas compressors, engines, and pumps. The complexity and unpredictability of spare part demand increase significantly as equipment ages, creating challenges for traditional inventory management systems. Understanding these four key demand characteristics is essential for optimizing inventory levels, reducing downtime, and ensuring operational continuity for aging equipment.

Criticality

Item criticality refers to the importance of a spare part to the overall functioning of the equipment and operations. Critical components are those whose failure could cause major production stoppages, safety hazards, or significant financial losses. As equipment ages, certain parts become more critical to operations, and failure of these parts can result in substantial downtime. [3] explain that criticality-based inventory management is essential for ensuring that high-priority spare parts are always available, especially for aging equipment where failures are more frequent and unpredictable [3].

For aging rotating equipment, critical parts, such as rotors, blades, and other core mechanical components, may require higher levels of availability. [14] propose that spare parts for aging equipment should be classified based on criticality rather than usage frequency or cost, as the failure of critical components can have far-reaching effects on operational continuity [14].

Obsolete Item

Managing spare parts for aging rotating equipment presents significant challenges, particularly the risk of obsolescence. As equipment ages, spare parts may become obsolete, meaning they are no longer produced by manufacturers, leading to operational and financial difficulties [18, 19]. The rapid advancement of technology and equipment design changes contributes to the discontinuation of older spare parts, where equipment reliability is critical, the unavailability of obsolete parts can cause extended downtime and increased operational costs [20]. This situation forces companies to either retrofit equipment or delay maintenance, both of which can compromise safety and efficiency.

The complexity of inventory management further complicates the handling of obsolete spare parts. Companies often struggle to forecast the demand for parts of aging equipment with unpredictable failure rates, resulting in either excess inventory of obsolete parts or stock shortages [21]. To address these risks, organizations must adopt proactive inventory management strategies, including risk-based methodologies, to prioritize critical spare parts, build strong supplier relationships, and explore alternative sourcing methods such as remanufacturing [22, 23]. These approaches can help mitigate the effects of obsolescence, ensuring the continued reliability of aging equipment [24, 25].

Lead Time

Lead time is the amount of time it takes to procure and receive spare parts from suppliers. For aging rotating equipment, lead times can vary significantly, especially for obsolete or hard-to-find parts. [2] notes that long lead times are a common issue when dealing with spare parts for aging equipment, particularly when original equipment manufacturers (OEMs) no longer produce or stock certain components [2]. This often forces companies to source parts from third-party vendors or rely on aftermarket solutions, which further extends lead times and increases procurement costs.

Long lead times are particularly problematic for critical spare parts, where delays in availability can lead to extended equipment downtime and operational disruptions. [7] suggest that inventory strategies for aging equipment must account for lead time variability by maintaining higher levels of safety stock for critical parts, ensuring that they are available when needed, even if supplier delays occur. Incorporating supplier collaboration and vendor-managed inventory (VMI) agreements can help mitigate the risk of long lead times for aging equipment.

Demand Unpredictability

Managing spare parts for aging equipment is challenging due to demand unpredictability, which arises from irregular wear and tear, inconsistent maintenance history, and varying operating conditions. As equipment ages, the rate at which components degrade can differ significantly, making it difficult to forecast spare part needs. For example, some parts may wear out faster under harsh conditions, while others may last longer than expected, resulting in erratic failure patterns that complicate inventory planning. [15, 2] highlight that the unpredictable nature of aging equipment's spare part demand often renders traditional forecasting methods, like those based on historical usage, ineffective.

The irregular demand leads to two primary risks: stockouts and overstocking. Stockouts occur when parts are unavailable during unexpected equipment failures, resulting in downtime and production losses. Conversely, overstocking involves holding excessive inventory to avoid shortages, leading to higher holding costs and potential obsolescence of parts. [4] emphasize that companies must balance these risks carefully, as both scenarios can negatively impact operational efficiency and costs.

