Evaluating the Strategic Value of Maintenance in Swedish Manufacturing – A Survey Study

Master’s Thesis in Production Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY

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Cover: Quantifies the economic and operational value of maintenance in Swedish manufacturing

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Abstract

This Master's thesis examines the strategic importance of maintenance in the manufacturing industry, focusing on how annual investments in maintenance influence operational efficiency and financial performance. The research utilizes a mixed-methods approach, combining literature review and surveys conducted across various Swedish manufacturing firms. It assesses the impact of maintenance strategies on annual investments and the required skills for workers, emphasizing the increasing need for continuous training due to rising labor costs associated with skilled personnel.

Key findings indicate that firms adopting advanced maintenance strategies, which integrate predictive and proactive techniques supported by modern technologies, significantly reduce operational costs and minimize downtime. These strategies not only enhance the sustainability of manufacturing processes but also address environmental challenges, making a strong case for their broader adoption. However, the study identifies challenges such as the high initial costs of technology and the continuous need for upskilling workers to keep pace with technological advancements.

The thesis supports viewing maintenance as a strategic investment within the manufacturing sector, crucial for improving productivity and achieving a competitive advantage while promoting sustainable practices.

KEYWORDS: Maintenance strategies, Operational Efficiency, Manufacturing Industry, Industry 4.0, Swedish manufacturing Sector, Economic Impact, Technological Innovation, Sustainability, Preventive Maintenance, Predictive Maintenance, Proactive Maintenance

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Sagar Khatri

Gothenburg, December 5, 2024

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List of Acronyms

Machine Learning – ML

Artificial Intelligence – AI

Internet of Things – IoT

Corrective Maintenance – CM

Preventive Maintenance – PM

Digital Twins – DT

Predictive Maintenance – PdM

Proactive Maintenance – PoM

Total Productive Maintenance – TPM

Reliability-centered Maintenance – RCM

Root Cause Analysis – RCA

Failure Modes and Effects Analysis – FMEA

Life Cycle Cost – LCA

Technical Availability – TA

Overall Equipment Effectiveness - OEE

Cyber-Physical System – CPS

Key Performance Indicators – KPIs

Sustainable Maintenance Practices - SMP

1 INTRODUCTION

Maintenance is important in manufacturing but often doesn't get attention. Many businesses recognize the importance of maintenance but are hesitant to invest in it. This is mainly because it is difficult to pinpoint clear, mathematically based benefits that justify the cost. This difference in understanding not only affects the company's profits but also prevents the industry from adopting better maintenance practices.

1.1 Background

Maintenance plays an important role in manufacturing to ensure continuous production and increase the lifespan of the equipment. However, in business strategy, it frequently fails to receive sufficient financing and recognition, despite its significance. Maintenance, which has historically been viewed as a cost center, is commonly disregarded despite its potential to increase productivity and save operating expenses. The growing complexity of manufacturing systems and the technological advancements in industrial equipment have shaped the evolution of maintenance strategies. From the early focus on corrective maintenance, where actions were reactionary and based solely on equipment failure, the industry has moved towards more proactive strategies that emphasize prevention and prediction to avoid downtime and enhance equipment reliability (Gackowiec, 2019). Maintenance in Swedish industries is commonly viewed as a necessary expense rather than an integral component of operational success (Alsyouf I. , 2009). The study highlighted that about a third of maintenance activities in Swedish firms are unplanned, underscoring a significant gap in maintenance planning and execution (Alsyouf I. , 2009). This unplanned maintenance contributes to substantial financial costs.

In Sweden, maintenance costs have been estimated at about 20 billion SEK annually, with a significant portion of these costs identified as waste due to unplanned maintenance and downtime (Salonen, 2020). This points to a pressing need for a more strategic approach to maintenance that minimizes waste and aligns more closely with production goals (Salonen, 2020). The strategic positioning of maintenance can vary greatly from one company to another—it can either be internalized using dedicated, in-house teams or outsourced to maintenance service providers. The choice between these approaches involves balancing considerations such as cost, control over processes, confidentiality of manufacturing secrets, and preservation of technical expertise (Alexopoulos, 2021).

As maintenance strategies evolve, a growing focus is on integrating predictive maintenance, leveraged by advancements in information technologies such as artificial intelligence (AI) and machine learning (ML). Predictive maintenance not only aims to predict equipment failures before they occur but also contributes to the modernization of manufacturing processes, thereby enhancing business performance and maximizing profits in terms of productivity, quality, and logistics management (Alexopoulos, 2021). Trends in maintenance have been changed to more focused on smart technologies and extensive data analytics, which support predictive maintenance strategies. These strategies are particularly interesting as they significantly reduce downtime and maintenance costs while extending the life of machinery. Such smart maintenance systems are integral to Industry 4.0, where interconnected technologies streamline and optimize manufacturing processes. The ongoing integration of automation and cyber-physical systems in manufacturing is set to redefine maintenance roles further, shifting the focus from manual interventions to strategic management and data analysis (Garetti & Taisch, 2011). This transformation will increase the efficiency of maintenance practices and ensure their alignment with sustainable and intelligent manufacturing goals. Maintenance is transitioning from a traditional support function to a crucial enabler of operational success and sustainability. This shift highlights the need for strategic reevaluation of maintenance practices to ensure they are cost-effective and integral to manufacturing enterprises' long-term viability and competitiveness.

1.2 Objectives & Deliverables

The thesis focuses on a comprehensive analysis to understand and quantify how investments in maintenance influence the bottom line and operational dynamics within the manufacturing sector. This study investigates into the direct and indirect benefits of effective maintenance, assessing aspects such as cost implications, necessary skills for maintenance personnel, and the overall return on investment in maintenance activities. The objective is to provide a robust, numeric foundation that will help justify maintenance expenditures by demonstrating their impact on operational efficiency and financial performance.

For the deliverables, the thesis will produce a set of comprehensive internal and external communications to disseminate the findings effectively. Internally, a detailed academic report and a presentation at Chalmers University will summarize the research outcomes, methodologies, and implications. Externally, the thesis will investigate current maintenance practices across the manufacturing industry, focusing on understanding the diverse approaches being employed. By comprehensively analyzing existing strategies, this study will provide Svenskt Underhåll with a detailed overview of industry trends and methodologies. This insight will enable Svenskt Underhåll to stay informed about the latest developments and potentially influence future maintenance practices across manufacturing sectors.

1.3 Research Question

Research questions are designed to guide the purpose of a study, to be addressed through the study findings. The study outlines the following 3 questions.

- How do current maintenance practices in manufacturing impact investment decisions, and what are the measurable effects on costs and required competence?
- How can the value of maintenance be quantified and optimized to enhance overall operational efficiency, cost-effectiveness, and sustainability?
- How can a balance be achieved between operational efficiency, cost-effectiveness, and eco-friendly maintenance approaches with digital innovations?

To address the research questions, a comprehensive survey has been designed to collect targeted data from manufacturing organizations. The survey will explore how current maintenance practices influence investment decisions and their effects on costs and required competencies, thereby answering the first research question. Analyzing responses related to budget allocation, staffing for maintenance, and the nature of maintenance costs will provide insights into the financial and strategic impacts of current practices.

For the second question, the survey will gather data on how organizations quantify the value of maintenance and its contribution to operational efficiency, cost-effectiveness, and sustainability. This will involve evaluating methods used to measure indirect costs and the perceived benefits of sustainable maintenance practices.

The third question will be explored through responses concerning the adoption of digital tools and the challenges of integrating eco-friendly approaches with maintenance strategies. By assessing the current state of digital innovation adoption and its alignment with cost-effective and sustainable practices, the survey will help identify how a balance can be achieved between efficiency, cost savings, and environmental responsibility.

1.4 Scope & Delimitation

The goal of this thesis is to conduct a detailed analysis of the strategic importance of maintenance in the manufacturing sector, with a special emphasis on how maintenance affects sustainability, cost-effectiveness, and operational efficiency. This study includes a broad variety of manufacturing industries in Sweden and makes use of information obtained from a thorough survey that was given to a large number of manufacturing firms. This method enables a thorough examination of the maintenance procedures used today, their effects on the economy, and how they support sustainability objectives in these industries.

In particular, the study focuses on measuring the advantages of advanced maintenance approaches, such as predictive maintenance—which integrates digital advances like AI and the Internet of Things (IoT). The thesis will offer insights pertinent to local industry players and global stakeholders interested in the implications of maintenance practices shaped by advanced technological integrations and sustainability considerations by concentrating on the Swedish manufacturing landscape.

However, this research has some delimitations. It is the possible challenge of obtaining thorough, complete data. Sensitive information is frequently included in maintenance initiatives, which businesses might be unwilling to disclose. This could reduce the amount of comprehensive data that is available, especially when it comes to specific financial indicators or insights into exclusive maintenance technologies—both of which are essential for a full study. Another anticipated challenge is the varying response rates from participants across different company sizes. Large companies' personnel might respond slowly and small companies provide less detailed responses. This variance in the rapidness and quality of responses may impact the consistency and dependability of the data gathered, which might distort the findings or make comparative analysis more difficult—in-depth examination.

1.5 Thesis Outline

This study is organized into various sections. The introduction establishes the fundamental significance of maintenance in manufacturing. The methodology is the execution of work combining literature reviews and surveys. The results section details the analysis of survey data along with a discussion section with findings and future work. Finally, the conclusion summaries the study with research questions.

2 METHOD

The study's methodology consists of a mixed-method approach combining quantitative and qualitative research techniques to comprehensively analyze the strategic value of maintenance in the manufacturing industry. The methodology is structured to capture a broad spectrum of data from various manufacturing organizations in Sweden through surveys, focusing on small, medium, and large-scale sectors.

2.1 Literature Review

This literature review aims to create a wide selection of perspectives and insights to not only show the current landscape but also to forecast future directions in maintenance practices. By focusing on maintenance, the study examines methods to streamline processes and reduce waste, thereby enhancing operational efficiency. The review also addresses the associated risk factors, identifying potential challenges and proposing mitigation strategies to manage and minimize these risks effectively. In addition, the analysis includes a critical look at the emergence of eco-friendly maintenance practices. As sustainability becomes increasingly crucial in manufacturing operations, this study highlights innovative techniques that reduce the environmental impact and increase the organization's outcome.

The comprehensive approach to this review ensures that the findings are relevant and applicable, providing valuable guidance for industry professionals looking to implement best practices in maintenance. Through careful selection of literature from trusted scientific databases provided by the Chalmers Library, this review establishes a solid foundation for understanding the evolving dynamics of the maintenance field in the manufacturing industry.

- Google Scholar
- Scopus
- Web of Science
- IEEE Xplore
- ScienceDirect
- JSTOR

To find relevant literature regarding the theoretical framework following keywords were used

- Manufacturing
- Production
- Maintenance
- Sustainability
- Performance
- Trends
- Eco-efficiency
- Preventive Maintenance
- Predictive Maintenance
- Maintenance 4.0
- Cost
- Digital Maintenance
- OEE
- Strategies

Additionally, the selection of further readings was influenced by suggestions from the thesis supervisor and by the bibliographies of related existing literature. This literature review creates foundations for a theoretical framework for the thesis, shaping the content of the questionnaire informing the discussion, and validation of the findings presented in this thesis.

2.2 Qualitative Research: Survey Study

To understand annual maintenance expenditures within Swedish industries, I recognized the absence of comprehensive data in publicly accessible platforms. To address this, A short online meeting with the Dutch Maintenance Society NVDO which did the same kind of study in 2023. Their research utilized a Monkey Survey methodology to collect benchmark data, providing valuable insights into maintenance spending trends. Unfortunately, their information isn't readily available on online platforms, making our independent study all the more crucial. For this study the survey, an online questionnaire was designed and distributed via email and LinkedIn, ensuring reached a broad audience across the targeted sectors, and Google Forms was used instead of Monkey Survey. Google Forms does not impose a response limit for its free version, unlike Monkey Survey, which restricts users to 50 responses in its free tier. This study targets of reaching approximately 250 manufacturing firms focused on the western part of Sweden, Google Forms ensures to collection of data extensively without encountering barriers.

According to (Ruliyanti et al., 2022) Google Forms offers extensive customization options and integrates seamlessly with other Google tools like Sheets. This integration proves invaluable in managing large volumes of data securely and efficiently, ensuring real-time analysis and visualization. Furthermore, the platform's wide compatibility across various devices and operating systems enhances accessibility, making it an optimal tool for conducting comprehensive research across diverse sectors within the manufacturing industry.

2.2.1 Structure of the Questionnaire

The format of the questionnaires was carefully designed to increase respondent engagement and ensure the collection of high-quality data. There was a total of 17 questions in this survey: 13 multiple-choice questions, 1 fill-in-the-blank question, and 3 checkboxes with multiple-choice answers. This question format's variety was in keeping with best practices in survey techniques, particularly those stated by (Dillman et al., 2014). They tell the significance of question and response styles that make responding to surveys easier and less taxing. The majority of the survey's questions were multiple-choice, which works very well for a number of reasons. This allows respondents to quickly select an answer from a list of pre-defined options, which can speed up the survey process and reduce the cognitive load on participants (Dillman et al., 2014). These kinds of questions helped to standardize answers, which facilitated data analysis and comparison. Additionally, it reduces the uncertainty that frequently accompanies open-ended inquiries, strengthening the data's dependability.

Checkbox questions, which are used three times in this survey, offer respondents the flexibility to select more than one answer. This format is beneficial when multiple responses are applicable, providing a richer dataset that captures the complexity and nuance of respondent experiences and opinions. According to (Conrad & Schober, 2000), providing respondents with the ability to express all applicable options without restriction can lead to more accurate and reflective data. The single fill-in-the-blank question is strategically used to gather specific numerical data—such as the exact number of personnel involved in maintenance tasks. This question format was critical where precision is essential and allows for the capture of data that cannot fit into predefined categories, thus offering insights that multiple-choice or checkbox questions.

2.2.2 Pre-testing of Questions

According to Dillman et al. (2014), pre-testing a questionnaire with a prototype is crucial for assessing its effectiveness and clarity before distributing the final version. In this study, an initial draft was provided to an individual for functionality testing. Following the completion of the questionnaire, feedback was collected through both telephone and email interactions, focusing on the structure and content of the questionnaire. After receiving feedback, it was confirmed that no changes were needed to the questions. As a result, it was decided that the survey was prepared for distribution to other manufacturing firm stakeholders.

2.2.3 Distribution of Survey

The survey has been designed to engage participants from key manufacturing sectors, (Tools, Machinery, Automobiles, and Process). This study more focused on the western part of Sweden but also included few participants from other areas of Sweden. To facilitate easy access and enhance response rates, this survey was distributed the link through emails and LinkedIn invitations. This approach allows to connect with a broad spectrum of professionals and stakeholders within these industries. LinkedIn enables reach professionals within specific industries, ensuring that the respondents are relevant to this study. This targeted outreach can significantly improve the quality of the responses, as individuals are more likely to provide valuable insights from their expertise (Blank & Lutz, 2017). Questionnaires were opened from April 25 to 18 September.

