Exploring Innovative Total Productive Maintenance [TPM] Approaches to Drive Productivity in Construction Process Plants

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Abstract:

Total Productive Maintenance (TPM) has traditionally played a vital role in enhancing equipment performance and minimizing downtime in industrial environments. As construction process plants face heightened demands for greater productivity and cost-efficiency, conventional TPM methods must adapt to new challenges. This paper investigates the latest advancements in TPM aimed at improving productivity within construction process plants by incorporating state-of-the-art technologies and methodologies. The study delves into the integration of predictive and condition-based maintenance, automation, data analytics, and augmented reality as key components in modernizing maintenance strategies. These innovative approaches promise considerable benefits, such as reduced operational interruptions, prolonged equipment life, cost reductions, and increased workforce efficiency. Through practical case studies and real-world examples, this research demonstrates the successful application of these innovative TPM strategies in construction plant environments. Additionally, the paper addresses the obstacles associated with adopting these new technologies and offers solutions to facilitate their integration into existing maintenance frameworks. In providing an in-depth analysis of contemporary TPM practices, the study offers valuable perspectives for plant managers, maintenance teams, and researchers striving to enhance the operational efficiency of construction process plants. Ultimately, it stresses the importance of adopting a forward-thinking, data-driven maintenance approach that aligns with the evolving demands of the construction industry.

Keywords: Construction plants, innovative techniques, construction industry, automation, process utilization, TPM method

INTRODUCTION

1. Introduction to Total Productive Maintenance (TPM)

- **Overview of TPM**: TPM is a comprehensive approach to improving the productivity of manufacturing plants by focusing on proactive and preventive maintenance. Its goal is to maximize equipment effectiveness and minimize downtime, breakdowns, and defects.

- **Importance of TPM in Construction Process Plants**: Construction process plants (such as batching plants, cement factories, asphalt plants, etc.) rely heavily on machinery and equipment for smooth operation. TPM helps reduce unexpected breakdowns and maintain steady operations in these plants, which directly impacts productivity [1] [2].
- **Need for Innovative Approaches**: Traditional TPM practices may need to be adapted or innovated to meet the specific demands and challenges of construction process plants, which often operate in harsh environments and under tight project schedules [8] [9] [10].

2. Challenges in Construction Process Plants

- **Harsh Operational Environments**: Construction plants often face extreme conditions (dust, heavy loads, extreme temperatures) that lead to wear and tear on equipment, causing more frequent breakdowns.
- **High-Cost Implications of Downtime**: In construction, downtime in plant machinery can significantly delay project timelines and increase costs. Even short delays can cascade into broader inefficiencies [3][4].
- **Skilled Labor Shortage**: There is often a shortage of skilled workers who can effectively operate and maintain complex machinery in construction process plants, making it harder to implement effective TPM.
- **Complexity of Equipment**: Construction process plants use various types of machinery that often require different maintenance strategies, making it difficult to apply uniform TPM practices [5].

Figure 1. Construction equipment

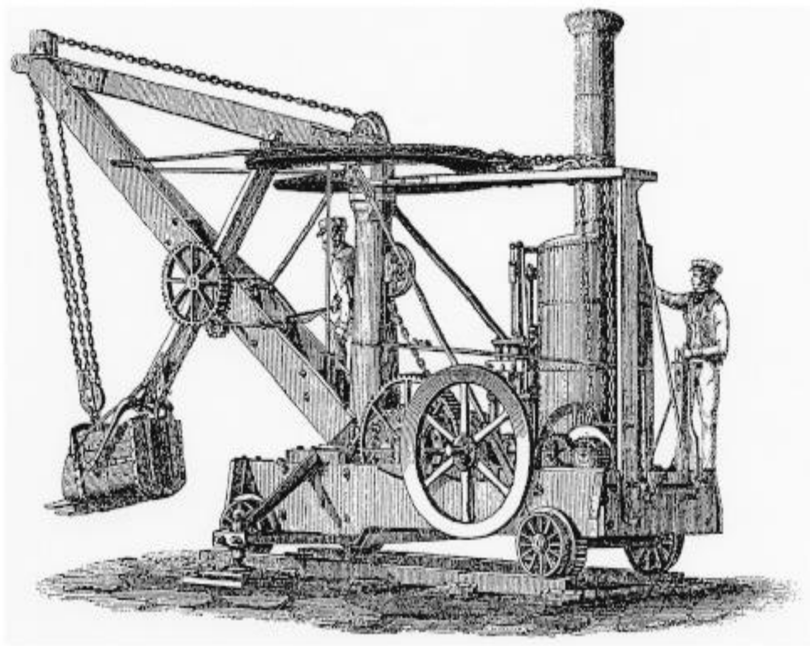

Figure 2. The Otis steam shovel; this machine was mounted on steel wheels that ran on rails

Machines serve as mechanical or electrical systems designed to enhance human energy and improve control over various tasks. In the present era, many machines are equipped with on-board computers that process information instantaneously and automate numerous operational functions [6][7]. These modern machines have become essential resources for efficiently completing most construction projects (see Figure 1). One prominent challenge in construction projects involves transporting heavy materials, and machines offer a viable solution. The success of a project planner can be measured by the financial outcome when the contract is fulfilled. Did the company achieve a profit or incur a loss?

Throughout history, construction projects were predominantly carried out using human and animal muscle power. From simple structures built for protection from the elements to grand endeavors like the Egyptian pyramids and the extensive Inca road system spanning 25,000 miles, the hard labor of humans and animals was the primary force behind construction activities [8] [9]. The legendary figure of John Henry, known for his incredible strength and hammering skills, exemplifies the manual labor involved in construction during those times.

