Review: Optimizing Maintenance Management in Modern Industrial Facilities

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Abstract

The aim of this research paper is to highlight the importance of efficient maintenance management to enhance productivity within production systems and improve workplace management in industrial facilities. Maintenance management refers to a structured approach aimed at preserving the assets and resources of industrial or service facilities, particularly in the context of advanced machinery necessitated by rapid technological progress. It focuses on minimizing downtime through regular maintenance activities, including scheduled services, inspections, and emergency repairs while ensuring compliance with regulations and enhancing operational efficiency. Key objectives include optimizing maintenance costs, extending asset life, reducing unexpected equipment failures, and maintaining safety and product quality. The systematic inspection, maintenance, and repair of machinery not only helps prevent breakdowns but also includes calibration, cleaning, and sanitation to ensure reliable and efficient performance.

Keywords:

Objectives and Types; Preventive Maintenance; Corrective Maintenance; Predictive Maintenance; Proactive Maintenance; Organizing Maintenance; Classification of Industrial Equipment; Industrial Safety and Security.

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Highlights:

- Preventive Maintenance
- Corrective Maintenance
- Predictive Maintenance
- Organizing Maintenance
- Classification of Industrial Equipment
- Industrial Safety and Security

1. Introduction and Historical Review

1.1 Introduction

Maintenance is maintaining machines, engines, machine tools and equipment and keeping them in good condition throughout their life. It is all the work that is done to repair or maintain fixed assets and make them fit to work with high efficiency. It is a continuous process and must be performed by specialized workers whose responsibilities are summarized as follows [1] and [2] – [5]:

i. Periodic inspection and checks (i.e. preventive maintenance).

ii. Repairs carried out in emergency cases (i.e. unscheduled corrective maintenance).

iii. Administrative supervision and optimal use of existing labor to make the most of it.

iv. Collecting statistical data on malfunctions, performance, etc., in order to benefit from them in the future.

v. Prepare a plan to replace equipment, including machines, machine tools, hydraulic and pneumatic machinery etc., and submit it to senior management to take the appropriate decision.

The research paper emphasizes the critical role of efficient maintenance management in boosting productivity in production systems and improving workplace management within industrial facilities. In a competitive industrial environment, organizations must ensure their machinery operates optimally to minimize downtime, which leads to increased output and profitability. Effective maintenance practices also enhance workplace safety by proactively addressing potential issues, thereby reducing accidents and fostering employee morale.

The paper explores various maintenance strategies, including predictive maintenance and total productive maintenance (TPM), which help optimize resource allocation and extend asset lifespan, contributing to sustainability and environmental goals. Additionally, it discusses the impact of technological advancements such as data analytics, IoT, and AI in enabling real-time monitoring of equipment for timely decision-making, further enhancing productivity and mitigating risks.

In summary, the research underscores the connection between well-managed maintenance practices and the sustainable success of industrial enterprises, advocating for the adoption of effective strategies and technologies to improve operational efficiency, safety, and competitiveness.

1.2 A Brief History of Maintenance

Historically, maintenance was a straightforward process focused on fixing equipment after it broke down which is a reactive approach known as corrective maintenance. This method was sufficient in pre-industrial times, where customers simply waited for repairs. One early exception was the Montgolfier paper mills in the early 1800s, which implemented regular maintenance practices.

With the Industrial Revolution, the need for maintenance grew due to the hazardous nature of steam engines, which often exploded, prompting safety checks and the establishment of organizations like the German TÜV to prevent accidents. However, machines were still typically repaired only after failures occurred.

As manufacturing evolved with complex supply chains and diverse product lines, costly breakdowns spurred the development of preventive maintenance (PM), which aims to fix equipment before it fails. This method gained traction in Henry Ford's factories in the early 20th century, though challenges remained in predicting which failures could occur and how to effectively maintain equipment.

World War II further advanced the importance of maintenance, giving rise to various terms such as corrective maintenance, maintenance prevention, and productive maintenance. Although these terms have subtle differences, they share a common goal of enhancing maintenance practices, often seen as a marketing strategy in consulting.
The concept of productive maintenance evolved in Japan post-World War II into Total Productive Maintenance (TPM), spearheaded by Seichi Nakajima. This approach emphasizes proactive care and responsibility for machinery by operators.

Despite these advancements, many companies continued with reactive maintenance until the 1960s when more structured norms emerged. The introduction of predictive maintenance took this further by utilizing data analytics and algorithms to foresee issues before they occur, thus optimizing maintenance schedules and reducing unnecessary repairs.

2. Maintenance Department Duties

2.1 Installation of New Machines and Equipment

When planning the installation of industrial machines, we take into account the individual needs of each client. The installation carried out during the plant construction phase requires careful planning. However, it is usually the case that clients want to expand their business and decide to purchase new machinery to be installed without significantly interfering with other processes taking place on site. Therefore, the work should be coordinated with the clients to ensure that all installation stages take place as quickly as possible and without interrupting other logistics or production operations. The work is planned in advance and the client is informed about any restrictions so that they can take this into account when planning their internal processes.

The installation of a machine is usually a rather time-consuming and complicated project, so one of the main tasks of the concerned specialists is to create an appropriate work schedule. This ensures that the client always knows exactly what work will be carrying out and in what location. In this way, they can redirect employees to another location, ensuring the efficiency of processes and safety of employees. Together, the next steps are planned so that the installation of industrial machines has as little impact as possible on what is currently happening on the shop floor [1], [6] – [8].

2.2 Taking Care of Machines, Buildings, Devices, and All Fixed Assets

Fixed assets management is a common term in the business field. With the need to be well aware of the end of the financial year.

Fixed assets management plays a pivotal role in business, as it has a direct impact on supporting the organization’s future planning and vision. Not only that, but with proper planning and data-driven information, your business can lead to effective decision-making to enhance results.

Fixed assets are the basic assets owned or managed by institutions for continuous use in their industrial and commercial activities. They include long-term tangible assets of property, plant and equipment (PP and E). Fixed assets are of great importance in the field of accounting, as their value is calculated and depreciated in a specific way, and then converted into cash.

In accounting for fixed assets, it is important to determine how to calculate their depreciation or convert them into income, and this is not expected to be done within one year.

Within the balance sheet These fixed assets are incorporated as property, plant, and equipment (PP and E).

Here are a Few Examples of Fixed Assets:

1. Office equipment.
2. Computer equipment.
3. Buildings.
4. Furniture.
5. Manufacturing equipment.
6. Vehicles.
7. Machinery.

Basically, these assets depreciate over their useful life.