2.2.4 Criteria for Selecting Survey Respondents

The selection of respondents followed the approach of (Bokrantz, Skoogh, Ylipää, & Stahre, 2016). This study aims to gather high-level strategic expert opinions, particularly in the areas of production and maintenance management. According to available online information, it was believed that the selected respondents had specific maintenance-related knowledge, which is necessary to ensure the reliability of production systems. Production and maintenance managers, along with other stakeholders engaged in maintenance operations inside their firms, were also included in the study. A total of 96 responses were received for this study, which was distributed to 245 companies of varying sizes. This represents a response rate of 39%. The majority of the surveys were directed toward the maintenance department, with 72% of the surveys sent to this group. In contrast, 28% of the surveys were distributed to the production department.

2.2.5 Overview of Participating Companies and Respondent

The participant companies were categorized into three groups: small-scale companies (1-99 employees), medium-scale companies (100-499 employees), and large-scale companies (500+ employees). Out of the total, 110 small-scale companies were selected, along with 70 medium-scale companies and 65 large-scale companies. The study received the highest number of responses from small-scale companies, with 47 respondents, while large-scale companies provided the lowest response rate, contributing only 21 respondents. Medium-scale companies accounted for 28 responses.

Data regarding the companies were gathered from various online sources, including Wikipedia, Dun & Bradstreet, and Lusha. From the available information, the majority of respondents have over five years of experience in their respective fields.

2.3 Quantitative Data Analysis

The data was collected using numerical responses due to the structure of the questionnaires. This study utilized the JMP software which is more suitable for statical data analysis and visualization. JMP is a powerful tool for statical data analysis that can calculate and present data in a good way (Robert, 2019).

2.3.1 Data Collection

The survey questionnaires were designed to collect the nominal data. Nominal data categorized the answers which is ideal for this study because responses are different from each other and it do not require ranking (Weiss & Universitat de València, 2010). This study questionnaire, which collects nominal data asks which types of assessment tools and approaches the company is currently using. This allows for collecting information on a wide range of topics and provides a method to gather data from the large number of respondents.

2.3.2 Data Analysis

JMP supports the statistical analysis of many types of measurement including ordinal and nominal level data. Descriptive statistics is more suitable to summarize and present categorical and numerical data in an informative manner, both numerically and graphically. Even though data is inherently random, descriptive statistics offer a useful way to reduce information to a more understandable shape. Descriptive statistics are frequently regarded as one of the simplest types of analysis since they allow researchers to condense data into easily comprehensible figures and graphs (Marshall & Jonker, 2009).

The method for analyzing and displaying the distribution of responses to determine the frequency distribution mentions to the count of cases within each category and response option. To compare variables and groups and uncover distinguishing patterns between them, researchers often utilize contingency tables. These tables are analyzed by the process of cross-tabulation. Researchers can identify patterns more quickly, by just looking at the bars and tables that show the frequency of each category. This approach makes it possible to spot patterns and trends in the data, showing how various business types rank maintenance tasks (Martin Lee Abbott, 2013).

Inferential statistics also be taken into consideration, even though cross-tabulations and descriptive statistics offer insightful information. The statistical significance of observed variations in maintenance procedures can be determined using methods like ANOVA or Chi-square testing. However, due to the varying size of companies in this study, the data from the small firm may not be fully get. The method like the fisher exact test, could be justified in these circumstances where sample numbers are insufficient (Nowacki, 2017).

2.3.3 Presentation of Data

The results are presented using a combination of tables, bar charts and pie charts, and graphs. This multifaceted strategy promises that the data is both readable and interesting for readers, promoting a thorough comprehension of the results. Key statistical measures, including averages, frequencies, and percentages, will be compiled using tables. Tables are deployed throughout to present raw data alongside summary statistics. These tables are accurately labeled and include detailed captions that explain the significance of the data presented, ensuring that they can be understood independently of the text. This format is particularly effective for detailing the frequency of specific maintenance practices. furthermore, to enhance the clarity and visibility of the tables and graphs obtained in this study, Microsoft Excel was utilized to refine these visual elements.

3. Theoretical Framework

The following section provides the reader with theoretical knowledge to understand the factors influencing the maintenance practice in manufacturing sectors. This framework incorporates a number of theories and ideas from organizational behavior, and maintenance management.

3.1 Maintenance Fundamentals

This study applies the theory to maintenance activities within the manufacturing sector. Maintenance is an essential part of managing industrial processes and guarantees the dependability and effectiveness of machinery and equipment. It includes a variety of actions meant to maintain an asset's functionality and increase its longevity. Organizations looking to maximize operational performance and reduce downtime must have a basic understanding of maintenance. Maintenance can be defined as keeping equipment and facilities in good working order through preventive, predictive, and corrective measures. Most people think that maintenance is a failure, due to function stops. It is important to understand failure is not the only reason however insufficient resources can lead to downtime. Well-maintained manufacturing machinery is essential to producing high-quality products that allow producers to effectively and reliably satisfy consumer demand. Equipment maintained in good condition runs smoothly and reduces downtime, increasing the production of items that satisfy exacting quality requirements. On the other hand, poor maintenance of manufacturing equipment can result in a considerable drop in the volume and caliber of goods produced. Such machinery could produce fewer goods that frequently fall short of quality standards, increasing customer waste and unhappiness (Smith & Hawkins, 2004). Traditionally it is thought that maintenance is a threat to the company because it uses more of the budget of the company (Grag & Deshmukh, 2006).

3.2 Maintenance Policy

There are two main strategies for maintenance. Preventive maintenance (PM) aims to decrease equipment failure after maintenance has been performed. However, the corrective maintenance (CM) goal is to minimize the impact of equipment failures once they happen (Löfsten, 1999).

3.2.1 Preventive Maintenance

PM is defined as “to prevent failure before it arises addressing possible problems with planned inspection, services, and replacements” (Bokrantz et al., 2014). PM is important for managing equipment to identify failures that are not detectable. Manufacturers planned maintenance ranges from daily, weekly to yearly to increase the equipment's dependability but also reduce breakdowns (G.W.A. Dummer et al., 1997). However, PM performed at the set time rather than the equipment condition which may not show the usage of resources accurately (Tsang, 2002). This challenges address with the help of digital PM utilizing the real-time sensor data and digital twins (DT) technologies which enables PM. Digital tools continuously monitor equipment health, enabling maintenance decisions based on actual machine performance rather than fixed schedules (Neto et al., 2021).

The PM strategy is also defined using the “bathtub curve” (See Figure 1). This curve has three phases: the infant mortality phase, the normal life phase, and the wear-out phase (Mobley, 2004). In the infant mortality phase, failure rates are high due to manufacturing defects or early-life issues, making early preventive maintenance critical. Failure rates stabilize and stay low during the normal life period, and PM treatments can be less frequent but are still necessary to sustain performance. In the wear-out phase, failure rates increase as equipment ages, and more frequent maintenance or replacement is necessary to avoid breakdowns (Jiang, 2013).

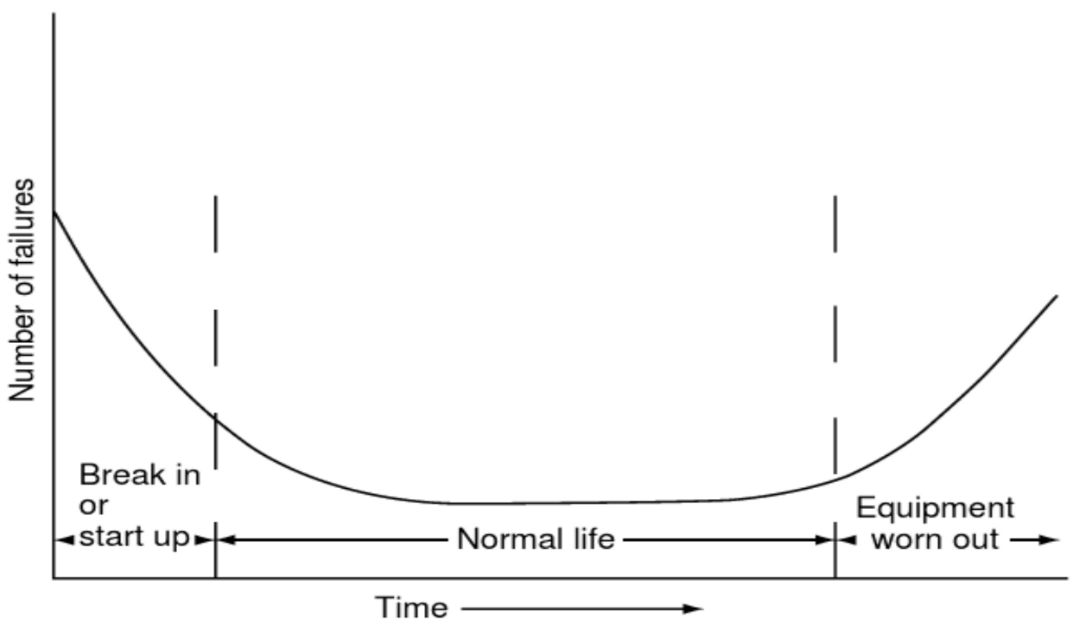

Figure 1 Bathtub Curve, adapted from (Mobley, 2004)

Digital PM technologies improve the efficiency of interventions during the wear-out phase by predicting potential failures before they occur, thus minimizing downtime and reducing unplanned breakdowns (Neto et al., 2021).

3.2.2 Predictive Maintenance

Predictive maintenance (PdM) is defined as “to monitor the condition of the equipment’s with the help of data-driven to predict the future failures before they occur” (Mobley, 2004). In PdM the condition of the machinery is continuously monitored through sensors and IoT devices that capture the data. This data is analyzed through various methods such as ML, statical modeling, and time-series analysis that provide early signals of possible failures that reduce the unplanned downtime and improve asset longevity (Selcuk, 2016). With PdM cost can be reduced and increase the productivity, quality and overall effectiveness of the production plant. According to Turnbull and

Carroll (2021), 8% of cost can be saved along with 11% production loss and 25% of equipment failures reduced through PdM techniques.

In the bathtub curve using the PM to prevent failure is not always reliable. Equipment fails when it is new, works fine for a while, and fails when it gets older. It disregards the fact that every piece of equipment has varied circumstances, and changing equipment too soon might make matters worse because new equipment may break down sooner. However, Predictive maintenance (PdM) helps to increase dependability and decrease unplanned failures by using real-time data to better understand the condition of equipment (Hashemian, 2010).

3.2.3 Proactive Maintenance

Proactive maintenance (PoM) is defined as "to prevent failure before it arises by identifying the root cause of failure". This includes key parameters to signals of instability which allows to take corrective actions before failure occurs. PoM is the combination of PM and PdM to minimize both planned and unplanned equipment downtime. Companies that use PoM techniques see a drop in operating expenses as a result of less downtime and expensive repairs (Swanson, 2001). Additionally, PoM importance increasing in the manufacturing sector combining industry 4.0 technologies. This predicts the equipment failure before occurs which allow firms to schedule maintenance activities to reduce downtime and cost consumption. PoM with digital technology can extend the lifespan of equipment, reduce waste, and lower energy consumption, contributing to both economic and environmental sustainability (Talamo et al., 2019).

3.2.4 Corrective Maintenance

Corrective Maintenance (CM) is defined as "an action is to be taken when the failure has occurred". CM is reactive, when the machines stop fix it. In this strategy, companies don't spend expenditures on maintenance. This method is more expensive three times higher as compared to others (Inventory, labor, high downtime, low reliability) (Mobley, 2004). However, CM can be effective where the equipment is not critical to overall production, and on-time decision keeps the system operational (Quintana et al., 2008).

3.3 Maintenance Concepts

There are several maintenance strategies are discussed however this study explains the most common method (Total productive maintenance TPM, Reliability-centered maintenance RCM). In industry, the central activity is production where the inputs (material, energy, and manpower) are changed into useful products. This method utilized the technical system which are assemblies of physical components designed to perform a specific function. To effectively achieve production goals and ensure the desired output, maintenance plays a critical role in maintaining and restoring the functionality of production systems. Effective maintenance helps ensure that machines and equipment are operating at optimal levels, which directly impacts production efficiency and product quality (Gits, 1992).

3.3.1 Total Productive Maintenance, TPM

TPM was first introduced in Japan in 1970 as maintenance concept widely adopted methodology in manufacturing industries focusing on improving equipment reliability, enhancing production efficiency, and minimizing unplanned downtime (Nakajima, 1988). In this approach, the participation of all employees from operator to management level in the maintenance. TPM can significantly increase productivity and quality, optimize equipment life cycle costs, and improve the knowledge and skills of all employees (Smith & Hawkins, 2004). TPM provide the ownership to the operator to perform maintenance which increases the knowledge of the operators rather than maintenance technician.

TPM builds on several key principles that work together. In autonomous maintenance, operators take responsibility of the equipment where they perform the cleaning, lubricating, and inspection of the machines. According to Guariente et al., (2017), autonomy increases productivity by giving responsibility to operators (availability 10% increase and Overall Equipment effectiveness 8%) however operators must be aware of their responsibility while performing their work. The planned maintenance failure rates are measures for the equipment and maintenance is scheduled based on the predicted failures. Furthermore, unplanned downtime is reduced, which allows maintenance to be carried out when the production processes are not active (Agustiady & Cudney, 2018). Quality maintenance aims to identify errors and implements preventive measures within the production process. Methods like root cause analysis RCA are integrated into quality control to prevent issues. Quality maintenance adopts a zero-defect mindset to improve projects and cost reduction strategies are applied in early phases. TPM encourages continuous improvement through focused problem-solving and initiatives aimed at eliminating the root causes of equipment failures. It seems that companies achieve significant progress in operational excellence by focusing on critical areas for improvement, such as decreasing downtime, removing bottlenecks, and increasing efficiency (Nakajima, 1988). Education and training for all employees must be provided to understand the working of the equipment and maintenance. According to Agustiady and Cudney, 2018, it is essential to fill the knowledge gap by providing proactive and preventative techniques, while managers receive high-level TPM training focused on empowering, developing, and coaching employees. However, the below-average skill level in maintenance can lead to increased reliability issues and higher maintenance costs (Smith & Hawkins, 2004). Johan Day provides the "Best maintenance Practice approach" by identifying the areas of improvement with potential solutions (See Figure 1).

BEST MAINTENANCE PRACTICE STANDARDS (Sampling)

Measurement Standard	Possible Causes	Solutions
No "self-induced" equipment failures (Note: statistics show that 70% of equipment failures in industry today are "self-induced")	Lack of skilled work force	Skills assessment and training
	Operator errors	TPM/operator procedures
	Reactive culture	Change measurement
	Preventive maintenance procedures (PMs) not performed properly	PMs must be managed as an experiment
30% of all labor hours should be on PM	PMs not being performed to a standard	Have detailed procedures
	PMs not a high priority	Measure PM compliance
90% of all work orders come from preventive maintenance	PM inspections are turning into repair activities	Train personnel in proper PM execution
	90% of all maintenance work is not planned and scheduled	Implement a true planned/scheduled maintenance program
Emergency work is less than 2% of total maintenance labor hours	No PM schedule compliance	PM schedules must be completed within 10% of the frequency (e.g., 30-day frequency/PM compliance to within 3 days plus or minus)

Table 1 Best Maintenance Practice adapted from (Smith & Hawkins, 2004)

3.3.2 Reliability-Centered Maintenance, RCM

RCM was initially developed in the aviation industry and focuses on ensuring that assets continue to perform their intended functions effectively and reliably. It is combination RCM prioritizes maintenance tasks based on the criticality of the equipment and the consequences of its failure, ensuring that resources are allocated efficiently to minimize the impact of equipment downtime on the overall system. Prioritizing maintenance for the most important equipment is the major objective of RCM, which also makes sure that resources are distributed effectively to reduce the impact of unscheduled downtime and failures (Ricky Smith, 2004).