Advancements in construction equipment coincided with significant changes in transportation methods. In regions where water systems were crucial for travel and commerce, builders envisioned machines capable of dredging ports, rivers, and canals to facilitate navigation. As early as 1420, the Venetian engineer Giovanni Fontana conceived and sketched designs for dredging machines [10]. Leonardo da Vinci, in 1503, also developed plans for such a machine, and one of his designs was even brought to life, though powered solely by a person running on a treadmill. These early attempts at machine development laid the foundation for the sophisticated construction machinery we have today [11].

In 1793, a group of individuals in Massachusetts united to undertake the construction of the Middlesex Canal, a 27-mile waterway connecting the Merrimack River to Boston. After years of effort, the canal finally began carrying water in December 1803. Subsequently, on July 4, 1817, groundbreaking took place near Rome, New York, for the momentous Erie Canal, stretching 363 miles in length. The construction of the Erie Canal, like its predecessor, relied on the labor of local workers and Irish immigrants [12]. However, by the 1830s, the landscape of construction in the United States underwent a transformation, shifting from canal development to railroad construction. The Middlesex Canal's economic life spanned only 32 years, as it ceased operations in 1835 when the Boston & Lowell Railroad, one of the country's earliest railroads, commenced its services. Despite this change, construction endeavors, whether involving canals or railroads, still primarily relied on the physical strength of humans and animals to accomplish the tasks (see Figure 2).

The Challenges can be further refined as follows:

Construction process plants, such as manufacturing facilities, assembly lines, and prefabrication units, play a crucial role in the construction industry by producing components, materials, and structures needed for construction projects. However, these process plants often encounter challenges that hinder their productivity, resulting in inefficiencies and setbacks throughout the construction process [13] [14] [15].

Some of the key problems faced by construction process plants include:

1) Outdated and inefficient practices: Many process plants still rely on traditional construction methods and techniques that are time-consuming, labor-intensive, and prone to errors. These practices limit the overall productivity and hinder the timely completion of construction projects.
2) Lack of automation and technological integration: The use of advanced technologies, such as robotics, automation, and digitalization, remains limited in many construction process plants. This lack of integration hampers efficiency, slows down production processes, and prevents the full realization of productivity gains.
3) Inadequate workforce training and skill development: The productivity of construction process plants heavily depends on the skills and expertise of the workforce. However,

there is often a lack of adequate training and development programs, leading to a shortage of skilled workers who can effectively operate and optimize the plant's operations.

Selection and implementation of specific TPM tools plays a very important role in the success of TPM programme. The current performance and the condition of the equipment must be determined before implementing TPM pillars [17] [18]. Based on these two factors the required number of specific TPM pillars may be designed and implemented to improve the equipment performance. TPM pillars are usually interconnected and hence it is necessary to analyze them thoroughly before implementation. Analysis of the responses shows that very few respondents (17.9%, i.e. 5 out of 28) are having no confusions in selecting a TPM pillar (figure 3). Hence it is necessary to arrange training sessions for TPM pillar selection.

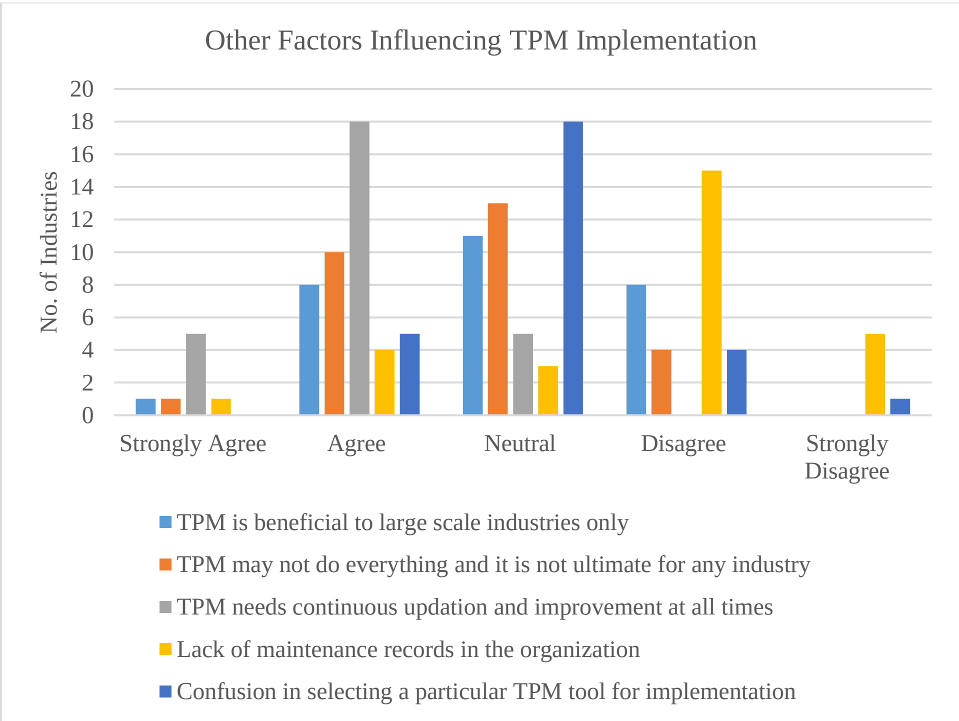

Figure no. 03. Other Factors affecting TPM implementation

Objective:

The objective of this study is to explore and evaluate the potential of innovative techniques in enhancing the productivity of construction process plants and propose practical recommendations for their successful implementation. By addressing the identified problems and leveraging innovative solutions, the construction industry can improve the efficiency, effectiveness, and overall performance of construction process plants, leading to enhanced productivity and successful project outcomes.