In simpler words, Asset management is an integrated program aimed at organizing and improving the use and maintenance of an organization's physical assets. This process requires a combination of careful planning, effective use, and organized maintenance to ensure obtaining the maximum return from these assets. Asset management allows organizations to accurately and effectively monitor their assets, achieve maximum benefit from these assets and prevent losses. It is managed by asset tagging or barcoding.

An organization can achieve the following benefits from implementing a fixed asset management system:

1 Track and monitor fixed assets.
2 inspect equipment and machinery at multiple locations.
3 Low maintenance costs.
4 Improves operational efficiency.
5 Maintain a record of retired, sold, stolen or lost assets.

One of the tasks of managing an organization's fixed assets is to track and monitor equipment and vehicles while evaluating their locations and maintaining them in good working order. It helps improve efficiency and reduce waste by reducing lost inventory, equipment breakdowns, and downtime, thus improving the overall value of the asset.

Fixed asset management is an umbrella term that describes the origin of the process of managing an organization's assets in every aspect (from the time they are acquired until they are disposed of).

It also maintains detailed asset records of the organization's valuable properties. The information it records is as follows:

Purchase details, inventory, maintenance schedules, upgrades, quantity, location, depreciation and usage pattern.

Asset management software integrated into the fixed asset management process helps improve visibility and control of assets.

3. Maintenance Objectives and Types

3.1 Objectives of Maintenance

1 Maintaining equipment, machines, mechanisms and buildings and keeping them in good condition throughout their lifespan.

2 Reducing the loss of life and equipment through regular periodic inspection.

3 Reducing repair and maintenance costs to the lowest possible value.

4 Increasing the level of production quality increases the reputation of the product and thus increases the demand for the service.

5 Maintaining buildings, roads and networks (i.e. electricity, water, steam networks) and installing new equipment.

6 Maintaining the general layout of the facility where new required modifications can be introduced.

7 Capital preservation.

8 Establish a timetable for maintenance of machines, mechanisms and equipment before they stop. This way, the machine can be avoided suddenly stopping and the serious loss caused by the impact of its stopping on the rest of the other production units associated with it can be avoided.

Figure 1 below shows the objectives and functions of maintenance management.

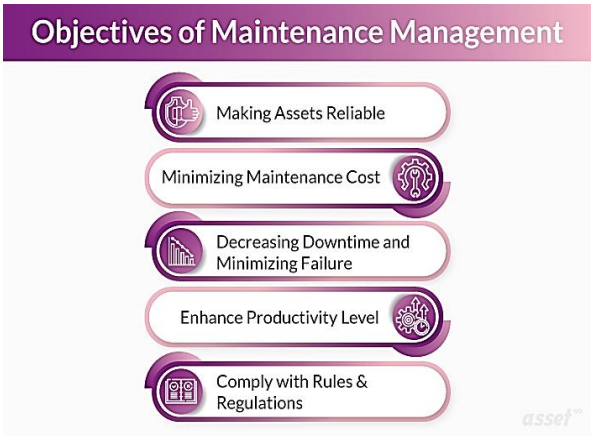

Figure 1. Objectives and Functions of Maintenance Management

3.2 Types of Maintenance

The term “industrial maintenance activities” is related to the processes directed to take care of machines in the industry. four main types are classified: corrective maintenance, preventive maintenance, predictive maintenance, and proactive maintenance. It is necessary to know about these in detail.

For effective maintenance plan, the manager must be familiar with all types of maintenance, both major and subtypes. This leads to determining the correct method for each piece of equipment. Once that decision is made, what, where, and when the maintenance plan should be executed is defined. [1], [9] and [10].

3.2.1 Preventive Maintenance

3.2.1.1 The Concept of Preventive Maintenance

Preventive maintenance is defined as a set of activities and procedures carried out by the maintenance department, with the aim of making the operational condition of machines and equipment in good and stable condition at all times while restoring them to their normal condition when they break down.

Avoiding sudden malfunctions and breakdowns, by addressing any shortcomings before they reach a state of malfunction or failure.

Which leads to obtaining high-quality production lines that conform to the required specifications of the product in terms of quantity and quality and within a reasonable cost with enhancing health and safety requirements.

A good preventive maintenance system is considered the heart of effective maintenance, as the success of the preventive maintenance program depends on achieving the least malfunctions, as well as the lowest repair costs, so it must be a kind of balance between corrective maintenance and preventive maintenance works, as preventive maintenance contributes to preventing the occurrence of malfunctions and breakdowns and discovering them before their occurrence.

Preventive maintenance occurs periodically, and according to a specific time plan, set by machine manufacturers, or by experienced technicians, taking into account reviewing and inspecting the condition of the equipment in a way that allows it to continue working without being exposed to any sudden stop. Productive maintenance is also concerned with punctuality.

3.2.1.2 The Importance of Preventive Maintenance

Preventive maintenance contributes to achieving the following:

1- **Reducing Breakdowns**: Reducing breakdowns by increasing the overall effectiveness of equipment, machines, and mechanisms, within worldly limits, ensuring the overall effectiveness of the equipment, maintaining product quality, and ensuring that outputs are within the required quantities, and at low costs, which makes production more efficient and less expensive.

2- **Good Preventive Maintenance**: Good preventive maintenance is followed to achieve consumer satisfaction and acceptance of the product, and reduce interruptions in production processes, and thus the organization's commitment to customers, in terms of transportation and delivery on time.

3- **High-Quality Products**: The quality of the product increases by conforming to the specified specifications.

4- **Avoid Sudden Malfunctions**: Continuous preventive maintenance prevents sudden malfunctions, which may lead to work stoppage.

5- Extending the Productive Life of Machines: Good maintenance ensures the use of equipment and devices for a long period, thus reducing the company's overall costs.

3.2.1.3 Preventive Maintenance Activities

Preventive maintenance activities are carried out using the following:

1- The human senses, such as smell, touch, sight, and hearing.
2- Examination or detection (inspection).
3- Installation or fixing.
4- Settings or Adjustment.
5- Cleanliness.
6- Oiling, lubrication and greasing.

Figure 2 below shows how to set a preventive maintenance plan in 5 steps.

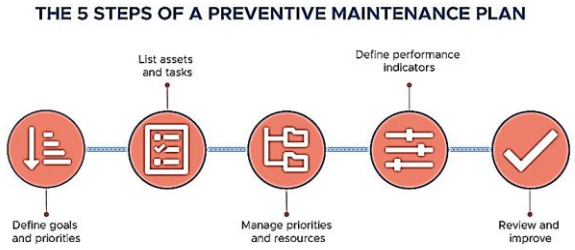

Figure 2. How to Set a Preventive Maintenance Plan in 5 Steps

The preventive maintenance plan is set up in five steps as shown below:

1- Setting goals and priorities.
2- Make a list of assets and tasks.
3- Managing priorities and resources.
4- Determine performance indicators.
5- Review and improvement.