Failure Modes and Effects Analysis (FMEA) is a key component of RCM. It helps organizations concentrate maintenance resources on the most important equipment by identifying failure modes, their causes, and their effects. Additionally, RCM combines predictive technology with condition-based monitoring, enabling maintenance to be carried out according to the equipment's real state rather than predetermined schedules. In RCM maintenance actions are only performed when needed this reduces the downtime and maintenance cost. Life cycle costs (LCA) are considered in the decision-making for long-term maintenance. This improves the overall system dependability and safety by implementing a risk-based strategy (Ricky Smith, 2004). RCM combines reactive, time-based, condition-based, and proactive maintenance approaches optimally. Instead of using these strategies separately, they are integrated to leverage their strengths, aiming to enhance the reliability of equipment and facilities while reducing overall life-cycle costs (Afefy, 2010).

3.4 Maintenance Cost and Measurements

Maintenance cost is defined as keeping the equipment and machinery in good working conditions. Cost is important part of manufacturing company's operational budget and is categorized into two types: Direct and Indirect costs. It is important to understand cost to improve operational efficiency, reduce downtime, and optimize the overall cost of ownership of machinery and equipment. Maintenance costs can include labor, materials, and the costs associated with both planned and unplanned maintenance. Additionally, poor maintenance practices can lead to significant hidden costs, such as production delays, quality defects, and lost sales. Proper maintenance is not only about repairing machinery but also about extending the life of equipment and preventing breakdowns through proactive measures. Traditionally, maintenance is seen as non-essential activity often observed as a burden (Thomas, 2018).

Recently, there has been a shift in viewing maintenance as a profit-generating function rather than just a cost. The focus has moved from LCA to life cycle profits, with researchers highlighting the potential savings and gains from more effective maintenance strategies. However, there has been little discussion on how to calculate or estimate life cycle cost factors or where to obtain the necessary data from accounting systems. it's easy to link breakdowns to insufficient maintenance, but it's harder to demonstrate how maintenance prevents. In Sweden, 37% cost in the maintenance is salaries for employees while 32% is spent on equipment. According to Alsyouf, 2004 companies that don't have maintenance strategy 28% and 48% have maintenance strategy while 24% oral strategy. Alsyouf 2004 (See Table 2 & Table 3) further explained the distribution of the direct and indirect costs within Swedish industries.

Category	Percentage of Total Maintenance Budget
Labor Costs	37%
Spare Parts	32%
Outsourcing	19%
Other Activities	8%
Education and Training	4%

Table 2 Direct cost data adapted from (Alsyouf, 2004)

Category	Percentage of Total Manufacturing Costs
Downtime Costs	23.9%
Impact on Planned Production	13.3%
Lost Sales and Rework Costs	Difficult to quantify
Energy Inefficiency	Estimated to be significant
Inventory and Spare Parts Costs	Variable based on inventory management
Quality Issues and Rework	Affects production and customer satisfaction

Table 3 Indirect cost data adapted from (Alsyouf, 2004)

According to Tabikh (2021) in Sweden, 83% have no method to evaluate the downtime cost. Moreover, maintenance is seen as an overhead cost that makes it difficult to improve. For better maintenance, it is important to integrate a performance measurement system that focuses on direct cost and indirect costs. This study covers the two most common methods; Technical availability (TA) and OEE.

3.4.1 Technical Availability

TA within a production system is a critical metric that assesses the degree to which equipment is ready and capable of performing its intended tasks within a specified timeframe. It goes beyond only tracking equipment failures and planned maintenance by incorporating a broad definition of maintenance downtime, including all maintenance-related interruptions - both planned and unplanned, such as breakdowns, inspections, and other stoppages.

$$TA = \frac{Available\ time - Stop\ time\ loss}{Available\ time}$$

In measuring TA, it is important to explain the time from the start of a maintenance stoppage until the equipment resumes normal operation, including any ramp-up and testing phases. This ensures that all time lost to maintenance activities is considered, providing a clear view of how maintenance affects the operational efficiency of the production system (Sielaff et al., 2023).

3.4.2 Overall Equipment Effectiveness

The primary focus of TPM is OEE. It is seen that unplanned losses or indirect losses are not visible on the balance sheet that impact the overall all production expenses. Implementing OEE can reduce these losses related to equipment availability (A), performance efficiency (P), and quality rate (Q).

Many organizations set their goal to achieve 85% OEE but it is always difficult to achieve. The mathematical representation is given below

$$OEE = Availability \times Performance \times Quality$$

OEE is based on the production planned time however integrating the Total Effective Equipment Performance (TEEP) based on the available time (Calendar hours) provides more clearer view of equipment performance.

$$TEEP = Loading \times OEE$$

Loading is the measurement of scheduled time

$$Loading = \frac{Scheduled\ time}{Calendar\ time}$$

OEE helps identify these losses by breaking down losses into categories such as downtime (A), speed losses (P), and defects (Q). This measurement is important because it provides a quantifiable metric that correlates the effectiveness of the equipment to the overall cost efficiency of the production process (De Ron & Rooda, 2006) (Stamatis, 2017).

$$A = \frac{Available\ time}{Scheduled\ time}$$

$$Available\ time = Planned\ time - unplanned\ time\ (other\ stoppages)$$

$$Scheduled\ time = Total\ shift\ time - planned\ Miantenance$$

$$P = \frac{Actual\ rate}{Standard\ rate}$$

$$Q = \frac{Good\ Units}{Units\ started}$$

According to Kumar et al. (2013) OEE maintenance performance metrics, Mean Time To failure (MTTF), Mean Time To Repair (MTTR), and Mean Time Between Failure (MTBF) are crucial indicators that quantify the reliability and efficiency of manufacturing equipment.

MTTF is measure of average time that a piece of equipment operates before it fails. This is used for non-repairable systems.

MTTR is the average time required to repair a system after failure. This is essential to measure as it impacts downtime. A lower MTTR indicates more efficient maintenance processes and a quicker return to operational status.

MTBF is the average time between failures of a machine. It indicates how frequently a piece of equipment fails and needs repair over its operational lifespan. A higher MTBF suggests greater reliability and less frequent need for maintenance.

3.5 Technological Advancements in Maintenance

In the era of Industry 4.0, the maintenance landscape gets a significant advantage by offering new ways to predict and prevent equipment failure. Nowadays industry relies on machinery made of several components that need to be maintained and avoid failures. The Integration of digital tools IoT, AI, CPS, and ML provides the best solutions. These tools enable real-time monitoring of equipment health and performance, allowing companies to transition from reactive maintenance to predictive and proactive approaches. Technologies like DT and condition-based monitoring are particularly valuable, as they provide a virtual representation of physical assets, enabling remote diagnostics, optimized maintenance scheduling, and reducing time, cost, and bottleneck (Aivaliotis et al., 2019).

Currently, manufacturing industries move towards smarter, more efficient operations, digital maintenance provides the power of real-time data, predictive analytics, and automation to improve asset management. In maintenance AI-driven approach, leverages ML algorithms to predict the Remaining Useful Life (RUL) of machinery. This technology can process huge amounts of data from equipment to identify unhealthy patterns and anomalies, enabling proactive maintenance scheduling. ML techniques such as neural networks and support machines are commonly used to analyze historical data, recognize patterns, and forecast future failures, ultimately helping companies plan maintenance more effectively. CPS in maintenance processes allows for the seamless connection of the physical and digital worlds. These systems enable self-maintenance, where machinery autonomously adjusts and performs standard maintenance tasks based on sensor inputs and pre-defined rules (Rødseth et al., 2017).

3.5.1 Trends and Future Directions

The future of maintenance is rapidly growing, with new trends reshaping maintenance approaches within the manufacturing industry. However, digital maintenance remains a significant trend. These trends aim to perform tasks proficiently and ensure sustainability. Unfortunately, the trend in many organizations has been to cut budgets for maintenance, despite its critical importance. This leads to maintenance technicians being overworked and spending most of their time responding to unplanned maintenance, affecting the production output. Unplanned downtime is more costly with average impact of 5% cost within the manufacturing industry. Without skilled labor, maintenance teams seem under pressure. The organization needs to invest in upskilling the workforce to handle the advanced technologies to ensure production systems key performance indicators (KPIs) remain efficient and profitable (Nugent, 2013). A case from of Norwegian automobile supplier highly automated plant has OEE 90%. The organization focuses on recruiting young workers with no prior experience by promoting the culture of learning, job rotation, and TPM (Rolfsen & Langeland, 2012).

Furthermore, PdM uses the data-driven algorithm to forecast and prescriptive maintenance not only predicts but also recommends specific action. Prescriptive maintenance systems provide precise instructions on when and how to perform a repair, what parts to use, and even adjust production schedules based on the machine's condition. (Fox, et al., 2022). Moreover, the role of edge computing in maintenance is critical to enhancing the efficiency of data processing by minimizing latency and reducing the bandwidth needed for transmitting large volumes of data generated by machines and sensors beneficial for time-sensitive maintenance actions (Mourtzis, et al., 2022).

With the rise of Industry 4.0 technologies, PdM and DT, there is a growing opportunity to integrate real-time data and advanced analytics into sustainable maintenance practices. These technologies provide valuable insights that help optimize maintenance schedules, predict equipment failures, and reduce waste, making sustainable maintenance not only an environmentally responsible choice but also a cost-effective strategy for companies. The integration of sustainable KPIs and Industry 4.0 will be key to reducing the economic, environmental, and social impacts of industrial operations (Franciosi et al., 2018).

3.5.2 Sustainable Maintenance Practices, SMP

Sustainability has grown in recent years; it aims to use minimum resources to achieve goals it can be defined as "increasing the equipment's life and efficiency while minimizing the organization's carbon footprint along with saving on operation cost". Sustainable development is also defined as triple bottom line (TBL) – People, Environmental, and Profit. Recently, SMP is gaining more value in the industry due to increasing efficiency and production capabilities. This shift is driven by increased community awareness and pressures regarding social and safety issues. According to Holgado et al., 2020, the companies that adopt SMP see a significant amount of savings. Furthermore, many industries focus on the technical and economic factors and neglect the environmental aspects, safety, and quality factors. Ignoring these practices can affect the production systems. Digital Technologies Maintenance 4.0 can achieve this goal. Strategy like PdM can forecast failures and optimize maintenance schedules, offering benefits like reduced waste, increased productivity, and improved product quality and safety (Karuppiah, Sankaranarayanan, & Ali, 2021). In the context of the circular economy (reuse, repair, and recycle) the design of the equipment never wastes. In maintenance, this approach increases the design of equipment durability, reliability, and upgradability supporting continuous cycles of use and reuse as long as possible (Cholewa & Minh, 2021).

SMP has many benefits in industry; however, some barriers exist, such as financial constraints, organizational challenges, skilled labor, and limited data sources. The size and type of company also affect the choice of maintenance practice, with smaller enterprises facing technological constraints and larger ones concerned about investment costs. Moreover, in industrial sector includes a lack of top management commitment, human resource challenges, and poor departmental coordination (Holgado et al., 2020).

4. Results

In this section, a comprehensive analysis of the data is presented, with a specific focus on examining companies of different sizes. The objective is to explore how company size influences various factors and to identify patterns and trends that emerge across different groups. The results are systematically organized into a cross-tabulation format, which enables a clear comparison between the various categories. This method of presentation allows for a more nuanced understanding of the relationships between company size and other key variables, providing valuable insights into the underlying data.

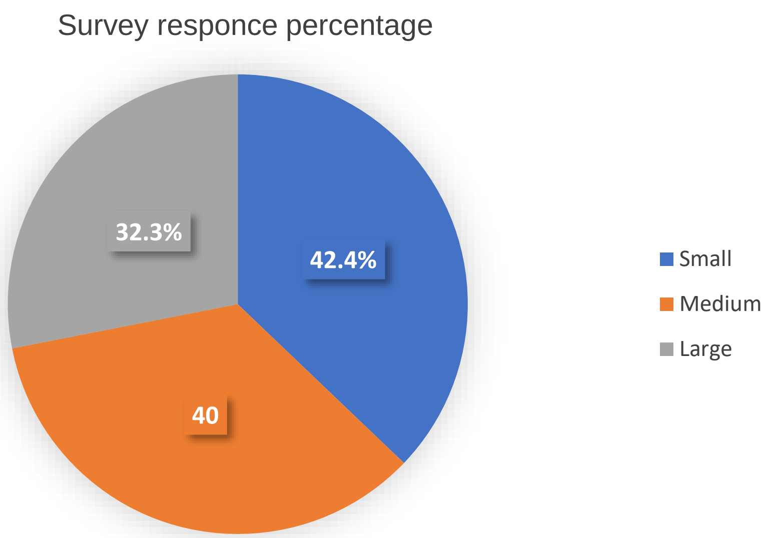

Figure 2 Response rate of the survey

Figure 2 provides a visual representation of the survey response distribution across different company sizes. Small-scale companies contributed the highest share of responses, accounting for 42.4% of the total, followed by medium-scale companies with 40%. In contrast, large-scale companies represented the smallest portion, with only 32.3% of the total responses. This distribution highlights that while small and medium-scale companies were more responsive to the survey, large-scale companies had a relatively lower engagement. Overall, the survey received a 39.18% response rate, indicating a moderate participation level but also revealing that larger organizations might have been less inclined to respond.

4.1 Budget Allocation and Cost Categorization

From the survey data, small-scale companies, the majority allocate between 11-20% of their budget to maintenance, as indicated by 29 responses (See in Figure 3). Only two small companies allocate less than 5% of their budget to these activities. Medium-scale companies show a diverse range of budget allocations. While no reported spending 5-10% and less than 5% of their budget on maintenance, 13 companies allocated between 11-20%, and 15 companies committed more than

20% to maintenance. On the other hand, large-scale companies showed a tendency towards higher maintenance budget allocations, with 16 companies spending more than 20% of their budget on maintenance tasks. Only one allocated between 5-10%, and no reported spending less than 5%. Four allocated between 11-20% of their budget to maintenance tasks.