- The research will focus on identifying and exploring various innovative techniques that can be implemented in construction process plants.
- The research will investigate how the implementation of these innovative techniques can enhance the productivity of construction process plants.
- The research will delve into the challenges and opportunities associated with integrating innovative techniques into existing construction process plants.
- Based on the research findings, the study will provide recommendations and best practices for implementing innovative techniques to enhance productivity in construction process plants.

3. Innovative TPM Approaches

- **Predictive Maintenance (PdM)**: Using advanced sensors and IoT technology, predictive maintenance allows for real-time monitoring of equipment conditions (temperature, vibration, pressure, etc.) to predict potential failures before they happen. This can reduce unplanned downtime and maintenance costs [19].
- **Condition-Based Monitoring**: Leveraging data analytics to monitor the condition of critical equipment continuously. This allows maintenance to be scheduled based on the actual condition of the machinery, rather than fixed schedules, optimizing maintenance and improving productivity[20] [21].
- **Automation of TPM Processes**: The use of robotics and AI to automate aspects of the maintenance process, including routine checks, cleaning, and even some repair tasks. This can improve precision and speed while freeing up human labor for more strategic tasks.
- **Augmented Reality (AR) and Virtual Reality (VR) for Training**: Using AR/VR technologies to train maintenance personnel on how to operate and fix equipment efficiently. This can reduce human error and increase the speed at which workers can troubleshoot and repair machinery [24].
- **Advanced Data Analytics for Decision-Making**: The integration of big data and AI to provide insights into the performance of construction plants. By analyzing historical performance, maintenance records, and environmental factors, operators can make data-driven decisions to improve equipment lifespan and reduce breakdowns [23] [25].
- **Total Employee Involvement (TEI)**: An extension of TPM where employees at all levels are encouraged to take ownership of maintenance activities. Innovations could include gamifying maintenance practices to encourage employee participation and engagement, which can lead to a more proactive maintenance culture [26].
- **Lean TPM Integration**: Integrating TPM with lean manufacturing techniques to eliminate waste and improve efficiency. Lean tools such as value stream mapping and

root cause analysis can be applied alongside TPM to optimize processes and minimize downtime.

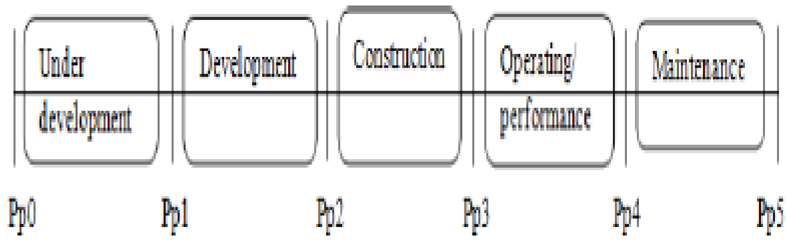

Figure no. 04. Total Productive Maintenance Policy to Increase Effectiveness and Maintenance Performance Using Overall Equipment Effectiveness

The prosperity of a nation's economy is closely intertwined with the achievements of its industries [30], especially within the construction sector, as shown in figure no. 04. This underscores the need for manufacturers operating in the construction industry to readily adopt advanced technologies in order to gain a competitive edge [29]. In the midst of intense global competition, the focus of the construction manufacturing sector is geared towards enhancing standards of quality, efficiency, and overall productivity [27][27][28].

4. Benefits of Innovative TPM Approaches in Construction Process Plants

- **Reduced Downtime**: With predictive and condition-based maintenance, unplanned downtime can be significantly reduced, leading to smoother operations and more consistent productivity.
- **Improved Equipment Lifespan**: Through regular and targeted maintenance, machinery and equipment will last longer, saving on costly replacements and repairs.
- **Cost Savings**: By minimizing the occurrence of breakdowns, repair costs are reduced, and productivity is increased.
- **Higher Employee Efficiency**: With better training and the automation of routine tasks, employees can focus on more critical operations, leading to better use of human resources.
- **Enhanced Quality Control**: By reducing machinery errors and breakdowns, the overall quality of the outputs from construction plants improves, which is crucial in construction where quality and timeliness are essential.

5. Case Studies and Real-World Applications

- **Example 1: Cement Plant**: Highlight how a cement plant used predictive maintenance techniques to monitor rotary kilns, reducing unexpected breakdowns and increasing production efficiency.

- **Example 2: Asphalt Plant**: Demonstrating the integration of IoT sensors and real-time data analysis to monitor asphalt mixing plants for defects, enabling the plant to proactively fix issues before they impact production.
- **Example 3: Concrete Batching Plant**: Discuss how a construction plant integrated AI-driven maintenance systems to predict failures in batching equipment, improving the accuracy and speed of concrete production.

6. Implementation Strategies

- **Training and Upskilling**: Implementing a strategy to upskill workers and maintenance teams on new technologies such as IoT, AI, and AR for effective use of innovative TPM approaches.
- **Technology Adoption Roadmap**: Outlining a clear roadmap for the gradual adoption of predictive maintenance, automation, and data analytics technologies in construction process plants.
- **Management Buy-in**: Exploring how to get buy-in from plant management and leadership to invest in new TPM technologies and the potential ROI for the plant's productivity.
- **Continuous Improvement**: Stressing the importance of fostering a continuous improvement culture in the plant where feedback loops are used to refine and adjust TPM strategies regularly.

In the survey, respondents were asked to indicate how the various factors like performance of machine, availability, breakdown, process changeover, maintenance cost, customer complaint, TPM cost, etc. affect the overall production rate of the company. The majority of respondents feel that machine performance, machine availability, quality defect and delivery are perceived to have the highest effect on the production rate (Figure 5). While breakdown, process changeover, maintenance cost, TPM cost, customer complaint and morale of the employee are reported to have less effect over production rate. Higher production rate indicates the company having better construction performance. The figure indicates that respondents feel that machine performance and availability still lead the highest impact on construction performance.