To manage demand unpredictability, strategies such as predictive maintenance, condition-based monitoring, and dynamic inventory policies can be adopted. Predictive maintenance uses data analytics to anticipate failures, while condition-based monitoring tracks equipment health in real time, allowing for proactive part replacement. [26] suggest that dynamic inventory policies, which adjust stock levels based on real-time data, can help optimize spare part management for aging equipment by addressing the variability in demand more effectively than traditional models.

Spare Part Control Policy

Several spare part control policies are widely used in industries such as oil and gas, manufacturing, and utilities to optimize inventory and ensure that spare parts are available when needed. These methods aim to balance inventory costs with part availability, but their applicability to mature or aging equipment can be limited due to the unpredictable nature of demand. As equipment ages, the frequency of breakdowns increases, and the demand for spare parts becomes less predictable.

Integrating a continuous review policy with condition-based monitoring and predictive maintenance offers a comprehensive approach to managing spare parts for aging rotating equipment. This integration is essential for optimizing inventory management and ensuring operational efficiency, particularly as equipment ages and becomes more prone to failures. A continuous review policy involves regularly monitoring inventory levels and making replenishment decisions based on real-time data. This approach allows organizations to maintain optimal stock levels of critical spare parts, ensuring that they are available when needed without incurring excessive holding costs. By continuously assessing inventory, companies can respond swiftly to fluctuations in demand, which is particularly important for aging equipment that may experience unpredictable failure patterns [27]. Condition-based monitoring complements this policy by providing real-time insights into the health and performance of equipment. By utilizing sensors and data analytics, organizations can monitor key performance indicators (KPIs) and detect anomalies that may indicate impending failures. This proactive approach allows for timely interventions, reducing the likelihood of unplanned downtime and the associated costs of emergency repairs [28]. For instance, if a sensor detects abnormal vibrations in a rotating component, maintenance can be scheduled before a complete failure occurs, thereby minimizing the impact on operations.

Predictive maintenance further enhances this integrated approach by leveraging historical data. By predicting when a component is likely to fail, organizations can optimize maintenance schedules and spare parts ordering, ensuring that the necessary components are available just in time for maintenance activities [29, 30]. This not only reduces inventory costs but also improves the overall reliability of aging equipment, as maintenance can be performed at the most opportune times based on actual equipment conditions rather than arbitrary schedules [31]. Moreover, the integration of these strategies allows for a more sophisticated risk management framework. By assessing the criticality of spare parts and aligning inventory levels with the operational importance of equipment, organizations can prioritize resources effectively. This risk-based approach ensures that essential components are readily available while minimizing excess inventory costs associated with less critical items [32, 33].

In addition, a safety stock policy serves as a crucial strategy to mitigate the risks associated with equipment failures and unplanned downtime. Safety stock refers to the additional inventory held to protect against uncertainties in demand and supply, ensuring that critical spare parts are available when needed. This is particularly important for aging equipment, which tends to have higher failure rates and unpredictable maintenance needs. Moreover, safety stock policy helps organizations maintain an adequate supply of essential components, thereby reducing the risk of stockouts that could lead to operational disruptions and costly downtime [17]. [34] also emphasizes the importance of determining minimum stock levels to reduce the incidence of stockouts while managing the costs associated with overstocking.

In conclusion, the integration of a continuous review policy with condition-based monitoring and predictive maintenance provides a robust framework for managing spare parts for aging rotating equipment. In addition, a safety stock policy is also critical for aging rotating equipment. By maintaining adequate inventory levels to address uncertainties in demand and supply, organizations can enhance operational efficiency, reduce downtime, and optimize costs associated with spare parts management. This approach enhances operational efficiency, reduces downtime, and optimizes inventory costs, ultimately contributing to improved asset management and sustainability in a sector where equipment reliability is paramount. In addition, this research employs a staged methodology combining literature review, case study analysis, and expert interviews to develop a theoretical framework for spare parts management."

Methodology

This study adopts a single case study design to investigate spare parts management for aging rotating equipment in the oil and gas industry. The case study approach allows for an in-depth exploration of real practices, challenges, and strategies within a company operating equipment beyond its average service life. The research process to develop the proposed theoretical framework was conducted in four sequential stages, combining theoretical foundations from the literature with empirical insights from company data and expert interviews.