3.2.1.4 Preventive Maintenance Goals

1. Achieving maximum operation of machines with minimum costs of facilities usage.
2. Creating suitable working conditions for all production departments and maintenance staff, by maintaining maintenance standards.

3. Developing maintenance skills through training.
4. Training workers on the machines to carry out daily maintenance work.

3.2.2 Corrective Maintenance

Corrective maintenance means efforts aimed at returning the equipment to an acceptable condition after the occurrence of a malfunction. Remedial maintenance activities refer to the detection, inspection, and replacement operations that take place on machines as a result of their stopping or breakdown. Some writers consider this type of maintenance to be unplanned maintenance.

It is also a group of operations that are carried out to repair machines according to a set time plan determined by the machine manufacturers or by experienced technicians carrying out maintenance work, in which repair operations are performed on some parts with the aim of reusing them again, such as repairing the corroded or cracked part by welding, and operations are also carried out in it. Adjusting and calibrating some parts of the machine that require this.

Remedial or corrective maintenance can be classified into two main categories: programmed or scheduled remedial maintenance, such as engine overhaul, and seasonal maintenance for industrial facilities. The second category is unprogrammed or unscheduled therapeutic maintenance, such as various repairs.

Corrective maintenance is carried out after failure occurs or when it is about to occur and is carried out by repair or replacement of components. Its disadvantages include delaying production and high financial costs, due to unplanned downtime and urgent repair costs as it is unscheduled maintenance.

Emergency corrective maintenance should be avoided, but not everything can be predicted or avoided. A balance is necessary between corrective maintenance and other maintenance types. It can be scheduled and included in the plan.

Managers must always be prepared to return equipment to its operational condition by repair or replacement downtime.

3.2.2.1 Unplanned Corrective Maintenance

Emergency" or "reactive" maintenance is a set of maintenance activities activated after a failure has occurred and is therefore classified as unplanned. It is based on the concept of machine failure that precedes corrective activity occurs in less critical equipment. According to this methodology the financial impact is minimal, allowing you to be cost-effective and continue production.

The managers should prioritize other maintenance techniques in the plan to ensure that the most important assets don't need emergency corrections. This can be realized by using tools such as condition monitoring of critical assets.

3.2.2.2 Planned Corrective Maintenance

Urgent corrective maintenance is used to solve problems that do not directly affect the full operation of the machine. Urgent or planned corrective maintenance occurs after a functional malfunction of the machine.

It is programmed kind of corrective maintenance, less expensive, safer, and faster than emergency corrective maintenance. When planning takes place, it can be applied to assets of both low and high importance.

Figure 3 below shows the two types of maintenance: preventive maintenance and curative or corrective maintenance.

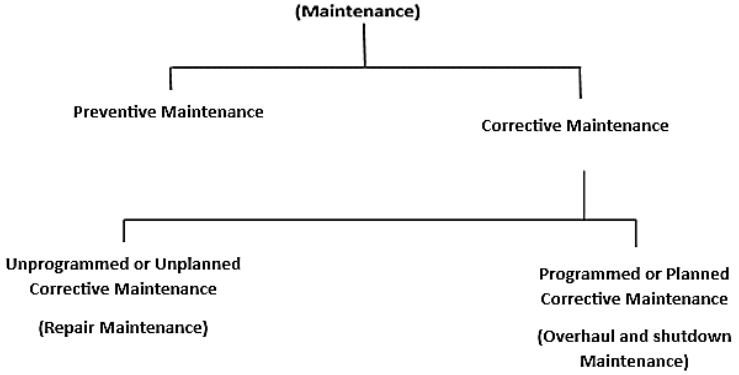

Figure 3. Types of Maintenance

3.2.2.3 Predictive Maintenance

Like the condition-based preventive maintenance, predictive maintenance is based on the current conditions of the asset. Predictive maintenance work can be classified as routine monitoring, ideally performed in real time. It can be done offline as well as online.

The objective Predictive monitoring is to reduce possible failures and equipment wear. This is done through data collection, data analysis, and the measurement of variables and performance parameters. the collected data, is then analyzed and the condition of assets is seen.

Condition monitoring software is considered as one of the most useful smart maintenance tools used with predictive maintenance.

Using these tools, managers are fully aware of what is happening inside and outside the equipment at all times. They can obtain accurate diagnoses and data to help preparation the strategic plan. Corrective and preventive maintenance activities can then be scheduled in a targeted manner that reduces downtime and improves equipment reliability.

3.2.2.4 Proactive Maintenance

It is known that a proactive maintenance strategy arises from predictive and preventive maintenance methods through collecting and analyzing machine data. The purpose is Identifying machine faults and fixing them before they turn into failures.

In the reality of machinery and mechanical systems, wear and tear are unavoidable companions, and this is where proactive maintenance comes into play by focusing on machine reliability and minimizing downtime. This helps managers delegate resources if and when necessary. The efficiency of machines and devices, extending their life and enhancing their reliability is achieved by establishing a proactive maintenance plan.

Proactive maintenance is not tied to a schedule. It targets common failures, and suggests interventions based on probabilities calculated from the analyzed data.

Figure 4 below shows the four common types of industrial maintenance.

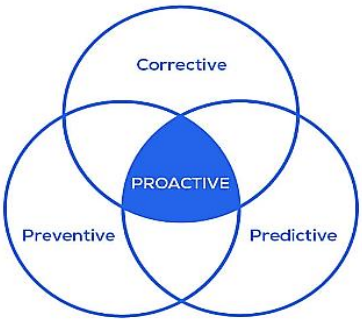

Figure 4. The Four Common Types of Industrial Maintenance

4. Organizing Maintenance Departments

Organizational design involves aligning an organization's structure, roles, processes, and culture with its strategic goals and environment. A forward-looking organizational design anticipates the organization's future needs and growth. It ensures that the structure can accommodate expansion without losing efficiency or diluting the organization's core values.

A well-designed organization inspires confidence among stakeholders including investors, customers, employees and regulatory bodies. It demonstrates the organization's commitment to effective governance and sustainable growth.

One of the key decisions in this design process is whether to adopt a centralized or decentralized approach. These two approaches define how decision-making authority and communication flow within an organization [1] and [2] – [5].

4.1 Centralized Organization

The process of centralizing activities related to planning and decision-making within an organization to a specific leader or location, is known as centralization. In a centralized organization, in the head office the decision-making powers are kept and all other offices receive directions from this office and accordingly communications flow from top to bottom. On the other hand, the process of enabling teams and departments to make decisions and enhance communication in all directions is known as decentralization.