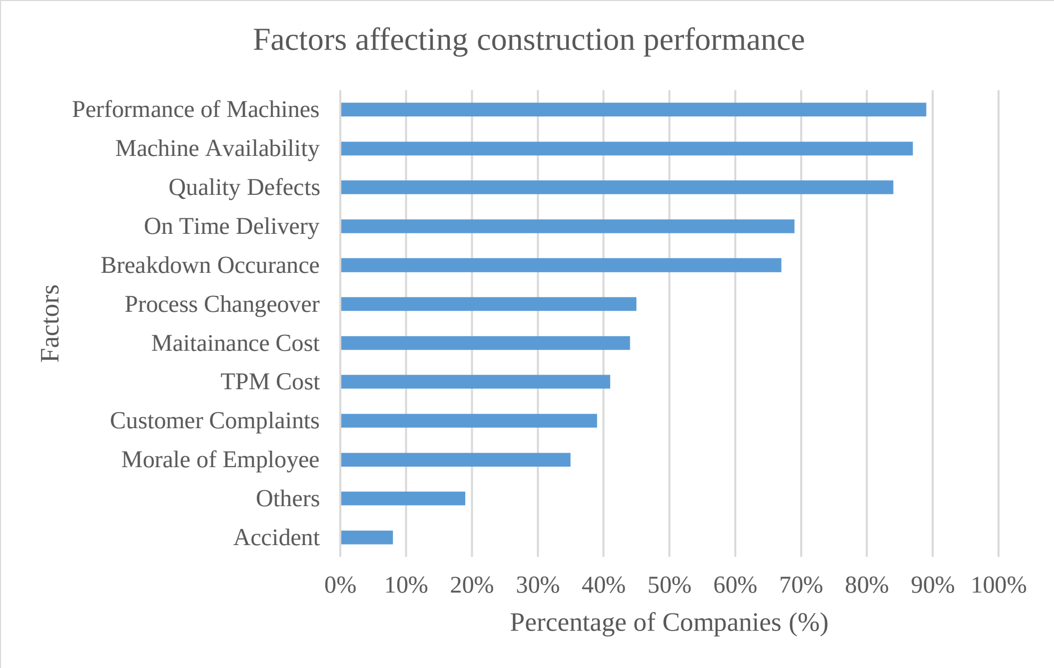

Figure No. 05. Factors affecting construction performance

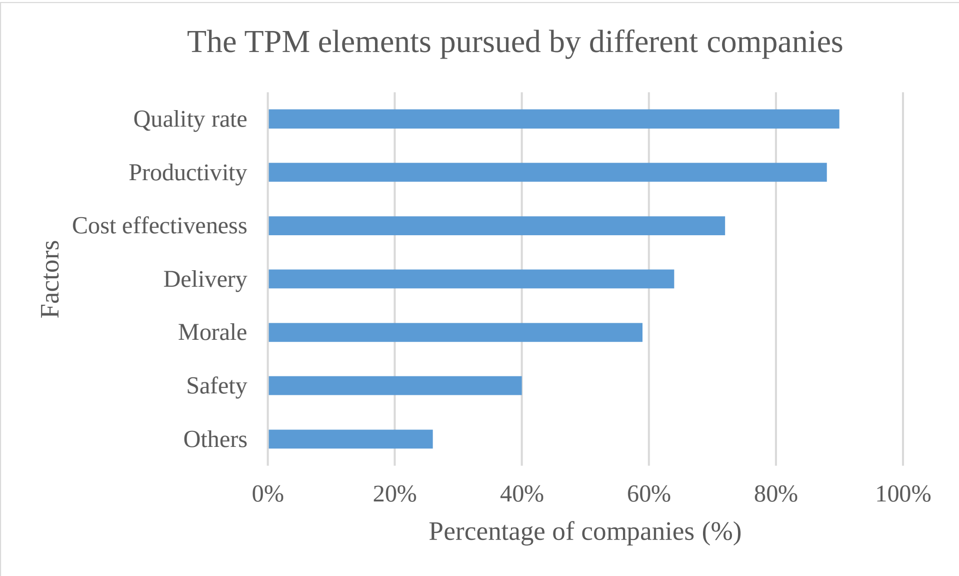

Figure No. 06. The TPM elements pursued by different companies

Our analysis is focused on the understanding of degree of association between TPM programme implementation and construction performance. The results of analyses allowed us to describe the correlation between variables, to understand how construction cost, quality and delivery time are related in a TPM environment. The success of TPM is measured through various indicators. As it is not feasible to include all such measures in the present paper, only representative salient measures and the most widely used metrics are considered and their influences on construction performance analysed in figure 6.