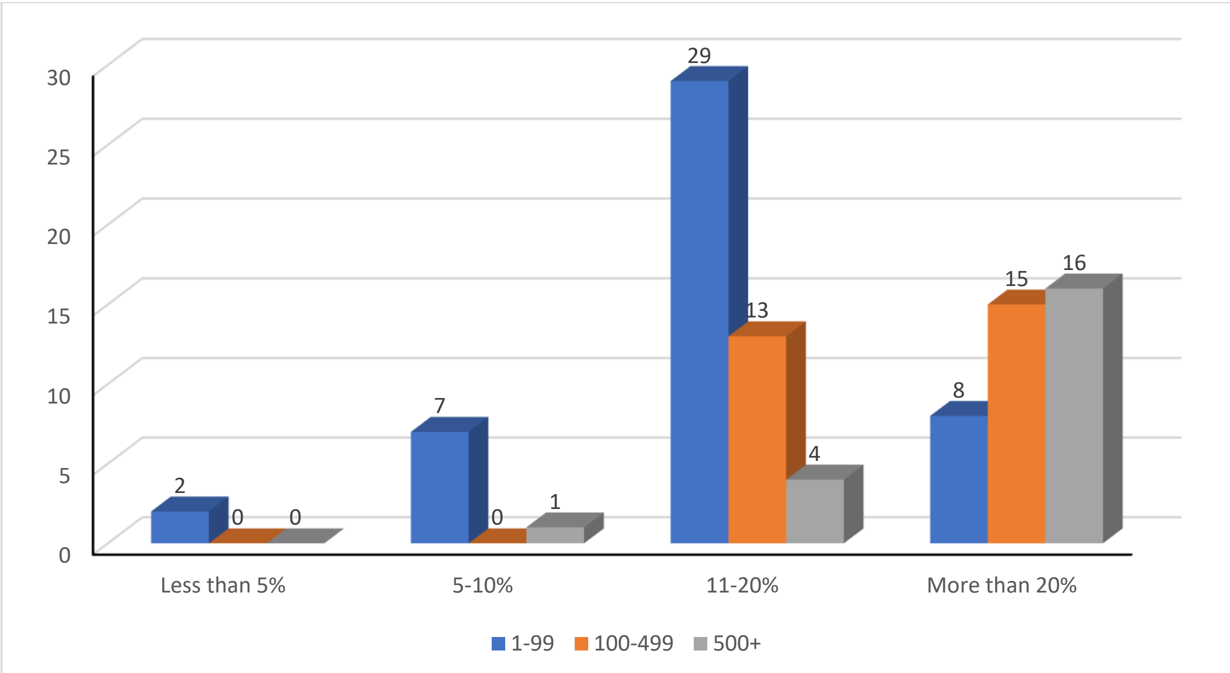

Figure 3 Annual budget allocation

According to small-scale companies, they heavily rely on outsourcing maintenance tasks, with 25 responses in this category, compared to only 7 for medium and 4 for large companies. In contrast, large companies show a higher emphasis on software and technology investments, with 12 responses, closely followed by medium-sized companies with 14 responses. Small companies, however, report fewer responses in this area, likely due to budget or resource constraints. Small companies report the highest number of responses 5, compared to 3 from medium and large companies, for labor and training. Large companies show less reliance on this category, possibly due to their ability to adopt technological solutions. Small companies, however, report fewer responses in this area, likely due to budget or resource constraints. Regarding labor and training, small companies report the highest number of reactions 5, compared to 3 each from medium and large companies (See Figure 4). large companies show less reliance on this category, may be due to their ability to adopt technological solutions.

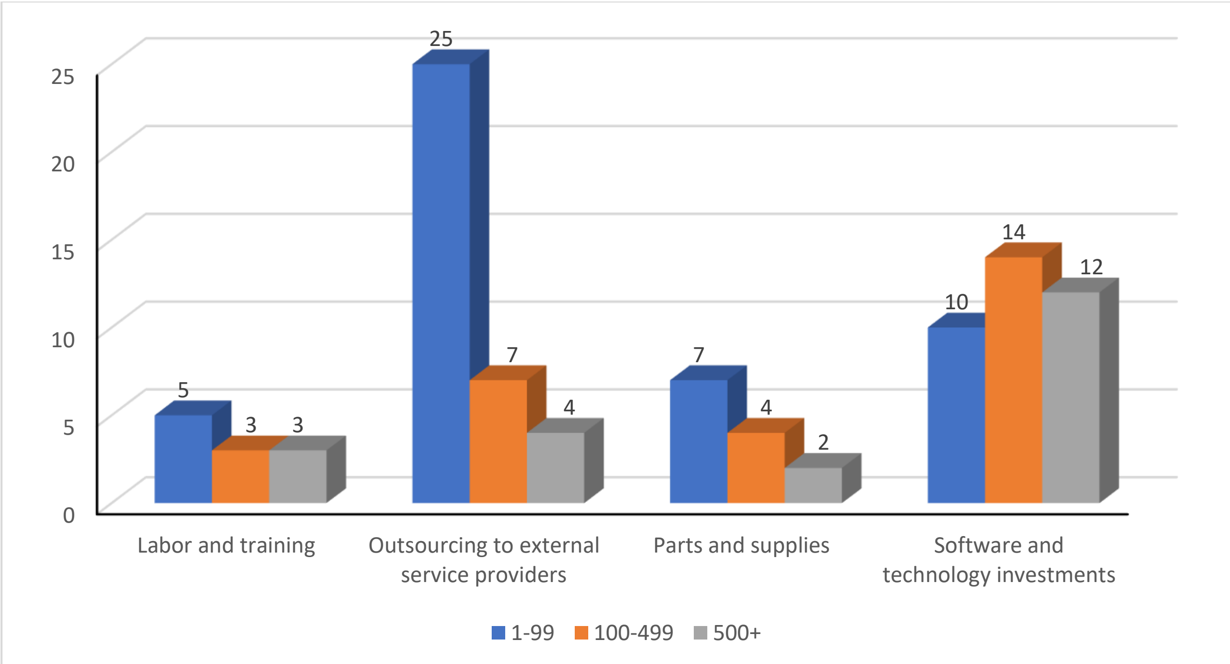

Figure 4 Majority budget spending category

4.2 Maintenance Strategies and Culture

Organizational maintenance cultures indicate a clear preference for preventive maintenance, which received the highest number of responses at 44. proactive strategies were favored with 28 responses, while predictive and reactive approaches garnered 16 and 7 responses.

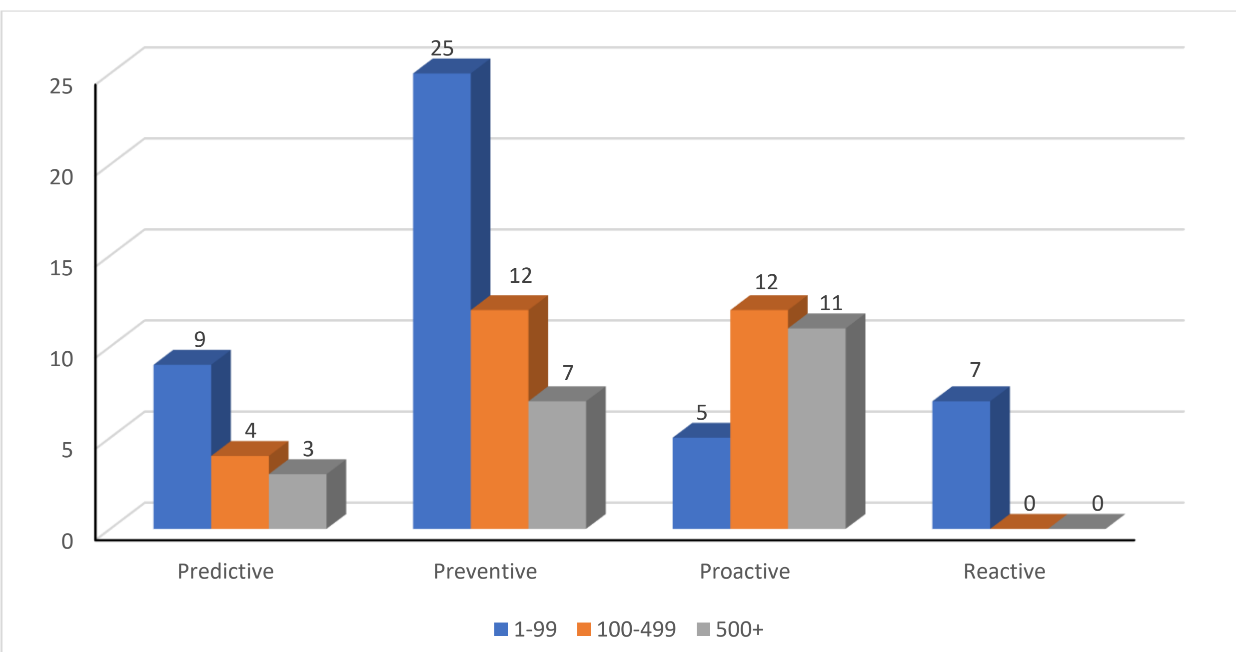

Figure 5 Maintenance culture

In terms of company size, small companies predominantly adopted preventive maintenance with 25 responses, showing a significant preference for this approach. However, Medium-sized companies showed an equal preference for preventive and proactive strategies, each receiving 12 responses. Large companies leaned more towards proactive maintenance, with 11 responses, but also maintained a strong focus on preventive strategies, with 7 responses. Small companies also engaged in predictive maintenance, contributing 9 responses, and were the only group to adopt reactive maintenance, with 7 responses. Medium and large companies showed lesser engagement in predictive maintenance. However, no one reported any reactive maintenance practices (See Figure 5).

Furthermore, "annually" updating maintenance strategies was the most common practice, with a total of 48 responses, closely followed by "continuous" updates at 42 responses, while "never" updating was the least common, with only 6 responses (See Figure 6).

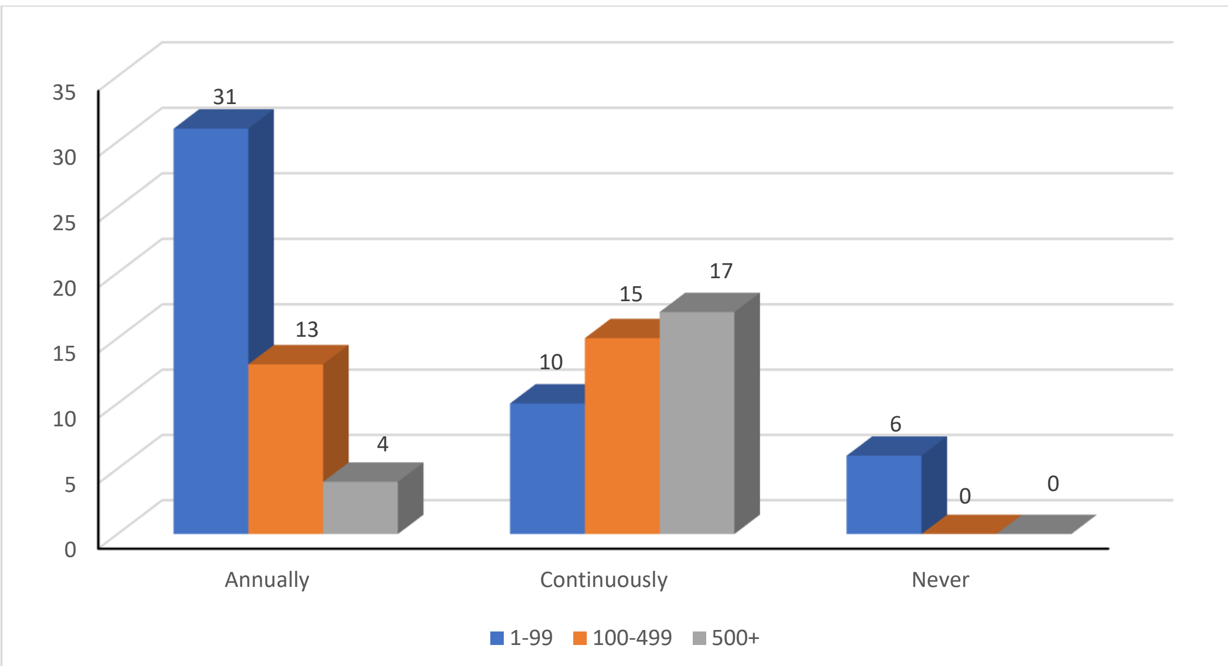

Figure 6 Maintenance Strategy Review

Breaking this down by company size, small companies primarily update their maintenance strategy annually, with 31 responses, whereas medium and large companies prefer continuous updates, with 15 and 17 responses, respectively. Small companies also reported 10 responses for continuous updates and 6 for never updating. In contrast, medium and large companies reported fewer annual updates with 13 and 4 responses respectively, and notably, there were no responses for "never" updating from these larger companies.

4.3 Workforce Dynamics and Maintenance Challenges

Based on the data analysis, this study observed a distinct pattern in the number of employees involved in maintenance across different company scales. Small-scale companies, on average allocate about 10 employees to their maintenance operations. Medium-scale companies, have a considerably higher average, employing approximately 37 maintenance personnel. The largest increase is seen in large-scale companies, where an average of about 51 employees are dedicated to maintenance tasks (See Figure 7).

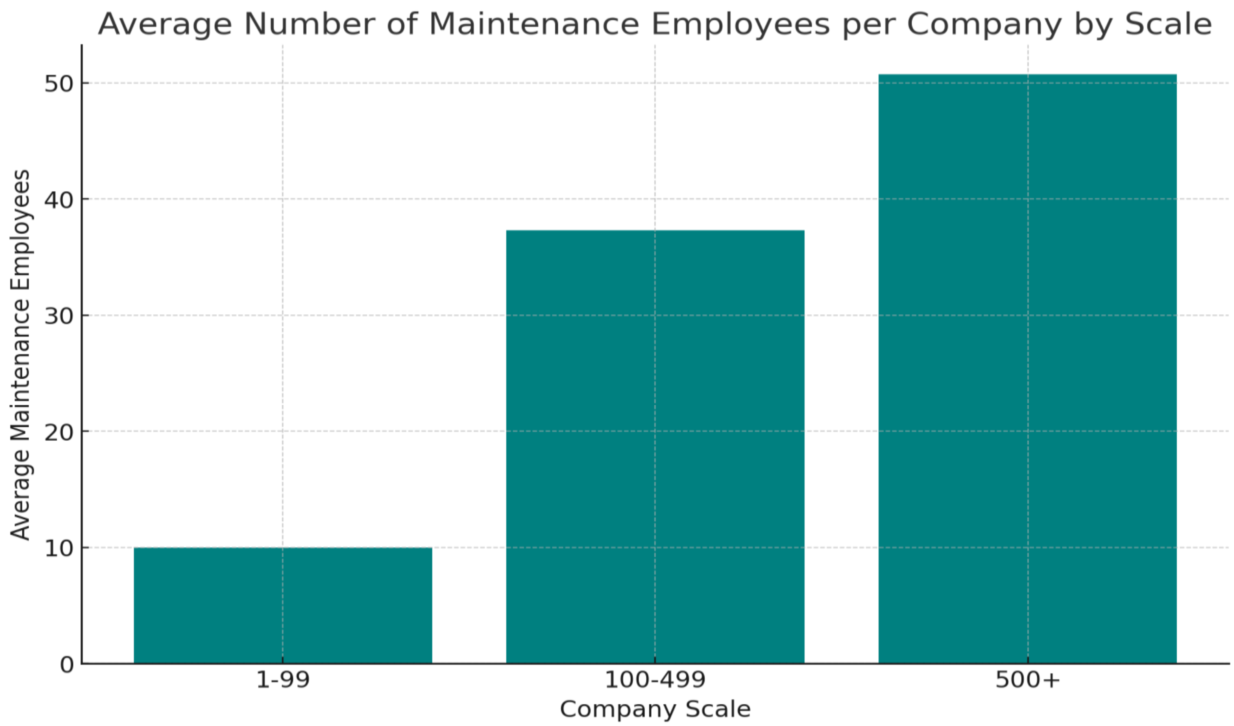

Figure 7 Average Number of Workforce

The challenge in maintaining assets was keeping up with technology, receiving 40 responses, closely followed by the difficulty in finding skilled personnel with 33 responses. Organizational support and cost issues were less, receiving 13 and 5 responses. Small companies reported significant difficulties in both finding skilled personnel 16 responses and keeping up with technology 15 responses. Large companies also highlighted these issues, giving 11 for technology and 7 for skilled personnel. Medium-sized companies reported 14 responses concerning technology and 10 regarding skilled personnel. organizational support is notably a concern for small companies, with 13 responses, compared to only 2 from both medium and large companies. Cost concerns were mostly mentioned by small and medium-sized companies, with 3 and 2 responses (See Figure 8).