Many businesses in rapidly changing technological environments have a centralized form of management structure. Decentralization on the other hand may be

effective in businesses that need individualized customer service, usually at the point of contact with customers or who have different business locations.

In the centralized institutions, all employees with their various specializations are in one department and are directed to the work area as needed.

4.1.1 Advantages of Centralized Organization

1. Exploiting the workforce by diversifying experiences and directing them as needed (i.e. the comprehensive labor).

2. Reducing maintenance expenses (i.e. performing the work with a small number of workers).

3. Familiarity of workers with maintaining machines in different departments.

4. Clarity of chain of command: Efficient decision-making in the presence of a simplified and well-defined hierarchy. When Everyone in the organization has questions, knows who to contact and report. This clarity ensures quick responses to employee concerns. Delegate authority to successful employees in specific positions is based on a plan followed by senior executives. Executives gain the confidence that comes from non-overlapping when delegating responsibilities to mid-level managers and other employees. The usefulness of a clear chain of command arises when the organization tends to implement decisions quickly and in a uniform manner.

5. Focused vision: Centralized management provides a clear direction for presenting and communicating the organization's vision, and messages are communicated coherently across clear lines of authority. These lines are activated by senior executives to communicate the organization's vision to employees and guide them towards achieving that vision.

6. Reducing costs: Reducing office and administrative costs is achieved by the centralized organization adopting standard procedures and methods, and accordingly, both administrative costs and operational expenses are reduced. The organization does not have to incur additional costs for hiring specialists for other parts of the organization as critical decisions are taken at the head office and then communicated outwards. Reducing duplication of responsibilities that lead to additional costs for the organization is achieved through a clear chain of command.

7. Quick Implementation: A centralized structure allows for faster decision making from the top since decisions are made by a small group of people and then communicated to the lower-level managers. The involvement of only a few people makes the decision-making process more efficient since they can discuss the details of each decision in one meeting.

8. Improved Quality of Work: The standardized procedures and better supervision in a centralized organization result in improved quality of work. Supervisors in each department ensure that the work outputs are uniform and of high quality.

4.1.2 Disadvantages or Limitations of Centralized Organization

1. The length of the communication line between the production and maintenance department and between the maintenance workers and the maintenance department.

2. Increase in wasted time for machinery and labor (i.e. movement of maintenance workers from the workshop to the maintenance area and vice versa).

3. Difficulty in monitoring (i.e. workers being away from management and changing work sites from time to time).

4. Bureaucratic Leadership: As decision making is restricted to individuals at the headquarters level, employees are unable to contribute to the decision-making process of the organization, and they are merely implementers of decisions made at a higher level. This lacks involvement in shaping decisions results in a loss of creativity, reduced performance, and motivation. Furthermore, when the employees face difficulties in implementing some of the decisions, senior executives will not

understand because they are only decision makers and not implementers of the decisions.

5. Remote Control: The organization's executives are under significant pressure to formulate decisions for the organization and they lack control over the implementation process leading to inefficiencies. The failure of senior managers to decentralize the decision-making process contributes significantly to their workload.

6. Delays in Work: Centralized communication may lead to productivity losses as employees rely on information flowing to them from the top to guide project implementation. This means that the employees will be less productive if they need to wait long periods to get guidance on their next task.

7. Lack of Employee Loyalty: Employees become loyal to an organization when they are allowed initiative in the work they do. Employee loyalty can decline in a centralized structure as their limited autonomy stifles creativity and loyalty due to the rigidity of the work.

4.2 Decentralized Organization

Maintenance workers are divided into different production departments, with each team carrying out the necessary work in the specific production department. This organization usually exists in large institutions, distributed over geographical areas, or with specific specializations, such as the Sudan Railways Authority, river transport, maritime transport, and land transport companies.

4.2.1 Advantages of Decentralized Organization

1. Ease of monitoring workers.

2. Reducing the wasted time of machines (i.e. speed of response to maintenance and repair).

3. Strengthening the relationship between maintenance department workers and production department workers.

4. Deepening knowledge in specific machines (i.e. precise specializations in specific machines and equipment).

4.2.2 Limitations of Decentralized Organization

1. Increasing the number of employees (i.e. resulting from the availability of different specializations in each department).

2. Disabling a large portion of workers' energy (i.e. not utilizing their time fully).

3. Decline in workers' familiarity with general-purpose and special-purpose machines in other departments.

4. Increased maintenance costs due to the reasons mentioned above.

4.3 Key Factors Influencing the Choice between Centralization and Decentralization

Several factors must be considered when deciding between centralization and decentralization. These factors include: Strategy and Vision, Size and Complexity, Culture and Values, Technology and Systems, People and Skills, and External Environment.

Figure 5 below shows the fundamental differences in organizational structure between centralized organization and decentralized organization.

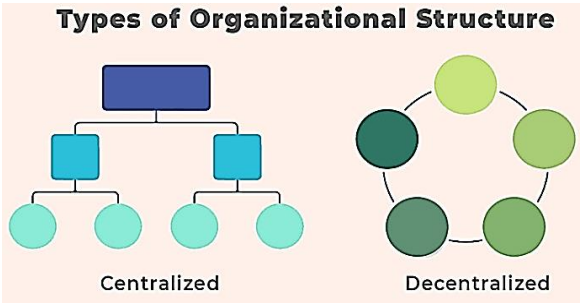

Figure 5. The Fundamental Differences in Organizational Structure between Centralized Organization and Decentralized Organization

4.3.1 Strategy and Vision

The organization's strategy and vision play a key role as centralization may be preferable for organizations with clear and stable strategies and environments, while decentralization suits those that value innovation and operate in unpredictable contexts. Decentralization can also provide some advantages for managing change such as increased flexibility and responsiveness to customer needs and market conditions.

4.3.2 Size and Complexity

The extent of an organization's scope, structure, and interdependence influences this decision as smaller, focused organizations might find efficiency in centralization, while larger and complex ones might benefit from decentralized flexibility.

4.3.3 Culture and Values

Centralization aligns with cultures that embrace a hierarchical, conformity-focused approach, whereas decentralized organizations align more closely with those valuing autonomy and collaboration.

4.3.4 Technology and Systems

Technology's role in facilitating communication and coordination, influences the choice. For example, centralization thrives where streamlined data supports central planning and monitoring, reducing uncertainty and risk, whereas a decentralized approach benefits from technology and systems that provide diverse data that supports decentralized experimentation and feedback.