Stage 1. Literature Review

The first stage involved a comprehensive review of academic and industry studies on spare parts management in capital-intensive industries. The review focused on:

- Traditional methods such as ABC classification and Economic Order Quantity (EOQ) and their limitations when applied to aging assets.
- The role of demand characteristics (criticality, unpredictability, obsolescence, and lead time) in spare parts planning, and.
- Existing frameworks and policies for spare parts control and comparable sectors.

This stage established the conceptual foundation and helped identify research gaps, which then informed the design of the semi-structured interview procedure used in later stages.

Stage 2. Data Collection through Case Study and Expert Interviews

In the second stage, data were gathered through a single in-depth case study of Nusantara with a fleet of aging rotating equipment. Two types of data were collected:

- Quantitative company data: Preventive Maintenance Material Requirement Planning (PMMRP), spare parts consumption records (five years), overhaul and maintenance schedules, downtime records, and inventory reports from the ERP system.
- Qualitative data from expert interviews: Semi-structured interviews were conducted with maintenance planning engineers and inventory analysts. The interviews explored challenges in managing spare parts for aging equipment, including variability of demand, long lead times, obsolescence risks, current inventory practices, and views on potential improvements for more adaptive inventory control.

This dual data collection ensured both historical operational evidence and practitioner perspectives were included.

Stage 3. Data Analysis

In the third stage, both qualitative and quantitative data were analyzed to identify critical patterns and recurring challenges:

- Quantitative analysis was applied to downtime statistics, spare part consumption, and procurement lead times to reveal trends in demand variability, aging asset performance, and costs.
- Qualitative analysis of interview transcripts was conducted thematically to highlight practitioners' perspectives on the weaknesses of existing control methods and their proposed solutions.

This combined analysis deepened the understanding of spare part characteristics (e.g., criticality, obsolescence, long lead items) and helped validate insights found in the literature.

Stage 4. Integration and Framework Development

The final stage synthesized the evidence from the literature review (Stage 1) with empirical findings from the case study and interviews (Stages 2–3). This integration ensured the resulting framework was both theoretically informed and grounded in real operational practice. The outcome of this synthesis is the proposed Spare Parts Control Policy Model, which integrates continuous review, predictive maintenance, condition-based monitoring, and safety stock policies.

This staged methodology thus provided a systematic and transparent approach to framework development. While the single case study design offers rich contextual insights, it also limits the extent of generalization. To address this, the developed framework is proposed as a theoretical model that can be tested and validated further in multiple organizational contexts. Additionally, this paper is also part of ongoing doctoral research, which will be further explored in the dissertation.

Proposed Theoretical Framework

The results from interviews with the maintenance planning engineer and inventory analyst align with previous research and literature, highlighting the difficulties in managing spare parts for aging equipment. Both respondents confirmed that the unpredictable nature of demand and long lead times are the main critical issues, adding efforts to maintain adequate stock levels. These challenges reflect the findings in existing studies, emphasizing the increasing complexity of spare parts management as equipment ages, leading to risks such as stockouts or overstocking, downtime, and increased inventory cost. During the interview process, both respondents raised concerns about the need for flexible contracts with suppliers to ensure that spare parts availability aligns with scheduled overhaul activities. They required more adaptable agreements that ensure both the timely availability of spare parts and alignment with the company's overhaul timelines.

A key finding from the interviews was the role of demand characteristics in managing spare parts for aging equipment. Both respondents emphasized that understanding factors such as usage frequency, lead times, and item criticality plays an important role in managing spare parts stock. This understanding forms the foundation for developing an effective spare parts control policy, helping to address the irregular demand patterns typical of aging equipment. By aligning spare parts control policies with demand characteristics, companies can optimize inventory levels, reducing both the risks of stockouts and excessive inventory costs.