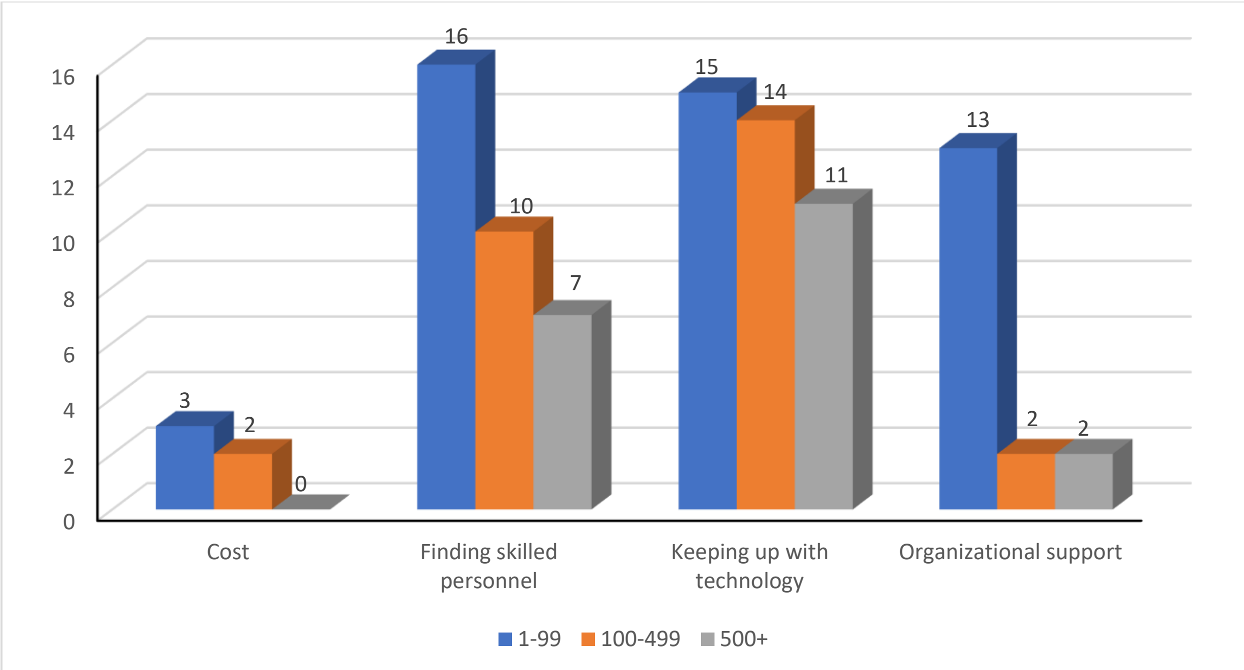

Figure 8 Challenges in Maintaining Assets

4.4 Future Maintenance Cost and Sustainability

Survey data on how organizations quantify the indirect costs of maintenance revealed diverse practices. The most favored approach across the board was a detailed quantification method, receiving the highest overall responses, with 42. Both large and medium-sized companies showed a strong preference for this method, each contributing 16 responses.

In contrast, small companies with the highest number of responses, 22, indicated that they do not quantify indirect costs. Regarding the use of past experiences to estimate costs, small companies with 13 responses compared to 6 and 4 from medium and large companies. Responses to not quantifying indirect costs at all were lowest among large companies, with only 1 indicating this approach, against 6 from medium companies. Meanwhile, responses from small companies for the detailed quantification method were 10 (See Figure 9).

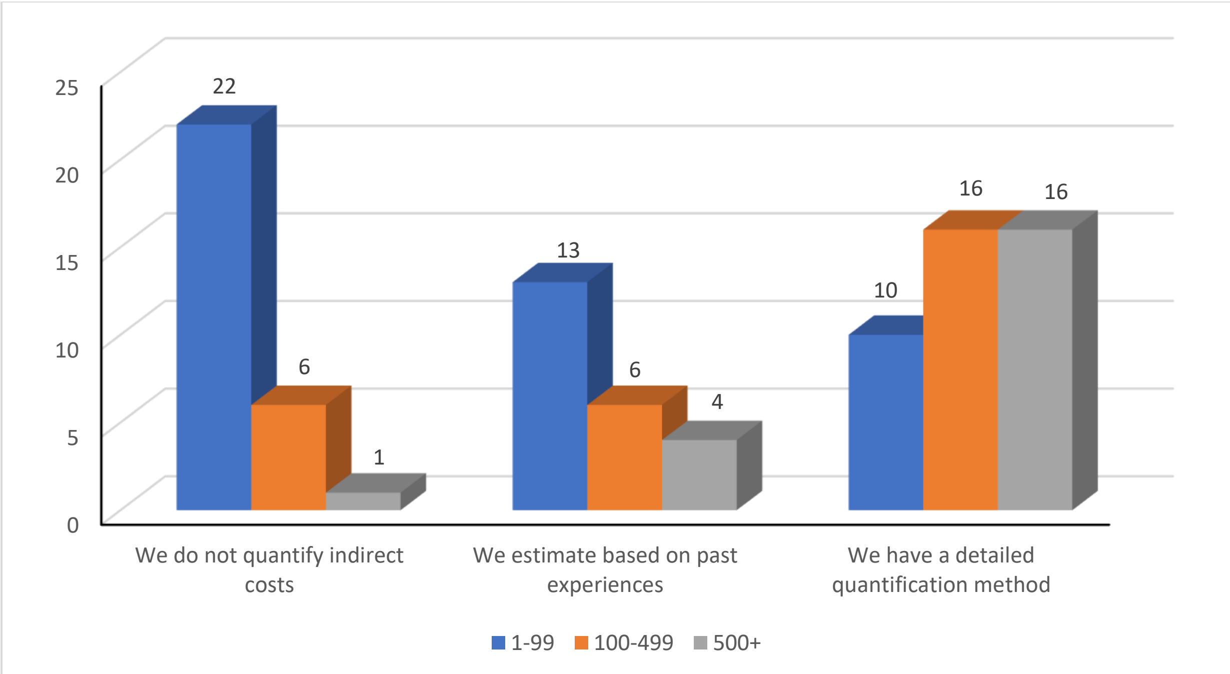

Figure 9 Indirect Cost Analysis Method

The analysis of the survey on key areas for investment in maintenance reveals distinct preferences and priorities among different scales of companies. "Advanced Maintenance Technologies" and "Sustainable Materials and Processes" emerged as the top investment areas, attracting the highest response with 59 and 54. "Workforce Development and Training" also received considerable attention, with 43 responses, however, "Compliance and Regulatory Technologies" was less emphasized, with only 17 responses. Small companies with the highest responses 25 and 29 directed towards "Advanced Maintenance Technologies" and "Sustainable Materials and Processes, and 8 responses from "Workforce Development and Training." Medium Companies showed preference 19 and 13 responses for integrating "Advanced Maintenance Technologies" with "Sustainable Materials and Processes" and 17 responses towards "Workforce Development and Training". Furthermore, Large Companies responses 15, 12, and 8 towards "Advanced Maintenance Technologies", "Sustainable Materials and Processes" and "Workforce Development and Training" (See Figure 10).

In survey data regarding maintenance-related costs distribution, the majority of responses, from 35 companies, indicated an increase in labor costs alongside decreases in technology and material costs. Close behind, 31 companies expected rising technology costs while labor and material costs were anticipated to decline. Meanwhile, 27 companies predicted no significant changes in their maintenance expenses. Interestingly, 3 companies foresaw an increase in material costs with a decrease in both labor and technology expenses. Small companies, with 16 expecting no significant changes, 15 anticipating higher technology costs, and 14 seeing labor costs rise. Only 2 small companies expected an increase in material costs. Medium-sized companies labor costs increase with 14 responses, technology costs increase with 8 responses, and 6 responses expect stable costs. No medium-sized companies reported increases in material costs. large companies, 8 responses showed an increase in technology costs, closely followed by 7 responses reporting higher labor costs. A small number also indicated no expected changes 5 responses, and only 1 reported an increase in material costs (See Figure 11).

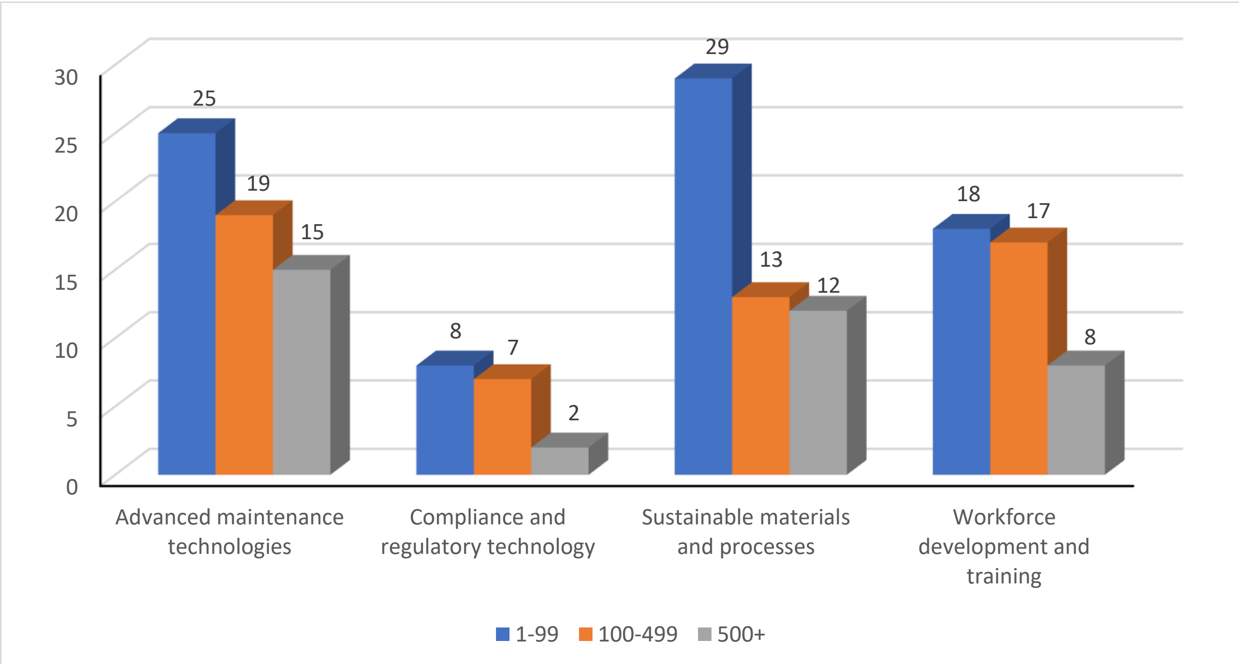

Figure 10 Areas for Investment

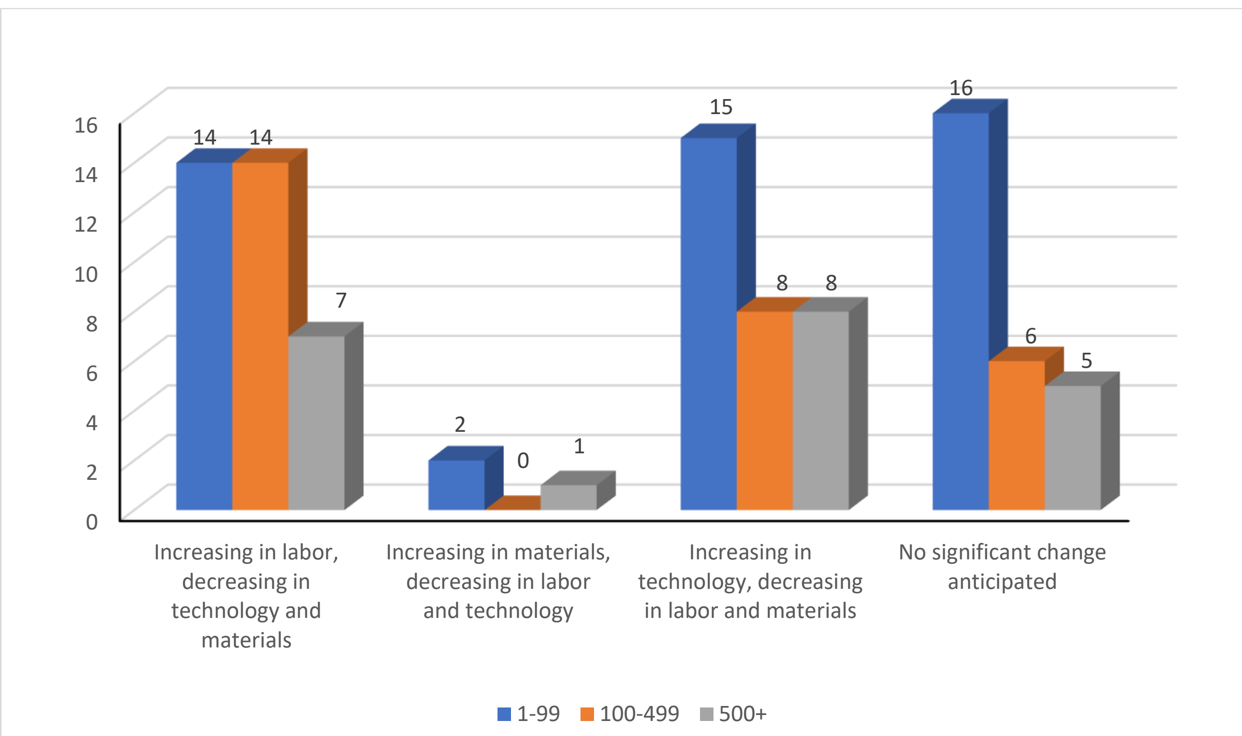

Figure 11 Maintenance Cost Distribution

Maintenance-related costs highlighted several key areas where costs will increase. The majority of respondents 39 identified "costs associated with adopting new technologies" as the primary area of increase. This was followed by concerns over "labor costs due to skilled worker shortages," which got 34 responses. Meanwhile, 17 responses pointed to "costs related to sustainability and environmental compliance" as a significant factor. The least concern, with only 6 responses, was "material costs due to supply chain issues."