4.3.5 People and Skills

The nature of the organization's workforce matters and centralization is more aligned to an organization where the roles and skills are specialized and standardized, following clear procedures, whereas a decentralized approach may be better suited to a generalist workforce that perform complex and creative tasks that adapt to changing and ambiguous situations.

4.3.6 External Environment

The external environment that the organization operates will influence the decision. Centralization works more effectively with stable environments, while decentralization adapts well to a dynamic environment.

Choosing between centralization and decentralization requires a deep understanding of an organization's strategy, size, culture, technology, employee engagement, external environment and the evolving nature of work.

Recognizing the advantages and disadvantages of each approach allows organizations to shape their decision to their unique context and objectives.

A well-informed choice in organizational design can lead to effective communication, streamlining decision making, and drive efficiency, innovation, and growth, leading to long-term success.

5. Typical Difficulties Organizations Encounter when Establishing a Preventive Maintenance Program, and Steps for Overcoming Maintenance Challenges

5.1 The Most Common Challenges Organizations Face When Implementing a Preventive Maintenance Program

Organizations often face several obstacles when implementing preventive maintenance (PM) programs. Key issues include:

5.1.1 Misguided Operational Focus

Operations often delay maintenance to avoid downtime, leading to more costly repairs later.

5.1.2 Lack of Schedule and Structure

Maintenance tasks may lack clear instructions, resulting in ineffective, superficial maintenance checks.

5.1.3 Reactive Routines

Over-scheduling maintenance due to past failures can lead to unnecessary work and future complications.

5.1.4 Lack of Cohesiveness

Isolated maintenance strategies can waste resources and create inconsistencies in managing similar assets.

5.1.5 Overreliance on Past Experience

Using outdated methods instead of data-driven approaches can lead to mismanagement of maintenance tasks.

5.1.6 Inadequate Task Instructions

Poor documentation can result in improperly executed maintenance tasks, worsening over time as knowledge leaves the team.

5.1.7 Neglect of Certain Failures

High-impact failures that occur less frequently may be overlooked in favor of daily maintenance tasks.

5.1.8 Assumptions About New Equipment

New equipment isn't immune to failure; teams should anticipate potential issues based on past data.

5.1.9 Doing What We Can Instead of What We Should

Maintenance teams may prioritize tasks based on skills rather than equipment needs.

5.1.10 Missing Improvement Opportunities

Without regular reviews of completed tasks, the quality of maintenance can decline, along with equipment reliability.

5.2 Steps for Overcoming Maintenance Challenges

To enhance the reliability and maintainability of assets, maintenance teams can employ a structured approach:

5.2.1 Upgrade Reliability and Maintainability

Collaborate with production management to identify critical equipment and develop plans for upgrades, ensuring consistent execution of maintenance tasks.

5.2.2 Utilize Simple Metrics

Implement effectiveness metrics to track PM compliance against equipment failure rates, establishing a baseline for improvements.

5.2.3 Implement Maintenance Dashboards

Create dashboards that allow real-time monitoring of KPIs to assess performance and effectiveness, similar to vehicle gauges.

5.2.4 Create a Plant Scoreboard

Display key metrics such as PM compliance and overall equipment effectiveness in visible areas throughout the plant for continuous awareness and improvement.

By following these steps and asking critical questions, maintenance teams can improve the reliability of their assets and streamline their processes [11] and [12].

6. Evaluating the Effectiveness of Maintenance Management Strategies

The effectiveness of maintenance management strategies can be assessed through Key Performance Indicators (KPIs), which are essential for measuring maintenance outcomes. KPIs help maintenance and reliability teams analyze routines, processes, and equipment, offering insights into operational capabilities.

By prioritizing the most relevant KPIs, teams can avoid less impactful metrics and enhance production efficiency. Key maintenance KPIs include [13], [14] and [15].

6.1 Mean Time Between Failures (MTBF)

Measures equipment reliability by evaluating the average operating time between failures.

6.2 Mean Time to Repair (MTTR)

Gauges the efficiency of repair efforts by capturing the average time needed to fix equipment.

6.3 Availability

Assesses an item’s ability to perform its designated function at specified times.

6.4 Reliability

Indicates the likelihood of equipment performing under specified conditions over time.

6.5 Backlog

Reflects the labor time required for pending maintenance tasks, indicating service demand versus capacity.

6.6 Machine Downtime

Tracks unplanned outages, which can lead to production losses and increased costs.

6.7 Maintenance Cost as a Percentage of Estimated Replacement Value (MC/ERV)

This financial metric evaluates the cost-effectiveness of maintaining versus replacing equipment.

6.8 Distribution by Maintenance Types

Displays the proportion of each maintenance type, with a goal of keeping unplanned maintenance below 20% to maintain efficiency.

By focusing on these KPIs, organizations can refine their maintenance strategies and boost operational performance.

7. Maintenance Training Programs

Maintenance training programs are designed to equip personnel with the skills necessary for the effective maintenance and repair of essential organizational assets and equipment. These programs help bridge the skills gap for technicians by enhancing their knowledge of company-specific systems.

7.1 Key Components of a Maintenance Training Program

7.1.1 Safety Training

Educates staff about workplace safety and injury prevention.

7.1.2 Technical Skill Development

Enhances understanding of the facility's equipment.

7.1.3 Problem-Solving Skills

Develops troubleshooting techniques and resourcefulness.

7.1.4 On-the-Job Training

Provides practical experience with equipment in a controlled setting.

7.1.5 Learning New Technologies

Ensures staff are current with new equipment and technologies.

7.2 Developing a Maintenance Training Plan

Organizations may need to create tailored training programs due to specific requirements or lack of access to third-party training. Key steps include:

7.2.1 Assess Training Needs

Identify skill gaps and training requirements specific to technician roles.

7.2.2 Define Learning Objectives

Customize goals to address unique organizational challenges.

7.2.3 Develop Training Content

Create tailored materials and instructional resources for various topics.

7.2.4 Determine Training Methods

Choose effective delivery methods based on content and objectives.

7.2.5 Implement Training Program

Schedule sessions to minimize operational disruption.

7.3 Establishing a Strong Maintenance Training Program

Incorporating best practices can lead to effective maintenance departments and reduced equipment downtime. Key strategies include:

7.3.1 Establish a Training Schedule

Plan training around operational needs and employee availability.

7.3.2 Select Competent Trainers

Use skilled staff to deliver training effectively.

7.3.3 Implement Assessments

Measure training effectiveness through tests and interactive methods.

7.3.4 Invest in Technology

Utilize IT tools for enhanced training and assessment capabilities.

7.3.5 Evaluate Training Outcomes

Regularly refine the program based on feedback and changing needs to ensure it remains challenging yet attainable.