Additionally, the respondents emphasized the importance of integrating spare parts planning between the maintenance section, inventory control, and suppliers. This collaborative approach would enhance the accuracy of spare parts planning by improving communication, data sharing information, and aligning the requirements of all stakeholders. By integrating stock management, maintenance schedules, and supplier capabilities, companies could optimize their spare parts inventories, ensuring the right parts are available at the right time.

One of the significant suggestions from the interview was the development of a new overhaul strategy, such as implementing an engine swap system. This method is expected to lead to both cost and time efficiency, especially during major overhauls. Instead of waiting for the entire overhaul process to be completed on-site, swapping engines would allow the company to minimize downtime and make the overhaul process more streamlined. Another finding from the interviews related to the company's annual work plan adjustments, which contribute to overstocking spare parts. Respondents noted that frequent changes in company work plans, specifically regarding maintenance schedules, lead to unnecessary accumulation of spare parts that may not be used in the near term. This issue highlights the need for better alignment between the work plan and spare parts procurement to avoid overstocking and excess inventory costs.

Fig. 3 summarizes the discussion on the theoretical framework above as a proposed spare parts control policy model.

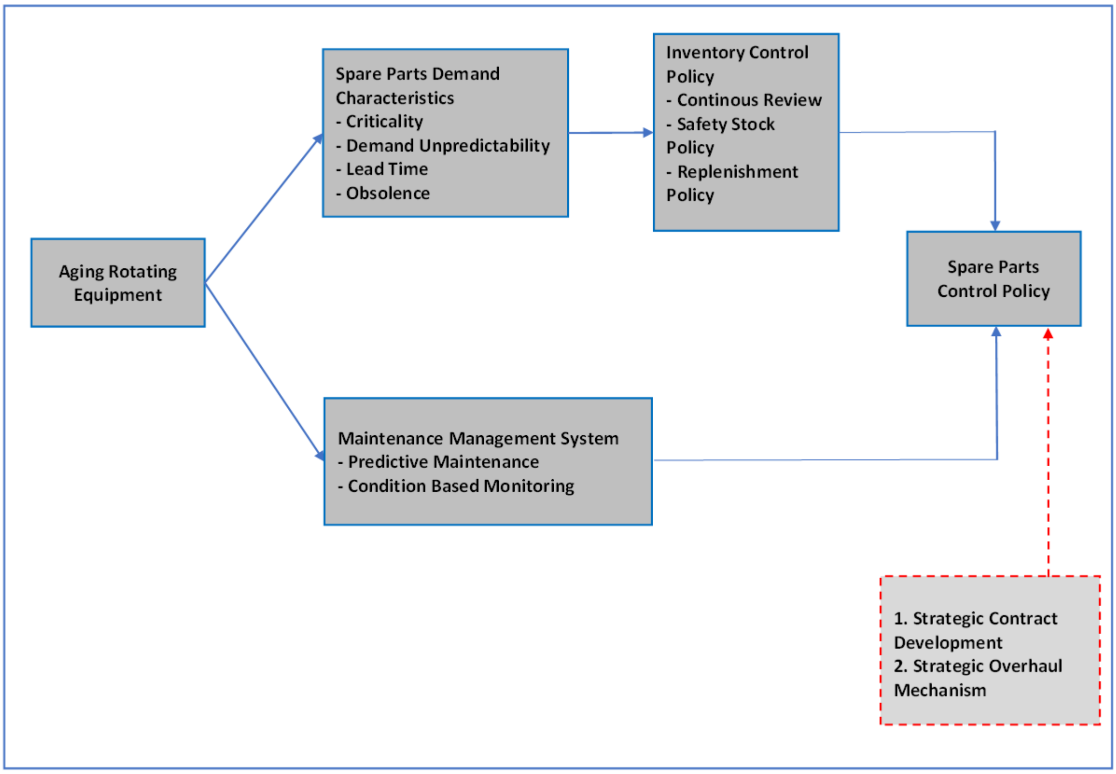

Fig. 3. Proposed Theoretical Framework Model Development After Interview and Literature Review.