The OEE and overall plant effectiveness (OPE) values have been collected for six consecutive years from all selected companies and their mean values are presented in Figure 7 The trends are clear that the means of OEE and OPE are generally increasing year by year. Despite the ups and downs it is clear that the Indian companies are very close to world class. An overall 85 per cent benchmark OEE is considered as world class performance (Blanchard, 1997; McKone et al., 1999). Based on the responses from the respondents' companies, Figure 6 presents the managerial views on OEE which may work as an effective tool for resource utilization, monitoring and control, to identify bottlenecks, etc. in construction companies. Figure 7 shows that resource utilization is supported by OEE as a highly efficient tool (92 per cent of the total respondents use OEE for this purpose). Respondents are also using OEE as an efficient tool in the other functional areas related to construction performance such as "monitoring and controlling equipment effectiveness", "to identify bottlenecks", "to identify hidden capacity", "decision support", "overall performance improvement", "opportunity for improvement", "safety improvement" and other. It has also been observed that OEE is widely used beyond the maintenance function. However, respondents believe that the successful implementation and execution of TPM helps to identify the factors that hinder the value of OEE

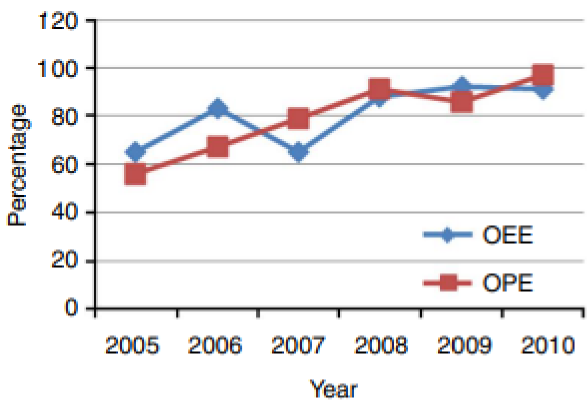

Figure no. 7. Trends of OEE and OPE during the years 2005-2010

Organization's management plays a vital role in the successful implementation of TPM. Management must be totally committed and strongly determined to accept TPM as a performance enhancement tool. They must have a thorough knowledge of TPM concepts, its implementation procedure, time required for implementation, level of training required at each implementation stage, financial and manpower requirements and possible benefits that could be achieved through TPM implementation. They should also be aware that return on investments from TPM is not immediate. It needs certain time period to get fully stabilized and start giving the returns for the money invested during its implementation. Management must motivate their employees to upgrade their skills, attitude, and knowledge and ensure their overall development for the effective implementation of TPM. Management should ensure the cooperation and coordination of their employees at different levels during TPM implementation. Management should spare their time and energy for the effective implementation of TPM in the organization to improve its overall performance. The question numbers 3 to 10 in the questionnaire were related to management factors in TPM and their responses are tabulated in Table 4 and plotted using bar charts in Fig. 8.

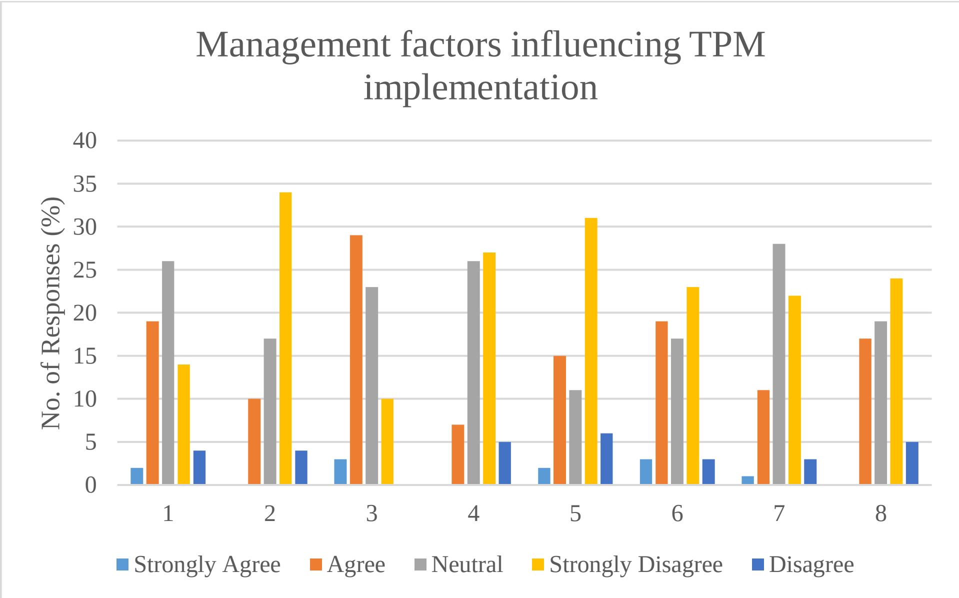

Figure no. 08. Management Related Factors in TPM

TPM can be implemented in any department of an organization. It includes complete involvement of every employee from the management to shop floor level. Management has a great role to play in the successful implementation of TPM programme. A query was added in the questionnaire to know the extent of management involvement in TPM implementation in the selected industry. It is found that there is no much appreciable support from the management in implementing TPM in construction industries. About 42.8% (12 out of 28) of the respondents remained neutral in responding this query and 25% (7 out of 28) respondents said that their management supports TPM implementation. A drastic change in employee skills and behaviour is essential in order to move from the existing maintenance system to TPM. An employee has to put a lot of efforts in achieving this change. Management has to recognize and reward its employee's hard work and efforts in implementing TPM. About 42.8% (12 out of 28) of the responses reveal that there are no recognition and reward systems in the industry for its employees. This shows that employees lack motivation from the management side. The employees are not ready to express their views (a greater number of neutral responses) against the management. These responses are tabulated in table 1 and shown graphically in figure 9.