By following these guidelines, organizations can successfully develop and implement comprehensive maintenance training programs, leading to improved performance and efficiency within their maintenance teams [16], [17] and [18].

8. The Future Trends in Maintenance Management

The future of maintenance management is poised for significant changes driven by automation, remote monitoring, and artificial intelligence (AI). Key trends shaping this evolution include:

8.1 Predictive Maintenance

The use of IoT sensors and machine learning will lead to more effective real-time data collection, allowing organizations to perform maintenance as needed, thereby extending equipment lifespan and minimizing unnecessary repairs.

8.2 AI and Machine Learning Adoption

These technologies will automate maintenance scheduling and task management, enhancing data analysis for better decision-making and identifying failure causes, making the handling of extensive equipment data more efficient.

8.3 Augmented Reality (AR) in Training

AR will enhance technicians' training and troubleshooting by visualizing complex systems and providing real-time guidance, which is especially beneficial for novice workers, thereby reducing downtime.

8.4 Advanced CMMS and EAM Systems

There will be an increased demand for comprehensive management platforms that integrate advanced technologies like AI and IoT, shifting from basic scheduling to complete asset management solutions.

8.5 Sustainability Focus

Maintenance practices will prioritize eco-friendly strategies aimed at reducing energy use, minimizing waste, and prolonging asset life, leading to both environmental benefits and cost savings.

8.6 Enhanced Safety

The integration of AI will facilitate the use of robots and drones for maintenance tasks in hazardous environments, improving task efficiency and worker safety.

8.7 Cybersecurity in Maintenance

As more systems become interconnected, it will be crucial to incorporate cybersecurity measures to protect against vulnerabilities and potential cyberattacks.

8.8 Proactive Decision-Making

Advances in data collection and analytics will allow for proactive maintenance strategies, enabling organizations to anticipate failures and improve overall machinery performance while lowering costs.

8.9 Evolving Workforce Skills

With the shift towards digital technologies, maintenance roles will become more analytical and tech-driven, necessitating training to prepare technicians for new systems and to address the gap left by retiring experts. Maintenance will continue to evolve, with automation, remote monitoring, and AI playing key roles in driving these transformations. Refer to references [19], [20] and [21].

9. Enhancing Productivity and OEE through Production and Maintenance Collaboration

In today's competitive and low-margin manufacturing landscape, effective collaboration between production and maintenance teams is crucial for optimizing operations, minimizing downtime, and enhancing productivity and overall equipment effectiveness (OEE). It is essential to create efficient communication channels that allow operators to report issues promptly, which could otherwise result in downtime. Meanwhile, well-defined work orders that

include insights into potential root causes allow maintenance teams to respond swiftly.

Here, we outline key strategies to strengthen the collaboration between production and maintenance and how this partnership can lead to significant improvements in productivity and OEE [22], [23] and [24]:

9.1 Optimizing Time Efficiency

Strong collaboration between maintenance and production can yield substantial time savings. By assigning preventive tasks such as lubrication and cleaning to production operators, maintenance teams can allocate more time to complex repairs and proactive maintenance. This forward-thinking strategy reduces unplanned breakdowns, maximizes machine uptime, boosts overall production output, and enhances OEE availability.

9.2 Enhancing Equipment Knowledge

Regular conversations with the maintenance team provide production staff with a deeper insight into the equipment they operate, increasing their awareness of potential equipment failures. This enhanced understanding helps them supply more precise descriptions in work orders regarding possible root causes. Greater awareness results in more comprehensive job descriptions, quicker troubleshooting, and improved machine performance.

9.3 Streamlining Communication through a Common Language

Sharing a common terminology between production and maintenance enhances communication clarity and efficiency. By breaking down silos, both teams can clearly identify problems and collaboratively discuss solutions. This mutual understanding cultivates a collective "we're in this together" mindset, with a shared focus on maximizing asset reliability and production output, which positively influences OEE quality.

9.4 Emphasizing Preventive Maintenance

Insights that production offers to maintenance drive a strategic transition towards preventive maintenance practices. This proactive stance helps reduce unexpected breakdowns and their disruptive effects on production. Working within a unified system allows production to gain visibility into scheduled maintenance, facilitating greater flexibility for operations to adapt around planned downtime, thus minimizing disruptions that adversely affect OEE.

9.5 Optimizing Resource Allocation

Collaboration between production and maintenance enables strategic resource management. With an understanding of production priorities, maintenance can plan critical tasks around peak production times, reducing disruptions and optimizing output. An integrated maintenance system further enhances this process by providing real-time visibility and facilitating data-driven decision-making.

10. Classification of Industrial Equipment

Industrial equipment can be classified into two main categories as shown in the narrative below:

A general-purpose machine is designed to perform a wide range of tasks or functions, such as a personal computer or a smartphone. It is versatile and can be used for various applications.

On the other hand, a special-purpose machine is designed for a specific task or set of tasks. It is optimized to perform a particular function with high efficiency and often has limited or no capability to perform other tasks. Examples of special-purpose machines include industrial robots for specific assembly tasks or dedicated machines for specific manufacturing processes.

In summary, the main difference lies in the range of tasks they can perform, with general-purpose machines being versatile and special-purpose machines being optimized for specific functions [1], [10], and [25].

10.1 General-Purpose Machines

Features and Specifications of General-Purpose Machines (Advantages and Limitations of General-Purpose Machines):

1. Performing multiple functions instead of one specific function (Versatile Machines).

2. Its operation requires individuals with a high degree of skill and talent to perform the necessary adjustments in accordance with the specifications required in production.

3. They work more slowly than special-purpose machines and their production capacity is lower, so the cost of the unit produced with them is greater than the cost of the unit produced with specialized machines.

4. It requires careful examination and inspection while the worker or technician is performing his work.

5. They can continue to be used in production even in the event of a change or modification in the design of the products.

6. They can always be disposed of by selling them as used machines at reasonable prices.

7. Its design is not complicated; therefore, its repair and maintenance costs are not large, and its spare parts are always available at reasonable prices.

Figure 6 below shows some general-purpose machines.

Figure 6. Some General-Purpose Machines

10.2 Special Purpose Machines

This type of machine is designed to perform specific industrial operations faster, more accurately, and at a lower cost than general-purpose machines. It requires a small number of people to operate it and performs most operations automatically without significant intervention on the part of the worker or technician.

Features and Specifications of Special-Purpose Machines (Advantages and Limitations of Special Purpose Machines):

1. Larger in size than general-purpose machines.

2. It performs the work with high precision and does not require careful inspection of production.

3. Purchase and operating costs are greater than general-purpose machines.

4. It is only used to perform one purpose.

5. Repairing and maintaining them requires great technical expertise and huge repair costs.

6. Due to technological progress in maintenance, its design changes rapidly, which requires changing the used machine with a newer one to keep pace with the production of competing companies, even though the current machine may be usable.