Conclusion

This study highlights the limitations of traditional inventory management strategies, such as ABC analysis and Economic Order Quantity (EOQ), in managing spare parts for aging rotating equipment in the oil and gas industry. These conventional methods struggle to address challenges like unpredictable demand, extended lead times, and the increased risk of obsolescence. To create an effective spare parts control policy, it is essential to understand demand characteristics—such as usage frequency, lead time variability, and obsolescence risk. Additionally, data from maintenance management systems plays a crucial role in developing strategies that tackle the unique challenges posed by aging equipment. The theoretical framework model developed in this study integrates predictive maintenance, condition-based monitoring, continuous review, safety stock, and replenishment policies to manage these complexities better.

However, the proposed model presented in this paper has not been tested in real business situations. It needs to be validated through triple validation methods to ensure the proposed model is robust through simulation modeling using real data from the company, conducting sensitivity analysis to understand how the proposed model performance under different situations or scenarios, and at the end of the validation model, the result from two previous validations need to be discussed with experts from maintenance and inventory as a final validation method. For extended research, exploring dynamic sourcing strategies and implementing artificial intelligence (AI) and machine learning (ML) to improve forecast accuracy and process automation to reduce human error in administrative tasks are recommended. These advancements can significantly enhance spare parts management, especially for aging equipment, by optimizing inventory levels, reducing downtime, and improving operational efficiency.

References

[1] W.J. Kennedy, J. Wayne Patterson, L.D. Fredendall, An overview of recent literature on spare parts inventories, Int. J. Prod. Econ. 76 (2002) 201-215.

[2] J. Huiskonen, Maintenance spare parts logistics: Special characteristics and strategic choices, Int. J. Prod. Econ. 71 (2001) 125-133.

[3] A. Syntetos, J. Boylan, J. Croston, On the categorization of demand patterns for spare parts, J. Oper. Res. Soc. 56 (2005) 495-504.

[4] R. Dekker, M.J. Kleijn, P.J. de Rooij, A spare parts stocking policy based on equipment criticality, Int. J. Prod. Econ. 56 (1998) 69-77.

[5] P. Glasserman, Bounds and asymptotics for planning critical safety stocks, Oper. Res. 45 (1997) 244-257.

[6] A. Diaz, M. Fu, Models for multi-echelon repairable item inventory systems with limited repair capacity, Eur. J. Oper. Res. 97 (1997) 480-492.

[7] S. Cavalieri, M. Garetti, M. Macchi, R. Pinto, A decision-making framework for managing maintenance spare parts in MRO operations, Prod. Plan. Control. 19 (2008) 379-396.

[8] K. Hui, L. Hee, M. Leong, Equipment aging, aging detection, and aging management: A review, J. Appl. Mech. Mater. 575 (2014) 935-938.

[9] H. Zheng, X. Qiao, Reliability analysis method of rotating machinery based on conditional random field, Comput. Intell. Neurosci. 2022 (2022) 1-12.

[10] H. Wei, Fault diagnosis of rotating machinery: A highly efficient and lightweight framework based on a temporal convolutional network and broad learning system, Sensors 23 (2023) 5642.

[11] S. Zhang, K. Huang, Y. Yuan, Spare parts inventory management: A literature review, Sustainability 13 (2021) 2460.

[12] M. Hosseinzadeh, M. Foroushani, H. Ghayem, M. Mehregan, Sustainable maintenance planning in the petroleum industry: An application of system dynamics approach, Int. J. Qual. Reliab. Manag. 40 (2023) 2083-2113.

[13] M. Calder, M. Sevegnani, Stochastic model checking for predicting component failures and service availability, IEEE Trans. Depend. Secur. Comput. 16 (2019) 174-187.

[14] M. Bevilacqua, M. Braglia, The analytic hierarchy process applied to maintenance strategy selection, J. Reliab. Eng. Syst. Saf. 70 (2000) 71-83.

[15] P. Martón, R. Martorell, A. Mullor, S. Sánchez, S. Martorell, Optimization of test and maintenance of ageing components consisting of multiple items and addressing effectiveness, Reliab. Eng. Syst. Saf. 153 (2016) 151-158.