Small companies reported the highest number for technology adoption costs with 22 responses, whereas medium and large companies contributed fewer responses, with 9 and 8. In terms of labor costs due to skilled worker shortages, both small and medium companies reported 13 responses each, compared to 8 from large companies. Regarding responses to sustainability and environmental compliance small and medium companies each reported 6 responses, and large companies slightly less at 5. Only small companies reported increased material costs due to supply chain issues, with 6 responses, while no medium or large companies reported this as a concern (See Figure 12).

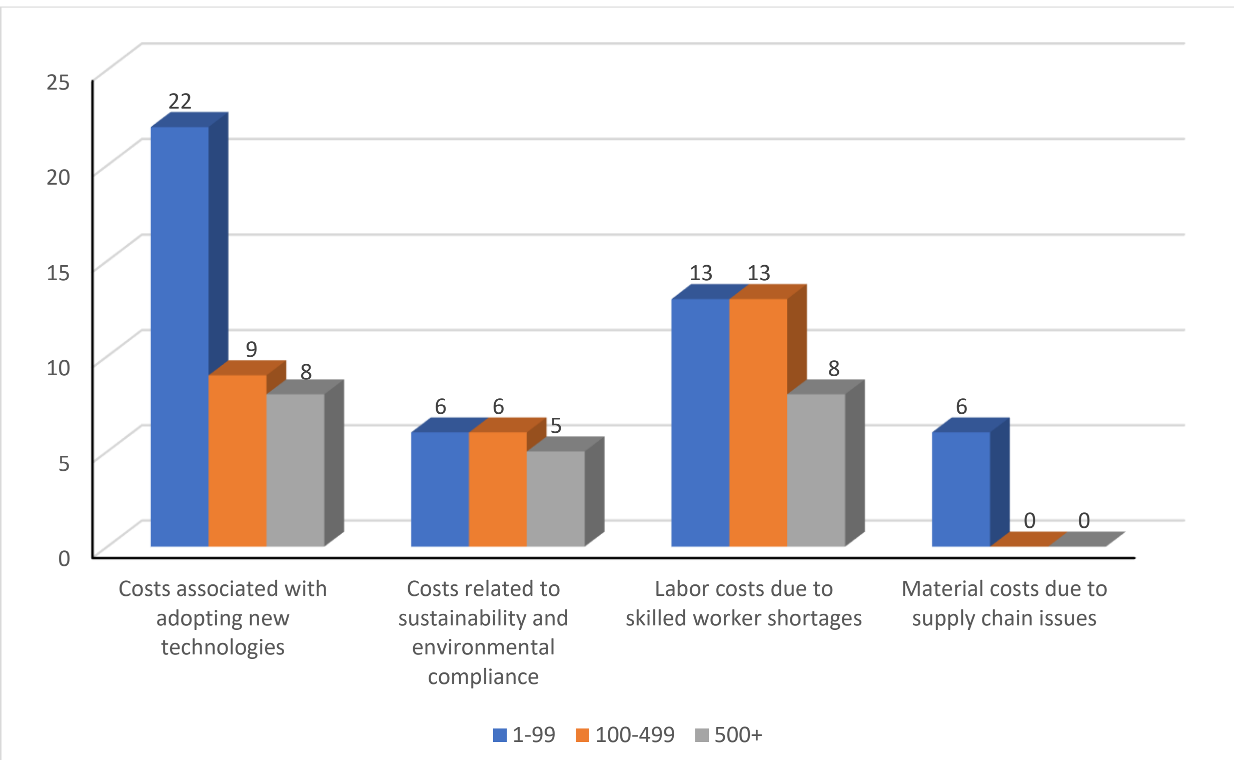

Figure 12 Rise in Maintenance Cost

The survey on the cost savings resulting from SMP within organizations revealed encouraging outcomes. The majority, with 48 companies, reported "significant savings," underscoring the substantial financial benefits of sustainable practices. "Moderate savings" were reported by 33 companies, suggesting a noticeable but less pronounced financial impact. On the other hand, a smaller group of 12 companies observed "minimal savings," indicating limited financial returns from their sustainability efforts, and a mere 3 companies reported "no savings."

When analyzed by company size, both small and large companies each recorded 17 responses indicating "significant savings," with medium-sized companies slightly behind at 14 responses. For "moderate savings," small companies led with 18 responses, followed by 12 from medium-sized companies, and only 3 from large companies. "Minimal savings" saw 10 responses from small companies, with medium-sized companies contributing just 2 responses and large companies reporting none. Finally, the category of "no savings" was reported by 2 small companies and 1 large company, with no medium-sized companies reporting a lack of savings (See Figure 13).

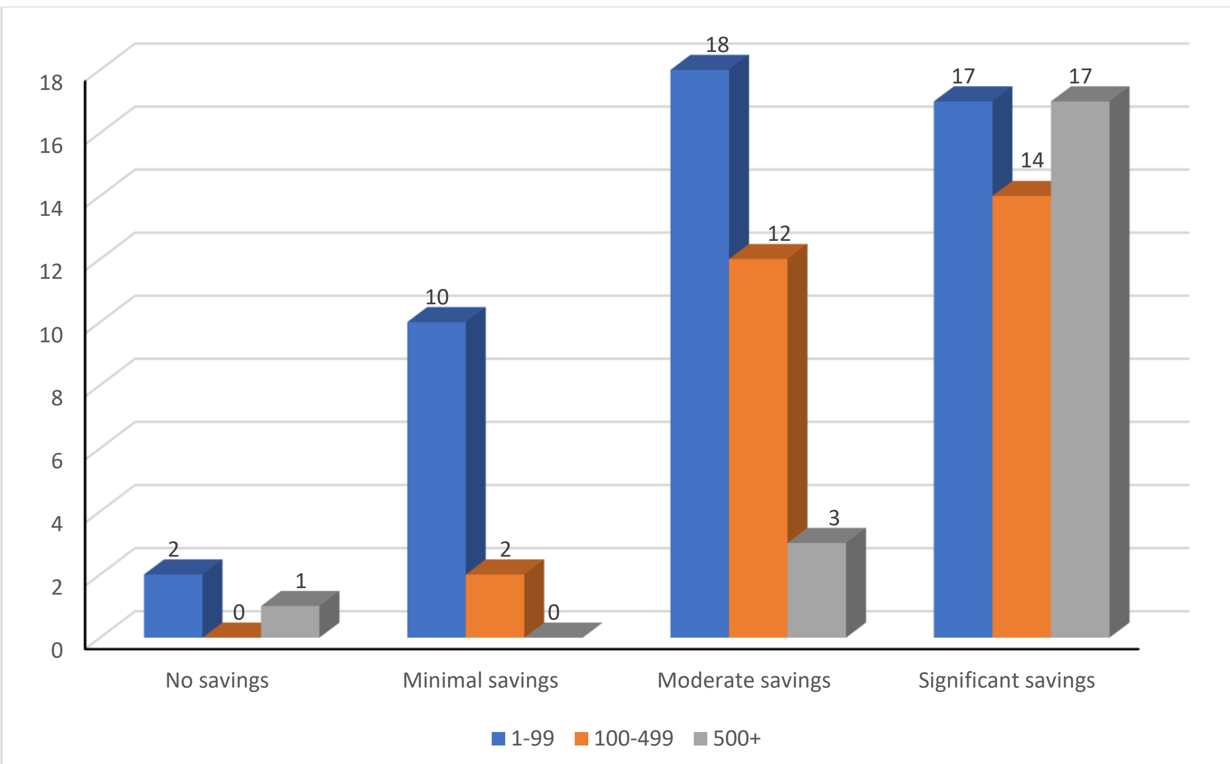

Figure 13 Impact of SMP on Cost

4.5 Technological Adoption and Future Trends

The study on the implementation of digital tools within maintenance processes shows a strong inclination towards technology adoption across various company sizes. A majority of the companies, 53 responded "Yes" to using digital tools. Meanwhile, 38 companies are currently "planning to" adopt such tools, indicating a proactive approach towards future implementation. Only 5 companies, all small-scale, responded with a "No," showing minimal resistance to the trend.

large companies 20 responded saying "Yes" utilize digital tools, followed closely by medium companies, with 19, and small-scale companies, with 14. In terms of planning to implement digital tools, small-scale companies are the most proactive with 28 responses, whereas medium and large companies have 9 responses and just one response (See Figure 14).

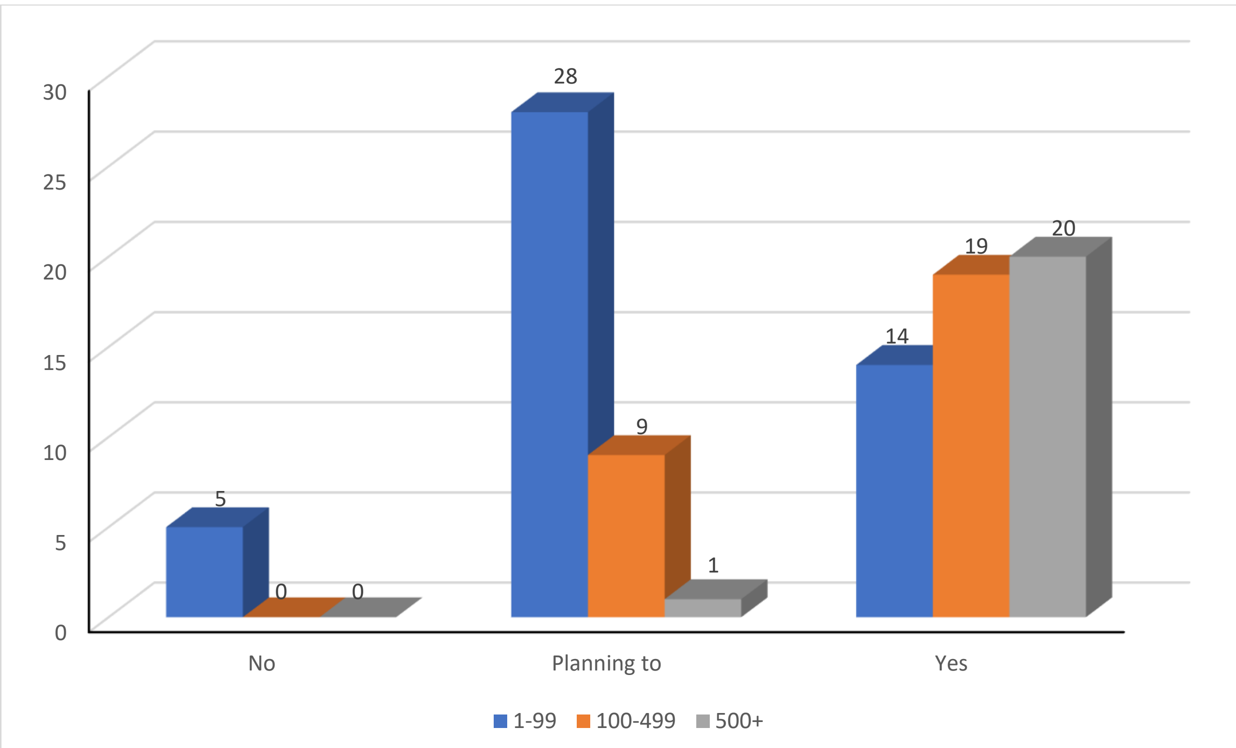

Figure 14 Digital tools in Maintenance

The survey data on future maintenance trends shows companies are most actively preparing for sustainable practices and predictive analytics. Sustainable practices lead with 48 total responses, with the highest engagement from small companies with 23 responses, followed by medium with 14 responses and large companies with 9 responses. Predictive analytics also shows strong interest, garnering 35 responses across the board 14 from small, 11 from medium, and 10 from large companies. Workforce development and automation and robotics received considerably fewer responses, indicating these areas may be of less immediate concern or strategic focus. Workforce development had 10 responses overall, with 7 coming from small companies, 2 from medium, and just 1 from large companies. Automation and robotics saw the least emphasis, with only 5 responses total: 3 from small and 1 each from medium and large companies (See Figure 15).

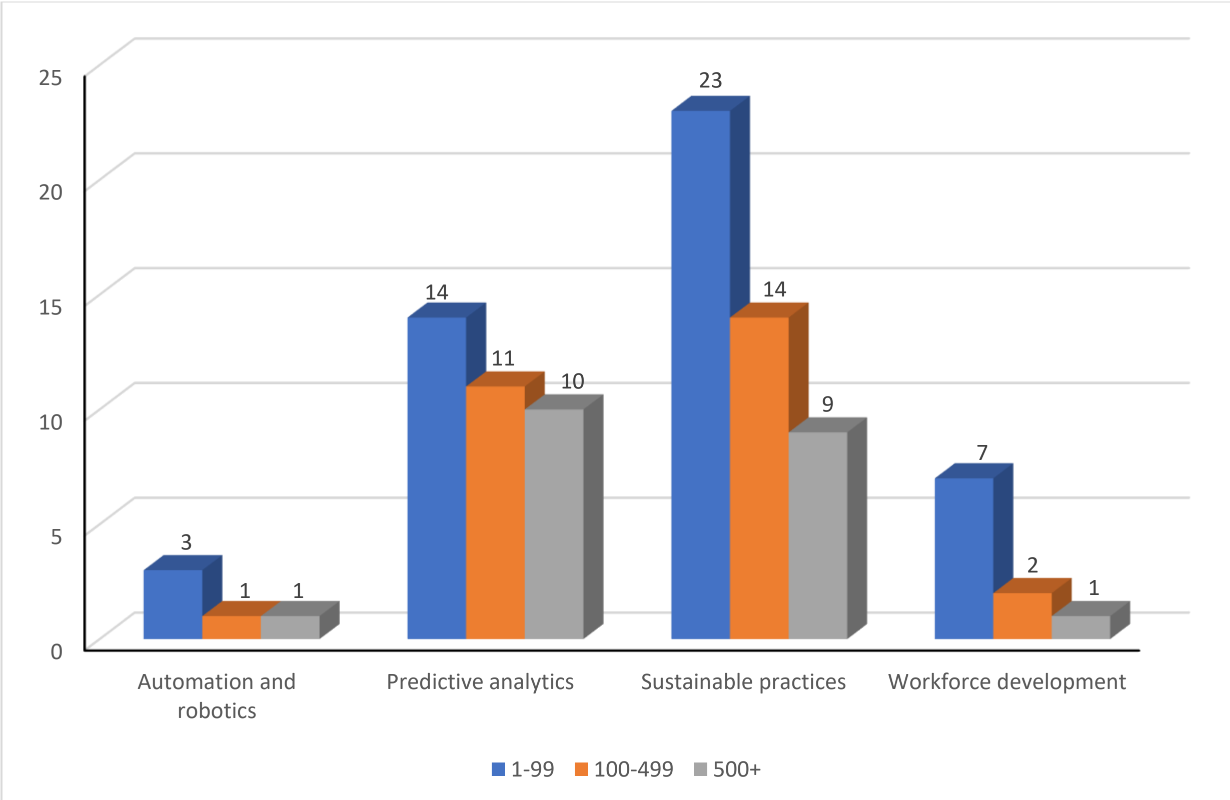

Figure 15 Trends in Maintenance

4.6 Evaluating Maintenance Efficiency and Sustainability Challenges

The survey data reveals that most companies actively monitor their equipment conditions in real time for maintenance needs, with 65 responses indicating that "more than 75%" of their equipment is monitored.