TABLE 1. Responses related to TPM awareness and Management involvement in TPM

Query	Strongly Agree (5)	Agree (4)	Neutral (3)	Disagree (2)	Strongly Disagree (1)
We are aware of TPM concept	07	15	03	03	00
Lack of management support in TPM implementation	03	06	12	07	00
Lack of rewards and motivation for the management	02	10	08	07	01

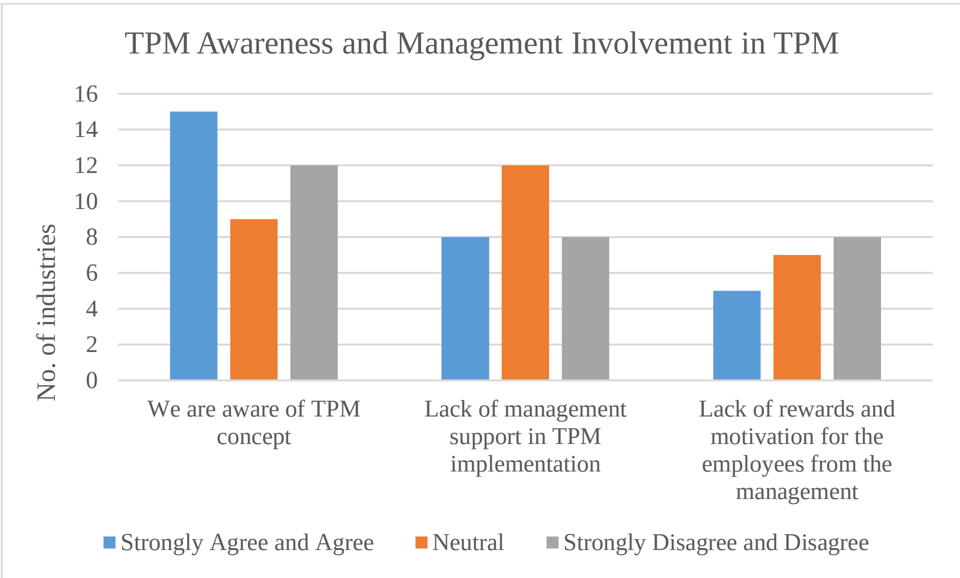

Figure No. 09. Responses related to TPM awareness and Management involvement in TPM

These initiatives resulted in significant reduction in the performance losses over a period of time as depicted by Figure 10. The trends in total equipment loss, manpower loss and material loss reveal a significant improvement in the system performance through drastic reduction in performance losses, and validated the extremely high potential of TPM initiatives toward addressing equipment related losses.