Figure 7 below shows a special-purpose machine used for the purpose of material handling.

Figure 7. a Special-Purpose Machine used for the Purpose of Material Handling

10.3 Replacement of Machines

Changing machines may be necessary for the following reasons:

1. Obtaining abundant and economical production.
2. Obtaining high accuracy of products.
3. Reducing the cost of production to the minimum possible.

10.4 Policies followed during Replacement of Machines

1 It depends on the expected, productive or economic life.

2 The machine must be changed if it has been in use for ten years or more.

3 The change is made based on a comparison between continuing to use the old machine or purchasing a new machine, and the comparison element is often the cost.

10.5 Meaning of Costs

I. Investment capital (i.e. the purchase price of machinery, equipment and machines).

II. Operating costs include direct and indirect labor, raw materials, energy used, maintenance and repair operations, insurance premiums, interest on invested capital, annual depreciation, and the remaining value after the end of the expected life.

1. According to the available space in the factory.
2. The number and quality of skilled workers required.
3. The suitability of safety devices on the machine to protect workers from industrial accidents.
4. Modern equipment and facilities are available with the machine.
5. The warranty period allowed by the supplier or agent.
6. Viewpoints of supervisors and workers on the machine.
7. The period it takes to train on the new machine.
8. Abundance of spare parts.

11. Organizing Maintenance Equipment

11.1 Maintenance Programming

1. It is considered one of the most important means of reducing costs due to the possibility of carrying out various maintenance activities at the appropriate times.
2. Despite the importance of programming maintenance work, it cannot be applied to all machines and equipment in the designated facility, especially machines that are quickly consumed and old, and machines that do not fully utilize their capacity and do not cause significant damage if they stop for reasonable periods.

11.2 Planning Preventive Maintenance

When planning preventive maintenance, the organization must make an inventory of all machines and equipment and classify them according to the following principles:(Figure 8 below shows the classification of maintenance resource planning and task programming) [1].

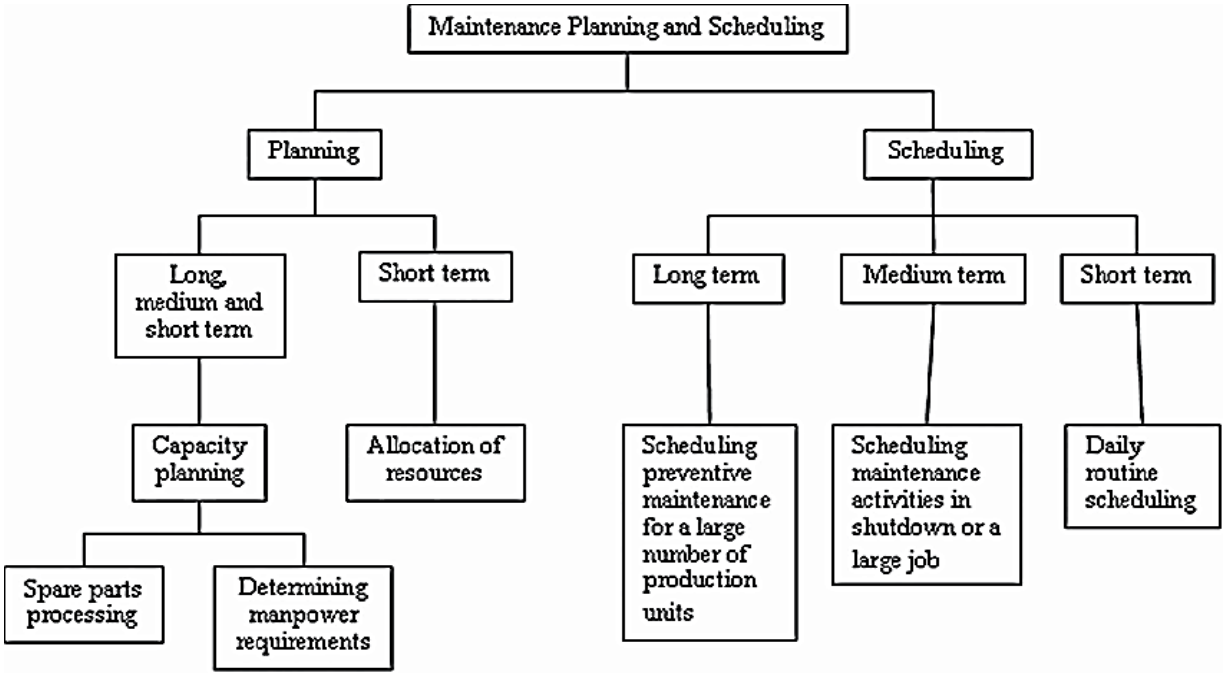

Figure 8. the Classification of Maintenance Resource Planning and Task Programming

12. Industrial Safety and Security

The Sudanese Health Insurance Law of 1990 stipulates that an employer who employs a number of workers reaching 30 must appoint an industrial security officer, and if the number exceeds that, an industrial security committee or department must be formed [1], and [25] – [29].

12.1 Importance of Industrial Security and Safety

The importance of industrial security is focused on three main axes:

1. Maintaining the facility and the safety of its machinery and equipment.
2. Maintaining a healthy work environment and preventing air, soil or water pollution.
3. Taking care of and preserving the worker's physical, psychological, and social safety and avoiding risks from him, especially those related to organic injury or occupational diseases. By achieving this, we guarantee the safety of the facility and push the worker to increase effort and production.

12.2 The Objective of the Industrial Security Law

1. Creating healthy and safe working conditions free from the causes of accidents, all injuries, and all occupational diseases, and informing workers of the dangers of the profession.
2. Regular, programmed and unplanned presence at work sites to ensure that the work complies with safety rules.
3. Guidance and warning of the risks to which workers are exposed to protect them from accidents, injuries, and occupational diseases.
4. Monitoring improper conditions and behavior that lead to accidents and losses at work sites.
5. Guiding and training workers on the correct methods to protect them, protect production components, monitor the environment and its cleanliness, and provide health services to workers.

12.3 The Role of Industrial Security and its Relation with Production

The role of industrial security lies in preserving the components of production, which are as follows:

12.3.1 The Human Element

Preparing the human elements of work and avoiding environmental risks that hinder its performance, which are:

1. Exposure to high levels of heat, cold, and humidity.
2. Exposure to noise.
3. Strong or weak lighting.
4. Preparing safe eating and drinking places.
5. Preparing bathrooms and toilets.
6. Wages are proportionate to the mental and physical effort of the worker.