[16] S. Rizal, The importance of adapting and updating the new supply chain capabilities for sustainability in the business of supply equipment in oil and gas industrial projects, J. Econ. Bus. UBS 12 (2023) 2974-2987.

[17] F. Oliveira, C. Vaz, Spare parts inventory management using quantitative and qualitative classification, in: Proceedings of the 9th International Conference on Industrial Engineering and Industrial Management (2016) 233-241.

[18] O. Bounou, Contribution overview to the evaluation and development of spare parts management models: Meta heuristics and probabilistic model, J. Manag. Prod. Eng. Rev. 12 (2021) 24-37.

[19] Y. Jiang, M. Chen, D. Zhou, Joint optimization of preventive maintenance and inventory policies for multi-unit systems subject to deteriorating spare part inventory, J. Manuf. Syst. 35 (2015) 191-205.

[20] A. Martinetti, J. Braaksma, J. Ziggers, L. Dongen, On the initial spare parts assortment for capital assets: A structured approach aiding initial spare parts assortment decision-making (SAISAD), in: Proceedings of the International Conference on Asset Management (2017) 429-442.

[21] Y. Qin, H. Ma, F. Chan, W. Khan, A scenario-based stochastic programming approach for aircraft expendable and rotable spare parts planning in MRO provider, Ind. Manag. Data Syst. 120 (2020) 1635-1657.

[22] J. Hassan, F. Khan, M. Hasan, A risk-based approach to manage non-repairable spare parts inventory, J. Qual. Maint. Eng. 18 (2012) 344-362.

[23] Y. He, W. Hong, X. Zhao, Joint optimization of bi-level imperfect maintenance and spare parts inventory considering order quantity, Qual. Reliab. Eng. Int. 40 (2023) 261-276.

[24] K. Sharif, A risk-based technique based on spare parts quantity and cost for optimizing inventory level in plant maintenance, Int. J. Acad. Res. Bus. Soc. Sci. 8 (2018).

[25] X. Chen, D. Xu, L. Xiao, Joint optimization of replacement and spare ordering for critical rotary component based on condition signal to date, J. Maint. Reliab. 19 (2016) 76-85.

[26] B. Fleischmann, H. Meyr, Planning hierarchy, modeling, and advanced planning systems, in: Handbook of Operations Research and Management Science 11 (2003) 455-523.

[27] K.-A. Nguyen, P. Do, A. Grall, Multi-level predictive maintenance for multi-component systems, Reliab. Eng. Syst. Saf. 144 (2015) 83-94.

[28] X. Lei, P. A. Sandborn, PHM-based wind turbine maintenance optimization using real options, Int. J. Progn. Health Manag. 7 (2020).

[29] R. Guo, Y. Peng, A. Wan, Communication equipment maintenance decision method based on equivalent service coefficient, in: Destech Transactions on Materials Science and Engineering (2021).

[30] K.-S. Wang, Z. Li, J. Braaten, Q. Yu, Interpretation and compensation of backlash error data in machine centers for intelligent predictive maintenance using ANNs, J. Adv. Manuf. 3 (2015) 97-104.

[31] Y. Chen, Z. Wang, Z. Cai, Optimal maintenance decision based on remaining useful lifetime prediction for the equipment subject to imperfect maintenance, IEEE Access 8 (2020) 6704-6716.

[32] A. Börütecene, J. Löwgren, Designing human-automation collaboration for predictive maintenance, in: Companion Publication of the 2020 ACM Designing Interactive Systems Conference (2020) 251-256.

[33] J. Lee, M. Mitici, Predictive aircraft maintenance: Modeling and analysis using stochastic petri nets, in: Proceedings of the International Conference on Aircraft Maintenance (2021) 146-153.

[34] S.R. Pardede, I. Vanany, Analysis and control for heavy equipment spare parts inventory in the Nickel Mining Industry, IPTEK J. Proc. Ser. 6 (2021) 478.