Medium-sized companies lead in this category with 25 responses, followed closely by small companies with 23 and large companies with 18. Small companies reported the most for the "25-75%" monitoring range, with 16 responses, while medium and large companies showed lesser engagement with 4 and 2 responses. The "Less than 25%" category saw small companies again leading with 6 responses, and only 1 response came from large companies, with none from medium companies. "None", where no real-time monitoring is implemented, was reported only by small companies, with 2 responses (See Figure 16).

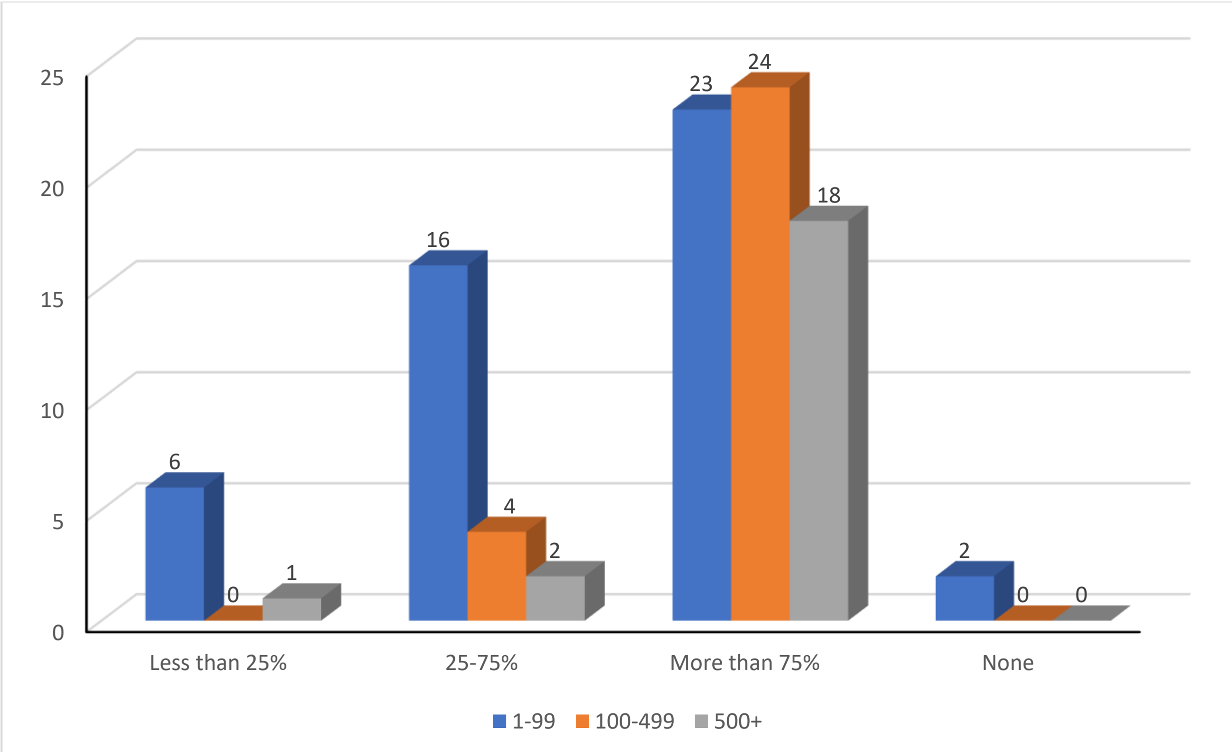

Figure 16 Equipment Condition Monitoring

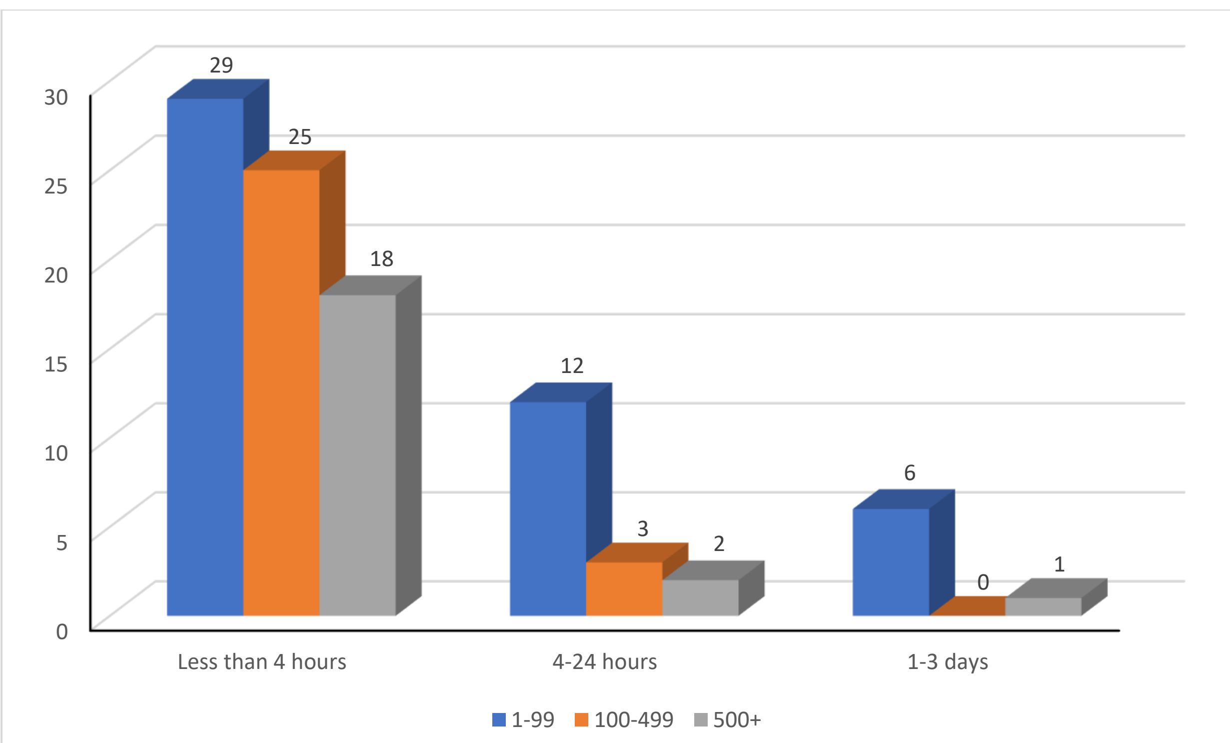

Figure 17 Response Times to Maintenance-Induced Production Stoppages

The survey data concerning maintenance-related production stoppages shows that most companies are capable of resuming operations with 72 companies indicating they can restart production in "less than 4 hours." This response category received the highest number of replies, with small companies leading with 29 responses, followed by medium companies at 25, and large companies at 18. For stoppages that take "4-24 hours" to resolve, 12 small companies reported such durations, while medium and large companies had fewer instances, with 3 and 2 responses respectively. Longer delays, classified as "1-3 days," were the least common and reported primarily by small companies with 6 responses and only one response from a large company. Medium companies did not report any stoppages falling into this longer timeframe (See Figure 17).

Furthermore, the survey reveals that companies face significant challenges in implementing eco-friendly maintenance practices, with "higher initial costs" being the most prominent issue, according to responses from 67 companies. This concern is particularly marked among small companies, which reported the highest number of responses at 32, compared to 19 from medium-sized companies and 16 from large companies. Another major challenge is "insufficient expertise," mentioned by 54 respondents. Breakdown by company size shows 22 responses from small companies, 16 from medium-sized, and 11 from large companies. Additionally, 35 responses pointed to a "lack of available technology" as a barrier, with small and medium companies each contributing 13 responses and large companies adding 9. "Regulatory compliance issues" also pose a challenge, although less frequently cited, with 24 total responses. Among these, small companies reported 15 responses, medium companies had 6, and large companies reported the fewest with 3 (See Figure 18) and (**Appendix – Survey Questions**).

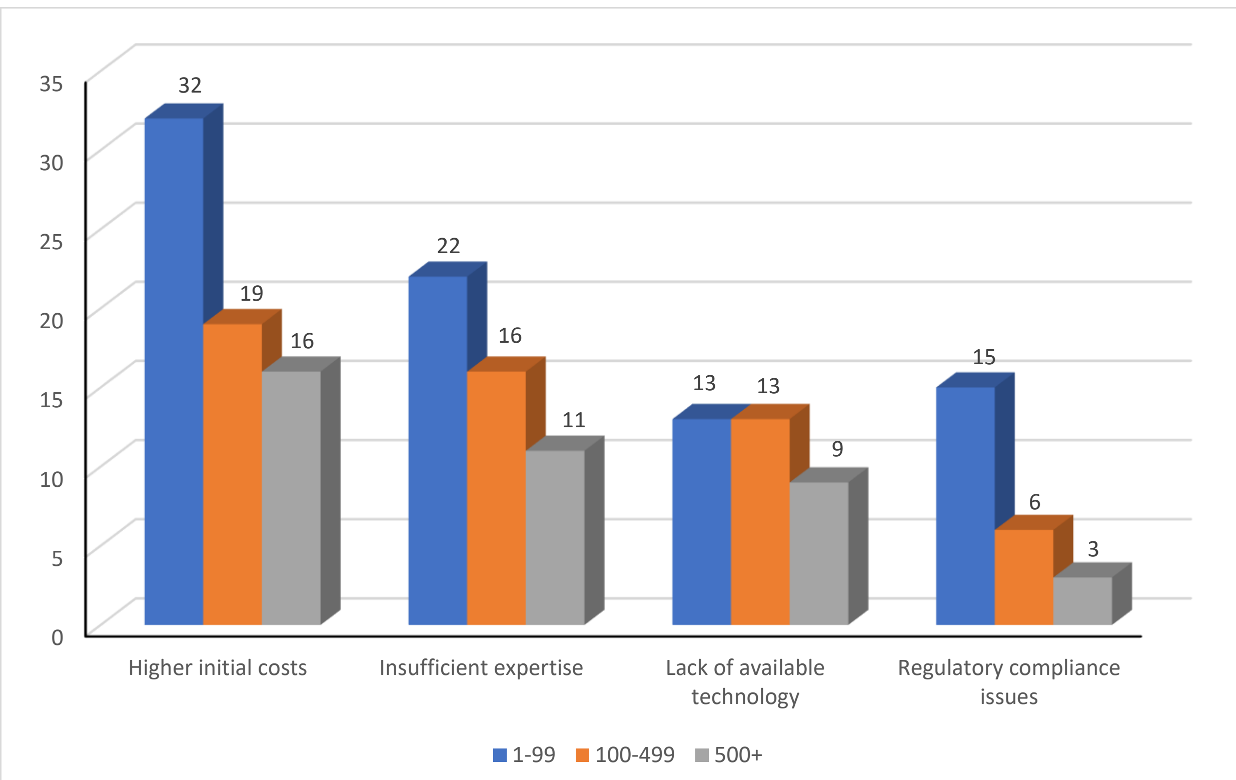

Figure 18 Challenges in Eco-Friendly Maintenance Practices

5. Discussion

This study's findings provide a comprehensive view of how maintenance strategies improve performance, minimize expenditures, and extend equipment life in the manufacturing environment. By reviewing the literature, conducting surveys, and analyzing data from Swedish manufacturing companies, it explores the financial and operational benefits of advanced maintenance practices. The findings show how maintenance impacts manufacturing outcomes and suggest ways to enhance maintenance strategies for better sustainability and efficiency in the industry.

5.1 Maintenance Budget, Strategy, and Investment Trends

The findings from the survey clearly show that maintenance budget allocation varies significantly across company sizes, with small companies often allocating less than larger ones. Most small companies allocate between 11-20% of their budget to maintenance, which may think a careful approach is likely due to limited financial resources. While medium and large companies tend to allocate more, many medium and large companies spend over 20% of their budget on maintenance. Salonen (2020) reports that maintenance costs in Sweden total 20 billion SEK annually, with a significant portion of this cost arising from unplanned maintenance tasks. However, the current study did not find any literature specific to the manufacturing industry that provides insights into the percentage of the budget allocated to maintenance, which could have offered more context to the findings. Furthermore, the results show that small companies tend to rely heavily on outsourcing their maintenance activities, likely due to resource constraints and the need for cost-effective solutions. In contrast, medium and large companies are more likely to invest in advanced software and technologies to manage and optimize their maintenance operations, indicating a higher degree of internal capability and investment in long-term solutions.

Small companies primarily adopt PM strategies. These companies focus on scheduled maintenance tasks to prevent failures before they occur, a strategy that aligns with their more limited resources. In contrast, medium and large companies take a more balanced approach, combining both PM and PdM strategies, which together form a PoM approach (Swanson, 2001). This dual strategy reflects a more comprehensive maintenance culture that aims to not only prevent failures but also predict and address potential issues before they cause disruptions. It is important to note that the survey questions did not clearly define PoM as a combination of PM and PdM, which may have led to some confusion among respondents. This lack of clarity could have affected how some companies understood and categorized their maintenance strategies. Despite this, the overall trend from the results indicates that companies, regardless of size, lean heavily toward PM and PoM practices.

According to Rødseth et al., 2017 manufacturing industries are moving toward smarter investing in technology can help companies plan maintenance more efficiently. Moreover, updating the maintenance strategies shows how they focus on operations excellence. Large and medium companies continuously update their strategies. However, small companies do so annually. The results found that companies that regularly review and improve their maintenance plans are better at adopting new technologies and methods to boost the efficiency and reliability of their equipment. This flexibility helps meet both immediate and long-term goals.

Furthermore, larger and medium-sized companies like to measure their indirect maintenance costs in detail. This means that these companies are careful about understanding their indirect losses and downtime which helps them plan their budgets better and they can quantify indirect losses. On the other hand, smaller companies often skip measuring this cost. This might mean smaller companies either find it too complex to track these costs or they think it's not crucial for their business. According to Thomas, 2018 insufficient maintenance practices can lead to higher indirect losses. To mitigate these risks, firms can adopt PdM policies. PdM involves the continuous monitoring of equipment conditions through sensors and IoT devices, offering early warnings of potential failures (Selcuk, 2016). Additionally, companies can integrate performance metrics such as TA and OEE into their operations. These metrics are crucial for identifying and quantifying both direct and indirect maintenance losses, thus enhancing the overall strategic management of maintenance activities (Sielaff et al., 2023; De Ron & Rooda, 2006; Stamatis, 2017).