12.3.2 Machines and Equipment

Inspecting the necessary equipment for the safety of machinery and equipment, such as firefighting equipment and water pipes, keeping flammable goods in safe places, and creating barriers to cover machine belts and dangerous places on sidewalks, etc. Installing warning posters and educating workers about the dangers of moving vehicles.

12.3.3 Raw Materials and Goods

Ensure that goods are stored in the proper manner so that they are not vulnerable to fire, getting wet, or falling and being damaged. Preserving every type of goods in the appropriate places designated for them, such as fertilizers, chemicals, pesticides, etc., so that they do not cause damage or injury to buildings or workers.

12.3.4 Awareness or Enlightenment and Training

Developing preventive awareness among workers by having industrial security informs the worker of the dangers of his work. This is done through:

1. Symposiums, forums, workshops, lectures, and developing instructions on risks in all lines of work.

2. Training some employees in the various departments on safety and industrial security sciences as trainers to create a nucleus for new supervisors.

12.3.5 Guidance Inspection and Preventive Procedures

1 Conduct successive field visits to all units in workshops, warehouses, and workers' residences to ensure safety procedures for machinery and workers, and to inspect drinking water and washing places, bathrooms and cafeterias to ensure their cleanliness and safety.

2 Focus on areas that lead to pollution of the work environment, including dust, fumes, and chemicals (i.e. cement factories, grain mills, engine maintenance workshops, etc.) and work to reduce this damage and remove its causes in coordination with the Occupational Health Department to conduct periodic checks on workers and their work environment for early detection and prevention of occupational diseases (i.e. such as asthma, pulmonary tuberculosis, cancer, etc.).

12.4 Work or Industry Injuries

Minor or serious injuries usually occur to industry workers as a result of their handling of machines, engines, and heavy machinery during maintenance or operating operations.

Cost due to Injuries:

I. Direct Cost:

1. The cost of treating the injured person.
2. The injured person's wages during his absence from work.
3. The injured person's benefits in light of the outcome of the injury.
4. Loss resulting directly from damage to materials and machinery as a result of the accident.

II. Indirect Cost:

Production stopped at the time of the accident in order to:

1. Help or aid the injured person.

2. Gathering for curiosity.

3. The spread of panic among workers who perform the same or similar work.

4. Appointing and training a replacement worker for the injured person so that he can perform the work with the same efficiency as the injured worker.

5. The wages of the persons entrusted with aiding and treating the injured person, such as doctors, supervisors, and the like.

12.5 Industrial Safety Requirements

Taking the necessary precautions to protect workers from health risks and work hazards.

1. Conducting accurate medical examinations on workers who work in professions that inherently contain dangers that threaten the health of the worker, such as casting factories, spinning and weaving, blacksmithing, plumbing, etc., while conducting periodic medical examinations on them.

2. Notifying the competent authorities about cases, work injuries, occupational diseases, and the number of suspected cases.

3. Providing health prevention and safety conditions in the workplace while adjusting the work environment to a level appropriate to the health of workers.

4. Taking precautionary measures against accidents in terms of installing safety and security devices in production machines or during maintenance operations for machines, buildings, etc.

12.6 Duties and Functions of the Industrial Security Officer

1. Periodic inspection (i.e. daily, weekly, monthly and yearly) of work sites and recording notes in the status textbook.
2. Providing injury-protective devices and tools, such as masks, earplugs, industrial shoes, head helmets, welding glasses, etc.
3. Monitor the use of protective clothing in the correct manner and its suitability to the work.
4. Contact the Labor and Occupational Health Office regarding injuries and accidents.
5. Counting injuries and accidents and submitting monthly reports on their type.
6. Working as a rapporteur for the accidents and injuries committees in the various departments.
7. Working to improve the natural working conditions related to places, such as lighting, ventilation, and noise.
8. Make signs, posters, advertisements, and warnings in all locations where he sees dangers.
9. Ensure the availability of first aid boxes at all work sites, review their medication contents, and determine what medications must be available in them, or provide a medical dispensary within the work site in the case of large institutions or companies that accommodate large numbers of workers.
10. Review and ensure that all fire extinguishers are maintained and placed in their appropriate places.
11. Issuing leaflets and booklets on industrial security to intensify industrial awareness.

Figure 9 below shows some of the industrial safety equipment required in industrial facilities. This equipment includes industrial shoes, head helmets, earplugs, masks, welding goggles, thermally and electrically insulated fastening and loosening tools, and other injury-preventive devices and tools.

Figure 9. Some of the Industrial Safety Equipment Required in Industrial Facilities

13. The Development of Maintenance Management in Saudi Arabia

The maintenance management framework in Saudi Arabia has significantly evolved over recent decades due to rapid industrial growth and modernization. Previously reliant on reactive maintenance, the region has shifted towards more effective proactive strategies, particularly in the oil, gas, petrochemical, and construction sectors. Since the early 2000s, integrated asset management systems have transformed practices, fostering preventive and predictive maintenance approaches to minimize downtime and enhance asset longevity. Technological advancements, including computerized maintenance management systems (CMMS) and condition-monitoring tools, have supported sophisticated maintenance planning. Staff training has become crucial for the implementation of these systems. The Saudi Vision 2030 initiative further emphasizes modernizing maintenance management across industries by diversifying the economy and investing in smart technologies, thereby aiming for a robust maintenance framework that prioritizes safety and efficiency [30] and [31].

14. Conclusions

The paper underscores the crucial role of efficient maintenance management in improving productivity and safety in industrial settings. In a competitive market, organizations need to optimize machine performance to minimize downtime, thereby enhancing output and profitability while also boosting employee morale through effective maintenance practices.

Historically, maintenance was reactive, primarily addressing equipment failures, which sufficed in pre-industrial scenarios. However, the Industrial

Revolution demanded more organized maintenance due to steam engine hazards, leading to safety organizations' formation. As manufacturing grew more intricate, preventive maintenance (PM) emerged to proactively tackle potential failures, gaining traction in early factories like those of Henry Ford.

World War II further emphasized the need for maintenance, resulting in the development of various improvement strategies. In Japan, Total Productive Maintenance (TPM) was introduced, focusing on the responsibility of operators in machinery upkeep. The 1960s saw the rise of predictive maintenance, leveraging data analytics to anticipate issues and streamline repair schedules.

Maintenance engineers play a pivotal role in boosting system efficiency and reliability through strategic upgrades across various sectors, including manufacturing and energy. Key objectives of maintenance management include reducing idle time from equipment failures, lowering repair costs and duration, and optimizing the use of maintenance resources.

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