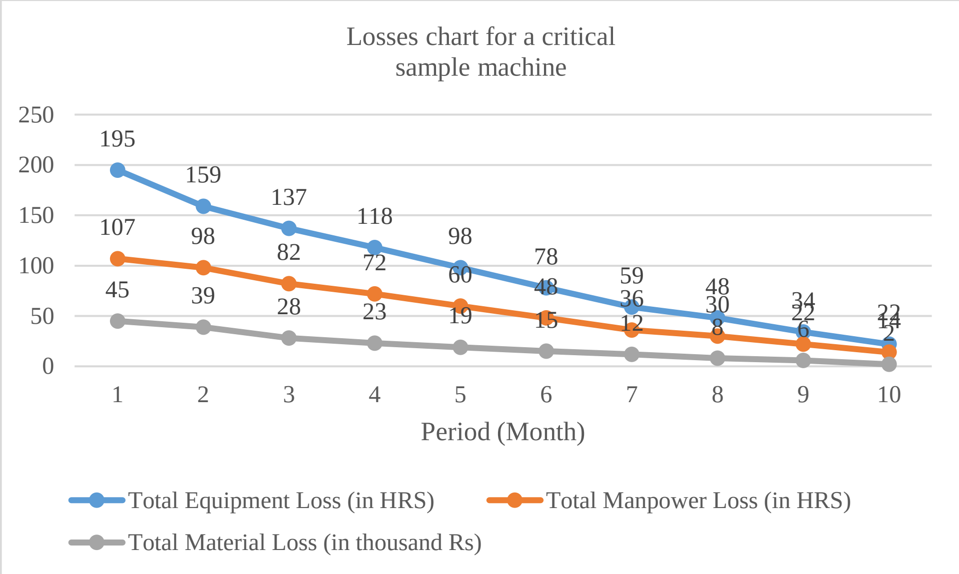

Figure 10. Losses chart for a critical sample machine

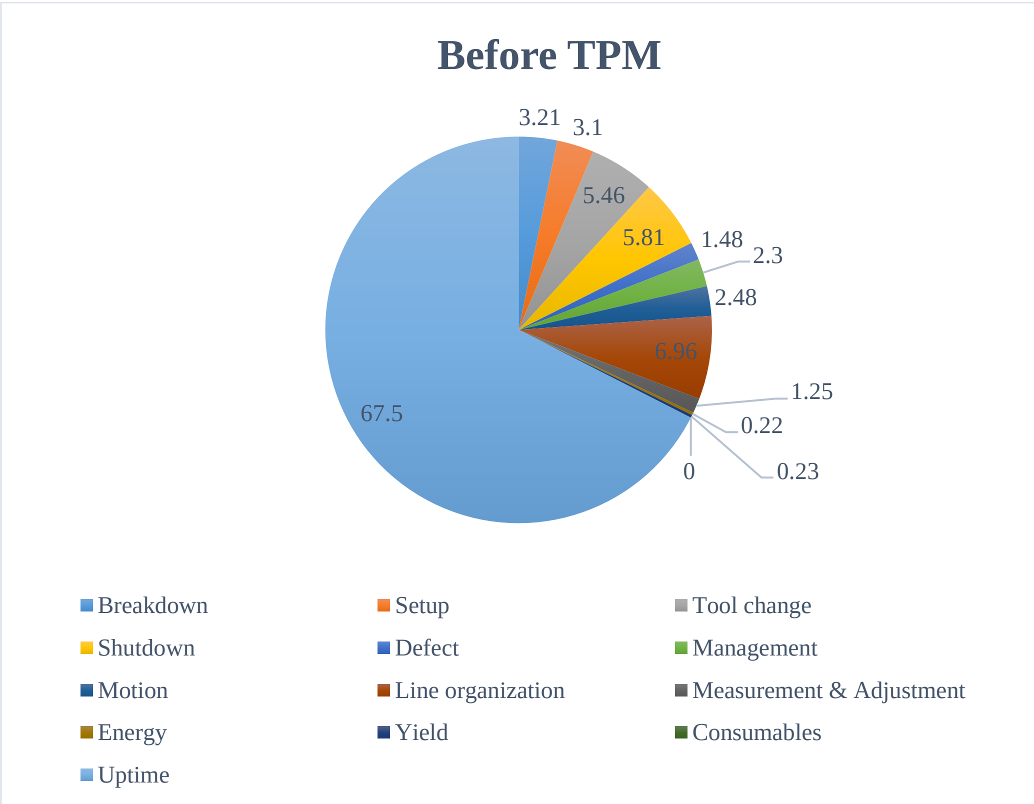

Figure no.11. Before TPM

This was followed by horizontal deployment of TPM implementation initiatives to all the production facilities at the plant (As shown in figure 11). The benefits accrued by the enterprise through strategic TPM implementation included productivity enhancement (P) by way of enhanced equipment, manpower and materials productivity; quality improvement (Q) through reduced process defects, defective products, customer complaints and improved conformance to specifications; cost reduction (C) through reduction in manpower, maintenance cost, power consumption, breakdown, rework and operating cost; improved delivery (D) through reduced inventories, dependable deliveries; improved safety (S) through zero accidents and zero pollution; improved morale through increased motivation, acceptance of improvement initiatives (kaizens), small group activities; improved morale (M) through ownership and better familiarity with the equipment, improved cooperation and coordination, free flow of information and competitive advantages in the form of value addition and customer delight.

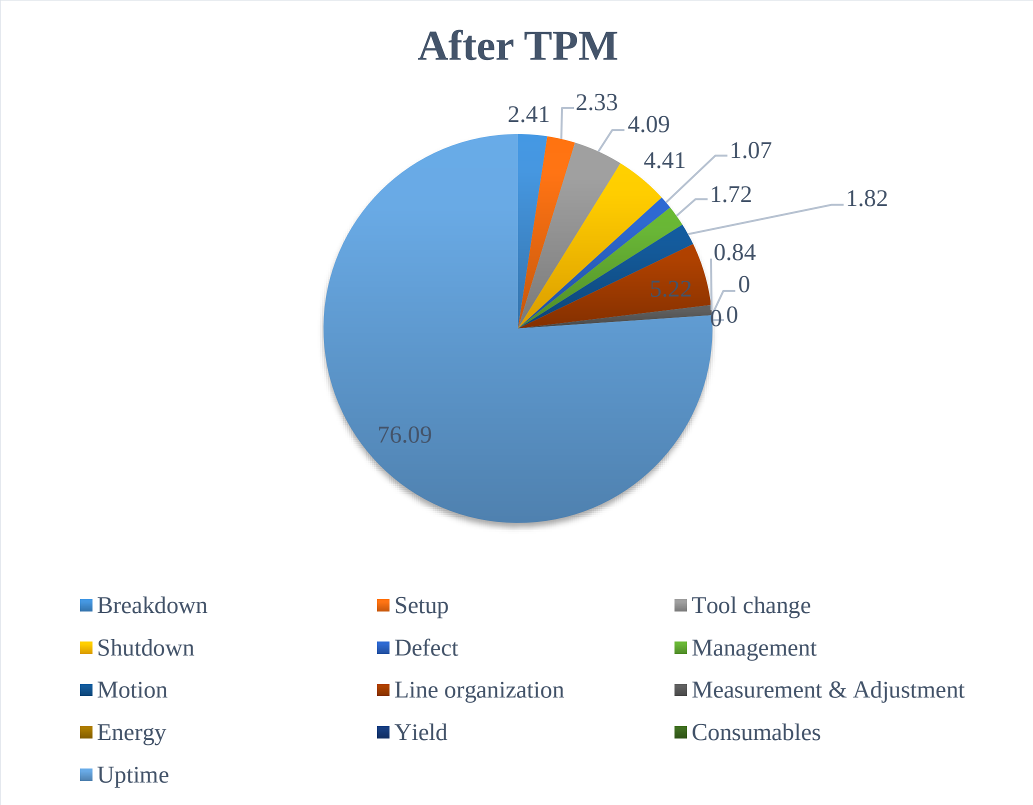

Figure no. 12. After TPM

The benefits realized through effective TPM implementation program included:

- OEE improvement: 14-45 percent;
- Inventory reduction: 45-58 percent;
- Improvement in plant output: 22-41 percent;
- Reduction in customer rejections: 50-75 percent;
- Reduction in accidents: 90-98 percent;
- Reduction in maintenance cost: 18-45 percent;
- Reduction in defects and rework: 65-80 percent;
- Reduction in breakdowns: 65-78 percent;

- Reduction in energy costs: 8-27 percent;
- Increase in employee suggestions: 32-65 percent; and
- Total savings resulting from effective implementation of kaizen themes as a result of significantly enhanced participation across the organization: Rs. 80 million.

Thus, TPM has proven to be a continuous improvement strategy that works. Successful implementation of TPM requires at least three to four years of continuous efforts to reach the world-class status. TPM can help an industrial organization in the move toward world-class construction (WCM) through achievement of distinctive benefits as gain of productivity, quality, safety, cost-cutting, flexibility and morale. Figure 12. Losses distribution for construction facility.

The need for TPM implementation must be addressed seriously in the Indian industries in order to survive and excel in the global competition.