All companies face challenges in finding skilled personnel but this more affects the small companies however large and medium think that it is challenging to keep up with technology the one reason may be fast fast-paced environments. According to the OECD, 2016 in Sweden 33% of companies say it is difficult to find skilled workers due to a lack of workers. Nugent 2013 said that organization needs to upskill the workforce to handle advanced technologies to ensure production systems remain efficient and profitable. When it comes to investing, many organizations are interested in advanced maintenance technologies and sustainable materials and processes. However, small companies are particularly keen on these areas, possibly trying to keep up with or get ahead of bigger competitors by adopting new technologies and green practices. The survey also looks at how companies expect their costs to change. Many companies think their labor costs will go up, which can be due to a shortage of skilled workers. The concept of TPM and the case study from a Norwegian company recruiting young workers with no experience by promoting a learning culture can increase productivity (Agustiady & Cudney, 2018; Rolfsen & Langeland, 2012). Moreover, small companies expect their technology costs to increase, likely because they are just starting to invest in new technology, which can be expensive at first. This study showed that maintenance has a direct impact on operational efficiency. Companies that engage in regular maintenance reviews and adopt integrated maintenance strategies tend to experience lower downtime and higher equipment reliability. This connection highlights the importance of strategic maintenance planning and execution as a core component of operational excellence.

5.2 Equipment Monitoring and Production Stoppages

The survey results showed that majority of companies, over 75%, monitor their equipment condition in real time. This proactive approach allows businesses to prevent equipment failures and minimize operational downtime by identifying potential issues before occur. Leveraging technology in this manner is crucial for maintaining continuous operations and avoiding unexpected equipment breakdowns.

Despite the benefits of real-time monitoring, the results highlighted an inequality between large and small companies. Half of smaller companies often do not monitor their equipment as comprehensively as their larger and medium. This difference may be primarily due to the limited resources available to smaller businesses, or maybe they heavily rely on outsourcing or lack access to cutting-edge technology. Consequently, these companies face longer downtimes because they may not detect and address breakdowns quickly which leads one day to resolve.

To bridge this gap, smaller companies need to consider integrating PdM and PoM strategies. These systems utilize real-time data collected through sensors and the Internet of Things (IoT) to not only predict potential equipment failures but also prescribe preventative measures and solutions (Selcuk, 2016) (Swanson, 2001). Implementing such technologies can significantly enhance the ability of small businesses to respond promptly to issues, thereby reducing downtime and improving overall operational efficiency.

5.3 Impact of Sustainable and Digital Innovation

This study provides significant insights. The majority of SMP companies are experiencing significant cost savings. The respondents from small and large companies tell of significant savings compared to medium companies. This means sustainability is not only a regulatory compliance measure but also a strategic asset that can drive financial performance. Digital transformation in maintenance operations has been widely accepted and integrated at various levels within the industry. The proactive adoption of digital tools, particularly by all group companies, highlights their agility and readiness to embrace new technologies. This allows companies to predict changes quickly and prevents failures and downtime in production processes.

From the findings, companies are preparing for predictive analytics and sustainable practices to perform progressive maintenance plans that put long-term operational efficacy and sustainability. According to Aivaliotis et al., 2019 digital technologies can enable real-time monitoring of equipment health and performance. Moreover, integrating DT and condition-based monitoring provides virtual representation of physical equipment performance through this companies can remotely diagnose the performance of the machines and they can take proactive action against problems.

Moreover, challenges firms face when implementing eco-friendly practices include high initial costs, a lack of expertise, limited technology availability, and regulations. Small companies, face more difficulties with cost and compliance due to their limited resources. Insufficient expertise is a common problem across all companies, suggesting a widespread skills gap in sustainable technologies.

To address these challenges, companies could explore innovative financing options like leasing to reduce upfront costs. Investing in training can help close the expertise gap, ensuring employees are well-equipped to handle new technologies. Collaborations between companies, technology providers, and regulatory bodies could also enhance access to appropriate technologies and simplify compliance processes. These strategies could make adopting sustainable practices more feasible for companies of all sizes, fostering a more environmentally friendly approach to maintenance.

5.4 Limitations

This study centers on the manufacturing sector in Sweden, specifically targeting industries (Tools, Machinery, Automobiles, and Process). A comprehensive review of 30 scientific papers informed the design of the survey questions used in this research. However, the survey design may have limitations. The inclusion of numerous close-ended questionnaires reduces the detailing of the answers. Open-ended questions, allowing for more detailed answers, could enhance data collection and provide deeper insights.

Additionally, the slow pace of survey responses has extended the timeline of the study. Given the rapid technological advancements in maintenance practices, especially predictive maintenance, there is a risk that the study's findings may quickly become outdated as new technologies and strategies emerge. Access to detailed financial data from the participating companies was limited due to the sensitive nature of such information. This restriction has led to a focus on general budget allocations and costs rather than a comprehensive financial analysis, which would offer a clearer view of the cost-benefit dynamics of maintenance strategies. While this thesis primarily discusses predictive and preventive maintenance, other significant strategies like reliability-centered maintenance (RCM) and total productive maintenance (TPM) have not been extensively covered. Expanding the scope to include these methods could provide a more complete assessment of their impact on operational efficiency.

5.5 Future Research

The findings from this thesis open several paths for future research that could further explain the dynamic value of maintenance in Swedish manufacturing. Given the rapid evolution of technology and its integration into maintenance practices, subsequent studies could explore the longitudinal impacts of predictive and proactive maintenance under the framework of Industry 4.0. This would offer deeper insights into how real-time data analytics and advanced diagnostic tools contribute to maintenance efficacy and cost efficiency over time.

There is also the opportunity to expand the maintenance practices in other industries such as Energy, Infrastructure, food, and pharmaceutical. Future studies could compare maintenance strategies across different industries within Sweden. Such comparative studies would enhance the understanding of Swedish maintenance strategies and their scalability and adaptability across various contexts. Moreover, the integration of qualitative research methods could enrich the quantitative findings of this thesis. Interviews and case studies with maintenance managers and technicians could provide nuanced perspectives on the challenges and opportunities of implementing advanced maintenance technologies. This qualitative depth would add a layer of practical insights to the theoretical and numeric data presented.

6. Conclusion

This master's thesis critically evaluated how important maintenance is in the manufacturing industry. This study aimed to find out how maintenance practices affect a company's operations and finances and how new approaches help environmentally friendly while using new technologies.

The findings from this research offer substantial evidence that maintenance is not a cost to be managed but a strategic approach that can significantly enhance operational effectiveness and financial outcomes. RQ1 The study examined how maintenance practices affect investment decisions within the manufacturing sector. The findings indicated that firms with proactive and predictive maintenance strategies could significantly reduce their operational costs and minimize unplanned downtime. This enhances overall equipment effectiveness and operational reliability, directly influencing the strategic allocation of investments toward maintenance. Firms leveraging advanced maintenance technologies have a better alignment of their maintenance activities with their financial and production goals, demonstrating the tangible benefits of integrating strategic maintenance planning. RQ2 quantification of maintenance value has traditionally been a complex aspect due to its indirect cost and benefit nature. By adopting a strong analytical approach, the thesis established that effective maintenance could be quantified in terms of reduced costs, enhanced productivity, and prolonged equipment lifespans. The results convincingly showed that investments in maintenance yield substantial returns showing the traditional view of maintenance as merely a cost center. Instead, it should be regarded as a vital component of the operational strategy that directly contributes to the bottom line. Moreover, RQ3 the balance between operational efficiency and sustainability, revealing that modern maintenance strategies enabled by digital innovations offer a pathway to achieving this equilibrium. Companies that integrated sustainable practices within their maintenance operations not only followed environmental standards but also saved costs and enhanced system reliability. In the era of Industry 4.0, where the integration of cutting-edge technologies with sustainability principles is essential, this balance is especially crucial.

Overall, maintenance in manufacturing, particularly within the Swedish context, is not just a support function but a strategic asset. The ability of a company to integrate advanced maintenance strategies effectively can lead to superior operational performance, cost efficiency, and alignment with broader sustainability objectives. These findings advocate for a shift in perception among stakeholders, from viewing maintenance as a necessary expense to recognizing it as a critical investment for long-term success in the manufacturing sector.

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APPENDICES

A. Appendix – Survey Questions

The following section provides a comprehensive list of all survey questions included in the study, along with their corresponding response in tables. This data is integral to understanding the detailed insights and responses discussed in the main sections of the thesis.

How Many employees are working within your organization?

1. 1-99
2. 100-499
3. 500+

1-99	100-499	500+
47	28	21

In total, 96 responses

What percentage of your annual operating budget is allocated to maintenance activities?

1. Less than 5%
2. 5-10%
3. 11-20%
4. More than 20%

Company Size	Less than 5%	5-10%	11-20%	More than 20%
1-99	2	7	29	8
100-499	0	0	13	15
500+	0	1	4	16
All	2	8	46	39

How do you categorize the majority of your maintenance costs?

1. Labor and training
2. Parts and supplies
3. Outsourcing to external service providers
4. Software and technology investments

Company size	Labor & training	Outsourcing to external service provider	Part & Supplies	Software & Technology investments
1-99	5	25	7	10
100-499	3	7	4	14
500+	3	4	2	12
All	11	36	13	36

How would you describe your organization's maintenance culture?

1. Reactive
2. Preventive
3. Predictive
4. Proactive

Company Size	Predictive	Preventive	Proactive	Reactive
1-99	9	25	5	7
100-499	4	12	12	0
500+	3	7	11	0
All	16	44	28	7

How often do you review and update your maintenance strategies?

1. Never
2. Annually
3. Continuously

Company Size	Annually	Continuously	Never
1-99	31	10	6
100-499	13	15	0
500+	4	17	0
All	48	42	6

Have you implemented any form of digital tools or software for maintenance management?

1. Yes
2. No
3. Planning to

Company Size	No	Planning to	Yes
1-99	5	28	14
100-499	0	9	19
500+	0	1	20
All	5	38	53

What future trend in maintenance are you most preparing for?

1. Automation and robotics
2. Predictive analytics
3. Sustainable practices
4. Workforce development

Company Size	Automation & robotics	Predictive Analytics	Sustainable Practices	Workforce Development
1-99	3	14	23	7
100-499	1	11	14	2
500+	1	10	9	1
All	5	35	46	10

How many employees are involved in maintenance?

	Column 7																								
Column 1	Missing	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	20	25	27	28	31	32	34	35	36
1-99	1	1	2	2	4	4	5	1	6	2	6	2	3	5	2	1	0	0	0	0	0	0	0	0	0
100-499	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	2	2	2
500+	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
All	5	1	2	2	4	4	5	1	6	2	6	2	3	5	2	1	1	1	1	1	1	1	2	2	2

Column 1	38	39	40	41	42	43	45	47	48	50-70	55	56	60-70	60-75	61	63	65	68	69	70-75	70-80	All
1-99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	47
100-499	2	3	1	1	2	3	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	28
500+	0	0	0	0	0	0	1	0	0	1	3	1	2	1	1	1	1	2	1	1	1	21
All	2	3	1	1	2	3	3	1	1	1	3	1	2	1	1	1	1	2	1	1	1	96

In this table, it is difficult to understand the number of employees so this study calculates the overall averages for all groups of organizations.

Company Size	Number of Employees in Maintenance
1-99	10
100-499	37
500+	51

How does your organization quantify the indirect costs of maintenance, such as production downtime, reduced quality, or energy inefficiency?

1. We have a detailed quantification method.
2. We estimate based on past experiences.
3. We do not quantify indirect costs.

Company Size	We do not quantify indirect cost	We estimate based on past experiences	We have a detailed quantification method
1-99	22	13	10
100-499	6	6	16
500+	1	4	16
All	29	23	42

To what extent have sustainable maintenance practices led to cost savings in your operations?

1. Significant savings
2. Moderate savings
3. Minimal savings
4. No savings

Company Size	No savings	Minimal savings	Moderate savings	Significant savings
1-99	2	10	18	17
100-499	0	2	12	14
500+	1	0	3	17
All	3	12	33	48

How do you foresee the cost distribution between labor, technology, and materials changing in the next 5 years due to maintenance trends?

1. Increasing in labor, decreasing in technology and materials
2. Increasing in technology, decreasing in labor and materials
3. Increasing in materials, decreasing in labor and technology
4. No significant change anticipated

Company Size	Increasing in labor, decreasing in technology and materials	Increasing in materials, decreasing in labor and technology	Increasing in technology, decreasing in labor and materials	No significant change anticipated
1-99	14	2	15	16
100-499	14	0	8	6
500+	7	1	8	5
All	35	3	31	27

What are the key areas for investment in maintenance that you believe will contribute most significantly to operational efficiency, cost savings, and sustainability?

1. Advanced maintenance technologies (AMT)
2. Workforce development and training (WDT)
3. Sustainable materials and processes (SMP)
4. Compliance and regulatory technology (CRT)

Companies size	AMT	AMT, CRT	AMT, SMP	AMT, SMP, CRT	AMT, WDT	AMT, WDT, SMP	CRT	SMP	SMP, CRT	WDT	WDT, CRT	WDT, SMP	All
1-99	5	1	12	0	6	1	2	7	2	1	3	7	47
100-499	1	2	7	0	7	2	1	0	0	0	4	4	28
500+	2	0	7	1	4	1	1	1	0	1	0	2	20
overall	8	3	26	1	17	4	4	8	2	2	7	13	95

This survey question is in the checkbox from the respondent can answer multiple. Furthermore, this table simply which is given below.

Company Size	Advanced maintenance technologies	Compliance and regulatory technology	Sustainable materials and processes	Workforce development and training
1-99	25	8	29	18
100-499	19	7	13	17
500+	15	2	12	8
All	59	17	54	43

What is the biggest challenge in maintaining your assets?

1. Cost
2. Finding skilled personnel
3. Keeping up with technology
4. Organizational support

Company Size	Cost	Finding skilled personnel	Keep up with technology	Organizational support
1-99	3	16	15	13
100-499	2	10	14	2
500+	0	7	11	2
All	5	33	40	17

what maintenance-related costs do you think will rise most significantly?

1. Costs associated with adopting new technologies
2. Labor costs due to skilled worker shortages
3. Costs related to sustainability and environmental compliance
4. Material costs due to supply chain issues

Company Size	Costs associated with adopting new technologies	Labor costs due to skilled worker shortages	Costs related to sustainability and environmental compliance	Material costs due to supply chain issues
1-99	22	6	13	6
100-499	9	6	13	0
500+	8	5	8	0
All	39	17	34	6

What percentage of your equipment is monitored in real-time for maintenance needs?

1. None
2. Less than 25%
3. 25-75%
4. More than 75%

Company Size	None	Less than 25%	25-75%	More than 75%
1-99	2	6	16	23
100-499	0	0	4	24
500+	0	1	2	18
All	2	7	22	65

In case of maintenance-related production stoppage, how quickly can operations resume?

1. Less than 4 hours
2. 4-24 hours
3. 1-3 days

Company Size	Less than 4 hours	4-24 hours	1-3 days
1-99	29	12	6
100-499	25	3	0
500+	18	2	1
All	72	17	7

What challenges do you face in implementing eco-friendly maintenance practices,

1. Higher initial costs
2. Lack of available technology
3. Insufficient expertise
4. Regulatory compliance issues

Company	Higher Initial Costs	Insufficient Expertise	Lack of Available Technology	Regulatory Compliance Issues
1-99	32	22	13	15
100-499	19	16	13	6
500+	16	11	9	3
All	67	49	39	24

This survey question in the checkbox forms the respondent can answer multiple.

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