Critical success factors in TPM implementation

The case study has revealed that the success of TPM in a typical Indian construction organization is largely dependent on the organization’s endeavor to holistically implement TPM initiatives. The successful implementation of TPM in the construction enterprise is a function of the ability of an enterprise to approach and practice TPM holistically; demonstrating top management commitment, support and involvement; developing a realistic TPM implementation plan by employing project management principles; ensuring alignment to mission and existing organization; providing empowerment and incentive, reward mechanisms in the organization; ensuring synergy between various business functions; eliminating the reactive maintenance culture; inculcating self-belief in the workforce; ensuring the motivation of workforce toward participative management and continuous improvement; promoting cross functionality and teamwork; instilling skills and knowledge related to autonomous maintenance and equipment improvement; developing and maintaining standard operating practices; allocating time and resources for efficient TPM implementation practices; establishing and adhering to laid out practices; putting in place relevant measures of performance, and continually monitoring and publicizing benefits achieved in financial terms. In order to ensure the successful implementation of TPM initiatives and practices in the challenging Indian construction scenario the organizations must be willing to foster a favorable and motivating environment and support change in the workplace, and create support for TPM concepts. Further, in order to ensure the alignment of employees toward the organization's goals and objectives toward a sustainable TPM implementation program, an appropriate understanding of underlying TPM principles and strategies must be provided to employees at all levels in the organization. Moreover, for successful TPM implementation, the organizations must harness competencies for improving the traditional maintenance performance in the organization, besides holistically adopting proactive TPM initiatives. It becomes imperative for the Indian organizations to evolve proactive strategies for indigenous TPM implementation program capable of leading the organizations successfully in the competitive environment. Thus there is an urgent need for establishing and holistically adopting key enablers and success factors in the organizations to ensure the success of TPM implementation program for garnering construction competencies for meeting the challenges posed by the global competition.

This paper highlight, what respondents say, are the long-term impact of TPM programmes on organizational performance within Indian construction companies. The TPM deployment has contributed towards improving construction performance such as productivity, quality and safety, on-time delivery, morale and besides ensuring the cost effectiveness of the construction function within the organization. The most widely used performance indicator and their measurement units used in TPM environment have been identified; the management expectation during TPM implementation have been gathered; the influence of TPM elements on construction performance has been analysed through correlation analysis; and finally, the effective use of OEE as a powerful TPM metric have been explored and the degree of satisfaction of the management in respect of construction performance with increasing value of OEE has been shown.

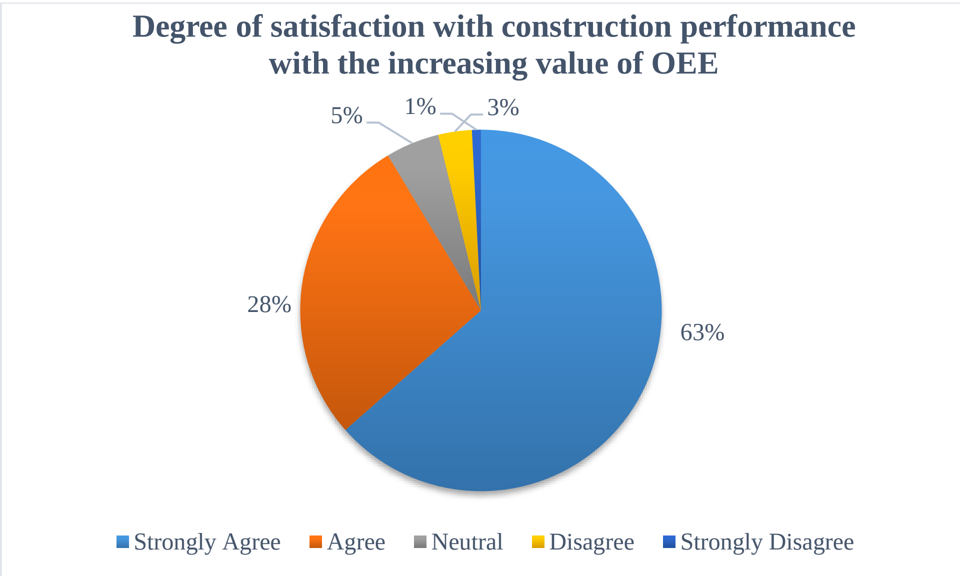

Figure no. 13. Degree of satisfaction with construction performance, with the increasing value of OEE

The main research finding can be summarized as follows:

(1) It has been observed that TPM elements described by Johansson and Nord (1996) are widely accepted within Indian construction companies;

(2) The factors having greater impact on the performance of production have been summarized and the machine availability and performance of machine have been identified as the most critical factors;

(3) To counter production disruption, management prefers performance improvement of the existing resources;

(4) Analyses reveal that safety and morale of employee are the key areas on which more attention is still required;

(5) Correlation analysis shows that TPM elements are related to the construction performance with strong – positive correlation coefficient; and

It is observed that the OEE metric and its parameters are the most relevant equipment performance indicators, capable of measuring and monitoring the resource utilization and production losses (As shown in figure no.13).

7. Future Trends and Research Directions

- **Integration of AI and Machine Learning in TPM**: Looking ahead, the role of AI and machine learning in creating self-learning maintenance systems that automatically adjust maintenance schedules and strategies based on machine performance data could be transformative.
- **Collaborative Robots (Cobots) in Maintenance**: Discussing the potential future role of cobots in assisting human workers with maintenance tasks, improving efficiency and safety.

8. Conclusion

Summarizing the importance of adopting innovative TPM techniques to drive productivity in construction process plants. Emphasizing the potential for reduced downtime, improved cost-efficiency, and longer-lasting machinery. Reinforcing the idea that innovation in TPM is crucial for staying competitive in the construction industry.

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